PROMPT2MAP: MAPS GENERATION FROM NATURAL LANGUAGE QUERIES USING LARGE LANGUAGE MODELS (LLM)

José Miguel Cordero Carvacho

Dissertation presented as partial requirement for obtaining the degree of Master in Geographical Information Systems and Science

NOVA Information Management School

NOVA Information Management School
Instituto Superior de Estatística e Gestão de Informação
Universidade NOVA de Lisboa

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Adviser: Professor Pedro da Costa Brito Cabral

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Resumo

Prompt2Map: Geração de Mapas a partir de Consultas em Linguagem Natural Utilizando Grandes Modelos de Linguagem (LLM)

Os Sistemas de Informação Geográfica (SIG) e as tecnologias web tornaram a criação de mapas mais acessível do que nunca. No entanto, ainda é necessário um conhecimento técnico das ferramentas de SIG para produzir resultados cartográficos. Esta tese apresenta o Prompt2Map, um sistema que converte consultas em linguagem natural em mapas web utilizando Grandes Modelos de Linguagem (LLMs). A nossa abordagem baseia-se em *Retrieval-Augmented Generation* (RAG), envolvendo uma etapa inicial de extração de dados a partir de fontes geoespaciais, seguida de uma etapa de mapeamento para visualizar os dados. Testes de desempenho realizados com consultas sintéticas demonstram a eficácia do sistema. Discutimos também as implicações éticas desta abordagem. Este trabalho contribui para reduzir a lacuna entre consumidores e produtores de mapas, oferecendo uma interface em linguagem natural para dados geoespaciais autoritativos, aproximando assim a informação espacial do público em geral.

Palavras-chave

Grandes Modelos de Linguagem

Sistemas de Informação Geográfica

Cartografia

IA Generativa

RAG

Abstract

Prompt2Map: Maps Generation from Natural Language Queries Using Large Language Models (LLM)

Geographic Information Systems (GIS) and web technologies have made map creation more accessible than ever before. However, a technical understanding of GIS tools is still required to produce cartographic outputs. This thesis introduces Prompt2Map, a system that converts natural language queries into web maps using Large Language Models (LLMs). Our approach is based on Retrieval-Augmented Generation (RAG), involving an initial step to extract data from geospatial sources, followed by a mapping step to visualize the data. Performance tests conducted over synthetic prompts demonstrate the system's effectiveness. We also discuss ethical implications of this approach. This work contributes to bridging the gap between map consumers and producers, offering a natural language interface to authoritative geospatial data, thereby bringing spatial information closer to the general public.

Keywords

Large Language Models

Geographic Information Systems

Cartography

Generative AI

Retrieval-augmented generation

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Introduction

1.1 Motivation

Geographic Information Systems (GIS) have become indispensable tools in various disciplines, including urban planning, environmental management, public health, and transportation. These systems enable professionals to visualize, analyze, and interpret spatial data, facilitating informed decision-making based on geographic relationships and patterns. Despite the proliferation of GIS technologies and the increasing availability of geospatial data, the process of creating meaningful maps and conducting spatial analyses often remains confined to experts with specialized training. This expertise barrier limits the accessibility and utility of GIS for a broader audience, including policymakers, educators, and the general public (Haklay, 2013).

The democratization of GIS has been an ongoing pursuit, with efforts focused on making spatial data and mapping tools more accessible to non-specialist users. Advancements in technology, such as web-based GIS platforms and open-source software, have lowered some barriers, allowing users to access spatial data and perform basic analyses without requiring extensive technical knowledge. However, these platforms often still necessitate familiarity with GIS concepts, terminologies, and interfaces, which can be intimidating for those without specialized training. This gap underscores the need for more intuitive and user-friendly interfaces that can cater to a diverse range of users with varying levels of expertise.

Simultaneously, the field of Artificial Intelligence (AI), particularly Natural Language Processing (NLP), has witnessed significant advancements. Large Language Models (LLMs), such as OpenAI's GPT series, have demonstrated remarkable capabilities in understanding and generating human-like text. These models can interpret nuanced queries, generate coherent responses, and perform tasks like code generation and translation. The integration of LLMs with GIS presents an opportunity to bridge the gap between expert GIS practitioners and non-specialist users. By enabling users to interact with GIS platforms through natural language queries, we can lower the barriers to entry, allowing a wider audience to leverage spatial data for various purposes.

Such integration could revolutionize how users access, analyze, and visualize geospatial information, making GIS more inclusive and user-friendly. For instance, policymakers could generate complex spatial analyses without needing to write queries in technical language or manipulate GIS software interfaces manually. Educators could create interactive maps for teaching purposes with simple verbal instructions, enhancing the learning experience for students. Additionally, the general public could engage with spatial data to better understand community planning initiatives, environmental changes, and public health trends.

However, this integration is not without challenges. Accurately interpreting natural language queries in a geospatial context requires the LLM to comprehend spatial concepts, relationships, and terminologies. Ensuring that the system retrieves the correct data and generates accurate maps is critical to maintaining trust and utility. Ethical considerations, including data privacy, trustworthiness, and potential biases, must also be addressed to ensure responsible deployment. Misinterpretations of queries could lead to incorrect data retrieval and misleading visualizations, which could have serious implications in fields like public health or urban planning.

This thesis proposes the development of Prompt2Map, a system that leverages LLMs to convert natural language queries into interactive web maps. The system aims to facilitate geospatial data retrieval and map generation, making GIS more accessible to non-expert users. Through this work, we seek to contribute to ongoing efforts to democratize GIS and explore the intersection of AI and geospatial technologies. By addressing both technical and ethical challenges, Prompt2Map aspires to provide a reliable and user-friendly tool that empowers a diverse range of users to engage with spatial data effectively.

1.2 Objectives

The objectives of this thesis are threefold. First, to develop the Prompt2Map system, which is capable of converting natural language queries into interactive web maps by leveraging LLMs in conjunction with geospatial data retrieval techniques. The system should be able to interpret a wide range of queries, retrieve relevant data from various sources, and generate accurate and informative maps. This involves integrating advanced NLP capabilities with robust data processing and visualization tools to create a seamless user experience.

Second, to evaluate the effectiveness of Prompt2Map through a series of validation tests using synthetic prompts tailored to specific datasets. The evaluation will analyze metrics such as accuracy in data retrieval and map generation. This comprehensive evaluation aims to ensure that the system meets its performance goals and can handle diverse user needs and data complexities.

Third, to analyze the ethical implications associated with using LLMs for map generation. This includes issues of data privacy, potential biases in data and algorithms, alignment with user intent, risks of misinformation, and the potential for misuse. Strategies for mitigating these risks will be proposed and integrated into the system design. Ensuring ethical integrity is paramount to maintaining user trust and preventing harmful outcomes resulting from AI-generated maps.

By achieving these objectives, the thesis aims to contribute to making GIS tools more accessible and user-friendly, fostering greater engagement with spatial data among non-specialists, and promoting responsible use of AI in geospatial applications.

1.3 Thesis Structure

The thesis is organized into six chapters. The introduction provides the motivation for the study, outlines the objectives, and summarizes the thesis structure. The background chapter reviews the evolution of GIS towards greater accessibility, discusses the role of neogeography and self-service GIS platforms, introduces LLMs in the context of GIS, and addresses ethical considerations related to AI-generated maps.

The methods chapter details the system architecture of Prompt2Map, describes the datasets used for evaluation, and outlines the methodologies for system testing and ethical assessment. It delves into the technical aspects of how natural language queries are processed, data is retrieved, and maps are generated, providing a comprehensive overview of the system's components and workflows.

The results chapter presents the outcomes of validation tests, showcasing the system's ability to generate maps from natural language queries. It analyzes system performance in terms of accuracy, response time, and scalability, supported by various figures and tables that illustrate the findings. This chapter provides empirical evidence of the system's effectiveness and identifies areas where it excels or requires improvement.

The discussion interprets the findings, discusses the system's effectiveness in meeting its objectives, explores ethical implications, and identifies limitations and areas for improvement. It contextualizes the results within the broader landscape of GIS and AI, offering insights into how Prompt2Map contributes to the field and what future developments could enhance its capabilities.

Finally, the conclusions summarize the key findings, highlight the contributions to the fields of GIS and AI, discuss potential future work, and reflect on the broader impact of natural language interfaces in GIS. This chapter synthesizes the research, drawing connections between the objectives, methods, and results, and proposing directions for future exploration and innovation.

1.4 Background

1.4.1 Democratization of GIS

Geographic Information Systems have evolved significantly since their inception, transitioning from specialized tools used primarily by experts to more widely accessible platforms. Initially, GIS required substantial technical expertise, including knowledge of programming, database management, and spatial analysis techniques. The steep learning curve and high costs associated with GIS software limited its use to specific professional domains.

Advancements in technology and the proliferation of geospatial data have catalyzed the democratization of GIS. The development of user-friendly interfaces, open-source GIS software (e.g., QGIS), and web-based platforms (e.g., ArcGIS Online) has lowered barriers to entry. These tools have enabled a broader audience to engage with spatial data, perform basic analyses, and create maps without requiring extensive technical training. The increasing availability of high-quality geospatial data, coupled with more intuitive tools, has empowered non-specialist users to harness the power of GIS for various applications, from community planning to environmental monitoring.

The concept of neogeography emerged as individuals outside traditional geographic professions began using mapping tools for personal and community projects. Goodchild describes neogeography as the use of geographical techniques by non-expert users for non-professional purposes (Goodchild, 2009). This movement has been facilitated by platforms like OpenStreetMap, which allow users to contribute to and utilize geospatial information collaboratively. Neogeography has expanded the scope of GIS, enabling everyday users to participate in mapping activities, share spatial data, and contribute to collective knowledge bases. This participatory approach has democratized map-making, making it a communal and accessible activity.

Despite these advancements, a gap persists between the capabilities of expert GIS practitioners and those accessible to non-specialists. Complex spatial analyses, custom data queries, and advanced cartographic designs often remain beyond the reach of general users. This gap underscores the need for innovative approaches to further democratize GIS, making advanced functionalities more accessible and intuitive. Enhancing user interfaces, integrating intelligent assistants, and leveraging AI-driven tools are potential strategies to bridge this gap (Frez & Baloian, 2023), enabling a wider audience to perform sophisticated GIS tasks without specialized training.

1.4.2 Self-Service GIS

Self-service GIS platforms represent an important step toward making GIS more user-friendly. These platforms provide tools that simplify spatial data analysis and map creation through intuitive interfaces, often featuring drag-and-drop functionalities, guided workflows, and pre-configured templates (Rowland et al., 2020). Users can perform tasks such as data visualization, basic spatial analysis, and thematic mapping without deep technical knowledge. By abstracting the complexity of GIS operations, self-service platforms enable users to focus on their specific analytical needs and visualization preferences.

However, self-service GIS platforms have limitations. They may not fully accommodate the diverse and complex needs of users, especially when dealing with sophisticated analyses or custom data queries. Users still need to understand GIS concepts, data structures, and the specific functionalities of the platform. The interfaces may not be flexible enough to handle unique or nuanced user requests. For instance, advanced spatial analyses like network analysis, spatial interpolation, or multi-criteria decision analysis often require specialized tools and a deeper understanding of GIS methodologies, which are not typically supported by self-service platforms.

To overcome these limitations, integrating natural language interfaces into GIS platforms has been proposed. Natural language interfaces allow users to interact with systems using everyday language, potentially reducing the learning curve and making GIS functionalities more accessible. By expressing queries and commands in natural language, users can bypass complex menus and technical commands. This approach leverages the advancements in NLP and AI to create more intuitive and responsive GIS tools that can cater to a wider range of user needs and expertise levels. Natural language interfaces can facilitate more dynamic and conversational interactions with GIS systems, enabling users to ask complex questions and receive immediate, contextually relevant responses.

1.4.3 Large Language Models in GIS

Large Language Models have revolutionized the field of NLP, offering new ways to interpret and generate human-like text. Models like GPT-4 have been trained on extensive datasets encompassing a wide range of topics, enabling them to understand context, disambiguate meanings, and generate coherent responses. These models excel at tasks such as language translation, text summarization, and question-answering, demonstrating a high level of proficiency in understanding and generating natural language.

In the context of GIS, LLMs can serve as intermediaries between the user and the system, interpreting natural language queries and translating them into actions that the GIS platform can execute. For example, a user could input a query like "Show me the areas in Lisbon with the highest unemployment rates,"and the LLM would process this request, retrieve the relevant data, and generate the appropriate map.

Furthermore, the concept of Retrieval-Augmented Generation (RAG) enhances LLM capabilities by combining retrieval mechanisms with generation. In a RAG system, the LLM retrieves relevant information from external data sources to inform its responses (Fan et al., 2024). In GIS applications, RAG can enable the system to access geospatial databases dynamically, allowing for up-to-date and context-specific map generation. This approach ensures that the system can provide accurate and relevant visualizations based on the most current and pertinent data, enhancing the overall utility and reliability of the GIS platform.

Literature on the application of LLMs in GIS showcases various use cases where AI-driven natural language interfaces have significantly improved user interaction and data analysis capabilities. For instance, studies have explored how LLMs can assist in automated map generation and interactive spatial querying (S. Wang et al., 2024). These applications demonstrate the potential of LLMs to transform traditional GIS workflows, making spatial data analysis more efficient and accessible. Additionally, research has highlighted the benefits of integrating LLMs with GIS for educational purposes, allowing students to engage with spatial data through conversational interfaces and enhancing their learning experiences (Mooney et al., 2023; Redican et al., 2024).

Moreover, advancements in function calling and tool integration with LLMs have opened new avenues for enhancing GIS functionalities (Qu et al., 2024). Function calling enables LLMs to execute specific functions or access external tools based on user queries, thereby extending the capabilities of the GIS platform beyond standard data retrieval and visualization tasks. This integration facilitates more sophisticated spatial analyses and dynamic map generation, catering to a broader range of user needs and enhancing the overall user experience.

1.4.4 Retrieval-Augmented Generation

Traditional RAG systems primarily rely on semantic proximity through embeddings to retrieve relevant documents or text snippets from large corpora. These systems encode both queries and documents into high-dimensional vector spaces, enabling the identification of semantically similar content based on their proximity in the embedding space (Gao et al., 2024). This approach is effective for tasks such as question-answering and information retrieval, where the goal is to provide contextually relevant textual information to the user.

In the context of geospatial data, RAG holds significant potential. Geospatial information is inherently dynamic, with frequent updates and changes in data due to various factors such as urban development, environmental changes, and demographic shifts. RAG allows GIS systems to access and incorporate the most recent data, ensuring that the generated maps and analyses reflect the current state of the spatial environment. This is crucial for applications that rely on real-time or near-real-time data, such as disaster management, traffic analysis, and environmental monitoring.

The state-of-the-art in RAG involves sophisticated retrieval algorithms and indexing techniques that enable efficient access to vast amounts of data. Advances in vector-based retrieval, where data is represented in high-dimensional vector spaces, have significantly improved the speed and accuracy of information retrieval in RAG systems (Gao et al., 2024). Additionally, the integration of RAG with transformer-based architectures has enhanced the model's ability to understand and leverage retrieved information effectively, leading to more coherent and contextually appropriate responses.

1.4.5 Text-to-SQL

Structured Query Language (SQL) is a standardized programming language specifically designed for managing and manipulating relational databases. It provides a robust framework for performing a wide array of operations, including querying data, updating records, inserting new information, and deleting existing entries. SQL's declarative syntax allows users to specify what data they need without detailing the exact procedures to retrieve it, thereby simplifying complex data interactions. This language is fundamental for data analysts, database administrators, and applications that require efficient and precise data management. In the context of Geographic Information Systems, SQL is often extended with spatial functions that enable the querying and analysis of geospatial data, facilitating tasks such as spatial joins, proximity searches, and geographic aggregations.

The task of translating natural language to database SQL queries is well-established in NLP, known as text-to-SQL. This task involves converting a natural language statement into a SQL query that can be executed against a database. Modern text-to-SQL models leverage deep learning architectures, particularly transformer-based models, which excel at capturing the complex relationships between language and database schemas. These models are trained on large datasets that pair natural language questions with their corresponding SQL queries, enabling them to learn the patterns and structures necessary for accurate translation. Techniques such as schema linking, where the model identifies and aligns entities in the natural language query with database schema elements, have been instrumental in improving performance (Z. Li et al., 2024). In addition to handling simple queries, state-of-the-art text-to-SQL models are capable of managing complex queries involving multiple tables, nested subqueries, and advanced SQL functions.

LLMs' ability to perform text-to-SQL translation can be harnessed in GIS to facilitate data retrieval. By integrating LLMs with GIS databases, users can query spatial data using natural language, and the system can generate the corresponding SQL queries to retrieve the data. This integration simplifies the data retrieval process, making it more accessible to users who may not have expertise in SQL or database management. Additionally, it allows for more dynamic and flexible querying capabilities, enabling users to perform complex spatial analyses through simple verbal instructions.

1.4.6 Function Calling

Function calling in LLMs refers to the capability of language models to invoke specific functions or access external tools based on the context of the input they receive. This feature extends the functionality of LLMs beyond text generation, allowing them to interact with external systems, perform computations, and access specialized tools dynamically. Function calling is a crucial advancement in the development of intelligent assistants, enabling more interactive and context-aware responses.

Function calling works by informing the model about the available external functions, including their names, descriptions, and expected parameters. When the model identifies a need to perform a specific task that aligns with an available function, it generates a function call with the appropriate arguments. This call is then executed by the system, and the results are incorporated into the model's response. The process ensures that the model's outputs adhere to the constraints and requirements of the external tools, enhancing the reliability and accuracy of the responses.

In the context of GIS, function calling enables the integration of specialized mapping and spatial analysis functions. For instance, when a user requests the generation of a choropleth map based on certain criteria, the LLM can invoke a predefined mapping function with the necessary parameters, such as data layers, color schemes, and attribute values. This automation streamlines the map creation process, allowing users to generate complex visualizations with simple natural language commands.

Function calling also facilitates the extension of the system's capabilities without necessitating continuous retraining of the LLM. As new functions are developed or existing ones are updated, they can be integrated into the system's function library, and the LLM can be instructed to utilize them as needed. This modular approach ensures that Prompt2Map remains adaptable and can incorporate advanced GIS functionalities seamlessly, catering to evolving user needs and technological advancements.

Moreover, function calling enhances the system's ability to maintain consistency and standardization in map generation. By relying on predefined functions with well-defined parameters, the system ensures that the generated maps adhere to specific cartographic principles and visualization standards. This consistency is crucial for producing reliable and professional-quality maps that meet user expectations and project requirements. Additionally, the use of predefined functions facilitates replicability, as the same functions can be invoked with identical parameters to reproduce maps under similar conditions. This replicability is essential for verifying results, conducting comparative analyses, and ensuring that map generation processes can be reliably repeated in future applications.

1.4.7 Ethical Considerations

The deployment of LLMs in GIS introduces several ethical considerations that must be addressed to ensure responsible use. These include bias and fairness, data privacy, accuracy and misuse, and trustworthiness and reproducibility.

Bias and fairness are significant concerns, as LLMs are trained on large corpora of text that may contain biases reflecting societal prejudices. Such biases can manifest in the model's outputs, potentially leading to unfair or discriminatory results (Gallegos et al., 2024; Y. Wang et al., 2023). In GIS, this could result in biased data retrieval or misrepresentation of certain areas or populations. Mitigating bias requires careful dataset selection, bias detection and correction mechanisms, and continuous monitoring of system outputs.

Data privacy is critical, especially since geospatial data often includes sensitive information, particularly when dealing with demographic data at granular levels. Protecting user privacy and complying with data protection regulations, such as the General Data Protection Regulation (GDPR), is essential. Systems must implement measures to anonymize personal data, secure data storage and transmission, and ensure that sensitive information is not inadvertently disclosed.

Accuracy and the potential for misuse are also important ethical considerations. LLMs can generate incorrect or misleading information, known as hallucinations, where the model produces plausible but false outputs (Shuster et al., 2021). In GIS applications, inaccuracies in data retrieval or map generation can have significant consequences, potentially leading to incorrect conclusions or decisions. There is also a risk of misuse, where the system could be employed to generate maps that infringe on privacy, security, or propagate misinformation. Implementing validation checks, transparency measures, and usage policies can help mitigate these risks.

Trustworthiness and reproducibility are crucial for users to rely on AI-generated maps. The system must be transparent about how outputs are produced and allow for reproducibility of results (Z. Li & Ning, 2023; S. Wang et al., 2024; Zhang et al., 2023) Providing access to information about data sources, processing methods, and limitations enables users to understand and verify the results.

Addressing these ethical considerations is essential for the responsible deployment of LLM-integrated GIS systems. By proactively identifying potential risks and implementing mitigation strategies, the system can enhance trust, fairness, and reliability.

2

Data and methods

2.1 System Architecture

The Prompt2Map system is designed to convert natural language queries into interactive web maps by integrating LLMs with geospatial data retrieval and mapping functionalities. The system architecture comprises two main components: the Geospatial Retriever and the Map Generator. This structure is inspired by the Retrieval-Augmented Generation (RAG) architecture, although it differs in that it retrieves geospatial features instead of documents.

The system workflow involves several key steps. When a user inputs a natural language query expressing their mapping needs, the Geospatial Retriever interprets the query and retrieves relevant geospatial data from the data source. Subsequently, the Map Generator transforms the retrieved data and the user's intent into an interactive web map. [Figure @fig:syscomp] shows this process in detail.

2.1.1 Geospatial Retriever

The Geospatial Retriever is responsible for interpreting the user's natural language query and retrieving the relevant geospatial data from the data source. This process involves several subcomponents, including geospatial data sources, text-to-SQL translation, SQL dialect adaptation, SQL processing and validation, and query execution.

2.1.1.1 Geospatial Data Sources

Geospatial data sources constitute the foundation of any GIS application, encompassing a variety of data formats and storage systems that manage the spatial relationships and attributes of features on the Earth's surface. These data sources can take many forms, such as vector and raster datasets, and are stored in specific formats like Shapefiles, GeoPackage, GeoJSON, GeoParquet, and specialized geospatial databases such as PostGIS and DuckDB. Each data source has unique capabilities, optimized for particular types of spatial data, and supports varying levels of data complexity and query functionality.

Geospatial data sources constitute the foundation of any GIS application, encompassing a variety of data formats and storage systems. Examples of geospatial data sources include Shapefiles, GeoPackage, GeoJSON, GeoParquet, and geospatial databases such as PostGIS and DuckDB. Each data source offers different capabilities and supports various types of spatial data and queries. The type of geospatial data source used in a system like Prompt2Map defines the range and complexity of queries that can be performed.

2.1.1.2 Text-to-SQL Translation

As Prompt2Map adopts a RAG-inspired approach, the first step in addressing user queries is to retrieve data relevant to the request. In this context, the target structured language is SQL, which will be executed against DuckDB to query the geospatial data sources. Traditional text-to-SQL models are trained on generic SQL, focusing on "core SQL"keywords like SELECT, GROUP BY, WHERE, etc. Database-specific syntax, such as spatial extensions, are not inherently recognized by these models.

To address this limitation, instead of fine-tuning the model or extensively modifying the prompts to include spatial extensions, the system translates the user query into regular SQL without explicit mentions of geospatial columns. Subsequently, the query is processed to incorporate geospatial features deterministically. This two-step approach ensures that the text-to-SQL translation remains efficient and cost-effective while enabling the integration of spatial functionalities required for accurate data retrieval.

2.1.1.3 SQL Processing and Validation

The generated SQL query undergoes a processing phase that includes validation and correction. Validation involves checking the query for syntactic correctness, security (e.g., preventing SQL injection), and adherence to read-only constraints to protect data integrity. This ensures that the query is safe to execute and will not compromise the underlying database.

Beyond mere validation, the system actively repairs queries by identifying and rectifying potential issues that could lead to incorrect or empty results. For example, if the WHERE clause contains incorrect literals or references nonexistent fields, the system attempts to correct these errors by aligning them with the actual data schema and available metadata. This dual approach of validation and correction enhances the reliability and accuracy of the data retrieval process, ensuring that the resulting datasets are both relevant and correctly structured for subsequent mapping tasks.

After validation, the SQL query is converted to a geospatial DuckDB SQL query by injecting the necessary spatial features. This deterministic modification ensures that the query leverages DuckDB's spatial functions appropriately, enabling accurate and efficient data retrieval based on the user's natural language input.

2.1.1.4 Query Execution

The validated and corrected SQL query is executed against the geospatial data source. The choice of DuckDB as the database engine allows for efficient handling of both single-table and multi-table environments. DuckDB's support for various geospatial data formats and its in-process architecture facilitate seamless data access and manipulation, ensuring that the system can handle a wide range of geospatial queries with high performance.

2.1.2 Map Generator

The Map Generator component transforms the retrieved geospatial data and the user's intent into an interactive web map. This process involves function calling with LLMs, mapping function selection, parameter specification, and map rendering.

2.1.2.1 Function Calling with LLMs

The system utilizes the function-calling feature provided by major LLM API providers, including OpenAI, Claude, and Groq. Function calling allows the LLM to invoke predefined functions with specific parameters based on the user's query and the data characteristics. In this context, the functions correspond to mapping operations, such as generating a choropleth map, a heatmap, or a proportional symbol map. Each function has defined parameters, such as data layers, visual variables, styling options, and interactivity settings.

The LLM analyzes the metadata of the retrieved data, including geometry types, attributes, and spatial relationships. Based on this analysis and the user's intent, the LLM selects the most appropriate mapping function. For example, if the data consists of polygons with quantitative attributes and the user requests to visualize rates or densities, the LLM may select a choropleth mapping function. For point data representing events or occurrences, a heatmap function might be appropriate. Once the mapping function is selected, the LLM specifies the parameters required for the function. These include data layers to be visualized, visual variables to represent attributes through color, size, shape, or texture, styling options like color schemes and classification methods, and interactivity settings such as tooltips, pop-ups, and legends.

The mapping function is executed to render the interactive web map. The system employs web mapping libraries such as Leaflet or Plotly, which support interactive features and responsive design. The final map allows users to interact with the data, providing functionalities like zooming, panning, clicking on features to display attribute information, and toggling layers on and off.

2.2 Implementation

The implementation of Prompt2Map follows a modular architecture, organized into three primary modules: interfaces, providers, and application. This structure adheres to the principles of Clean Architecture, ensuring that the core application logic remains decoupled from external dependencies and infrastructure concerns. Each module serves a distinct purpose within the system, facilitating scalability, maintainability, and ease of integration with various components. In this design paradigm, the application layer is decoupled from the infrastructure layer (providers) by relying on abstract interfaces rather than concrete implementations.

This approach ensures that the core business logic remains unaffected by changes in external systems or technologies. Specifically, Prompt2Map defines interfaces such as GeoDatabase, Embedding, and LLM within the interfaces module, which outline the essential functionalities required by the application. The providers module contains concrete implementations like GeoDuckDB and OpenAIProvider, which fulfill these interfaces. This modular structure offers significant advantages, including ease of maintenance, scalability, and flexibility. For instance, integrating support for a different geospatial database, such as PostgreSQL with PostGIS, would simply involve creating a new class that implements the GeoDatabase interface without altering the core application logic. This decoupling facilitates adaptability to evolving technological landscapes and simplifies the extension of system capabilities.

Python serves as the primary programming language for implementing Prompt2Map, chosen for its versatility, extensive library support, and strong presence in both the AI and geospatial communities. Python's rich ecosystem includes powerful libraries like GeoPandas, which extends Pandas to enable spatial operations on geospatial data, making it an ideal tool for managing and analyzing geographic information within the system.

2.2.1 Application

The application component constitutes the core functionality of the prompt2map package, orchestrating the end-to-end process of converting natural language queries into interactive web maps. This component is responsible for managing the workflow from query interpretation to data retrieval and finally to map generation. By leveraging the abstract interfaces defined within the interfaces module and utilizing the concrete implementations provided by the providers, the application layer ensures seamless interaction between different system modules. This modular approach not only enhances the system's scalability but also facilitates easier maintenance and future enhancements.

Within the application component, key classes such as 'SQLGeoRetriever', 'LLMPrompt2SQL', 'LLMMapGenerator', and 'Prompt2Map' play pivotal roles. 'SQLGeoRetriever' handles the translation of natural language queries into SQL statements and manages the retrieval of geospatial data from the database. 'LLMPrompt2SQL' utilizes the capabilities of LLMs to accurately convert user prompts into executable SQL queries, ensuring that the data retrieval process aligns with the user's intent. 'LLMMapGenerator' is tasked with transforming the retrieved geospatial data into visually coherent and interactive maps, selecting appropriate visualization techniques based on the nature of the data and the user's requirements. Finally, the 'Prompt2Map' class serves as the primary interface for users, integrating the functionalities of the retriever and generator to deliver a cohesive mapping experience. This structured separation of responsibilities within the application component ensures that each aspect of the system operates efficiently and cohesively.

2.2.2 Interfaces

The interfaces component serves as the foundational layer of the prompt2map package, defining the abstract contracts that dictate how different modules interact with one another. By establishing clear and standardized interfaces, the system ensures that each component adheres to a consistent set of functionalities, promoting interoperability and flexibility. This abstraction is crucial for maintaining a decoupled architecture, allowing individual modules to be developed, tested, and maintained independently without impacting the overall system integrity.

Key interfaces within this component include 'Embedding', 'LLM', 'GeoDatabase', 'GeoRetriever', 'Prompt2SQL', and 'MapGenerator'. The 'Embedding' interface outlines the methods required for generating numerical representations of textual data, which are essential for tasks like similarity matching and query understanding. The 'LLM' interface defines the interaction methods with Large Language Models, facilitating tasks such as prompt-based query generation and response handling. 'GeoDatabase' encapsulates the functionalities needed to interact with geospatial databases, including schema retrieval and geospatial data querying. 'GeoRetriever' specifies the methods for fetching geospatial data based on user queries, ensuring that the application can retrieve relevant and accurate datasets. 'Prompt2SQL' bridges the gap between natural language inputs and structured SQL queries, enabling the seamless translation of user intents into executable database commands. Lastly, the 'MapGenerator' interface outlines the methods for creating interactive maps from geospatial data, ensuring that visualizations are generated consistently and effectively. By defining these interfaces, the system promotes a high level of abstraction and modularity, allowing for easy integration of new functionalities and technologies as the system evolves.

2.2.3 Providers

The providers component encapsulates the concrete implementations of the abstract interfaces defined within the interfaces module. This layer is responsible for managing interactions with external services and tools, effectively bridging the gap between the system's core functionalities and the underlying technologies that enable them. By centralizing these implementations within the providers, the system achieves a high degree of flexibility and adaptability, allowing for seamless integration of new services or replacement of existing ones without disrupting the core application logic.

Within the providers module, classes such as 'GeoDuckDB' and 'OpenAIProvider' play critical roles. 'GeoDuckDB' implements the 'GeoDatabase' interface, managing all interactions with DuckDB, the chosen geospatial database engine. This includes handling data storage, executing spatial queries, and managing database connections. DuckDB's in-process architecture and robust support for various geospatial data formats make it an ideal choice for efficient data retrieval and management within Prompt2Map. On the other hand, 'OpenAIProvider' implements both the 'LLM' and 'Embedding' interfaces, facilitating interactions with the OpenAI API. This provider manages the communication with Large Language Models, enabling the system to leverage advanced natural language processing capabilities for tasks such as text-to-SQL translation and function calling. By abstracting these external dependencies into dedicated provider classes, the system ensures that changes or updates to external services can be accommodated with minimal impact on the overall architecture. Additionally, this separation of concerns enhances the maintainability and scalability of the system, allowing developers to focus on core functionalities without being bogged down by the complexities of external service integrations.

2.2.4 External Dependencies

The prompt2map package leverages several external dependencies to achieve its functionality, each chosen for its robustness, performance, and compatibility with the system's requirements.

2.2.4.1 OpenAI API

The OpenAI API is integrated into Prompt2Map to leverage the advanced natural language processing capabilities of LLMs like GPT-4. This API facilitates the system's ability to interpret and translate natural language queries into executable SQL statements through the text-to-SQL functionality. By utilizing the OpenAI API, Prompt2Map can effectively handle complex and nuanced user inputs, ensuring accurate data retrieval and meaningful map generation. The API provides access to powerful language models that excel in understanding context, disambiguating meanings, and generating coherent and contextually relevant responses. Additionally, the OpenAI API supports function calling, allowing Prompt2Map to invoke predefined mapping functions with specific parameters based on user queries. This integration enhances the system's ability to maintain consistency and standardization in map generation, as the predefined functions ensure that all maps adhere to established cartographic principles and visualization standards. Moreover, the use of the OpenAI API abstracts the complexities of managing and deploying LLMs, enabling Prompt2Map to focus on delivering a seamless and user-friendly GIS experience without the overhead of maintaining sophisticated NLP infrastructure.

2.2.4.2 DuckDB

DuckDB is employed as the primary geospatial database engine within Prompt2Map, selected for its high performance, in-process architecture (Raasveldt & Mühleisen, 2019), and comprehensive support for geospatial data types and functions. Unlike traditional SQL databases that require separate server infrastructure, DuckDB operates entirely within the application's process, eliminating the need for additional setup and reducing latency in data retrieval. Its geospatial extension provides robust capabilities for handling spatial queries, including spatial joins, proximity searches, and geographic aggregations, which are essential for generating accurate and informative maps. DuckDB's ability to efficiently manage large datasets and perform complex queries makes it an ideal choice for Prompt2Map, ensuring swift data processing and reliable performance. Furthermore, DuckDB"s compatibility with various geospatial data formats, such as GeoJSON, Shapefiles, and GeoParquet, enhances the system's flexibility and ease of data integration, allowing Prompt2Map to seamlessly incorporate diverse geospatial datasets without compromising on performance or functionality.

2.3 Data

The Prompt2Map system is designed to work with various structured spatial data sources. For this thesis, two datasets are used to evaluate the system: the Portuguese 2021 Census Data and the Chilean Elections Database. Detailed descriptions of the variables used in these datasets are provided in the appendix.

This dataset includes demographic and socioeconomic information collected during the 2021 census in Portugal. It is structured in a single-table format, suitable for testing basic SQL queries and simple map visualizations. The data attributes encompass population counts (total population, age groups), socioeconomic indicators (employment rates, education levels, household income), and geographic units (administrative boundaries at different levels, such as municipalities and regions). The dataset provides a comprehensive overview of the demographic and socioeconomic landscape of Portugal, making it ideal for evaluating the system's ability to handle standard geospatial queries and produce accurate visualizations with minimal complexity. The data is obtained from the Portuguese National Statistics Institute (INE) (Instituto Nacional de Estatística (INE), 2021).

2.4 Evaluation

Evaluating the performance of Prompt2Map poses several challenges due to the system's unique characteristics, including the integration of natural language processing, geospatial data retrieval, and map generation functionalities. Traditional evaluation metrics used in NLP, such as BLEU scores or F1 scores, may not fully capture the system's effectiveness in converting natural language queries into interactive web maps. Therefore, a comprehensive evaluation strategy is required to assess the system's performance across different dimensions, including accuracy, efficiency, usability, and scalability.

Nevertheless, for the scope of this thesis, the evaluation focuses on the text-to-SQL translation component of Prompt2Map, which corresponds to the Geospatial Retriever in the system architecture. This evaluation aims to assess the system's ability to accurately interpret natural language queries, generate SQL statements that retrieve relevant geospatial data, and execute these queries against the geospatial database. The evaluation of the Map Generator component, which involves the creation of interactive web maps based on the retrieved geospatial data, is more subjective and user-dependent, making it challenging to define objective metrics. Therefore, the focus of this evaluation is on the Geospatial Retriever, which forms the foundation of the system's functionality.

2.4.1 Metrics

Two main metrics are used to evaluate the Prompt2Map performancce: Soft F1-score and Consistency Score.

The primary metric used to evaluate accuracy is Soft F1-score. Regular F1-score is common in classification tasks, where the goal is to balance precision and recall.

2.4.1.1 The problem with text-to-SQL metrics

Can a question be represented as a SQL query? This is the main question that text-to-SQL systems aim to answer. However, evaluating the performance of these systems is challenging due to the inherent ambiguity and complexity of natural language queries. Even for human annotators, determining the correct SQL query for a given question can be a non-trivial task, as it requires an understanding of the underlying database schema, the semantics of the question, and the intended query result. Therefore, developing robust evaluation metrics that can accurately assess the performance of text-to-SQL systems is crucial for advancing the field and enabling fair comparisons between different approaches.

There are multiple benchmarks for text-to-SQL evaluation, such as Spider (Yu et al., 2018), BIRD (J. Li et al., 2023) and WikiSQL (Zhong et al., 2017). These benchmarks provide standardized datasets with natural language questions paired with their corresponding SQL queries, allowing researchers to evaluate the performance of their systems on common tasks. The two main evaluation metrics for the text-to-SQL task are Exact Matching (EM) and Execution Accuracy (EX). EM measures the syntax-level equivalence between the generated SQL query and the ground truth query, while EX evaluates the execution results of the generated query.

However, those metrics have limitations that can lead to biased results and inaccurate performance assessments (Lopez). While EM evaluates the syntax-level equivalence of queries, it often leads to high false negative rates, as the same logical intent can be represented through various query structures and alises. On the other hand, EX focuses on the execution results of the generated queries, providing a more robust evaluation metric. However, EX is not without its limitations, as it can produce false positives when incorrect queries yield correct results, and false negatives when extra fields are included in the output.

The hardness of EM and EX is that both require exact matches between the generated SQL query and the ground truth. This is a very strict requirement, as even small variations in the generated query can lead to a mismatch. To address this issue, the Soft F1-score was introduced as a more lenient evaluation metric that considers the data similarity between the generated and ground truth queries.

The original F1-score is a metric commonly used in classification tasks to balance the model's ability to correctly identify positive samples (precision) and to capture all positive samples (recall).

$$F1 = 2 \times \frac{precision \times recall}{precision + recall} \tag{2.1}$$

2.4.1.2 Consistency

To assess the consistency of the Prompt2Map outputs across multiple runs, we introduced a metric termed Consistency Entropy. This metric is derived from the normalized entropy of the model's output distribution across repeated trials for the same prompt. In this context, lower entropy signifies higher consistency, as the model consistently generates similar outputs for identical inputs. Normalized entropy was chosen to ensure comparability across varying levels of output complexity, where more complex maps naturally involve higher diversity. This metric provides insight into the stability and reliability of the system, which are critical for practical applications.

a measure of uncertainty, or of "poorness of a guess,"which will be high when the number of alternative possibilities is nigh, and low when some of the possibilities are much more likely than others

In addition to Consistency Entropy, the frequency of the mode is used. This metric provides a simple yet effective measure of the most common output generated by the system across multiple runs. A high mode frequency indicates that the system consistently produces a specific output, which can be beneficial for tasks requiring deterministic results. By combining Consistency Entropy and mode frequency, the evaluation framework captures both the diversity and stability of the system's outputs, offering a comprehensive assessment of its performance.

$$H(X) = -\sum_{i=1}^{n} p(x_i) \log_2 p(x_i) \tag{2.2}$$

$$H_{rel}(X) = \frac{H(X)}{\log_2 n} \tag{2.3}$$

Mode frequency: frequency of the most frequent item

$$\text{Mode Frequency (X)} = \frac{\text{Number of occurrences of the mode}}{\text{Total number of runs}} = \frac{\max_{x \in X} \text{count}(x)}{|X|} \tag{2.4}$$

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Results

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Discussion

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Conclusion

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A

NOVAthesis covers showcase

This Appendix shows examples of covers for some of the supported Schools. When the Schools have very similar covers (e.g., all the schools from Universidade do Minho), just one cover is shown. If the covers for MSc dissertations and PhD thesis are considerable different (e.g., for FCT-NOVA and UMinho), then both are shown.

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B

Appendix 2 Lorem Ipsum

This is a test with citing something (**ecoop12-dias**) in the appendix.

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