Outcomes of continuous monitoring of crucial infrastructure in the framework of "PROION" project.

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ABSTRACT

"PROION" is a research project, focused on the development of a platform for the continuous monitoring of high priority infrastructure (public infrastructure, dams, bridges, etc.) in the broader area of the Hellenic Supersite, named Enceladus. The project started on September 2020 and it was financially supported by the European Union and the Hellenic government. Three areas with different characteristic were selected as test sites. The infrastructures consist of: a) The concrete building of the department of Geology in the Patras University campus, b) a large earthfill dam near to the city of Patras, c) many small houses located in a small village named Krini which is established on an active landslide. In the three test sites, the installation of the following equipment was performed: a) three-axis accelerometers, b) aluminum corner reflector, c) low cost Global Navigation Satellite System sensor. A 3D base map (3D point cloud) derived from Terrestrial Laser Scanner and Unmanned Aerial Vehicle was also developed for each test area. The GNSS measurements, the accelerometer measurements and the ground deformation measurements derived by the interferometric processing of Sentinel-1 data were analyzed using soft computing algorithms in order to identify any possible displacement. Then another algorithm checked the fused result with the base map (3D point cloud). If the displacement overpasses a certain threshold an alert is generating through an innovative decision-making and support tool. The whole system is integrated in a modern Webgis platform. The results of the project are presented in the current study.

Keywords: infrastructure, monitoring, remote sensing, soft computing, web GIS

1. INTRODUCTION

The need for the development of reliable cost-effective systems for monitoring engineering infrastructure is increasing, especially considering the effects of ageing and the impact of natural hazards [1]. The use of remote sensing sensors (GNSS, SAR, LiDAR and UAV) for infrastructure monitoring has been increased during the last years, according to the plethora of respective publications [1].

"PROION" is a research project [2], focused on the development of a platform for the continuous monitoring of high priority infrastructure (public infrastructure, dams, bridges, etc.) in the broader area of the Hellenic Supersite, named Enceladus. The specific area concentrates more than 50% of the Greek population, great global heritage monuments like Acropolis, Mycenae and Delphi where millions of tourists gather every year and crucial infrastructure like the Rio-Antirio bridge. At the same time in the broader area of Enceladus Supersite, the highest seismicity and the highest ground acceleration in Europe are recorded.

"PROION" project started on September 2020 and it was financially supported by the European Union and the Hellenic government. Three infrastructures with totally different characteristics, located in the Prefecture of Western Greece were selected as test sites (Figure 1). The infrastructures consist of: a) The concrete building of the department of Geology in the Patras University campus, b) a large earthfill dam near to the city of Patras, c) many small houses located in a small village named Krini which is established on an active landslide. In the three test sites, the installation of the following equipment was performed: a) three-axis accelerometers, b) aluminum corner reflector, c) low cost Global Navigation Satellite System sensor. Continuous measurements of the accelerometers, and GNSS sensors are collected in a central server installed in the University of Patras. Meanwhile, Sentinel-1 SAR data are collected and processed. A 3D base map (3D point cloud) derived from Terrestrial Laser Scanner and Unmanned Aerial Vehicle was also developed for each test area. The GNSS measurements, the accelerometer measurements and the ground deformation measurements derived by the interferometric processing of Sentinel-1 data were analyzed using soft computing algorithms in order to identify any possible displacement. Then another algorithm checked the fused result with the base map (3D point cloud). If the displacement overpasses a certain threshold an alert is generating through an innovative decision-making and support tool. The whole system is integrated in a modern Webgis platform. The results of the project are presented in the current study.

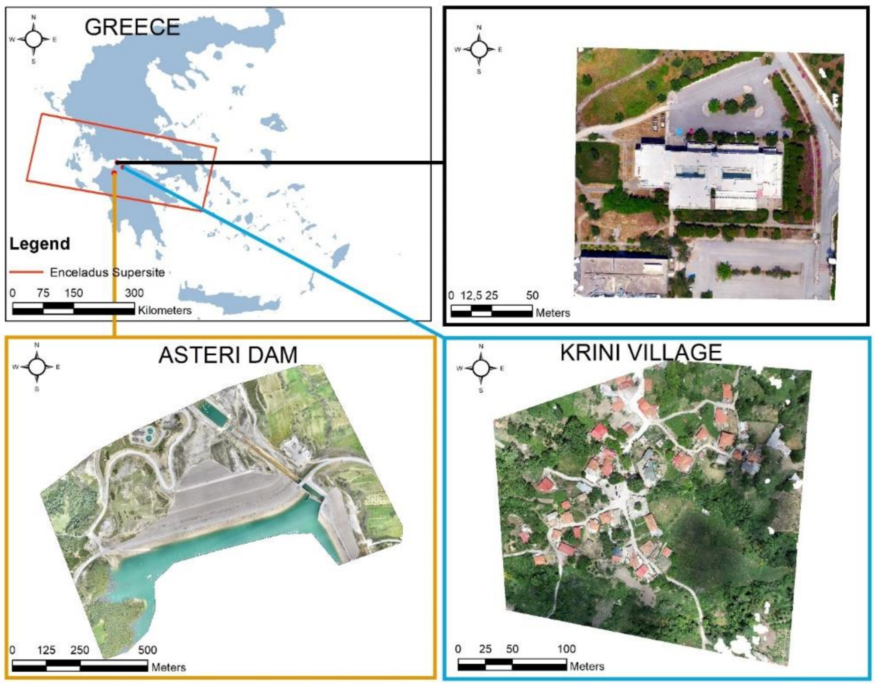

Figure 1. Location of the three study areas within the Enceladus Supersite area, in Western Greece.

2. "PROION" PROJECT MEASUREMENTS

2.1 GNSS measurements

With the aim of increasing the monitoring of the "PROION" service provision, we installed three "low-cost" GNSS stations in the study area of the supersite (Fig. 2). All three stations were installed in 2022 in pre-selected sites that were found suitable to host permanent GNSS instrumentation. Station KRHN was installed on the roof of a single-storey building in village Krini, about 12 km to the SW of the city of Aigion. Village Krini is located on the eastern slopes of Mt. Panachaikon at an average elevation of 750 m. A large part of this mountainous region of Achaia suffers from slope instability that is manifested in various degrees of ground displacement (detectable using space geodesy) affecting greatly its morphological features and inhabited areas, so this station is a key monitoring instrument [3,4]. Station ASTR was installed on the southern aspect of the Asteri dam (Fig. 3), a crucial infrastructure for regional water supply, about 20 km south of the city of Patras. Station GEDP was installed on the roof of the Department of Geology, University of Patras. All stations transmit multi-GNSS observations (1-s interval) to the acquisition server at NOA, Athens via internet (ssh protocol) using the 4G mobile network of a Greek provider. The data are archived at NOA, pre-processed and go through quality checks using the G-Nut/Anubis software [5]. The main hardware of this low-cost configuration includes a receiver module by Ardusimple (simplertk2b) that uses the multi-GNSS chip ublox ZED-F9P, mounted on a raspberry kit (Raspberry Pi compute module 4). The antenna AS-ANT2B is a calibrated survey GNSS Multiband antenna (IP67). The total cost of the station (including the box) amounts to 1300 euros (plus VAT where applicable).

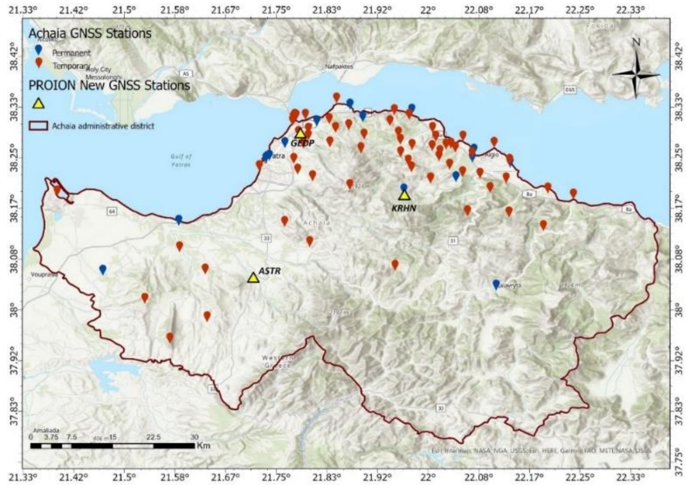

Figure 2. Map of Achaia prefecture Greece showing GNSS sites. The “PROION” stations are shown as yellow triangles.

Figure 3. Field photograph of GNSS station ASTR (Asteri) during observation. The view is towards the east.

To monitor the ground displacement, we use the GPS constellation signals that comprise code and phase observations at L1 & L2 frequencies. We processed the GEDP data using the open-source software PRIDE PPP-AR [6]. Our preliminary results (Figure 4) are in agreement with the kinematic behavior of the nearby GNSS station PAT0 [3] that shows linear motion towards south and east (in the ITRF 2014 reference frame). We provide to the users the “PROION” GNSS data through the NOA repository http://194.177.194.200/GPS/0-proion-lowcost/ The data are available as rinex v3.x files in 30-s observation intervals.

2.2 Accelerometers

One of the main sensors in the “PROION” platform is the MEMS accelerometer. It can record ground acceleration in continuous mode, in three components, and its main use is to provide the trigger to the “PROION” platform, for the initiation of the ground/building deformation estimation. Microelectromechanical systems (MEMS) are microscopic devices that contain both electronic and moving parts, to simulate a mechanical device or larger scale. In general MEMS devices generally range in size from 20 micrometers to a millimeter (https://en.wikipedia.org/wiki/MEMS). Although the initial designs of MEMS accelerometers didn’t have the necessary dynamic range for seismological purposes, modern sensors are able to accurately record the seismic event’s induced strong motion. The “PROION” platform MEMS sensor was selected among the available sensors in the market, having in mind two prerequisites, low cost, and sufficient dynamic range. The selected product was compared on a seismic table, with observatory grade acceleration sensors (Fig. 5). Thirtythree real acceleration recordings were used, the magnitude range was between 5.4 to 7.6, the epicentral distance range was between 2 to 160km, while the peak ground acceleration (PGA) varied between 0.1 to 1.4g. By comparing the recorded time histories and relevant spectra (Fig. 5) it was proved that the selected MEMS sensor was capable of recording accurately the strong motion above levels that may produce structural damage (~0.1g) to the infrastructures. The acceleration sensor, in its metal housing, is shown in Fig. 3. As described in details in [7] “PROION” system consists of two different modes one Real Time in case an event occurs and one Near Real Time, approximately every 12 days, when the data from the satellite are updated. The accelerometer is providing digital signal to the central processing unit of “PROION” platform, that are monitored in real time. In case of exceedance of a user defined acceleration threshold, the central processing unit triggers the procedure for evaluating the ground deformation study. Based on the data analysis a decision will be taken on whether the detected differences on the data pose a potential threat on the structural health of the building or not.

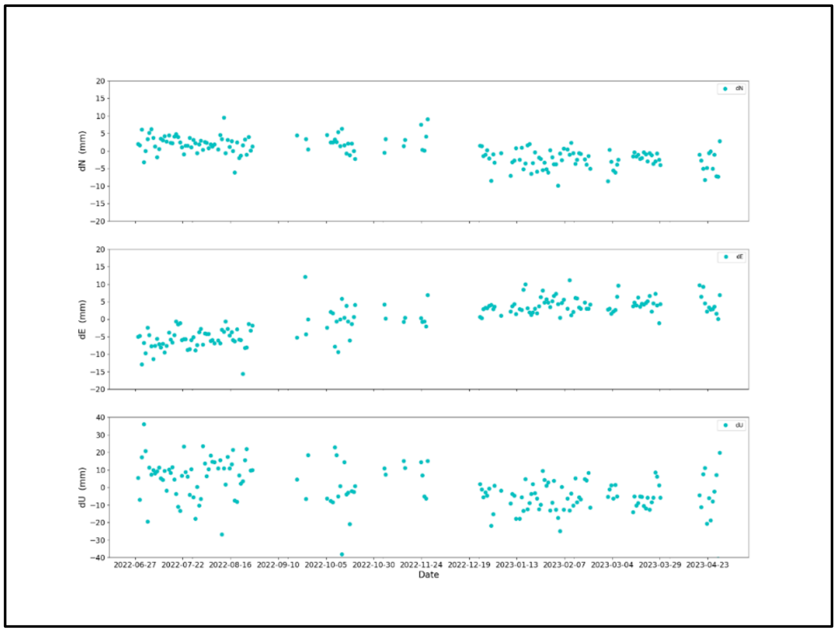

Figure 4. Position time series (North, East, Up) of GNSS station GEDP. The horizontal axes display weak trends of linear motion towards South and East, in agreement with station PAT0 which is located nearby [3]. Y-axis is in mm.

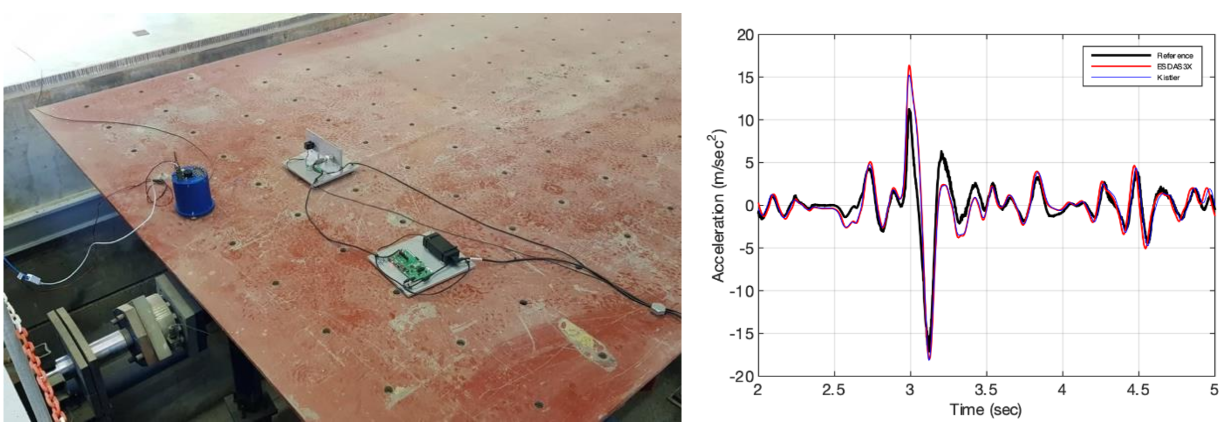

Figure 5 a) Sensor setup on the seismic table, b) comparison of the MEMS sensor used in “PROION”, i.e., ESDAS3X, red line, against two other sensors of MEMS type, blue line and of piezoelectric type, black line.

2.3 InSAR measurements

In light of SAR interferometry, an innovative type of corner reflector was designed by the GIS and Remote Sensing Laboratory team and manufactured by the University of Patras. These newly-developed corner reflectors are described in details along with their installation in the specified observation sites in a previous study [8]. Three corner reflectors were installed on the observation sites of the project, i.e. a) Asteri dam, b) Department of Geology, University of Patras and c) Krini village (Fig. 6).

Figure 6. Installation of the corner reflectors at the three study areas. a) University of Patras, b)Krini village, c) Asteri Dam.

For the InSAR measurements processing a fully automated methodology was selected. The specific interferometric process is based on “Small Baseline Subset” technique and on LiCSBAS software. In more details, LiCSBAS is an open source software operating on the web platform «COMET-LiCS Sentinel-1 InSAR» (https://comet.nerc.ac.uk/comet-lics-portal/). The project "Looking Inside the Continents from Space) is implemented by the “Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics” (https://comet.nerc.ac.uk/). A fully automated processing system called "LICSAR" is developed, able to process Sentinel-1 worldwide, creating freely accessible interferometric products [9,10]. Using the specific online platform there is no need of producing interferograms from SLC data, thus avoiding high data processing time and disk space consumption [11]. Furthermore, LiCSBAS automatically identifies and removes interferograms with many unwrapping errors by the loop closure test and estimates reliable time series and velocities with the help of masking based upon several noise indices [11]. The whole processing is based on batch scripts with adjustable processing parameters in order to obtain better results.

In Figure 7 the ground deformation for the broader study area of Achaia Prefecture is presented. The processing was performed using LiCSBAS platforma and Sentinel-1 data for the period Sept 2020-June 2023. In figure 8, 9 and 10 the ground deformations in the three study areas are presented. As it can be observed in Figures 8 and 9 the areas of the Dam and the Geology Department present a small stable deformation between 1 and 2.5mm/y while in Krini area the deformation is quite higher as the whole village is located inside the body of an active landslide.

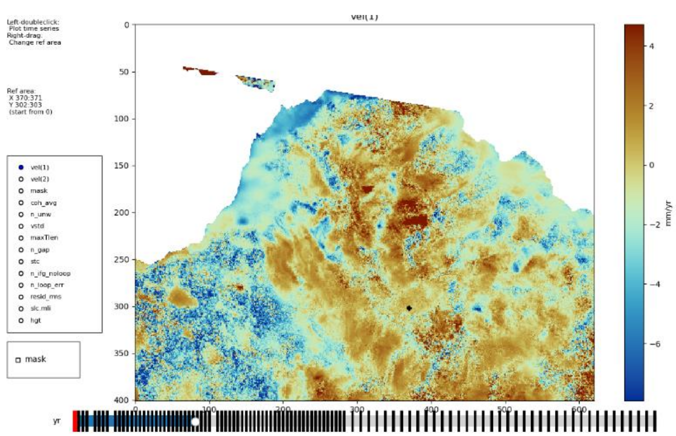

Figure 7. Ground deformation map for the broader area of Achaia Prefecture as produced from Sentinel-1 data processing on LiCSBAS platform.

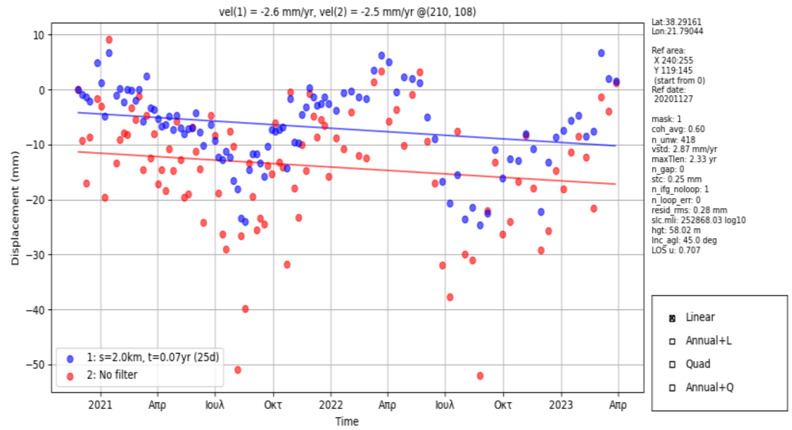

Figure 8. Ground deformation timeserie for the Geology Department test site as produced from Sentinel-1 data processing on LiCSBAS platform.

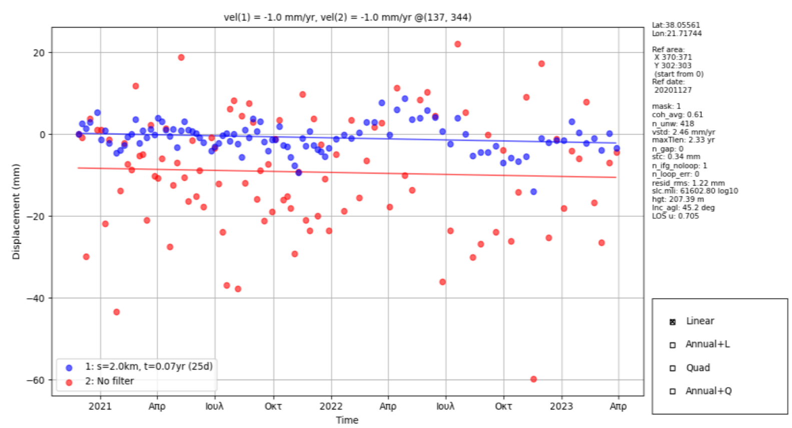

Figure 9. Ground deformation timeserie for the Asteri Dam test site as produced from Sentinel-1 data processing on LiCSBAS platform.

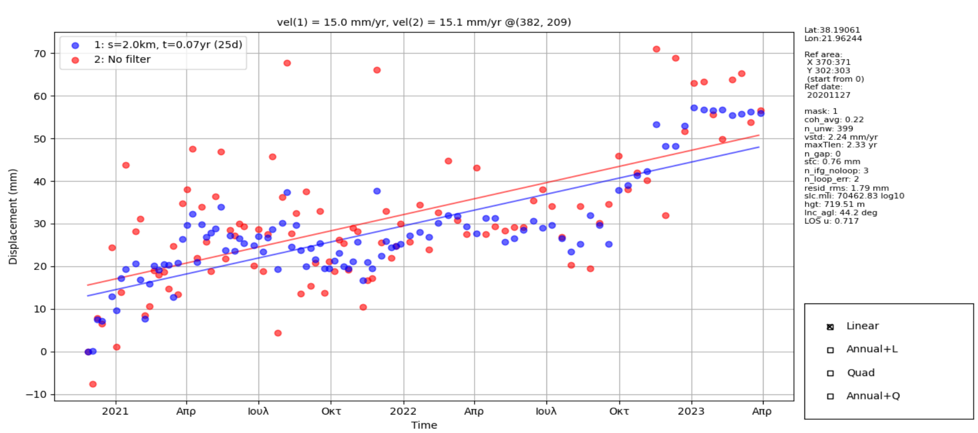

Figure 10. Ground deformation timeserie for the Krini village test site as produced from Sentinel-1 data processing on LiCSBAS platform.

2.4 UAV and TLS surveys

As described in a previous study [12] 3D representations of the observation sites derived from UAV and TLS sensors are an essential part of the monitoring procedure as the accurate 3D point clouds are used for the validation of any identified deformation. With regard to this, the spatial reconstruction of the observed sites should be performed at the best possible spatial resolution. Therefore, each observation site was surveyed twice per year on a regular basis. Each survey is consisted of a UAV flight for the collection of points on the top view as well as a terrestrial laser scanning for the acquisition of facades. UAV flights were carried out using a Trinity F90 fixed-wing Vtol, while scanning was executed with a Leica ScanStation P50. Both instruments were acquired within the "PROION" project. It is worth mentioning that square black and white targets (4.5") were distributed over the test sites during the UAV and TLS surveys in order to minimize the georeferencing errors. These targets were measured using a Leica GS08 GNSS receiver. Figures 11 and 12 present 3D representations of the Department of Geology from the TLS and the UAV respectively.

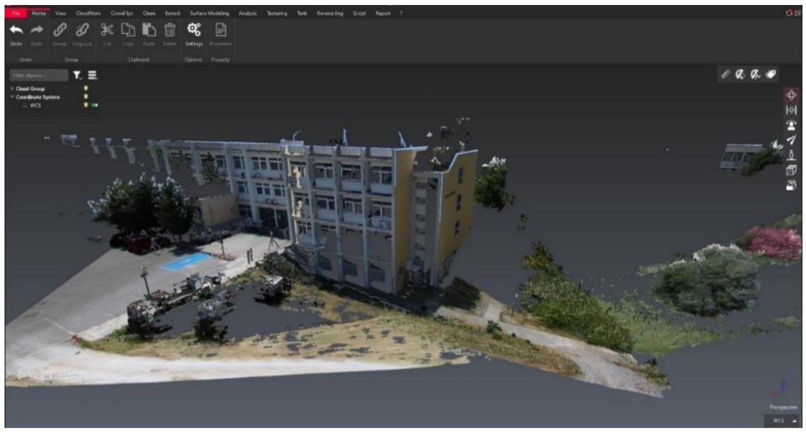

Figure 11. 3D point cloud derived from the P50 terrestrial Laser Scanner.

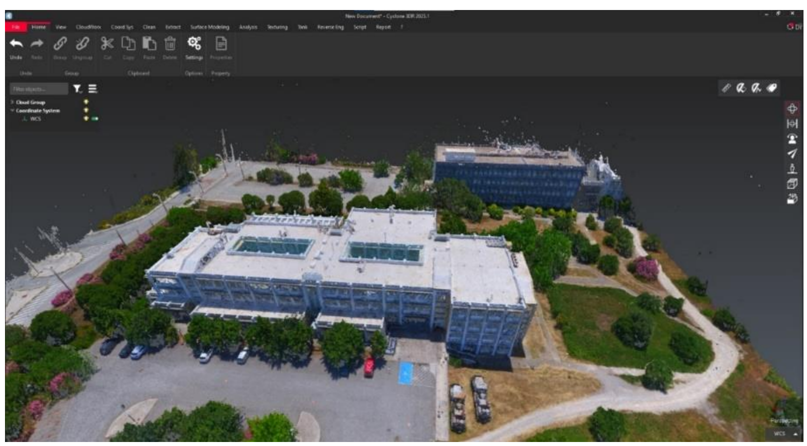

Figure 12. 3D point cloud derived from the Trinity F90 fixed-wing Vtol.

3. SOFT COMPUTIONG OUTCOMES FROM "PROION" PROJECT

The soft computing methods applied in "PROION" project are described in details in a previous published study[8]. The ability of the Long Short Term Memory (LSTM) networks to adjust to timeseries data and retain information for long as well as short term relationships between them, led us to choose them for analyzing the GNSS and InSAR data and thus creating algorithms that will help predict future measurements. The advantages of DNNs in discovering patterns in large sets of data, made them suitable for extrapolating information from the UAV and TLS data. Finally, by facilitating the combination of expert knowledge with typical forms of data, Fuzzy Cognitive Maps (FCMs) gave the opportunity to create a tool that can assess the health infrastructure of a building and decide whether further investigation is needed.

LSTM algorithm goal was to create an algorithm that would be able to predict the next position of the data, for both the GNSS and InSAR measurements. Regarding the GNSS data received, the study was performed in every dimension separately, as well as on the vector combining them. To evaluate the performance of the algorithm the available dataset was separated in 20 point subsets and in every iteration the initial subset is increased by the subsequent ones, until the whole dataset is used. When using the LSTM method, a parameter regarding how many previous points will be taken into consideration in order to make the prediction must be chosen. For the GNSS data 12 previous points were used. For the InSAR data this parameter differs for each location. In the following paragraphs a characteristic example for Krini area is presented.

3.1 Observation position 1: Krini

Table 1: GNSS data prediction for Krini

Dataset Length		East	North	Up	Vector
21	Train sore (m)	0.0146	0.0046	0.0535	0.0045
	Test score (m)	0.0815	0.0051	0.0411	0.0061
	Original point	584055.5	4227265	788.2327	4267423
	Prediction	584055.6	4227265	788.2737	4267423
	Deviation	0.081479	-0.00507	0.041074	0.006131
42	Train score (m)	0.0254	0.0061	0.0581	0.0068
	Test score (m)	0.0059	0.0006	0.0036	0.0004
	Original point	584055.6	4227265	788.2109	4267423
	Prediction	584055.6	4227265	788.2145	4267423
	Deviation	-0.00589	-0.00058	0.00365	0.000438
63	Train score (m)	0.0283	0.0102	0.0505	0.0080
	Test score (m)	0.0289	0.0082	0.0437	0.0043
	Original point	584055.7	4227265	788.1818	4267423
	Prediction	584055.6	4227265	788.2255	4267423
	Deviation	-0.02885	0.00823	0.04365	0.004322
84	Train score (m)	0.0133	0.0042	0.0297	0.0045
	Test score (m)	0.0129	0.0008	0.0169	0.0024
	Original point	584055.7	4227265	788.1733	4267423
	Prediction	584055.7	4227265	788.1902	4267423
	Deviation	0.012892	0.000834	0.016887	0.002366
105	Train score (m)	0.0109	0.0040	0.0275	0.0042
	Test score (m)	0.0180	0.0130	0.0271	0.0112
	Original point	584055.7	4227265	788.1991	4267423
	Prediction	584055.7	4227265	788.1719	4267423
	Deviation	-0.01797	0.013027	-0.02713	0.011219

By observing the results on Table 1 we can derive that the algorithm is effective even on small datasets. The predicted values do not deviate significantly from the actual ones. The small error of the algorithm applies both on small as well as on large datasets thus proving the ability of the algorithm to detect the trend of the movement of each point as well as to adjust to trend changes.

Table 2: InSar data prediction for Krini

Dataset Length		1 point back	3 points back	6 points back	12 points back
20	Train score (mm)	4.0964	3.6025	3.0536	2.6829
	Test score (mm)	8.0222	9.5799	10.0475	6.8226
	Original point	29.65999987	29.65999987	29.65999987	29.65999987
	Prediction	21.637846	20.08009	19.6125	22.837353
	Deviation	-8.02215387	-9.57990987	-10.0474998	-6.82264687
40	Train score (mm)	4.0827	3.4231	3.2216	3.8915
	Test score (mm)	9.4149	11.1382	10.8861	12.7295
	Original point	37.3000001	37.3000001	37.3000001	37.3000001
	Prediction	27.885078	26.161818	26.413868	24.570528

	Deviation	-9.4149221	-11.1381821	-10.8861321	-12.7294721
60	Train score (mm)	4.1012	3.5896	3.5961	3.5973
	Test score (mm)	8.5702	3.7215	2.1541	3.2269
	Original point	22.51999999	22.51999999	22.51999999	22.51999999
	Prediction	31.090199	26.24148	24.674088	25.74686
	Deviation	8.57019901	3.72148001	2.15408801	3.22686001
80	Train score (mm)	3.723	3.4028	3.1239	3.1295
	Test score (mm)	2.0122	2.8026	1.1616	1.0844
	Original point	29.69000123	29.69000123	29.69000123	29.69000123
	Prediction	27.677828	26.887379	28.528393	28.60557
	Deviation	-2.01217323	-2.80262223	-1.16160823	-1.08443123
102	Train score (mm)	8.1533	7.9283	7.8005	3.5894
	Test score (mm)	28.0287	27.6109	26.8022	3.036
	Original point	55.88000096	55.88000096	55.88000096	55.88000096
	Prediction	27.851324	28.269081	29.077751	58.916023
	Deviation	-28.0286769	-27.6109199	-26.8022499	3.03602204

The intense deviations of the InSar data make the prediction procedure much more challenging. While the methodology is the same as that of the GNSS data, in the case of the InSar, as mentioned, choosing the suitable parameter was more challenging. On Table 2 the results for different parameters are presented. For the Krini site the best prediction, for both in small and larger datasets, is achieved by using 12 previous measurements. The choice of the 12 points back parameter is also supported by the fact while making the final prediction all the parameters except for last one yield a very large error, bigger than 25mm while when using the 12 points back parameter the error in only 3mm.

3.2 UAV/TLS Data for the 3 locations

Due to the large volume of the data a DNN was developed to create a benchmark profile for each site. This profile will subsequently be compared to the new profiles created by the same DNN and in case of significant differences it will show possible movements to the examined location.
The designed DNN consists of 8 layers, during the training process batches of 100 points and 20 epocs where used. The dataset was divided 70% - 30% for training and testing.
The benchmark created for each location is based on the accuracy of the algorithm. The benchmarks for each location are the following.

- Krini: 83%
- Departement fo Geology: 100%
- Asteri: 100%

The acceptable deviation from the benchmark is set between 3-4%.

3.3 Fuzzy Cognitive Map for assessing infrastructure health.

The abundance of data that we process in the context of the "PROION" project inevitably raises the question of how all these data can be combined with each other and, if this is possible, how they can contribute to the assessment of the state of an infrastructure. Fuzzy Cognitive Networks are a method that can contribute to answering the above questions.

In this context, a tool was developed which will take into account the results of the individual algorithms, InSar and GNSS prediction and the accelerometer measurement and will suggest if any infrastructure needs further investigation to assess its suitability. It was deemed necessary to use the accelerometer measurement as a variable in order to avoid cases where individual instrument measurement values deviate significantly without an event having occurred. As the data is not immediately available every time, the Fuzzy Cognitive Maps algorithm has the ability to run either using the difference of the previous value from the prediction of the LSTMs algorithms, in order to have an early indication, or using the difference of the previous value from the next actual measurement in order to give a more accurate assessment of the condition of each location.

<u>Concepts of the FCM</u>

- C1: Deviation of predicted/actual value of the GNSS data from the previous value

- C2: Deviation of predicted/actual InSar value from the previous value
- C3: Deviation of TLS accuracy/actual value from benchmark
- C4: Accelerometer value
- C5: Decision on infrastructure health

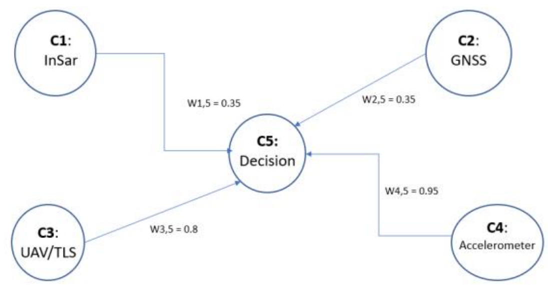

Figure 13. Fuzzy Cognitive Map of the “PROION” project (concepts and weights)

Since the values of the initial concepts don’t belong to the [0,1] interval the data are normalized using a sigmoid function. For normalizing the data different slopes for the sigmoid function are used, depending on the variable.

- GNSS: [-50,50] λ= 0,09
- InSar: [-20, 20] λ= 0.3
- TLS: [0,1] λ = 1.5
- Accelerometer: [0,1] λ = 1.5

To test the method the data for the Department of Geology on the 29/03/2023 where used, a date common for both the GNSS and InSar data.

Input data:

- Value of the previous point GNSS: 4276529.397
- GNSS prediction: 4276529.458
- GNSS actual value: 4276529.397
- Value of the previous point InSar: 0.56518185
- InSar prediction: 1.419912
- InSar actual value: -3.36

Since no event happened for the duration of the project the value of the accelerometer was 0. However, in order to prove the ability of the FCM to assess the health of the infrastructure in the following scenarios apart from the actual accelerometer value it is assumed that an event has taken place and the value shifts from 0 to 1. The method is applied to both real and predicted data.

Scenarios with predicted data

Scenario 1:

Deviation from benchmark TLS = 0

Accelerometer value = 0

Output 0.0106

Scenario 2:
Deviation from benchmark TLS = 0
Accelerometer value = 1
Output = 0.43

Scenarios with actual data
Scenario 3:
Deviation from benchmark TLS = 0
Accelerometer value = 0
Output 0.038

Scenario 4:
Deviation from benchmark TLS = 0
Accelerometer value = 1
Output = 0.45

The output of the algorithm is expected to yield values between the interval [0-1]. With 0 indicating that the building is safe for use and 1 indicating that the building needs immediate inspection.

In the above two cases the results are interpreted as follows:

Scenario 1-3: Since the differences between the new GNSS and InSar points are small, the TLS data does not indicate a deviation from the benchmark and no event has occurred in the area, the building is considered safe and no further investigation is required.

Scenario 2-4: Since the differences between the new points in GNSS and InSar are small, the TLS data does not indicate a deviation from the benchmark but an event occurred in the area then it is suggested to repeat the algorithm in 12 days and if the value exceeds 0.5 then the building should be examined by a group of experts in order to determine whether it is safe or not.

In the case of scenarios 2 and 4, this proposal is made since by using both the actual and forecast data the results are similar and around 0.45, which are very close to 0.5, a value which when exceeded indicates the necessity of site inspection.

By comparing the scenarios we notice that the result of each Scenario for both the prediction and the real data are very similar, which proves the robustness of the Fuzzy Cognitive Map.

4. WEB-GIS PLATFORM

The "PROION" project developed a novel multiparametric framework for the holistic monitoring of critical infrastructures, combining a wide dataset of different spatiotemporal observations and measurements. The "PROION" Web GIS platform is a modern web-based solution for encompassing, accessing, analyzing, and visualizing the data outcomes of the project, providing useful advanced spatial tools tailored to the needs of precise and multiparametric spatiotemporal analysis. Ground deformation measurements from InSAR data and GNSS measurements are controlled with soft computing algorithms and validated with high-resolution 3D point clouds derived from TLS and UAV. Several other data sets such as earthquakes and micro-accelerometer events, meteorological information and the geological map of the monitoring area, are available for presentation and processing. The end user has the possibility to pose spatial queries, to analyze the data and create diverse kinds of reports or maps. A characteristic example of the WebGIS platform is presented in the following Figure 14. The Figure depicts the time series of the GNSS and SAR observations as well as the corresponding FCM vertical predictions of the monitoring site of Patra's University Geology Department, visualized as a multidataset line chart.

Figure 14. Time series of the GNSS, SAR observations and FCM vertical predictions of the monitoring site of Patra's University Geology Department, visualized as a multiline-dataset line chart.

5. FUTURE WORK

"PROION" project incorporated a novel and quite sophisticated multi-parametric framework for the holistic monitoring of crucial infrastructures, combining a wide dataset of different spatiotemporal observations and measurements. In an area with very high seismicity and very high ground acceleration, automated monitoring and warning systems are of high importance. GNSS and InSAR measurements of ground deformation, in combination with their future spatial prediction resulting from the fuzzy logic networks (FLN) methods and the followed validation techniques based on high-resolution 3D point clouds, as well as several supportive measurements and data, such as earthquakes and accelerometer events are implemented, analyzed and presented in a WebGIS platform.

Future work will focus in the following axes:

- the real time processing of the data and
- Increase the number of the crucial infrastructures under monitoring
- the enhancement of the of the platform with Building Information Models.

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