Received: 25 June 2024 | Revised: 19 July 2024 | Accepted: 3 August 2024

DOI: 10.1002/itl2.574

LETTER

WILEY

Space-to-tree: Architectural framework for real-time monitoring of pines in natural and historical park

Costanza Fiorentino[1] | **Mohamed A. E. AbdelRahman**[1,2,3] | **Paola D'Antonio**[1] | **Francesco Toscano**[1] | **Maura Sannino**[4] | **Nicodemo Abate**[5] | **Domenico Conte**[6] | **Rosa Lasaponara**[7] | **Nicola Masini**[5]

[1]School of Agriculture, Forest, Food and Environmental Sciences (SAFE), University of Basilicata, Potenza, Italy

[2]Division of Environmental Studies and Land Use, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo, Egypt

[3]State Key Laboratory of Agricultural Remote Sensing, Ministry of Agriculture and Rural Affairs/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China

[4]Department of Agricultural Sciences, University of Naples, Federico II, Via Università, Naples, Italy

[5]CNR-ISPC, Tito Scalo, Italy

[6]Digimat SPA, Matera, Italy

[7]CNR-IMAA, Tito Scalo, Italy

Correspondence
Costanza Fiorentino, School of Agriculture, Forest, Food and Environmental Sciences (SAFE), University of Basilicata, Via dell'Ateneo Lucano, 10-85100 Potenza, Italy.
Email: costanza.fiorentino@unibas.it

Abstract

The conservation and promotion of natural and cultural heritage, including landscapes, constitutes a subject of great economic and social importance. In recent times, there has been an increasing emphasis on the debate around strategies for developing an integrated approach to environmental and cultural heritage. The United Nations Educational, Scientific and Cultural Organization (UNESCO) has highlighted these challenges in its conventions, emphasizing the need for proactive measures to protect cultural heritage. The European Space Agency project "From space to Tree" (S23) aimed to develop an alert system for real-time monitoring of trees stability. The experimental site was the Archaeological Park of Colosseum in Rome. Inside the park there are countless pine trees of historical-cultural interest. The System and Service Architecture (SSA) describes the structure of the pilot system, detailing the high-level architecture and its constituent components. The monitoring system follows an integrated multi-scale approach and combines the health status of trees monitored by multi-temporal Sentinel-2 remote sensing images, the movements of the trees in response to wind stress, monitored by four inertial measurement units (IMUs) installed at different heights on each individual tree to detect its movement in response to wind stress, a weather station equipped with an ultrasonic anemometer and the in-field surveys and analyzes carried out by expert forestry agronomists. The acquired data is transmitted in real time to a dedicated server, by using the 5G network. Results show that data transmission system becomes more complex as the number of monitored trees increases, consequently the transmission system was designed taking this criticality into account. The data are displayed and analyzed in a dedicated Web-GIS platform. The experimentation is still ongoing, during the first experimental year, the analysis algorithm was trained in the first 6 months. During the test period, an alert is generated when changes are found in the behavior of the pines, based on remote sensing images and trees' response to wind stress analysis, compared to the training period.

KEYWORDS

5G, IMU, remote sensing, tree stability

1 | INTRODUCTION

The preservation of natural and cultural heritage is crucial for economic and social development, particularly in countries with exceptional cultural heritage. Preserving these resources can serve as a catalyst for economic growth and human development. Wind stresses are among the main causes of tree falls[1] in forests and urban parks. To understand wind-tree interactions and the processes that lead to tree damage, it is necessary to study the impact of wind loads on trees and how their movements are modified by them over time.[2] Climate change is intensifying extreme weather events with intense winds[3] causing damage to vegetation, representing potential risks to property and people. Monitoring public parks and green spaces is crucial for urban and supra-urban management and planning.[4,5]

Various methods and techniques for monitoring the health and stability of trees are known from the literature, however, this remains an open and discussed topic. The increasing number of field studies in which the wind-induced response of trees has been measured contributes to improve the understanding of wind-tree interactions under different environmental conditions.[6]

Bio-mechanical models have demonstrated the ability to reproduce the dynamic characteristics of the trees,[7–9] however, to simulate and understand the behavior of the tree subjected to wind stresses it is necessary to accurately know the architecture of the trees.[10,11] In many recent studies the data acquired by terrestrial laser scanning (TLS) are used to reconstruct tree architecture in both urban and peri-urban contexts.[12] Another approach is based on the procedure known as operational modal analysis (OMA), it was borrowed from the structural stability analysis of buildings.[13] These are dynamic monitoring systems based on accelerometers positioned on trees that record the trees' responses to wind stress, these data can be processed using multiple methodologies that allow the identification of the dynamic characteristics of the sample in terms of fundamental oscillation frequencies and corresponding mode shapes of trees.[14–16]

Zanotto et al. in 2024 developed a monitoring system compared a sophisticated OMA analysis to identify the main modal parameters such as natural frequencies, damping ratios, and mode shapes with a detailed three-dimensional finite element model derived from TLS data for the tree's geometry reconstruction. They developed a monitoring system and demonstrated that, if high-sensitivity accelerometers are used in the measurements, the combination of the spectral analysis of the signal and the OMA describe with a good resolution the natural frequencies and modes of tree oscillations even in low wind conditions.

Currently, it is difficult to understand whether the causes of tree failure are static or dynamic or a combination of them. In this perspective, an integrated monitoring system is needed taking into account parameters related to the structure and state of health of the trees as well as their response to wind stress. This can be done through a multidisciplinary approach[17] understanding the tree behavior.[18]

Assessing wind loads and their impact on tree motion is a prerequisite for understanding wind-tree-interactions and the processes that lead to wind damage to trees and forests.[3] Modeling the problem differs depending on the purpose. There are two main categories of models, the physical ones, based on the study of the behavior of the monitored parameters and their interactions, and the black-box models. The development of a physical model can be very difficult due to the non-linear dynamics in the interactions between the involved parameters.[19] On the other hand, the black-box models are based on the system identification process, it depends on the on experimental input and output data. The use of such models allows obtaining reliable results, without having detailed knowledge of the physical phenomena involved in the process. To develop this class of model, a training and test data set are needed.

The proposed pilot system is a multi-scale, multi-sensor approach called "from space to tree" (S23), funded by the European Space Agency (ESA). It is an alert system, that aims to detect any changes over time in trees health status and in their response to wind stress by using the black-box approach.

The acquired data is transmitted in real time to a dedicated server, by using the 5G network. Internet of Things (IoT) technology is used as a monitoring system, resulting in digital matching or even digital twins on the Internet. In the IoT platform the data are displayed and analyzed.

2 | MATERIALS AND METHODS

2.1 | Experimental site

The experimental site was the Colosseum Archaeological Park in Rome. an archaeological site that includes the Roman Forum and the Palatine, but also an important green area with several species of trees, mainly pines (*Pinus pinea*) and olive trees. The ancient pines are an important part of the Italian landscape, in fact they are present throughout the city of Rome. In the Colosseum Archaeological Park, they are considered monuments as the ruins and cobbled streets. In Figure 1 is shown the study area, the pines trees involved in the experimentation are 23 (highlighted in Figure 1). The pine highlighted in red was involved in the pilot experimentation of the software for data analysis. The pilot experimentation lasted a year.

2.2 | System/service architecture

2.2.1 | Hardware architecture

The purpose of monitoring the tree trunk is to acquire acceleration, speed and orientation measurements induced by external stresses. Four inertial measurement units (IMUs) were then installed on each tree, equally spaced one to each other, according to the scheme shown in Figure 2, which acquire data with a frequency of 10 samples per second.[14] The wind parameters were measured with a 3-axis ultrasonic anemometer located inside the park. A dedicated computing unit collect, organize and transmit data, marking steps for preservation, cataloging and post-processing. Each tree is connected via WiFi to an assigned gateway, allowing it to transfer its measurements independently. In the prototype, the gateway will consist of a 5G router, the choice of WiFi connection allows other connectivity options. The acquired data is transmitted in real time to a dedicated server, by using the 5G network. The data transmission system becomes more complex as the number of monitored trees increases, consequently the transmission system was designed taking this criticality into account. The ESP WROOM32 MCU was chosen for its deep sleep mode capabilities and programmable timer, allowing it to manage and retrieve data from the IMU installed on each tree. The Bosch BNO055 is a System in Package (SiP) IMU that integrates a triaxial accelerometer, a gyroscope, a geomagnetic sensor and a 32-bit cortex M0+ microcontroller. Sensor fusion

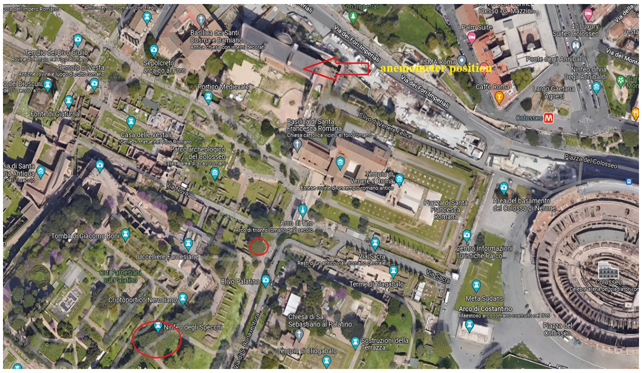

FIGURE 1 The Colosseum Archaeological Park. The monitored pines are highlighted in cyan; the red circles indicate the Pinus Tree monitored in the pilot. The red arrow indicates the position of the ultrasonic anemometer.

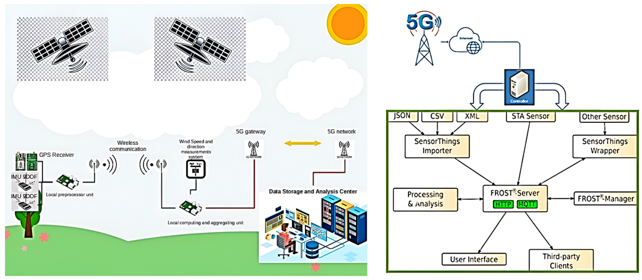

FIGURE 2 Schematic of the pilot project's hardware architecture.

modes calculate the device's orientation in space, distinguishing between non-absolute or relative orientation and absolute orientation. Absolute orientation calculates the direction of the magnetic north pole. Sensor titles are provided as quaternion data or Euler angles. Sensor fusion data separates linear acceleration and gravity vector, allowing a better understanding of sensor position and acceleration sources. The Raspberry Pi Zero W is a compact and affordable IoT and affordable project kit designed for on-board devices, with a wireless-lan, Bluetooth, a BCM2835 processor unique to 1 GHz, 512 MB of RAM and HDMI and USB mini and USB ports. It was chosen for its compatibility with the anemometer, which will be installed in less critical conditions with an external power source and Ethernet connectivity. The HD2003 is a 3-axis static anemometer for measuring wind speed and direction, U-V-W cartesian components of speed, wind gust, sound speed, sonic temperature, air temperature, relative humidity and barometric pressure. The API OGC Sensor Things standard is a unified way to manage sensors and their observations, allowing the interconnection of Internet objects (IoT) devices on the web. It is based on relational connections between system entities, allowing any IoT detection device to be modeled in the system. The UML data model defines different entities and their properties, and the API can be integrated into Frost-Server methods to allow sensors to insert measurements and save data in a geospatial database.

The communication between every tree and the Frost-Server is guaranteed by the Netgear MR5000 5G router. Thanks to its Hot-Spot functionalities it can provide a high bandwidth 5G connection up to 32 connected devices. Every MR5000 will be responsible for a group of trees, then a high level of scalability for each installation site can be reach and every expansion, if needed, will have no impact on the existing ones.

2.2.2 | Software architecture

The system high level architecture is structured as follow:

1. Portal: web application used as a privileged access point to the system. This subsystem is mainly used by operators for the typical activities provided by the system, for example cataloging of trees, loading of data related to trees, management of maintenance records, and so forth.
2. Geospatial services: services for cataloging and distributing 2D spatial data. This service uses a database with spatial extensions capable of handling vector data. 2D raster data are stored in a storage space.
3. Transformation services: services for cataloging and transforming 3D data in order to obtain data that can be distributed via the web and stored in a dedicated storage space.
4. Sensor services: services capable of collecting data from sensors in the field and allowing their interrogation. The data collected and appropriately processed are stored in a specific database.
5. Decision support systems (DSS): application capable of providing, in the form of a service, assessments for health status and stability of monitored trees based on sensor measurements and data from remote sensing.
6. Alert services: service capable of generating alerts based on the reports entered into the system by operators or automatically generated by DSS.
7. Identity services: services for managing user identities and roles, identification, authorization and access management.
8. Storage services: system capable of providing object storage functionality through a web service interface.

The system can be divided into two modules based on open-source software: arches to manage the tree and geonode files for 2D geographic data and 3D data. CESESIMJS is a JavaScript open-source library used to create world class globes with high performance, precision, visual quality and ease of use. Cataloges and documents all types of real estate, including buildings, archaeological sites, cultural landscapes, neighborhoods and complex heritage. Geonode is a web frame based on an open-source software technology which allows organizations to deploy and distribute geospatial content management systems (GEOCMS), public spatial data infrastructure

(SDI) and open cataloges of geospatial data. It supports standard metadata formats and provides a web style for real-time data style changes. Potree is a point cloud rendering engine that uses a spatial partition hierarchy to store the detail levels of the original model. This structure allows users to collect points and measurements on original data at any level of zoom without waiting for a leaf node to take care.

2.3 | Methodological approach

The S23 project aims to develop an integrated multi-temporal and multi-scale approach for monitoring natural heritage and monumental trees. The methodological approach to the problem consists of two main elements:

1. The proximal sensing data analysis, by using the acquisition system described in the previous paragraph, aims to monitor the response of trees to wind stress;
2. The remote sensing data analysis, by using time series of Sentinel-2 satellite image, provide information on the characterization of the territory surrounding and the monitored trees and allow to evaluate the presence of any stress or tree diseases.

The system aims to detect any changes over time in the response of trees to wind stress and in vegetation indices derived from remote sensing. The data collected from RS were loaded and displayed into a Web-GIS platform, allowing users to assess the studied pines in real time.

2.3.1 | The proximal sensing monitoring system

The literature has demonstrated how the data acquired by the anemometer are closely related to the movements of the trees recorded by the IMUs. In this work, a multivariate polynomial regression was used to process the parameters measured by the anemometer and the IMUs. Once installed the monitoring system, the algorithm was trained using the data acquired over the following 6 months. Both at the begin and at the end of the training phase, it was verified by the park's agronomists that nothing had changed in the state of health of the pilot tree. In the next phase, that is in the following 6 months, the system worked to predict the parameters provided by the IMUs which were compared with those actually acquired by the sensors. If the predicted deviations differ by a defined threshold value compared to the measured values, an alert is generated.[20]

Polynomial regression extends linear regression by allowing for the inclusion of polynomial terms of the predictor variables.[21] This enables the model to capture nonlinear relationships between the predictors and the response variable. The polynomial regression for multivariate data to capture nonlinear relationships and make predictions was implemented. Adjusting the degree of the polynomial and other parameters allow to suit the specific dataset and problem requirements.

2.3.2 | The remote sensing monitoring system

The normalized difference vegetation index (NDVI) time series from the Sentinel-2 satellite was used to assess tree health, which is the most widely used index for vegetation health analysis. To assess the reliability of Sentinel-2 data, a long time series of more than 350 images from 2015 to 2021 was processed. The NDVI was used as a proxy to characterize vegetation condition and distinguish between healthy and poor conditions.[22,23] Once the NDVI index is obtained for each image, a set of points corresponding to the area where the trees, considered of interest, are located is sampled, a temporal pattern is extracted and the NDVI trend over time is analyzed. Then, a classification with assignment of weights based on temporal pattern (via pixel-by-pixel analysis) and dynamic time warping (via object analysis) is performed to identify clusters of pixels with similar characteristics over time (e.g., areas of vegetation degradation) using machine learning. Google Earth Engine (GEE)[24] has been exploited in order to set, implement, assess and optimize the use of advanced tools based on indirect estimation of bio-physical parameters for an early plant stress and disease detection.

3 | RESULTS AND DISCUSSION

Figure 3A shows the scheme of IMU tree sensors. Each IMU Sensor is fixed on the trunk of the tree, with regular steps until it reaches a position below the crown. At the base of the tree is located the processor with the transmitter (Figure 3B) and the battery to power the system. The processor is also a controller; first it performs the diagnosis of IMUs sensor operation and data transmission system to the router. When both systems work, the processor calculates the degree of anomaly in the movement of the monitored tree, measured on the basis of the algorithm illustrate in the previous paragraph. The Web-GIS platform shows the location of each tree and the associated technical sheet containing the main characteristics detected by the agronomists and close-range analyses, including 3D photogrammetric modeling and infrared thermography (IRT), performed using drone and ground penetrating radar (GPR) prospection.[25] All data are cataloged and dated.

During the training period, a comparative analysis was carried out between the data acquired by the four IMUs located on the trees and the wind speed and direction acquired by the sonic anemometer. A correlation level of about 87% was found when the wind speed exceeded 4 km/h. Figure 4A shows an example of tree technical sheet that can be consulted and updated periodically by park operators.

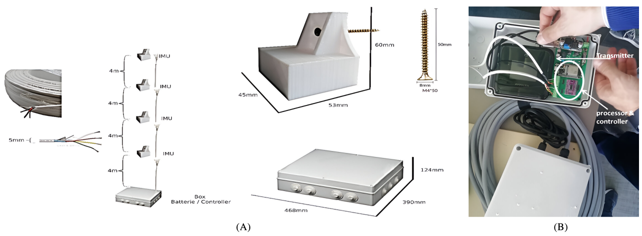

FIGURE 3 (A) Scheme of the installed inertial measurement units prototype for monitoring the tree movement induced by wind. (B) Microcontroller main board and transmitter system.

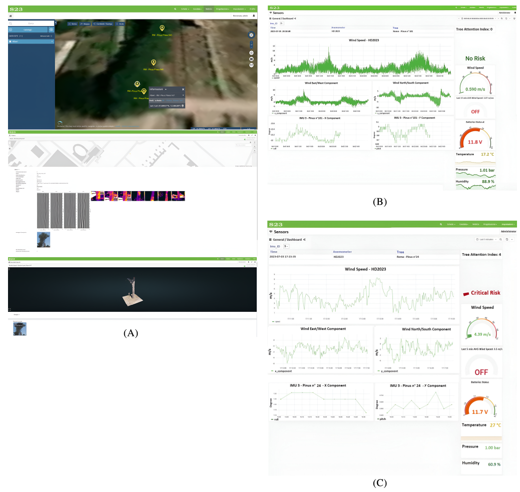

FIGURE 4 (A) Tree 547 technical sheet linked from popup window on GIS. (B) and (C) Dashboard with the real time data from sensors network in Parco del Colosseo.

On the selected tree, it will be opened the page of the real-time proximal sensing monitoring that shows the data of wind speed and direction, IMUs data and status, batteries status, air temperature, pressure and humidity. Figure 4B,C show the layout of the page. The first graph is relative to the wind speed, the four graph below shows the data detected by the 4 IMUs. On the right side of the page, in green, there is the alert report. During the 6 month of system testing, only one time was generated an alert as shown in Figure 4C.

Although the wind speed was not high (8 km/h), the IMU recorded an anomalous response in the movement of the tree. Park operators were alerted and investigations and measurements on the tree were carried out, but they did not detect any evident changes in its state of health. At the moment it is not possible to talk about the sensitivity of the developed system because further training periods are probably required. In fact, the anomaly recorded could represent a further way of oscillation of the shaft not detected during the testing phase. As highlighted in Schindler et al. (2016) the complex vibrational behavior, with multiple modes localized to the sampled shaft parts, made it difficult to isolate specific vibration components related only to the sampled shaft parts from the measured vibration signals. The training of the algorithm can also be refined by having more data and contexts available. However, it is important to emphasize the involvement of end-users in this process because the changes observed in the trees through both proximal and remote sensing could be due to external factors such as damage caused by the presence of fauna or factors related to natural variations. For example, changes in the canopy can alter the tree's response, generating a false alert. A technological limitation, for the infield monitoring system, that must certainly be refined to allow its use in different urban and peri-urban contexts concerns the power supply to the monitoring system installed on the tree and the transmission of the acquired data. In the context of the Colosseum Park, a battery was used which is periodically replaced and recharged. The battery requires support (e.g., photovoltaic panels), but the main issue concerns landscape constraints. Long time series analysis of Sentinel-2 images, as explained in paragraph 2.3.2, aimed to detect NDVI variations in trees classified as healthy or unhealthy by in-field inspections.[24] During the experimental period, no significant variations in the vegetation index were detected in the monitored trees.

4 | CONCLUSION

The system S23 is actually in use in Colosseum Archaeological Park in Rome. It aims to detect anomalies in tree health state. A dedicated IoT platform has been developed and the acquired data are transmitted in real time, by using the 5G network. The data transmission system becomes more complex as the number of monitored trees increases, consequently the transmission system was designed taking this criticality into account. Data from remote sensing, data from tree response to wind stress and the technical data sheets with the structural characteristics of the trees. In the IoT Platform, associated to each monitored tree, are also recorded, and periodically updated, the instrumental investigations carried out in the field as morphological characterization of the trunks[25] and crowns on a photogrammetric basis, the thermal anomalies detected on the bark with IRT, reflectors recorded in the radargrams. These data were used to complete and validate the S23 monitoring system.

Further monitoring and developments are still underway, especially to refine the data analysis algorithms and improve the training of S23 system.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Costanza Fiorentino https://orcid.org/0000-0002-0598-6548

REFERENCES

1. Van Haaften M, Liu Y, Wang Y, et al. Understanding tree failure-a systematic review and meta-analysis. *PLoS One*. 2021;16:e0246805. doi:10.1371/journal.pone.0246805
2. Schindler D, Jung C, Buchholz A. Using highly resolved maximum gust speed as predictor for forest storm damage caused by the high-impact winter storm Lothar in Southwest Germany. *Atmos Sci Lett*. 2016;17:462-469. doi:10.1002/asl.679
3. Gardiner B. Wind damage to forests and trees: a review with an emphasis on planted and managed forests. *J For Res*. 2021;26(4):248-266. doi:10.1080/13416979.2021.1940665
4. Caneva G, Bartoli F, Zappitelli I, Savo V. Street trees in italian cities: story, biodiversity and integration within the urban environment. *Rendiconti Lincei Scienze Fisiche e Naturali*. 2020;31:411-417. doi:10.1007/s12210-020-00907-9
5. Alkama R, Cescatti A. Biophysical climate impacts of recent changes in global forest cover. *Science*. 2016;351(6273):600-604. doi:10.1126/science.aac8083
6. Jackson TD, Sethi S, Dellwik E, et al. The motion of trees in the wind: a data synthesis. *Biogeosciences*. 2021;18(13):4059-4072. doi:10.5194/bg-18-4059-2021
7. Sellier D, Suzuki S. Age dynamics of wind risk and tree sway characteristics in a softwood plantation. *Front For Glob Change*. 2020;3:89. doi:10.3389/ffgc.2020.00089
8. James KR, Dahle GA, Grabosky J, Kane B, Detter A. Tree biomechanics literature review: dynamics. *Arboric Urban For*. 2014;40(1):1-15. doi:10.13140/RG.2.1.1089.1765
9. Spatz H, Theckes B. Plant science oscillation damping in trees. *Plant Sci*. 2013;207:66-71. doi:10.1016/j.plantsci.2013.02.015
10. Moore JR, Maguire DA. Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. *Tree Physiol*. 2008;28:75-83. doi:10.1093/treephys/28.1.75
11. Jackson T, Shenkin A, Wellpott A, et al. Finite element analysis of trees in the wind based on terrestrial laser scanning data. *Agric For Meteorol*. 2019;265:137-144. doi:10.1016/J.AGRFORMET.2018.11.014
12. Moravčík L, Vincúr R, Rózová Z. Analysis of the static behavior of a single tree on a finite element model. *Plan Theory*. 2021;10:1284. doi:10.3390/PLANTS10071284
13. Varasano AF, Piccioni MD, Andria G. Development and characterization of an IoT cloud platform operating in 5G network for structural health monitoring of civil constructions. *2023 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv)*. IEEE; 2023:269-275. doi:10.1109/MetroLivEnv56897.2023.10164062
14. Schindler D, Mohr M. Non-oscillatory response to wind loading dominates movement of scots pine trees. *Agric For Meteorol*. 2018;250:209-216.
15. Schindler D, Mohr M. No resonant response of Scots pine trees to wind excitation. *Agric For Meteorol*. 2019;265:227-244.
16. Giachetti A, Zini G, Giambastiani Y, Bartoli G. Field measurements of tree dynamics with accelerometers. *Forests*. 2022;13:1243. doi:10.3390/F13081243
17. Zanotto F, Marchi L, Grigolato S. Wind-tree interaction: technologies, measurement systems for tree motion studies and future trends. *Biosyst Eng*. 2024;237:128-141. doi:10.1016/J.BIOSYSTEMSENG.2023.12.005
18. Sellier D, Fourcaud T, Lac P. A finite element model for investigating effects of aerial architecture on tree oscillations. *Tree Physiol*. 2006;26:799-806. doi:10.1093/treephys/26.6.799
19. Finamore AR, Calderaro V, Galdi V, Piccolo A, Conio G. A wind speed forecasting model based on artificial neural network and meteorological data. ***2016** IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*. IEEE; 2016:1-5. doi:10.1109/EEEIC.2016.7555671
20. Sinha P. Multivariate polynomial regression in data mining: methodology, problems and solutions. *Int J Sci Eng Res*. 2013;4(12):962-965.
21. Goodfellow I, Bengio Y, Courville A. *Deep Learning*. MIT Press; 2016 http://www.deeplearningbook.org.
22. Fiorentino C, D'Antonio P, Toscano F, Donvito A, Modugno F. New technique for monitoring high nature value farmland (HNVF) in Basilicata. *Sustainability*. 2023;15:8377. doi:10.3390/su15108377
23. Masini N, Strano G, Fiorentino C, et al. From space to tree: multisensor and multiscale remote sensing-based approach for monitoring monumental trees. *The Case of Archaeological Park of Colosseum in Rome. Preliminary Results*. IMEKO; 2023:181-185. doi:10.21014/tc4-ARC-2023.035
24. Amani M, Ghorbanian A, Ahmadi SA, et al. Google earth engine cloud computing platform for remote sensing big data applications: a comprehensive review. *IEEE J Sel Top Appl Earth Obs Remote Sens*. 2020;13:5326-5350.
25. Feng D, Liu Y, Wang X, et al. Inspection and imaging of tree trunk defects using GPR multifrequency full-waveform dual- parameter inversion. *IEEE Trans Geosci Remote Sens*. 2023;61:1-15.

How to cite this article: Fiorentino C, AbdelRahman MAE, D'Antonio P, et al. Space-to-tree: Architectural framework for real-time monitoring of pines in natural and historical park. *Internet Technology Letters*. 2024;e574. doi: 10.1002/itl2.574