Abstract

The framework of landscape heritage conservation is extremely complex due to the historical stratification, territorial extension, and heterogeneity of such context. In fact, it is not possible to study and preserve landscapes without a thorough knowledge of the geographic relationships that landscapes, as cultural and environmental heritage, establish with the territory they occupy and the people who inhabit them.

Considering this complex context, remote sensing methodologies are nowadays increasingly crucial for acquiring accurate spatial data for heritage documentation processes. In fact, the technological development of surveying sensors and operating platforms over the last decades has been directed toward the enhancement of consistency, richness, expeditiousness, and resolution of the acquired dataset. However, although the Cultural Heritage (CH) domain could benefit from recent advancements, issues arise while managing such extensive and high-resolution datasets. Specifically, automating the semantic structuring of raw spatial data is a well-known challenge when dealing with extended data, where machine learning (ML) techniques provide several methodologies that are studied to overcome manual labeling activities. In this regard, the Geographic Information Science (GIS) environment adequately supports multi-dimensional and interdisciplinary 2D/3D data interpretation and analysis. Yet, these methodologies are not fully addressed and consolidated, especially considering the landscape and built heritage contexts. Thus, finding an automated, efficient approach for analyzing, mapping, and preserving landscape heritage becomes crucial.

Given the aforementioned issues and challenges, the present doctoral thesis focuses on the integration of airborne Light Detection and Ranging (LiDAR) data with ML methods for the semantic classification of both landscape and built heritage. Namely, this work proposes a systematic approach of identification and mapping at the base of conservation processes by using high and low-scale airborne LiDAR data and tailored ML models toward CH sites analysis, with particular interest in terrains difficult to access or presenting complicated geographical conditions. The research is based on the application of a methodological framework in two different case studies in Italy: Spina Verde Park in Como and the defensive landscapes of Sardinia. Each of these case studies is characterized by challenges ranging from highly vegetated areas, hiding archaeological structures in the Como Park, to extended and poorly documented defensive systems across both coastal and rural surface areas in Sardinia. The scheme of this research in Spina Verde Park involves high-density airborne LiDAR data for detecting and mapping anthropogenic features, such as trails related to ancient settlements.

In this regard, the leverage of a high-resolution dataset has been useful to test specific deep learning (DL) pipelines that have been studied more by exploiting similar-scale datasets. The Sardinian case study concerns historical defensive landscapes characterized by several fortification systems, such as Spanish coastal towers and bunkers from the Mediterranean Wall, which demand advanced data structuring pipelines considering the widespread distribution of artifacts and chrono-typological heterogeneity. Moreover, the second case study addresses the specific challenges of automating the semantic classification of low-resolution airborne point clouds.

In this regard, key methodologies include supervised ML and DL, supported by unsupervised techniques, such as point cloud semantic segmentation and object class identification methods. These approaches develop a semi-automated, repeatable process for data structuring and generating Digital Terrain Models (DTMs). This thesis demonstrates how the application of neural network models to airborne LiDAR data can accomplish highly accurate landscape classification with a high level of automation. Nevertheless, the results presented in the thesis also highlighted the efficiency of such ML workflows by reducing the time required for data processing while ensuring standards in data accuracy towards heritage conservation.

Specifically, during this research experience, different automated methods have been proposed for the semantic classification of raw 3D data and the mapping of anthropogenic features related to landscape microtopography characteristics. The contribution also addresses accessibility gaps in geospatial analysis by exploring software and coding solutions that enhance the usability of AI-powered tools for heritage professionals, therefore developing flexible workflows for the application of data structuring and analysis strategies for CH.

Finally, the originality impact of the thesis is linked to knowledge enhancement in the field of landscape heritage conservation through the development of a transferable and scalable methodology that exploits machine learning methodologies for multi-sensor remote sensing applications.