prof. dr hab. inż. Bogusław Szlachetko
Katedra Akustyki, Multimediów i Przetwarzania Sygnałów
Wydział Elektroniki, Fotoniki i Mikrosystemów
Politechnika Wrocławska

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Review of the Ph.D. Thesis

Thesis Title:	**Deep Learning Methods for Automated Urban Monitoring System Using Synthetic Aperture Radar**
Author:	I Made Sandhi Wangiyana, M.Sc.
Supervisor:	prof. Piotr Jerzy Samczyński, Ph.D., D.Sc.
Discipline of Science:	Information and Communication Technology
Field of Science:	Engineering and Technology

1 General Characteristics of The Thesis

The subject of the review is the doctoral dissertation of I Made Sandhi Wangiyana, M.Sc. The review was prepared at the request of the Scientific Council of the Discipline of Information and Communication Technology, Warsaw University of Technology expressed in a letter dated 4/12/2024. The dissertation was written in English; therefore, the review was also prepared in the same language.

The doctoral dissertation submitted for assessment discusses an innovative approach to monitoring the Earth's surface using Synthetic Aperture Radar (SAR) technology. This is a key issue in many fields, including environmental research, assessment of the impact of natural disasters on urban areas and the natural environment, urban development studies, and agricultural land use studies. In all of these fields, SAR technology has several advantages over satellite remote monitoring. SAR radar provides the ability to conduct observations even through clouds in all weather conditions. An unmanned aircraft with SAR radar can operate over the monitored area in ad hoc mode, and additionally, SAR images are available almost immediately after registration. The research problem addressed in the doctoral dissertation submitted for evaluation was the analysis of SAR images. Due to their specificity and the amount of data, human analysis, although possible with extensive experience, would be a time-consuming and difficult task. For this reason, deep learning algorithms were developed in the dissertation to automate the analysis process. The main issues of automatic analysis of SAR images focus on:

- segmentation and classification of buildings, urban/suburban areas, communication infrastructure, watercourses, etc.
- monitoring/detection of damage in the urban environment due to major natural disasters,
- monitoring/detection of changes in the natural environment before and after a significant event (flood, earthquake, fire).

The author discussed three main research theses.

1. It is possible to develop a set of transformations (e.g. geometric) of SAR images (data augmentation) to increase the quality of building segmentation.
2. It is possible to detect large changes in multitemporal SAR images using an auto-encoder that was trained unsupervised.
3. It is possible to perform an urban Land Use Land Cover (LULC) classification on a single polarization SAR image.

In the research section of the dissertation, the author extensively examined various technological aspects of neural networks and machine deep learning. The discussion then moved to the experimental studies conducted, referencing each of the aforementioned hypotheses and presenting the results that confirm these research theses.

The topics discussed in the doctoral dissertation are highly relevant, and it should be noted that this research aligns with the global trend of employing artificial intelligence (AI) algorithms to analyze extensive measurement data. SAR images are valuable sources of information because of the rapid speed of data acquisition, particularly in the aftermath of natural disasters. They enable rescue services to quickly assess large areas, allowing a prompt response to critical locations. The methods developed for machine learning and automatic damage assessment using artificial intelligence can be a key element of the crisis response system.

Section 1 **Introduction** is 7 pages long and contains a short introduction to the issue of remote sensing using SAR technology. In addition, the author formulates research theses and indicates the main research contributions. The author's publications achievements are pointed out in this section and linked with the research theses and achievements described in the dissertation. It is worth mentioning that the author provides all source codes of the developed algorithms under an open license, which allows for verification of the results and further research.

Section 2 **Synthetic Aperture Radar** covering 13 pages presents SAR technology. The Ph.D. student explains how SAR images are created and describes how to interpret them. A very important aspect of these explanations is indicating the sources of erroneous/problematic pixels in the image, which affect later problems in visual analysis (by humans) and automatic analysis. There are numerous references to literature throughout the section that allow deepening knowledge of the discussed issues.

Section 3 **Deep Learning** consisting of 13 pages introduces basic issues related to artificial intelligence, machine learning, deep learning, and neural networks. In addition, this section defines all metrics used to assess the quality of the algorithms developed. The introduced concepts organize the reader's knowledge and are necessary to understand the essence of the research presented in the following sections. In this section, the author often refers to the literature, demonstrating a great understanding of the field of machine learning.

Section 4 **Deep Learning for Building Unit Damage Assessment using SAR: Progress and Challenges**, which consists of 14 pages, presents the current state of knowledge in the field of building damage assessment. Methods using satellite images taken in the visible band are presented. Reference is made to published results obtained by automatic damage assessment using convolutional neural networks (CNN). A comparison of satellite optical images with SAR images was made, showing fundamental differences. In addition, the doctoral student indicated the low availability of public databases containing SAR imaging, which is a fundamental challenge in conducting research. The section contains numerous references to the literature.

Section 5 **Data Augmentation for Building Footprint Segmentation in SAR Images: An Empirical Study** covers 20 pages and presents the results of experimental research related to data augmentation. The Ph.D. student proposed and studied many geometric transformations and image distortions in terms of the impact of the presence of additional images acquired in this way on the learning and generalization process achieved by the DL algorithm. The doctoral student experimentally investigated which transformations of SAR images are valuable in terms of learning improvements, and selected transformations that lead to worse results. In addition, evidence is presented that in the case of small sets of SAR images used during training, the use of augmentation improves the results of the segmentation.

Section 6 **Detecting Large Scale Event from SAR Time Series** consisting of 12 pages presents the results of experimental studies related to training an autoencoder to detect changes caused by natural disasters. Public databases containing multi-temporal SAR images were used in this problem. The Ph.D. student developed a method for automatic detection of changes in subsequent images. He also indicated problems related to this analysis and investigated their causes. The Ph.D. student presented experimental evidence that for a given area, based on multitemporal SAR images, it is possible to train an autoencoder without supervision so that it correctly detects large changes. The Ph.D. student also indicated that the training process for each new location should be carried out separately due to the specificity of microwave interaction in different parts of the Earth.

Section 7 **SAR Imagery for Urban Density Analysis** includes 18 pages and presents the results of experimental studies on the classification of urban areas. The Ph.D. student investigated the possibility of using SAR images recorded in different polarizations and analyzed which features of these images are important for automatic classification. The studies indicated that the features considered have a similar probability distribution, except for water areas. After analyzing the features, the Ph.D. student proposed a set of features and conducted experimental studies. The studies showed imperfections both on the side of automatic classification and on the side of the imprecisely designated database used in the studies. Despite this, it was possible to develop a learning and classification method that allows better results to be obtained compared to those reported in the literature, which was accepted as confirmation of the third (last) research thesis.

Section 8 **Conclusion** which covers 2 pages summarizes the doctoral thesis. The author synthetically describes the conducted experimental studies and the achieved results. The section also indicates possible directions for the development of the work in the aspect of SAR image analysis.

The dissertation is supplemented by a list of references **References**, which consists of 200 (instead of 201) items, including 5 (instead of 6) items authored or coauthored by the doctoral student. It should be noted that references [16] and [49] are identical. The literature is well selected and indicates the doctoral student's extensive knowledge of the disciplines of machine learning and data analysis, as well as radar technologies, with particular emphasis on SAR.

2 Evaluation of the Dissertation Topic and Objectives

The research carried out by the Ph.D. student uses a combination of deep learning techniques and SAR image analysis to develop a comprehensive monitoring system for urban areas or the natural environment. The proposed methodology consists of the following steps:

Data collection: SAR images were collected from publicly available datasets and commercial providers, providing a variety of environments. In the target system, SAR images can be relatively easily acquired using an unmanned aircraft as the SAR radar carrier.

Pre-processing: Standard SAR data processing techniques such as speckle reduction, radiometric calibration, and geometric correction were applied to improve image quality.

Model selection and training: Three deep learning approaches were implemented:

- Unsupervised learned autoencoders for detection of changes in multitemporal SAR images.
- Convolutional neural networks (CNN) for building segmentation.
- Land Use Land Cover (LULC) classification models using SAR intensity data.

Data augmentation: Techniques such as geometric transformations and synthetic data generation were applied to increase the size of the training set and improve the generalization of the model.

Evaluation Metrics: Models were evaluated using standard performance metrics, including Intersection over Union (IoU), Precision, Recall, and F1 score, ensuring reliable validation.

Implementation and validation: Experiments were conducted in different urban landscapes, comparing the results in different SAR imaging modes.

The experimental studies described in the assessed thesis indicate that unsupervised autoencoders can effectively detect large-scale changes in SAR images, confirming the feasibility of unsupervised event detection methods. At the same time, the Ph.D. student observed a strong dependence of SAR imagery on the geographic location of the monitored area. The studies also showed that building footprint extraction models, especially CNN-based approaches, showed improved accuracy after training using carefully selected datasets and advanced data augmentation techniques. Data augmentation strategies such as geometric transformations, synthetic data generation, and adaptive filtering significantly increased the robustness and generalization of the model in various urban environments. An important achievement is the demonstration that LULC segmentation and classification using single-polarization SAR images can be a viable alternative to traditional optical image analysis, although the variability of SAR data posed a challenge in achieving high generalization. However, the models developed enable an effective interpretation of the SAR-based classification results, making them more accessible for practical applications in disaster response and urban planning. In addition, a significant contribution is the provision of open-source code and test datasets, which will facilitate further research on SAR-based deep learning methodologies.

The structure of the assessed doctoral thesis is unobjectionable. An orderly and logical chain of reasoning is presented. At each stage, the developed argumentation indicates a broad knowledge and clear understanding of the complexity of the issue of SAR-based urban monitoring. The author systematically introduces subsequent research challenges, justifies methodological choices, and effectively supports claims with empirical evidence. The text is precise and technical, making complex deep-learning concepts accessible to readers familiar with the field. The organization of the content provides a smooth transition from theoretical foundations to practical implementation, increasing readability. In addition, the use of visual aids, including graphs and illustrations, effectively complements the textual explanations, facilitating the interpretation of the results. The clarity of the presentation contributes significantly to the comprehensibility and impact of the dissertation, making it a valuable resource for researchers and practitioners in the field of remote sensing and artificial intelligence.

3 Original Achievements of the Dissertation

The dissertation presents several original achievements that advance the field of deep learning applications in monitoring urban areas and the natural environment using SAR imaging. One of the key innovations is the development of an unsupervised autoencoder-based method for large-scale change detection in SAR images, a technique that has been shown to outperform conventional change detection algorithms in terms of precision and generalization level. Compared to previous studies that heavily rely on supervised learning approaches, the proposed method significantly reduces the dependence on labeled datasets that are rarely available in SAR applications.

In addition, the dissertation introduces a new data augmentation strategy specifically tailored to SAR imaging. Unlike traditional augmentation techniques commonly used in computer vision, this approach involves geometric transformations and synthetic data generation tailored to the unique features of SAR, such as speckle noise and variable acquisition geometry. The proposed training set augmentation method has demonstrated the potential to achieve better generalization and precision for building segmentation in various urban environments.

The study also contributes to a better understanding of the working mechanisms of deep learning models in SAR-based classification. Although many existing works use black-box AI techniques without interpretability, this thesis integrates AI methods with the ability to explain the impact of individual aspects of the model, providing clarity in design decisions and improving its applicability to practical urban monitoring tasks. The experimental results are in line with expectations and previous studies. However, at the same time, the proposed solutions can increase confidence in AI-based SAR analysis, which is a key aspect in disaster response and urban development planning applications.

According to the data contained in the *Web of Science (WoS)* database as of 31/01/2025, the Ph.D. student is a co-author of five scientific publications. One of the publications in the scientific journal *Remote Sensing* is on the JCR list: the **IF=4.9**, and the **MNiSW=100 pkt**. This publication is cited **9 times**. In two publications, the Ph.D. student appears as the sole author, and these are conference publications. The total number of citations is equal to **11** without self-citations. So far, conference papers have been presented at conferences thematically related to the field of radar signal processing, i.e.: *Signal Processing Symposium (SPSympo)* and *International Radar Symposium (IRS)*. This may be the reason for limiting the impact of the Ph.D. student's research results on the development of other scientific disciplines. However, I believe that the author's work has contributed to the development of SAR imaging-based monitoring methods, providing a basis for further research and development in this field. Providing publicly available code and datasets has further increased the accessibility and reproducibility of research, supporting collaboration between researchers and practitioners in remote sensing and AI.

4 Critical Remarks and Suggestions for Improvement

My assessment of the dissertation is positive, although I would like to mention a few **critical remarks**:

1. Equation (2.3) is incorrect because the result is a dimensionless quantity instead of $[m^2]$. This is probably an oversight because the correct relationship given in the literature is as follows:

$$\sigma = \lim_{r\to\infty} 4\pi r^2 \frac{||E_s|^2}{|E_l|^2},$$

   where r means the distance from the object and E_s, E_l means the scattered and incident electric field intensities of the far field, respectively. For simplicity, the symbol lim can be neglected, but the distance r should still be present in the equation.

2. In Figure 2.1 there is a lack of $\sin(\Theta_i)$ in the formula for ground resolution ρ_G. However, the picture is very clear and informative. The comments to Equation (2.7) provide information that to increase the azimuthal resolution ρ_A, one can increase antenna length L, but the Ph.D. student omitted other possibilities, e.g. increasing the SAR radar operating frequency, which is the most common solution.

3. The comments to equation (2.7) provide information that to increase the azimuthal resolution ρ_A one can increase antenna length L but the Ph.D. student omitted other possibilities, e.g. increasing the SAR radar operating frequency, which is the most common solution.

4. At the end of Section 2.3.1, the Ph.D. student wrote that $f_s = f_r$ without further explanation. It would be more beneficial to provide additional details on this relationship.

5. The term "bitemporal SAR images" was first introduced on page 47, but it lacks a precise definition. Does "bitemporal" refer to any time difference between two SAR images of the same area, or does it specifically pertain to the availability of SAR images taken before and after an event? It is important to establish a clear definition and use it consistently throughout the dissertation.

6. Equation (4.2) lacks a clear explanation; it is uncertain whether the matrix S and its four components represent the intensity of a specific pixel in the SAR image or it pertains to a tile or the entire SAR image. It is worth giving the definition even if the reader can find these definitions in the cited literature.

7. The author in the introduction referred to the publication [12] and emphasized that objects created by humans are characterized by "strong backscatter in radar images" while in Section 7 he stated that distinguishing them from natural objects is not so obvious.

8. The References section should contain only 200 items because the items at positions [16] and [49] are identical.

I also have a few **polemic comments**:

I. The author mentioned several times the possibility of using interferometric analysis of SAR images, but honestly added that this topic is beyond the scope of this dissertation. The dissertation contains section 4.2.2 Coherence, where the author devotes some space to this issue. However, it seems that due to the size of the buildings and the wavelength used for SAR imaging, the use of phase information for building unit damage assessment can be problematic due to the known phenomenon of phase ambiguities. Please explain this issue during the defense of the doctoral dissertation.

II. The dissertation indicates the basic sources of errors in SAR imaging, i.e. layovers, foreshortening, and shadows. The author did not propose any method to minimize these errors and indeed in a single flight, the SAR radar performs measurements at a constant relatively large angle to the ground surface. Consequently, tall objects, e.g. buildings, will cause layovers and shadows. With the rapid development of unmanned aviation, SAR radar can now be mounted on UAVs, enabling a variety of missions. As a result, the selected area can be covered with SAR images taken in different flight directions, e.g. perpendicular. Next, in post-processing, overlapping tiles can be determined from both flight directions, superimposed on each other and missing fragments of layovers and shadows from one tile can be supplemented based on the corresponding fragments from the other tile. It is worth noting that in the case of buildings whose walls will be perpendicular and parallel to the direction of flight, such flight missions should, in theory, eliminate both errors, i.e. layovers and shadows. In the case of buildings that are rotated at a specific angle to the flight direction, it may be necessary to operate the UAV with SAR radar in three directions intersecting at an angle of 60 degrees. I kindly request to analyze this concept during the doctoral defense, paying particular attention to the following questions. What will be the theoretical result for buildings with non-perpendicular walls? What results will be achieved for buildings with curvilinear walls? Can the height of the building be estimated based on the length of shadows in different flight directions?

III. The statement "limited set of SAR images" used in the research thesis and then repeatedly quoted in section 5 raises doubts. The doubts arise from the fact that the database on which the experiments were performed contained a relatively large number of SAR images. Please refer to this issue during the defense of the doctoral dissertation.

5 Summary and Recommendation

The Ph.D. student I Made Sandhi Wangiyana, M.Sc. originally and innovatively proved the three research theses stated in the doctoral dissertation. It should be emphasized that the Ph.D. student used broad and interdisciplinary knowledge in the field of radar signal processing (including SAR imaging), the use of AI methods, and the discipline of environmental research. The work properly selected the IT tools and the latest scientific achievements in the field of deep learning methods and neural networks were used. One crucial aspect of a doctoral dissertation is the extensive use of not so many public databases where SAR images collected and annotated by research teams around the world are stored. It is worth noting that the Ph.D. student made his algorithms and research results available on a public server. This demonstrates the Ph.D. student's extensive research horizons and his sensitivity to making knowledge widely accessible. The Ph.D. student has demonstrated in the dissertation that he has high research skills and advanced knowledge of an interdisciplinary nature. All these attributes of a Ph.D. student are necessary to independently conduct scientific research in the discipline Information and Communication Technology.

In conclusion, I state that the doctoral student I Made Sandhi Wangiyana, M.Sc., **proved the research theses by introducing his original solutions. Thus, he made a significant contribution to the advancement of the discipline Information and Communication Technology**.

The reviewed dissertation **meets the conditions** specified in art. 187 of the Law on Higher Education and Science (Journal of Laws 2023, item 742, as amended) in the field of Engineering and Technology sciences, in the discipline Information and Communication Technology. **I kindly request that the dissertation be accepted and allowed for public defense**.

Szlachetko Bogusław