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INTEGRATED ASSESSMENT OF TREE HEALTH AND STRUCTURAL STABILITY USING UAV MULTISPECTRAL IMAGING, 3D PHOTOGRAMMETRY, VTA AND ACOUSTIC TOMOGRAPHY: A CASE STUDY OF A LIME TREE

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Abstract: *Accurate assessment of the physiological and mechanical condition of trees in urban environments represents a key component of risk management and the planning of protection measures. This study presents the integration of four methodological approaches – multispectral UAS (drone) analysis, a photogrammetrically generated 3D model, Visual Tree Assessment (VTA) and acoustic tomography (Arbotom) – applied to an old lime tree (*Tilia platyphyllos*) located in the courtyard of the Bishop's Palace of the Šabac Eparchy. Multispectral analysis was used to calculate the NDRE index of physiological activity, while the 3D trunk model was employed for precise positioning of the Arbotom sensors. Tomographic measurements performed at heights of 40 cm and 200 cm identified degradation zones with a reduction in load-bearing cross-sectional area of 27–39% (lower section) and 43–52% (upper section). The NDRE index indicated localized areas of reduced physiological activity within the crown, while the VTA method confirmed the presence of fungi of the genus *Ganoderma*. The integrated results indicate that the tree currently maintains a stable mechanical structure, with localized degradation zones that do not yet affect its static stability. The presented multi-sensor approach is highlighted as an efficient tool for detection, evaluation, and risk management in urban forestry, however as this research was conducted on a single *Tilia platyphyllos* specimen, the findings should be interpreted as a case study and methodological demonstration rather than as results directly generalizable to a broader population of urban trees.*

Keywords: Remote sensing, UAS, multispectral, Arbotom, sonic tomography, non-destructive assessment.

INTEGRISANA PROCENA ZDRAVSTVENOG STANJA I STRUKTURNE STABILNOSTI STABALA PRIMENOM UAV MULTISPEKTRALNOG SNIMANJA, 3D FOTOGRAFIJE, VTA METODE I AKUSTIČNE TOMOGRAFIJE: STUDIJA SLUČAJA LIPE

Sažetak: *Precizna procena zdravstvenog i mehaničkog stanja stabala u urbanom okruženju predstavlja ključnu komponentu upravljanja rizicima i planiranja mera zaštite. U*

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ovom radu prikazana je integracija četiri metodološka pristupa – multispektralne UAS (dron) analize, fotogrametrijski generisanog 3D modela, vizuelne procene stabla (VTA) i zvučne tomografije (Arbotom) – primenjenih na staro stablo lipe (*Tilia platyphyllos* Scop.) koje se nalazi u dvorištu Vladičanskog dvora Eparhije šabačke. Multispektralna analiza korišćena je za izračunavanje NDRE indeksa fiziološke aktivnosti, dok je 3D model debela upotrebljen za precizno pozicioniranje Arbotom senzora. Tomografska merenja sprovedena na visinama od 40 cm i 200 cm identifikovane su zone degradacije sa redukcijom nosive površine poprečnog preseka od 27–39 % (donji presek) i 43–52 % (gornji presek). NDRE indeks ukazao je na lokalizovane zone smanjene fiziološke aktivnosti u krošnji, dok je VTA metodom potvrđeno prisustvo gljiva roda *Ganoderma* sp. Integrisani rezultati ukazuju da stablo trenutno poseduje stabilnu mehaničku strukturu, uz lokalizovane zone degradacije koje za sada ne utiču na njegovu statičku stabilnost. Predstavljeni multisenzorski pristup ističe se kao efikasan alat za detekciju, evaluaciju i upravljanje rizikom u urbanom šumarstvu, pri čemu treba naglasiti da obzirom na to da je istraživanje sprovedeno na jednom stablu vrste *Tilia platyphyllos*, rezultate treba tumačiti kao studiju slučaja i metodološku demonstraciju, a ne kao nalaze koji se mogu neposredno generalizovati na širi skup urbanih stabala.

Ključne reči: daljinska detekcija, UAS, Arbotom, zvučna tomografija, nedestruktivna procena.

1. INTRODUCTION

Urban trees provide important ecological and social benefits, but in densely inhabited areas they may also represent a safety risk when affected by physiological decline, internal decay, or mechanical instability. Therefore, reliable assessment of tree condition is essential for informed decision-making in urban forestry and risk management, particularly where tree failure could threaten people or nearby structures (Živanović et al., 2023).

Visual Tree Assessment (VTA) is widely used for recognizing external symptoms of decline, but visual inspection alone often cannot detect internal structural defects or early physiological stress. In this context, acoustic tomography is a valuable non-destructive method for assessing the internal condition of standing trees, because it enables detection of decay and weakened wood through analysis of stress-wave propagation (Deflorio et al., 2008; Živanović et al., 2020). At the same time, UAV-based multispectral sensing provides detailed insight into canopy physiological condition through vegetation indices. Among them, the NDRE index is particularly suitable for detecting subtle changes in chlorophyll-related activity and stress in mature vegetation (Gitelson & Merzlyak, 1994; Delegido et al., 2011).

The integration of multispectral UAV analysis, photogrammetric 3D modeling, VTA, and acoustic tomography offers a comprehensive framework for simultaneous assessment of physiological condition and internal structural integrity. The aim of this study was to demonstrate such an integrated approach on a mature urban tree in order to improve diagnostic accuracy and support tree risk evaluation in urban environments.

2. AIM OF THE STUDY

The aim of this study is to develop and demonstrate an integrated multi-sensor methodology for the assessment of health status, internal structural integrity, and mechanical stability of mature urban trees (Živanović et al., 2020; Živanović et al., 2023). Specifically, the study seeks to combine multispectral UAV-based vegetation indices, photogrammetrically derived 3D trunk geometry, and acoustic tomography to enable precise detection and spatial localization of physiological stress and internal wood degradation which should supplement and provide more insight over the traditional VTA method.

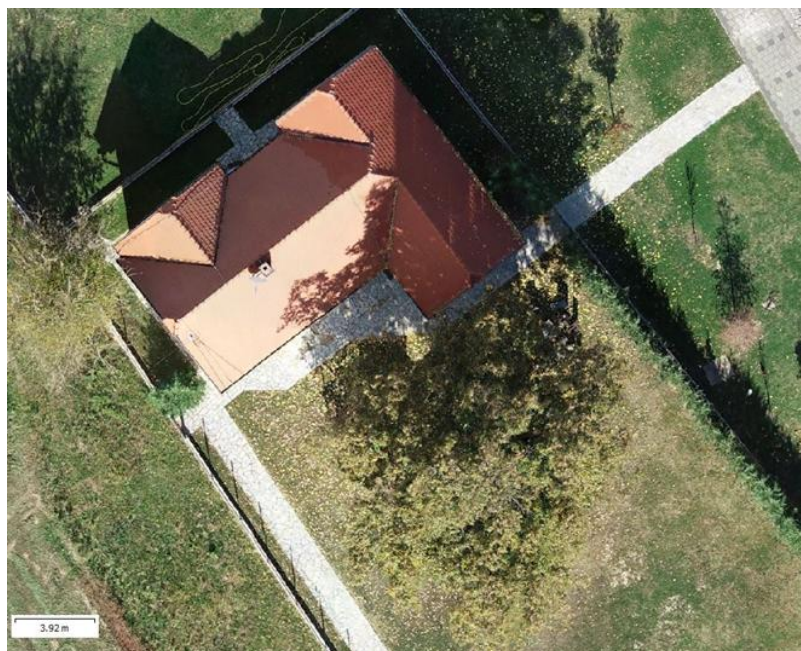


Figure 1. Location of the linden tree and nearby house

For the purpose of testing the multi-sensor approach a single linden tree (*Tilia platyphyllos*) was selected, at location of Bishop's Palace near Šabac (19°38'35.21" E; 44°44'21.56" N WGS 84). Height of the tree was ~17m. The selected tree represents a single case-study specimen; therefore, the obtained results describe the condition of this individual tree and cannot be directly generalized without additional testing on a larger sample and control trees.



Figure 2. Linden tree (*Tilia platyphyllos*) in courtyard of Bishop's palace

The vicinity of the tree to the nearby domicile of the bishop made the accuracy of the assessment of utmost importance due to the risk of damaging the house and endangerment of life for people living and working in and around the house (Živanović et al., 2023) (Figure 1; Figure 2).

By applying this approach to a mature *Tilia platyphyllos* specimen, the study aimed to improve the accuracy of tree risk evaluation and to support informed decision-making in urban forestry management through non-destructive, data-driven analysis (Živanović et al., 2023). The purpose of the study is therefore primarily methodological, while future research should include a larger number of trees and control specimens to evaluate the broader applicability of the approach.

3. METHODOLOGY

3.1 Remote Sensing

Data acquisition was performed using a quadcopter multirotor unmanned aerial system (UAS) equipped with a 20-megapixel RGB camera and a MicaSense RedEdge-M multispectral sensor (Figure 3a). The flight was conducted under sunny and cloud-free conditions, at a flight height of 50 m above ground level, capturing RGB and multispectral data simultaneously. The RedEdge-M sensor records reflectance in five narrow spectral bands centered at 475 nm (blue), 560 nm (green), 668 nm (red), 717 nm (red-edge), and 840 nm (near-infrared), enabling detection of subtle variations in vegetation spectral response associated with chlorophyll concentration, leaf cellular structure, and physiological activity (Hunt et al., 2013; Zarco-Tejada et al., 2013). Spectral bands of multispectral sensor are presented in Figure 4.



Figure 3. a) MicaSense RedEdge M multispectral sensor, b) DLS, c) calibrated panel

Radiometric calibration of multispectral imagery was conducted using a calibrated reflectance panel (CRP) shown on Figure 3c. prior and after each flight mission. Simultaneously, incident solar irradiance was continuously recorded during the flight using the integrated Downwelling Light Sensor (DLS) (Figure 3b), allowing correction of radiometric inconsistencies caused by changing illumination conditions during image acquisition. The combined use of CRP-based calibration and irradiance measurements enables conversion of raw digital number values into surface reflectance data, thereby improving the comparability and quantitative reliability of vegetation indices derived from UAS imagery (Turner et al., 2014; Aasen et al., 2018). Radiometric calibration was performed using the Downwelling Light Sensor (DLS / sun sensor) and a calibrated reflectance panel. The calibration panel was imaged before and after the flight mission, while incident illumination was recorded continuously by the sun sensor during acquisition. The calibration procedure and the application of radiometric corrections were carried out within the software environment according to the internal processing algorithms and predefined software workflow.

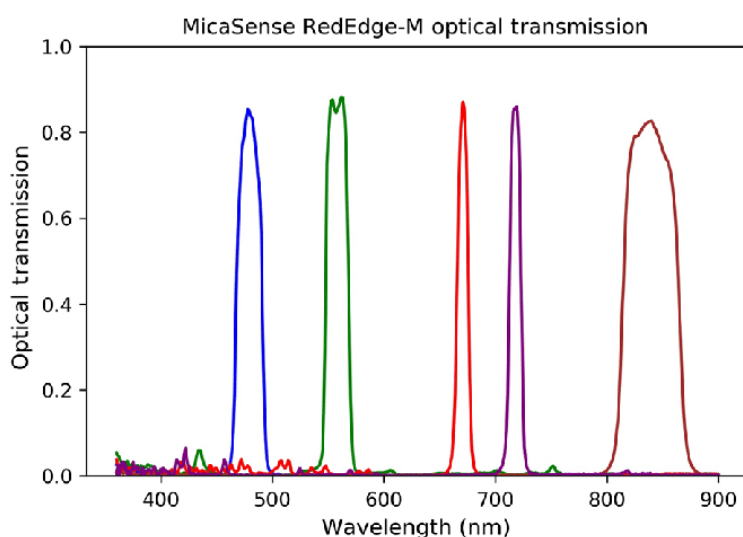


Figure 4. Narrow bands of multispectral sensor

Calibrated multispectral data were subsequently used to calculate the NDRE (Normalized Difference Red Edge) vegetation index, which utilizes reflectance in the red-edge and near-infrared spectral regions. NDRE is particularly sensitive to variations in chlorophyll content and canopy physiological condition, allowing detection of plant stress before visible symptoms become apparent (Gitelson & Merzlyak, 1994; Delegido et al., 2011). UAV-based multispectral sensing thus provides an effective means of quantifying spatial variability in canopy physiology and identifying early indicators of stress or decline in tree vitality (Zarco-Tejada et al., 2018).

Photogrammetric processing of the acquired data was processed in professional photogrammetry software Agisoft Metashape Pro. The result of the processing was RGB and multispectral orthomosaics with 1.5cm/pixel for RGB and 4cm/pixel resolution for multispectral orthomosaic. The resolution provided sufficient level of detail for assessment of the physiological activity of parts of the single tree through application of vegetation indices. Image alignment, calibration and orthomosaic generation were performed as software-defined internal processing steps in Agisoft Metashape Pro. Photograph overlap and the photogrammetric processing settings of aerial imagery was not treated as a relevant output parameter for the final orthomosaic in this study.

Multispectral UAV analysis provided detailed information on the physiological condition of the tree canopy. Physiological activity is quantified through application of vegetation indices which represent values based on levels of reflectance of different wavelengths from vegetation and provide rapid, scalable and interpretable insights into vegetation health (Vidican et al., 2023). Reflectance distribution of different wavelengths is presented in figure 5. Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge Index (NDRE) are among the most widely used spectral vegetation indices for assessing plant physiological condition based on reflectance characteristics in the red, red-edge, and near-infrared (NIR) regions of the electromagnetic spectrum. Although NDVI is the most widely used vegetation index so for this purpose the NDRE vegetation index is used due to its sensitivity in late season physiology assessment.

NDVI is calculated using reflectance in the red and NIR spectral bands and is primarily sensitive to chlorophyll absorption and vegetation biomass:

$$NDVI = (NIR - Red) / (NIR + Red)$$

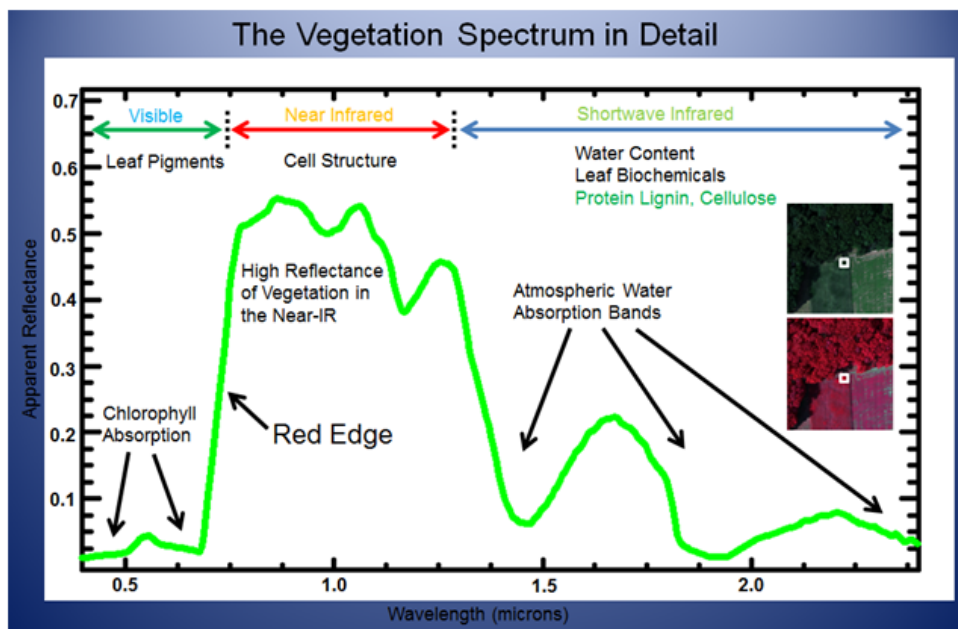


Figure 5. *Distribution of light reflectance from vegetation*

NDVI is effective for general vegetation detection, biomass estimation, and monitoring of canopy density and greenness (Rouse et al., 1974; Tucker, 1979). However, NDVI tends to saturate in dense vegetation canopies, limiting its sensitivity to physiological variability in mature or structurally complex tree crowns (Gitelson, 2004). This saturation effect reduces its effectiveness in detecting subtle stress conditions in high-leaf-area-index environments such as urban trees or forest stands.

NDRE incorporates reflectance from the red-edge region instead of the red band:

$$\text{NDRE} = (\text{NIR} - \text{RedEdge}) / (\text{NIR} + \text{RedEdge})$$

The red-edge spectral region is particularly sensitive to variations in chlorophyll concentration and leaf internal structure, making NDRE more responsive to early physiological stress and nutrient deficiencies that may not yet produce visible structural changes in the canopy (Delegido et al., 2011; Gitelson & Merzlyak, 1994). Unlike NDVI, NDRE maintains sensitivity across higher biomass levels and is therefore better suited for monitoring mature vegetation and detecting sub-canopy stress in woody species (Sims & Gamon, 2002).

3.2 Sonic Tomography

Internal structural condition of the trunk was assessed using acoustic (sonic) tomography with the Arbotom® system. The method is based on the principle of stress-wave propagation through woody tissue, where the velocity of sound transmission is directly related to the material density and mechanical stiffness of the wood. Sound waves propagate more rapidly through intact, structurally sound

wood and are significantly slowed in areas affected by decay, cavities, or fungal degradation due to reduced density and disrupted cellular structure (Gilbert & Smiley, 2004; Deflorio et al., 2008).

Measurements were conducted at two trunk heights, the first at 40 cm (Figure 6.) and the second at 200 cm above ground level using a circumferential arrangement of evenly spaced sensors. After mechanical impulse excitation, the travel time of stress waves between individual sensor pairs was recorded and used to reconstruct a two-dimensional tomographic image of internal trunk structure. The resulting tomograms represent spatial distribution of acoustic wave velocities, where low-velocity zones correspond to degraded or compromised wood tissue, while high-velocity zones indicate structurally sound material (Nicolotti et al., 2003).



Figure 6. Arbotom sensors at height of 40cm with data receiver

This approach allows for non-destructive detection and localization of internal defects that are not externally visible, including advanced fungal decay and loss of load-bearing capacity (Živanović et al., 2020). Quantification of the residual wall thickness and effective load-bearing cross-sectional area provides a biomechanical basis for assessing the remaining structural integrity of the trunk and its capacity to withstand mechanical loads such as wind stress (Smiley & Gilbert, 2003; Wang et al., 2007).

Sonic tomography has been shown to be particularly effective in detecting early-stage internal decay associated with wood-decaying fungi, enabling improved evaluation of tree stability and failure risk in urban environments where preservation of mature trees is often required (Deflorio et al., 2008, Živanović et al., 2020). In this study, tomographic results were interpreted in conjunction with Visual Tree Assessment (VTA) to improve diagnostic reliability and reduce uncertainty associated with singular assessment methods.

In addition to qualitative identification of internal decay, the tomographic analysis enabled quantitative assessment of residual wall thickness and effective load-bearing capacity of the trunk cross-section. The structural integrity of hollow

or decayed tree stems is commonly evaluated using the ratio between the thickness of the remaining intact wood wall (t) and the overall radius of the trunk (R), expressed as the t/R ratio. This parameter has been widely applied as an indicator of mechanical stability and failure risk in standing trees (Mattheck & Breloer, 1994; Mattheck et al., 2006).

According to established biomechanical models, a residual wall thickness of approximately 30% of the trunk radius ($t/R \geq 0.3$) is generally considered sufficient to maintain structural stability under typical loading conditions, whereas lower values may indicate increased susceptibility to mechanical failure due to bending or buckling stresses (Mattheck & Bethge, 1998). Sonic tomography enables indirect estimation of this parameter by delineating zones of compromised wood tissue and identifying the remaining ring of structurally sound material.



Figure 7. *Photogrammetric 3D model of tree trunk*

In order to precisely measure and position the sensors in Arbotom software the close-range photogrammetric survey of the tree trunk was performed using RGB imagery to generate a high-resolution three-dimensional model through Structure-from-Motion (SfM) processing (Figure 7.). The resulting 3D geometry enabled accurate spatial positioning, through simulating the changes of topography of tree trunk, and allowed better assessment of the distance between sensors which further increased the precision of acoustic tomography sensors for internal structural assessment (Figure 8). The 3D model of the trunk was produced in the same photogrammetric software Agisoft Metashape Pro, which was used for aerial imagery. Images for 3D model were acquired with handheld DSLR camera Nikon D5300, and fixed AF-S DX Nikkor 35mm f/1.8G lens. The images were captured by multistation-multidirectional approach. Trunk was imaged from multiple points around the tree with every point being used to capture multiple different segments of the trunk. Size calibration and scaling was done by using the same measuring tape positioned around the trunk for sonic tomography. Building of textured 3D model was performed through internal processing algorithms of photogrammetric software, through depth maps filtering and 3D mesh building.

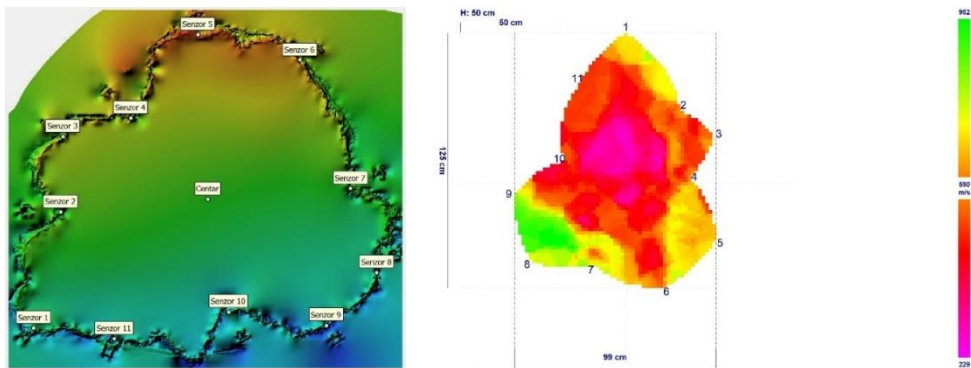


Figure 8. *Cross-section of 3D model of a tree trunk with resulting model in Arbotom software*

4. RESULTS

The NDRE vegetation index revealed clear spatial heterogeneity, with several localized zones of reduced physiological activity detected within the crown. Figure 9. shows the color-coded image with values of NDRE index distributed from Red (low values) to Green (high values). These areas suggest reduced photosynthetic efficiency and potential stress, likely linked to internal structural or biological factors. Due to the time of the year when imaging was done, the lower values of the NDRE vegetation index may be under the influence of natural autumn senescence, however the majority of the senescing was primarily localized to the one side of the crown. The high spatial resolution of the UAV data enabled precise identification of affected crown segments, supporting targeted interpretation of tree health.

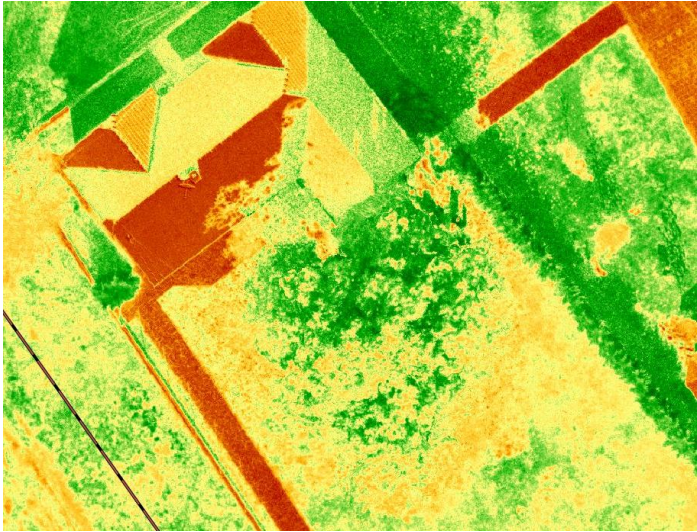


Figure 9. *Color-coded presentation of values of NDRE vegetation index of linden tree*

During further analysis of the multispectral orthomosaic, the NDRE (Normalized Difference Red Edge) vegetation index was applied to quantify the physiological activity of phytopigments, thereby indicating the physiological condition of the vegetation, in this case the assessed linden tree. The obtained results show a reduction in physiological activity in the upper part of the crown on the side facing the courtyard. Localized weakening of physiological activity was also observed in the crown section oriented toward the house.

It should be noted that the survey was conducted during the last week of October, when a decrease in physiological activity in deciduous vegetation and leaf senescence is expected. Therefore, physiological decline cannot be determined with certainty, although similar stress was not detected in the majority of the crown. For a more reliable distinction between seasonal senescence and physiological stress, repeated acquisitions during different phenological phases are recommended.

In the present study, tomographic cross-sections obtained at both measurement heights revealed the presence of continuous residual sound wood despite localized degradation. The spatial distribution of intact peripheral tissue suggests that the remaining load-bearing structure is capable of sustaining mechanical loads under current environmental conditions. The interpretation of residual wall thickness was further supported by Visual Tree Assessment (VTA), which provided external indicators of fungal decay consistent with tomographic findings.

The sensors were positioned at 10 locations along the circumference of the trunk cross-section, with their arrangement aligned to the geometry obtained from the 3D photogrammetric trunk model.

At a height of 40 cm, the tomogram revealed a pronounced zone of central and marginal wood degradation, with a reduction in load-bearing cross-sectional area of 32–50%.

Zones of reduced sound transmission velocity were observed along the west–east axis, corresponding to the location of external damage and the presence of fungal activity.

At a height of 200 cm, a similar pattern was obtained, with a reduction in load-bearing cross-sectional area ranging from 43–52%.

Sound transmission velocities in healthy wood (green–yellow zone) ranged between 1600–2800 m/s, while values below 600 m/s indicated zones of advanced internal decay.

Visual Tree Assessment confirmed the presence of wood-decaying fungi of the genus *Ganoderma*, supporting the tomographic findings (Figure 10). Despite the detected internal decay, the combined results indicate that the remaining sound wood provides sufficient structural integrity, and the tree currently exhibits stable mechanical behavior without immediate risk to static safety.

The bark is locally thickened, with the presence of minor longitudinal cracks and signs of physiological aging.

Several dead branches were observed in the inner part of the crown, along with the occurrence of lichens and moss in the root collar zone and lower sections of the trunk.

Fruiting bodies of fungi of the genus *Ganoderma* sp. (Figure 10.) were identified on the northern side of the trunk, indicating a localized white rot process in the lower part of the stem.



Figure 10. *Ganoderma* sp. fruiting bodies

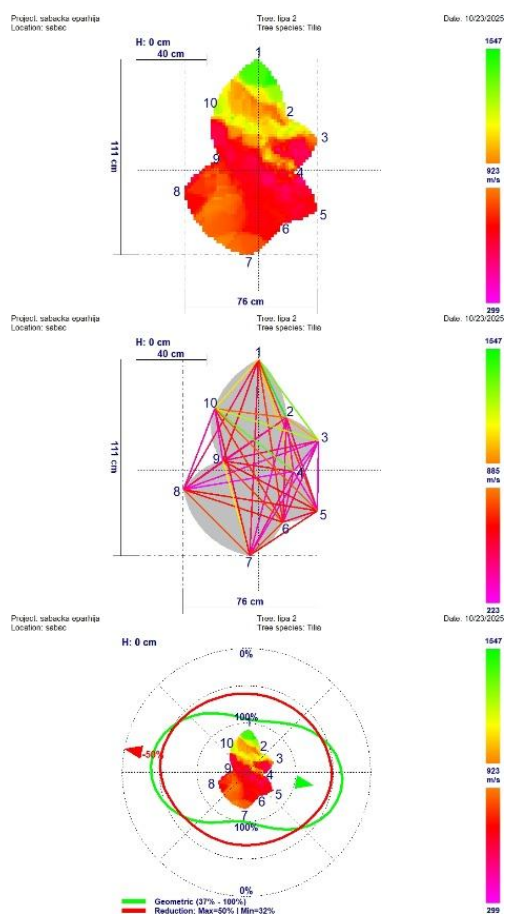
Table 1. Results of tomographic analyses of linden tree – lower cross-section

Parameter	Value
Tree species	<i>Tilia platyphyllos</i> (Lime)
Measurement height	40 cm
Number of sensors	10
Velocity range	580 – 2750 m/s
Estimated cross-sectional reduction	≈ 32 – 45 %
Minimum load-bearing area	≈ 60 – 68 %
Note	Central and marginal wood degradation localized along the W–E axis; correlation with external damage and presence of <i>Ganoderma</i> sp. fruiting bodies

Table 2. Results of tomographic analyses of linden tree – upper cross-section

Parameter	Value
Tree species	<i>Tilia platyphyllos</i> (Lime)
Measurement height	200 cm
Number of sensors	10
Velocity range	620 – 2800 m/s
Estimated cross-sectional reduction	≈ 43 – 52 %
Minimum load-bearing area	≈ 55 – 62 %
Note	Linear degradation zone in the upper part of the cross-section; sound peripheral tissue with stable acoustic velocities

By comparing the obtained values with reference data for healthy wood of deciduous species (Dackermann et al., 2014), it was observed that the measured values fall within the expected range for partially degraded but structurally stable wood.


Figure 11. Tomographs of linden tree – lower cross-section

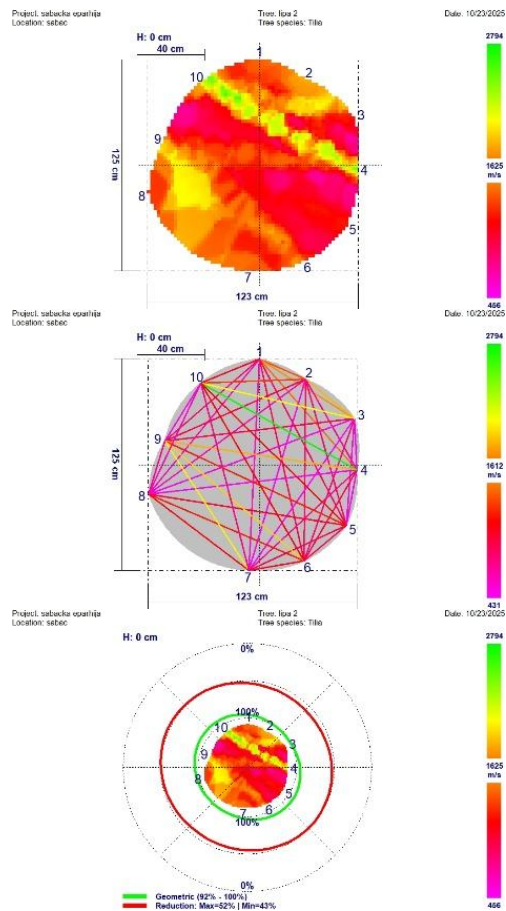


Figure 12. *Tomographs of linden tree – lower cross-section*

5. DISCUSSION AND CONCLUSION

The results obtained in this study demonstrate the applicability and complementary value of integrating multispectral UAV analysis with acoustic tomography for comprehensive assessment of urban tree condition (Živanović et al., 2023). Multispectral analysis based on the NDRE vegetation index enabled spatially explicit evaluation of canopy physiological activity, identifying localized areas of reduced photosynthetic performance within the crown. Given that NDRE is sensitive to chlorophyll concentration and internal leaf structure, its use allows for detection of early physiological stress that may not yet be expressed through visible morphological symptoms (Gitelson & Merzlyak, 1994; Delegido et al., 2011). However, it must be emphasized that data acquisition was performed in late October, during the period of natural senescence in deciduous species, which may influence reflectance-based physiological indicators and complicate interpretation of stress signals. The late-October acquisition represents an important limitation of the NDRE interpretation; therefore, the observed spatial pattern should be validated through multi-seasonal or temporally repeated UAV surveys.

Acoustic tomographic measurements revealed internal structural degradation within the trunk at both investigated heights, with a reduction in load-bearing cross-sectional area ranging from 32–50% at 40 cm and 43–52% at 200 cm. The spatial distribution of low acoustic velocity zones corresponded with the position of externally observed fungal fruiting bodies of the genus *Ganoderma*, suggesting an ongoing localized decay process consistent with white rot development. Despite this internal degradation, tomographic cross-sections indicated the presence of a continuous peripheral ring of structurally sound wood.

Biomechanical interpretation based on residual wall thickness suggests that the trunk retains sufficient load-bearing capacity to withstand mechanical loading under current environmental conditions. According to established failure criteria, trees may maintain structural stability even in the presence of internal cavities provided that the residual wall thickness remains above critical thresholds relative to trunk radius (Mattheck & Breloer, 1994). The measured sound transmission velocities within intact wood tissue were consistent with reference values reported for structurally functional hardwood species (Dackermann et al., 2014), further supporting the interpretation that the observed decay does not currently compromise static stability.

The integration of canopy-level physiological indicators with internal structural diagnostics provides a more robust basis for tree risk assessment than either method applied independently. While multispectral UAV analysis enables early detection of physiological stress and spatial mapping of canopy vitality, acoustic tomography provides direct insight into internal mechanical integrity. This multisensor approach is therefore particularly valuable in urban environments where preservation of mature trees must be balanced with safety considerations. The results are limited by the case-study design, the assessment of a single tree, the late-season timing of multispectral acquisition, and the absence of independent validation of tomographic results. Future work should include larger samples, control trees, repeated seasonal surveys, and additional diagnostic validation.

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REFERENCES

- Aasen, H., Honkavaara, E., Lucieer, A., & Zarco-Tejada, P. J. (2018). Quantitative remote sensing at ultra-high resolution with UAV spectroscopy: A review of sensor technology, measurement procedures, and data correction workflows. *Remote Sensing*, 10(7), 1090. <https://doi.org/10.3390/rs10071090>
- Dackermann, U., Li, J., Crews, K., & Riordan, J. (2014). Acoustic testing for evaluation of standing timber: A review. *Construction and Building Materials*, 65, 1–10. <https://doi.org/10.1016/j.conbuildmat.2014.04.117>
- Deflorio, G., Fink, S., & Schwarze, F. W. M. R. (2008). Detection of incipient decay in tree stems with sonic tomography after wounding and fungal inoculation. *Wood Science and Technology*, 42, 117–132. <https://doi.org/10.1007/s00226-007-0172-4>

Delegido, J., Verrelst, J., Alonso, L., & Moreno, J. (2011). Evaluation of Sentinel-2 red-edge bands for empirical estimation of green LAI and chlorophyll content. *Sensors*, 11(7), 7063–7081. <https://doi.org/10.3390/s110707063>

Gilbert, E. A., & Smiley, E. T. (2004). Picus sonic tomography for the quantification of decay in white oak and hickory. *Journal of Arboriculture*, 30(5), 277–281.

Gitelson, A. A. (2004). Wide dynamic range vegetation index for remote quantification of vegetation fraction. *Remote Sensing of Environment*, 92(3), 318–327. <https://doi.org/10.1016/j.rse.2004.06.016>

Gitelson, A. A., & Merzlyak, M. N. (1994). Spectral reflectance changes associated with autumn senescence of *Acer platanoides* leaves. *Journal of Plant Physiology*, 143(3), 286–292.

Hunt, E. R., Hively, W. D., Fujikawa, S. J., Linden, D. S., Daughtry, C. S. T., & McCarty, G. W. (2013). Acquisition of NIR–green–blue digital photographs from unmanned aircraft for crop monitoring. *Remote Sensing*, 5(2), 674–688. <https://doi.org/10.3390/rs5020674>

Mattheck, C., & Bethge, K. (1998). Failure criteria for trees. *Arboricultural Journal*, 22(2), 123–137. <https://doi.org/10.1080/03071375.1998.9747228>

Mattheck, C., & Breloer, H. (1994). *The body language of trees: A handbook for failure analysis*. HMSO.

Nicolotti, G., Socco, L. V., Martinis, R., & Godio, A. (2003). Application and comparison of three tomographic techniques for detection of decay in trees. *Journal of Arboriculture*, 29(2), 66–78.

Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. *Proceedings of the Third Earth Resources Technology Satellite-1 Symposium (NASA SP-351)*, 309–317.

Sims, D. A., & Gamon, J. A. (2002). Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sensing of Environment*, 81(2–3), 337–354.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8(2), 127–150. [https://doi.org/10.1016/0034-4257\(79\)90013-0](https://doi.org/10.1016/0034-4257(79)90013-0)

Turner, D., Lucieer, A., & Watson, C. (2014). Development of an unmanned aerial vehicle (UAV) for hyper-resolution vineyard mapping based on visible, multispectral, and thermal imagery. *Remote Sensing*, 4(12), 349–365.

Vidican, R.; Mălinaș, A.; Ranta, O.; Moldovan, C.; Marian, O.; Ghețe, A.; Ghișe, C.R.; Popovici, F.; Cătunescu, G.M. Using remote sensing vegetation indices for the discrimination and monitoring of agricultural crops: A critical review. *Agronomy* 2023, 13, 3040

Wang, X., Wiedenbeck, J., & Ross, R. J. (2007). Acoustic evaluation of wood quality in standing trees. *Forest Products Journal*, 57(5), 28–34.

Zarco-Tejada, P. J., González-Dugo, V., & Berni, J. A. J. (2013). Fluorescence, temperature and narrow-band indices acquired from a UAV platform for water stress detection. *Remote Sensing of Environment*, 117, 322–337. <https://doi.org/10.1016/j.rse.2011.10.007>

Zarco-Tejada, P. J., Camino, C., Beck, P. S. A., Calderón, R., Hornero, A., Hernández-Clemente, R., Kattenborn, T., Montes-Borrego, M., Susca, L., Morelli, M., & others. (2018).

Previsual symptoms of *Xylella fastidiosa* infection revealed in spectral plant-trait alterations. *Nature Plants*, 4, 432–439.

Živanović, I., Todorović, N., Rakonjac, L., & Jovanović, F. (2020). Potentials of the assessment of the wood quality in standing trees by applying acoustic methods. *Sustainable Forestry*, 81–82, 121–132.

Živanović, I., Todorović, N., Šurjanac, N., Kabiljo, M., & Jovanović, F. (2021). Physical and mechanical properties of northern red oak. *Sustainable Forestry*, 83–84, 93–105.

Živanović, I., Jovanović, F., Šurjanac, N., Filipović, Đ., & Lučić, A. (2023). Condition of northern red oak trees in the urban environment of Belgrade. *Sustainable Forestry*, 87–88, 89–98.

INTEGRATED ASSESSMENT OF TREE HEALTH AND STRUCTURAL STABILITY USING UAV MULTISPECTRAL IMAGING, 3D PHOTOGRAMMETRY, VTA AND ACOUSTIC TOMOGRAPHY: A CASE STUDY OF A LIME TREE

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Summary

This paper presents an integrated approach to the assessment of the physiological and mechanical condition of urban trees, based on the combined use of multispectral UAV imagery, photogrammetric 3D modeling, Visual Tree Assessment (VTA), and acoustic tomography (Arbotom). The methodology was applied to a mature lime tree (*Tilia platyphyllos*) located in the courtyard of the Bishop's Palace of the Šabac Eparchy, with the aim of obtaining a more reliable assessment of canopy vitality, internal trunk condition, and overall structural stability.

The NDRE index derived from multispectral imagery indicated localized areas of reduced physiological activity within the crown. Acoustic tomography identified zones of internal wood degradation at two measurement heights, while the 3D photogrammetric model of the trunk improved the accuracy of sensor positioning and cross-sectional interpretation. Visual inspection further supported the findings by confirming the presence of fruiting bodies of *Ganoderma* sp., indicating an ongoing localized decay process. Because the multispectral survey was performed in late October, the NDRE results should be treated as indicative spatial patterns and not as conclusive proof of physiological decline without repeated seasonal monitoring.

Although internal defects were detected, the results showed that the tree still retains a continuous ring of sound peripheral wood and sufficient load-bearing capacity under current conditions. The study indicates that the integration of canopy-level physiological indicators with internal structural diagnostics can improve the reliability of tree condition assessment and provide a stronger basis for decision-making in urban tree management and risk evaluation. The findings remain limited to a single case-study tree and should be further tested on larger samples, control trees and through additional validation of tomographic outputs.

**INTEGRISANA PROCENA ZDRAVSTVENOG STANJA I STRUKTURNE
STABILNOSTI STABALA PRIMENOM UAV MULTISPEKTRALNOG SNIMANJA,
3D FOTOGRAMETRIJE, VTA METODE I AKUSTIČNE TOMOGRAFIJE:
STUDIJA SLUČAJA LIPE**

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Rezime

U radu je prikazan integrisani pristup proceni fiziološkog i mehaničkog stanja urbanih stabala, zasnovan na kombinovanoj primeni multispektralnog UAV snimanja, fotogrametrijskog 3D modelovanja, vizuelne procene stabla (VTA) i akustične tomografije (Arbotom). Metodologija je primenjena na starom stablu lipe (*Tilia platyphyllos*) u dvorištu Vladičanskog dvora Eparhije šabačke, sa ciljem da se pouzdanije sagledaju vitalnost krošnje, unutrašnje stanje debla i ukupna strukturna stabilnost stabla.

Vrednosti NDRE indeksa, dobijene iz multispektralnih snimaka, ukazale su na lokalizovane zone smanjene fiziološke aktivnosti u krošnji. Akustična tomografija je registrovala zone unutrašnje degradacije drveta na dve merne visine, dok je fotogrametrijski 3D model debla omogućio preciznije pozicioniranje senzora i pouzdaniju interpretaciju poprečnih preseka. Nalazi su dodatno potvrđeni vizuelnom procenom, kojom je utvrđeno prisustvo plodnih tela gljiva roda *Ganoderma* sp., što ukazuje na lokalizovan proces truleži. Pošto je multispektralno snimanje obavljeno krajem oktobra, rezultate NDRE indeksa treba tumačiti kao indikativne prostorne obrasce, a ne kao konačnu potvrdu fiziološkog opadanja bez ponovljenih sezonskih snimanja.

Iako su unutrašnja oštećenja utvrđena, rezultati pokazuju da stablo i dalje poseduje kontinualni prsten očuvanog perifernog drveta i dovoljnu nosivost u postojećim uslovima. Dobijeni nalazi ukazuju da povezivanje pokazatelja fiziološkog stanja krošnje sa dijagnostikom unutrašnje strukture debla može doprineti pouzdanijoj proceni stanja stabla i pružiti čvršću osnovu za donošenje odluka u upravljanju urbanim zelenilom i proceni rizika. Nalazi su ograničeni na jedno stablo kao studiju slučaja i potrebno ih je proveriti na većem uzorku, uz kontrolna stabla i dodatnu validaciju tomografskih rezultata.