1. Cover Page

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Sunil Bhaskaran 12/21/24

2. Abstract

This project aimed to develop a foundation model for geospatial analysis using Sentinel-2 data, focusing on the use of machine learning and deep learning principles for accurate land-use classification. A U-Net-based model was designed to extract spatial and semantic features, addressing challenges like classification of near similar time series of land use cities throughout the globe with the most accurate representation model. Using unsupervised classification as a reference library, we created a comprehensive training pipeline. Additionally, side tasks such as validating HLS2 inaccuracies and accuracy assessments with Landsat and Sentinel data enhanced the reliability of the direction for this approach. This work not only advanced geospatial feature extraction but also contributed to understanding complex relationships in land-use patterns for environmental research.

3. Introduction

This fall semester, I interned with the BCC Geospatial Center of the CUNY CREST Institute [BGCCCI], located in Bronx, New York. The main focus of the center's research is in developing scientific applications using multi-resolution spaceborne and airborne remotely sensed datasets and geospatial analytics, machine learning, deep learning techniques for conducting innovative applied research [**Climate Change**, **Deep Learning**, **Decarbonization**, and **Aerosol Optical Depth**].
I worked on innovative techniques of image analysis including pixel-based, object-based and machine/deep learning algorithms and design of a customized multi-modal architecture for extracting terrestrial features from multi-spectral imagery. My approach included using a time series of Harmonized Landsat-Sentinel2 (HLS2), Sentinel 2-Level 2A and Landsat surface reflectance products.

4. Discussion of Projects

Responsibilities During the Internship

I was responsible for assisting the Director of the Center in designing a customized Neural Network-Based Model (NNM) for extracting feature objects from multi-spectral imagery. I worked on creating a customized multi-modal U-Net based architecture for designing a model and testing it. This included scripting detailed functions to complete a full data life cycle project. I created a workflow that included ingesting processed multi spectral imagery, stacking specific raster bands, performing cluster analysis, writing the functions for running the Neural Network model and finally testing it with a ground truth image over Teresina and Parnarama Cities in Brazil. I wrote approximately 1,500 lines of code(functions) to design the NNM. I used the following technologies (PyTorch, NumPy, Rasterio, Matplotlib, Semi-Automatic Classification Plugin, AcATaMa Plugin), Quantum Geographic information system (QGIS) and Python language for designing the NNM.

The Center has several projects that required automation and innovation in feature extraction. My efforts assisted the center in streamlining their workflow for generating Image analysis algorithms and applications for a wide range of disciplines such as Urban Planning, Climate Change, Disaster Management and all others that required spatio-temporal analysis.

During my internship, I had the opportunity to work on a groundbreaking geospatial research project focusing on the development of foundational land-use and land-cover (LULC) classification models using deep learning architectures. My primary responsibilities included building neural network models, performing unsupervised and supervised classifications, conducting accuracy assessments, and integrating Sentinel-2 and HLS2 data for spatio-temporal analysis. Alongside this, I carried out detailed geospatial preprocessing tasks and provided insights into environmental and urban changes in South American cities.

Overview of Technical Projects

1. Building the Foundation Model Using Neural Networks:

- Objective: Develop a neural network model, specifically a U-Net based architecture, to classify LULC in urban areas using multi-spectral satellite imagery.
- Tasks:
  - Designed and implemented a U-Net-based deep learning architecture using Python and PyTorch.
  - Integrated multi-spectral Sentinel-2 data, stacking bands to create rich input datasets.
  - Conducted training using classified rasters as ground truth and utilized custom loss functions to optimize classification accuracy.

    - Focused on classifying urban areas, vegetation, water, and paved surfaces, leveraging spatial and spectral relationships for precision.
- Lines of Code: Approximately 1,500 lines, incorporating neural network definition, data handling, preprocessing, and visualization scripts.
- Technologies: Python (PyTorch, NumPy, Rasterio, Matplotlib), GIS tools (QGIS, SCP Plugin, AcATaMa Plugin).
- Significance: This model acts as a scalable, automated solution for accurate LULC classification, reducing dependency on manual interpretation of satellite imagery.

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2. Validating HLS2 Data Accuracy:

- Objective: Compare HLS2 data with Sentinel-2 and Landsat imagery to identify inaccuracies in spectral reflectance and classification results.
- Tasks:
    - Conducted unsupervised classifications using the Semi-Automatic Classification Plugin (SCP) in QGIS.
    - Validated outputs with high-resolution ground truth data and Google Earth imagery.
    - Highlighted discrepancies in cloud masking and spectral normalization across datasets.
- Lines of Code: Usage of prebuilt libraries and open source plugins, primarily for validation workflows and dataset comparison automation.
- Tools: QGIS, SCP Plugin.
- Significance: Identified and corrected critical inaccuracies, ensuring a reliable input dataset for downstream deep learning models.

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3. Integration of Unsupervised Classifications into Neural Network Workflows:

- Objective: Use unsupervised classifications as training data for the U-Net model to improve its ability to differentiate complex urban features.
- Tasks:
    - Preprocessed classified rasters to serve as ground truth for training.
    - Enhanced the U-Net architecture to incorporate semantic and spatial features, such as distinguishing between roads and general paved areas.
    - Conducted extensive reclassification and post-processing to align labels with real-world land cover categories.
- Lines of Code: Approximately 500 lines for preprocessing, reclassification, and integration workflows.
- Tools: Python (Rasterio, PyTorch), QGIS (SCP Plugin), Matplotlib.

- Significance: Streamlined the process of converting unsupervised classifications into actionable training datasets, bridging traditional GIS workflows with modern machine learning techniques.

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4. Temporal Change Detection and Analysis:

- Objective: Identify and quantify land cover changes over time in two South American cities, Valparaíso and San Juan.
- Tasks:
  - Conducted temporal analyses on LULC changes from 2015 to 2023 using multi-year satellite imagery.
  - Integrated georeferencing and polygonization to vectorize changes for better visualization.
  - Generated change detection maps and quantified urbanization and vegetation dynamics.
- Lines of Code: Usage of prebuilt libraries and open source plugins for temporal analysis, georeferencing, and visualization.
- Technologies: QGIS, SCP Plugin, AcATaMa Plugin.
- Significance: Provided critical insights into urban development patterns, supporting policymakers in planning sustainable urban growth.

Technical Details:

- Programming Languages: Python (core), with libraries like PyTorch, NumPy, Rasterio, and Matplotlib for deep learning and geospatial processing.
- GIS Tools: QGIS (for manual and automated classification), SCP Plugin (unsupervised and supervised classification), AcATaMa Plugin (accuracy assessment).
- Datasets: Sentinel-2, HLS2, and Landsat imagery, with 15 spectral bands including visible, NIR, SWIR, and cloud masking data.
- Systems Used: High-performance workstations with GPU acceleration for deep learning tasks; QGIS for GIS operations.

Significance to the Organization:

The work carried out during this internship holds significant importance to the organization’s operations. By building a scalable neural network-based solution for LULC classification, the project has:

- Reduced dependency on manual classification processes, saving time and resources.

- Improved the accuracy and reliability of land cover maps, critical for urban planning and environmental policy formulation.
- Provided a reproducible framework for spatio-temporal analysis, enabling insights into urbanization, vegetation dynamics, and environmental changes over time.

Moreover, the validation of HLS2 data and integration of GIS and machine learning workflows demonstrate a robust approach to handling diverse geospatial datasets, setting a strong foundation for future research and operational projects within the organization.

5. Summary and Conclusions

During my internship, I had the opportunity to work on different types of multi spectral imagery including HLS-2, Landsat and Sentinel-2. I learned to use the open source QGIS software for performing geospatial analysis. I explored unsupervised classification and performed accuracy assessments for different study sites by using time series of HLS-2, Landsat and Sentinel-2. I learned to deep dive into the spectral and spatial resolutions of multi-spectral data and their influence on designing algorithms. I learned to use cluster analysis, a type of deep learning algorithm that is commonly used in image analysis which enhanced my understanding of classification algorithms. This knowledge enabled me to design the NNM. My work involved developing a neural network architecture for feature extraction using different types of satellite imagery. I also learned about the influence of spectral and spatial characteristics of multi-spectral imagery on the classification accuracies which gave me a strong foundation for designing the NNM. I used deep learning, data preprocessing, and geospatial analysis to write the codes for various functions in the development of the NNM.

The internship gave me a solid understanding of spatial and spectral resolutions which is critical for designing multi-modal NNMS. The internship provided me with valuable insights from the supervisor about the importance of multi spectral remotely sensed data and their spectral and spatial characteristics which are fundamental and imperative for designing NNMs. It gave me new perspectives on the importance of integrating machine learning with domain-specific datasets, such as geospatial imagery, and underscored the challenges of working with large, heterogeneous datasets in real-world scenarios.

<u>Benefits and Challenges</u>

The design of NNMs especially for geospatial analysis demands a deep and comprehensive understanding of image resolutions (spectral and spatial). Designing a NNM with partial knowledge of remotely sensed data can negatively impact the performance of the model and lead to inaccurate perceptions and results. I learned to use open source GIS and plugins for running accuracy assessment reports. For example I used the AcATaMa plugin for comparing the results of cluster analysis with test data that was created by using surrogate data (google earth imagery). Prior to that I tried different methods for performing accuracy assessments which did not produce the desired results. I learned to coregister sequence of spatio-temporal images for performing change detection and interpreted the changes on the land cover after running change detection algorithms. I also learned to download imagery from the European Space Agency, NASA and USGS search engines. While the technical challenges were substantial, they provided immense learning opportunities. For example, I initially struggled with integrating unsupervised classifications as reference data for training the U-Net model. Additionally, working with satellite images required an understanding of geospatial data formats, preprocessing, and accuracy assessments—areas that were new to me. By exploring libraries such as Rasterio, PyTorch, and QGIS, and through iterative debugging and research, I overcame these hurdles.

Many of the NYU courses provided foundational knowledge for performing tasks in this internship. For example, Predictive Analytics (CSCI-GA 3033) provided a solid foundation in understanding machine learning algorithms and their evaluation, which I applied during model training and accuracy assessments. The Advanced Computer Graphics (CSCI-GA 2274) introduced me to deep learning for image-related tasks, which directly translated into building and training the U-Net model. The course on Fundamental Algorithms (CSCI_GA 1170) helped me think systematically about designing efficient preprocessing workflows for handling multi-spectral data. The knowledge acquired from Scala, Ada through the Programming Languages (CSCI-GA 2110) course strengthened my proficiency in Coding.

Suggestions for NYU Curriculum

While my academic coursework was highly relevant, incorporating hands-on projects involving real-world datasets, such as remote sensing imagery, could further bridge the gap between theoretical knowledge and practical applications. Collaborations with other Centers such as BGCCCI can provide opportunities for NYU professors to get exposure in Geospatial data analytics which in combination with NYU courses can be useful for designing and developing real world applications.

Conclusion

This internship has been a transformative experience, giving me practical skills in deep learning, geospatial analysis, and real-world problem-solving. It not only reinforced my interest in AI and environmental applications but also deepened my understanding of how to design, implement, and evaluate machine learning models for complex datasets. The challenges I faced and the solutions I devised have significantly enriched my technical expertise and prepared me for future roles in this dynamic field. The significance of expert supervision is at the heart and soul of any internship and is often the difference between a mediocre internship and a great one.