METAMORPHISM OF ALS POINT DATA FOR MULTITUDE APPLICATION

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ABSTRACT:

Technologically assisted decision-making in urban planning and governance is significant to envisage Sustainable Development Goal (SDG) 11, of developing sustainable cities and communities. In the current millennium, planners and decision-makers require knowledge-rich virtual models for managing the man-made and natural resources in the city. To effectively utilize the technological advancement for sustainable urban development, there is a need for expeditious entail towards accurate urban resource mapping, development of flexible monitoring and information extraction framework, and enticing visualization. Airborne LiDAR Scanning (ALS) is capable of producing very precise 3D geometric data over expansive urban areas in a timely and economically efficient manner. However, it is challenging to derive viable outcomes from the unstructured and voluminous point cloud. This work proposes an intermediary metamorphosed point cloud storage framework to enhance the utility of point clouds for multiple pragmatic applications. The proposed methodological approach transforms the unstructured, massive point cloud into an ontologically stored urban object collection to utilize the large-scale urban point cloud in decision-making. Further, the paper demonstrates the direct applicability of the metamorphosed point cloud storage framework for two specific applications related to sustainable urban development. Experiments carried out using the proposed framework on DALES benchmark dataset show promising results.

1. INTRODUCTION

3D mapping of the urban infrastructure and the terrain is gaining increasing attention in the recent years with the developments in data acquisition techniques as well as advancement in processing algorithms (Deng et al., 2021). Digital replica of urban resources, both man-made and natural, over a digital platform can play a pivotal role in managing the urban infrastructure for sustainable development. The development of digital urban resource platform has the potential to increase the city's perception and decision-making abilities. Such platform will also provide a broader vision for future planning and sustainable advancement.

The growing imperative for sustainable development makes it more demanding to develop a sustainable digital urban asset with updating capability for conscious decision-making. The efficiency and the accuracy of the urban digital assets heavily relies on accurate geospatial data, efficient storage system with high processing capability with a powerful visualisation.

Airborne Laser scanning is considered to be an effective geospatial technology for acquisition of high resolution three dimensional data over city scale spatial extent. LiDAR scanning is an active remote sensing technique that employs near infrared wavelengths to capture elevation changes of the terrain with a very high precision.

However, the LiDAR point cloud acquired is highly unstructured and voluminous. Hence to effectively utilise the point cloud for knowledge-enhanced decision-making, the data has to be converted to a metamorphic form that is application ready. However, there has not been much effort made towards establishing a framework that may serve as the basis for transforming point clouds into knowledge assets that can be leveraged for decision-making in multiple domains. There have been works that individually and independently focus on different aspects of LiDAR point cloud processing: semantic segmentation, data storage, data management, information extraction, 3D rendering and applications. In this study, a broad prospect of contemporary methodologies in the existing domains is presented with reference to, point cloud segmentation, storage, data management for query and 3D rendering.

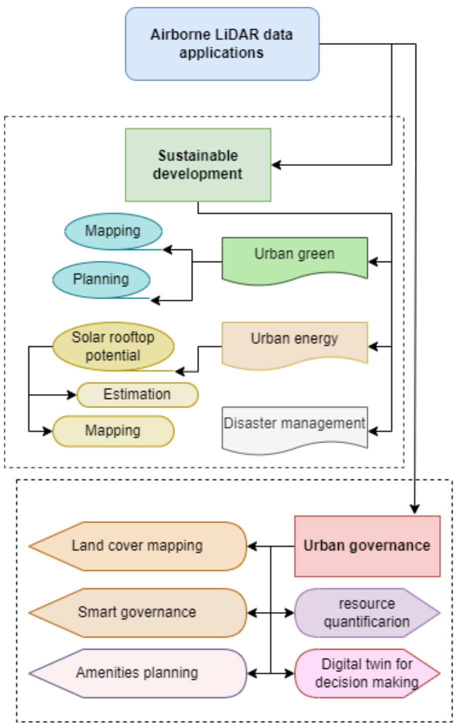

Figure 1. Point cloud to Utilitarian Applications

Prior to utilizing point clouds in any application, it is essential to assign a semantic label to each point in the point cloud. One of the approaches to label the point data is semantic segmentation. Recent years have seen an upsurge in the adoption of deep learning algorithms for the semantic segmentation of ALS point clouds. The literature available on deep learning approaches can be broadly categorized into three methodolo-

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gical approaches: point-wise MLP, convolution neural network-based architecture, and graph-based methods.
In point-wise multilayer perceptron-based approach, the inputs to the network are the coordinates, attributes, or the derived features (Hsu and Zhuang, 2020). Examples of the above approach include ALSNET (Winiwarter et al., 2019), FWNet (Shinohara et al., 2020), PointNET++ (Chen et al., 2021), etc. These methods have also been used with active learning (Lin et al., 2020), transfer learning (Lei et al., 2020) techniques, and have also been explored with different attributes as input data (Hsu and Zhuang, 2020). This method offers reduced information loss, does not involve projection or voxelization pre-classification, and is also computationally less expensive. The CNN-based deep learning network uses point cloud or projected images of point cloud data and convolution kernel as input. This approach performs well as it extracts and utilizes the data's high-level features extracted within the deep learning framework. This method excels with small datasets but is computationally complex and has limitations over datasets with substantial class imbalance. Sparse CNN (Schmohl and Sörgel, 2019), PointCNN (Li et al., 2018), and directionally Constraint CNN (Wen et al., 2019) are among its algorithmic adaptations. In the graph-based methods, the inputs are points/voxels/segments, or features, and the resultant graph primarily involves more than one network (Widyaningrum et al., 2021). Thus machine learning and deep learning approaches have shown significant contributions in the literature pertaining to semantic segmentation of ALS point clouds.
The point cloud is stored as a collection of independent points and can be thought of as an N-dimensional vector. The data is typically saved using the file-based format. The point cloud data is saved as an N*M dimensional array, where N is the number of points and M is the set of attributes that are attached to each point (Samberg, 2007). In addition to the X, Y, Z information, LiDAR point cloud can also store attributes such as return number, class, intensity etc. The most prevalent point cloud storage formats include the ASCII (Khalsa et al., 2022) and binary formats such as LAS format (Samberg, 2007), and LAZ format (Isenburg, 2013).
It is challenging to determine a data storage framework that enables speedy data access and information retrieval from multi-dimensional and voluminous point clouds. In order to use ALS data effectively for information extraction, data management is crucial and is still a subject of active research.
Optimal storage of data is vital to enable efficient information extraction and visualization. The point cloud data can be stored in a tabular design using point, multipoint, or user-defined geometry features. The point is ineffective at indexing data; multipoint satisfies this need, but random grouping compromises the quality of the point feature, thus making the semantic point-cluster as an entity the best alternative for point cloud databases (Cura et al., 2017). For storage, blocks and flat tables are the two main approaches to data storage. Since each row in the flat table mode represents a single point, this method is not space-efficient whereas in block storage each block (group of spatially connected points) corresponds to a row in the table and is not semantically alluring (Cura et al., 2017).
In terms of storage organization and the availability of tools for viewing and editing datasets, file-based formats are advantages. However, data parsing, updating, information enrichment, and querying are not compatible with this data storage type. This might also be one of the reasons point cloud data is not being used to its full potential in different utilitarian applications.
The point cloud becomes more useful when it can directly be used for decision-making in varied applications. This requires linking semantic information to the point cloud and its organized storage for information extraction to assist in decision-making. The major challenge with the data storage layout is inefficiency in data parsing.
In one of the recent works, a simple data layout that used the semantics to allow quick queries from large point cloud data was presented (El-Mahgary et al., 2020). Algorithmically, an index-based approach for storage and fast querying was explored and semantic data was used to partition the point cloud. This database layout framework to query was tested on small, medium, and large datasets using directories in file-based approach and PostgreSQL in the RDBMS approach. It was concluded that this approach is suitable for large-scale point cloud datasets but there is a scope for improvement in data storage and querying.
In a similar direction, an index-based approach could be an alternative efficient solution to parse through the point cloud data. The output of the queried data model can be effectively utilized when it is presented on a data visualization platform. There have been many software tools that have provided steady solutions and have been extensively used for visualization. A few of the standard models include VRM, CityGML Maya, Cinema4D, 3DMax format, etc. (Remondino, 2004). The cesium platform is one of the contemporary web-based platform used for visualizing geospatial datasets (Yang et al., 2023).
To summarize, there is potential to expand the utility horizon of large-scale urban point cloud data for decision-making in varied applications. This paper proposes a novel integrated algorithmic pipeline to metamorphose point cloud according to semantics and spatial extent, such that it can be converted to an Analysis Ready Point Cloud (ARPC) format which has temporal sustainability and is flexible for a wide range of applications. The proposed algorithm was implemented on Dayton annotated LiDAR Earth scan (DALES) benchmark dataset to test its efficacy. In this study, two elementary applications of information extraction are also demonstrated, and a perspective on their utility to aid in sustainable development is also discussed.

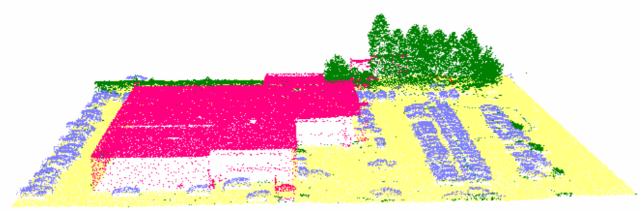

Figure 2. 3D cross sectional view of part of DALES dataset

2. METHODOLOGY

The methodology for the development of the proposed framework is shown in figure 3 and figure 8.
The urban landscape can be thought of as a collection of urban object entities. The point cloud of each individual object needs to be initially isolated and accessed to metamorphose the large point cloud. As a way towards this, the classified point cloud is initially separated into classes and then clustered into objects based on the spatial proximity of the points using Euclidean distance-based clustering (Xiangyang et al., 2017). Once the individual object point clouds are disassociated, their geometric features, such as shape, height, etc., are retrieved using different heuristic approaches. For instance, the alpha-shape algorithm is

used to extract the object shape in the case of buildings (Shen et al., 2008). Figure 4 shows the object instances of building class.

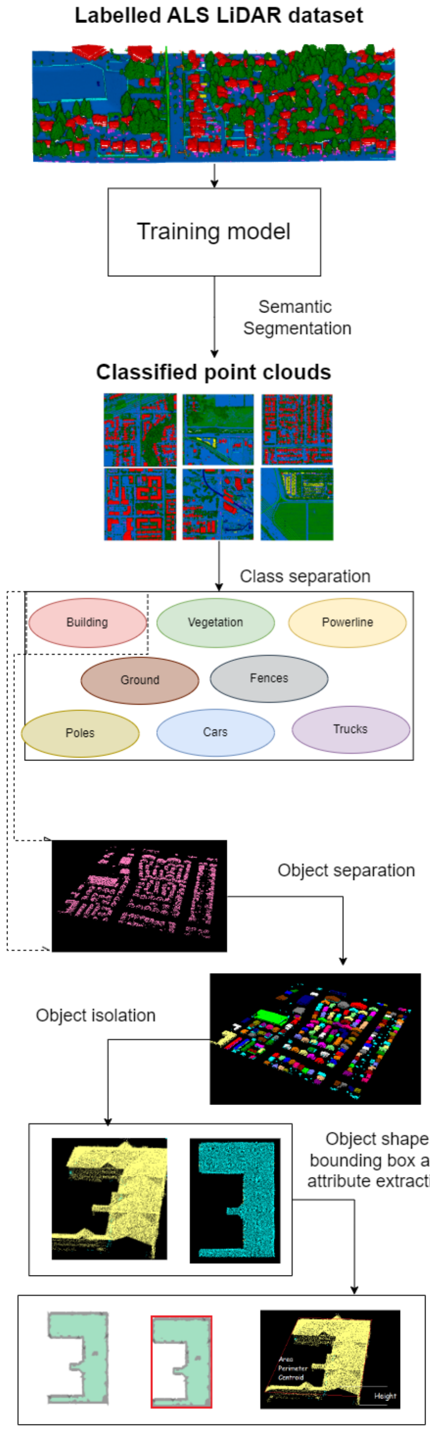

Figure 3. Methodology to convert point cloud to object entity

An efficient data storage architecture to ontologically archive the separated objects' attributes and their point cloud. The information for each object is to be saved in the database, while the point clouds are to be stored in a data repository. The Analysis Ready Point Cloud (ARPC), which may be utilized immediately for applications that extract pertinent information and integrate the outcome with 3D visualization, corresponds to this bi-modular structure data storage of database and data repository of objects. To demonstrate the applicability of this framework separate query module is further developed for extracting information and the 3D rendering, for two of the many possible applications.

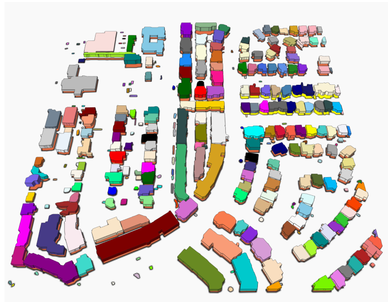

Figure 4. Buildings as individual objects

A master database and a master directory are the two components of the bi-modular data storage framework. Data is further distributed in both of the storage approaches according to class and spatial extent. In the master database, for each class individual databases having single or multiple object tables are created, as shown in figure 5.

Master database		
Class 1 database	Table C1_1	Table C1_N
Class 2 database	Table C2_1	Table C2_N
Class M database	Table CM_1	Table CM_N

Figure 5. Master database schema

Each entity or tuple in the object table represents an individual object stored with a unique ID explicitly customized for ease of understanding. A unique ID will consist of class information and an object identification number. The object identification number is created in the intermediary step of object extraction and isolation. The attributes vary with respect to application needs and object properties. For example, the building will have a polygonal shape; on the contrary, the powerline will be represented by a line feature and a pole by a point feature. Additionally, to the basic information, other non-spatial information about the object may be added as an attribute. For example, to the tree objects, the tree type may be added as an attribute which will assist in querying the database. The tuple entry corresponding to the individual object is shown in figure 6.

Object tuple	
Semantic information	Unique id, Class, Object id, Block
Geometric information	Shape, Height, Geolocation,etc.
Other information	Example: Area, application based attributes

Figure 6. Information stored in tuple

The entire process is automated including the creation of individual directories in the data repository. The class and object sub-directories are formed depending on the available classes and the object's spatial extent. Individual point clouds for distinct objects are saved in the object sub-directory using the naming convention of the unique ID assigned to the object in the object table. A pictographic representation of 3D data repository shown in figure 7.

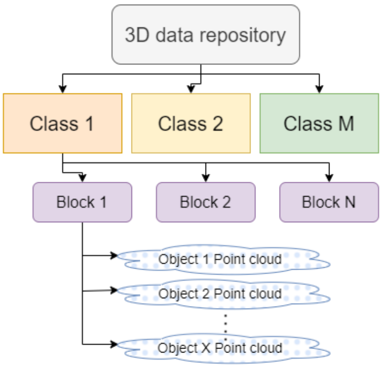

Figure 7. Data repository structure

Two instances of the applications of this proposed storage framework are shown to illustrate its utility. As a deliverable, the integrated framework provides the representation of objects from all available classes. From amongst the broad spectrum of applications, green cities, and urban infrastructure planning are used as examples to demonstrate the proposed approach.

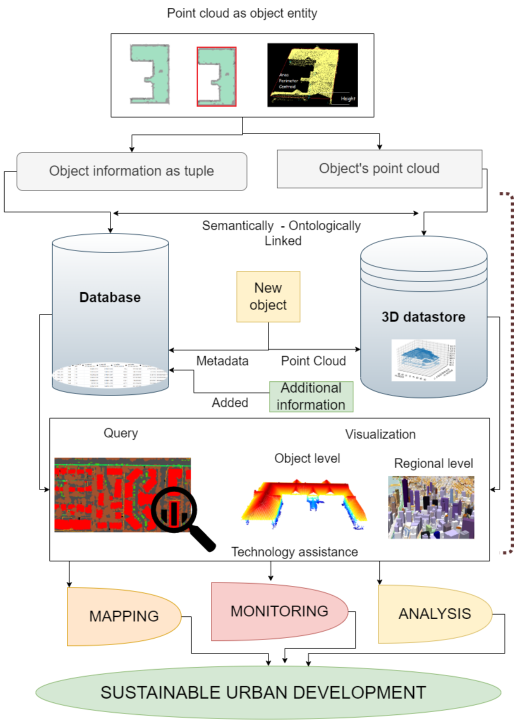

Figure 8. Methodology to store object entity for carious applications

One of the utilitarian applications to demonstrate the proposed methodology is using the building object class. Buildings, whether residential or commercial, have a lot of governance statistics and potential in urban planning. To name a few, the data on governance include house tax information, consumption of energy and water, location, amenities in proximity, etc. Energy, water, and green surroundings are the uncompromising utility. Thus, if visualized (3D thematic view based on energy consumption), monitored (based on solar roof top potential and utilization), this information with 3D visualisation can assist in efficient planning (Skondras et al., 2022),(Achbab et al., 2022), (Radosevic et al., 2022). This thematic 3D visualization will be helpful in planning and monitoring sustainable development by delivering geo-location tagged statistics and reports. Also, the 3D visualization can create social responsibility motivation for the community by showcasing their share of mapped and monitored contribution.

The second application is demonstrated for urban green mapping and planning. The tree data that is optimally, semantically, and ontologically stored in the proposed framework can be leveraged for applications pertaining to this domain. Some of the analysis include region-wise tree count in city (Schmohl et al., 2022), tree type classification using individual tree point cloud (Jombo et al., 2022), biomass calculation (Yang et al., 2022), etc. The analysis and geo-location enabled statistics can be used for efficient planning.

For instance, with a single click, the trees that are present within a road's buffer zone can be highlighted, geo-coded, and counted. Based on the available information about the trees in the database, relevant statistics can be derived. This analysis can be leveraged to determine the optimal location and tree type for an urban plantation/ afforestation. Accordingly, a technology-driven derivative with fundamental logic can be used for efficient planning.

Consider a 1-kilometer road that may accommodate 100 trees on either side (taking maximum tree diameter as 10 m, $1000\text{m}/10\text{m} = 100$ trees). Suppose there are approximately 150 trees in the road's buffer, thus route tends to be green. On the contrary, if the number of trees on both sides is between 50 and 70, the route can be designated to be a high priority for future plantation. Thus, this analysis across the urban roads, with visualization can assist decision-makers to plan urban afforestation campaigns on these routes.

Additionally, with each individual tree's point cloud available in the database, the possibility of canopy mapping, tree type identification, and post-analysis information integration can be performed. As a result, when the subsequent tree-level analysis is performed, the tree type attribute can be utilized to help derive statistics and determine the type of tree that can be sowed.

In conclusion, urban tree mapping, monitoring, planning, and analysis may utilize, the tree database ontologically linked with the tree point cloud repository. The framework is also designed to be adaptable to changing environments, making it possible to incorporate new data as information in the datastore database and if available point clouds in the data repository.

These are only two of the numerous possible applications of this approach using which technology can be leveraged for urban planning and governance.

3. RESULTS

A representative instance of the output from the two elementary query-based applications mentioned above is shown in Figure 9 and Figure 10. To showcase the flexibility of the visualization approach, the output is presented as an independent web visualization and as an HTML web page that can be integrated with the existing web interface. The first application is to highlight buildings located within a defined spatial extent. The query results in individual building objects with attributes such as geolocation, area, etc. This enables us to count the number of building objects in 3D within a scene. Further adding attributes such as an address, to individual buildings will allow exploring further applications. One such application of interest may be, to highlight the solar potential of each individual building.

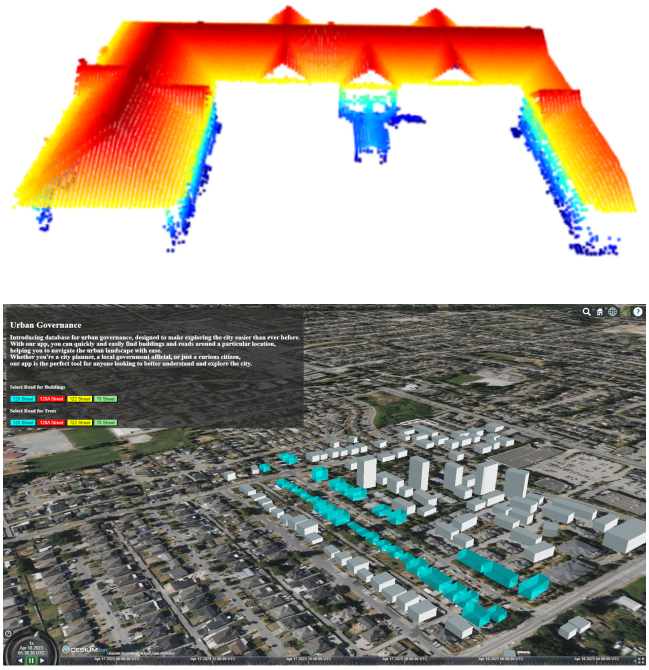

Figure 9. Individual object's point cloud and 3D visualization of the first application instance

This may be computed based on the rooftop area, the sun angle at a particular time of the day, and the shape and position of the roof. The addition of such attribute will allow the decision makers to make query such as "highlight buildings with solar potential > X" . Another application demonstrated as part of this study is to select the trees which are located in proximity to the main road. Such queries can help in finding the number of trees along with the tree type which relies on the shape of the tree. This sort of information are very essential for urban green space planning.

Figure 10. 3D visualization of the second application instance

4. DISCUSSION

Technological assistance for sustainable urban planning and governance can be provided by using three-dimensional data for better understanding, information extraction, and visual interpretation. There is potential for the use of large-scale ALS point clouds for sustainable development, specifically relating to urban green (Münzinger et al., 2022), energy management (Wang et al., n.d.), resource management and urban governance (Naber et al., 2022). The use of ALS point cloud for utilitarian and pragmatic applications is uncommon due to its large volume, unstructured nature, almost no attachment with semantics (Poux et al., 2016) and governance-related statistics. Thus, it becomes imperative to transform the city-scale point cloud into a data storage structure that can adapt to changing application requirements and urban growth over time. Such a framework can be effectively used for a wide range of applications, integrating conventional governance and planning with technological assistance for better decision-making.

An urban landscape consists of a variety of objects such as buildings, trees, powerlines, etc (Zhao et al., 2022). Individually each component is essential in its domain of application and analysis. These objects are spatially connected and thus, their analysis based on spatial correlation in 3D opens another dimension for planning. In order to effectively make maximal use of the capabilities of the ALS point cloud, prior research focused on independent and solitary prospective applications such as mapping urban forests/ solar rooftop estimation (Münzinger et al., 2022).

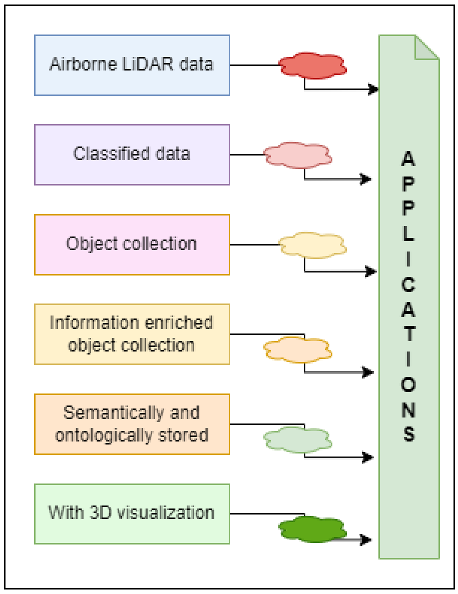

Figure 11. Point cloud to Utilitarian Applications

In this work, a novel bimodular framework that metamorphically stores point cloud to be used in multiple applications is proposed. This section describes the effectiveness of the proposed approach and emphasises to showcase its adaptability, scalability, and durability. The bi-modular storage framework in this approach aims to concentrate the point cloud search space to enable efficient and speedy queries with its output visualization. While metamorphosing the huge point cloud, the search space is significantly reduced and the semantic value of the point cloud is increased by the addition of spatial-semantic information. Also, there is no information loss at any level because the point cloud abstraction in the databases is connected to its equivalent in the data repository.

For instance, a small subset of ALS data which is 379 Mb was condensed to a 408 KB building database. Thus, the search space for an object (here, in this case, buildings) is reduced to merely 0.1 percent of the size of the original point cloud dataset. The computational time for generating the data store framework depends on the size of the data and the type of query being performed. The time required for extracting information depends on the number of objects in the specific class being queried.

For example, with a point cloud dataset spanning over 2500 square meters with an average point density of 50 points per square meter, for isolating complex objects such as buildings took approximately 84s. Further, to create the database it took an additional 148s. Notably, the time needed for isolating and generating the database for less geometrically complex urban objects such as power lines and poles, would be comparatively lesser. The response time for querying depends on the size of the database, the geometric complexity of the urban object as well as the complexity of the query. For instance, performing a simple query on one of the major class-like buildings, was within 27 milliseconds.
The prior research focused on queries centered on retrieving points from a particular class as a patch or collection of points. The aforementioned approaches didn't explore the prospect of comprehensive information extraction for all urban objects by compressing the search space while storing the point cloud and augmenting semantics for utilitarian applications. These methods could not be scaled to multiple applications because the search space for pertinent queries was so large, and they did not associate point cloud with additional semantics for regional and object-level information extraction.
In the proposed approach, the object data is saved as a tuple and the object point cloud is stored as point cloud collection in a block-based manner. The two instances also share an ontological relationship. The search space for queries is reduced by this storage framework. Additionally, each object's 3D data is comprehensive and is available for 3D visualization.

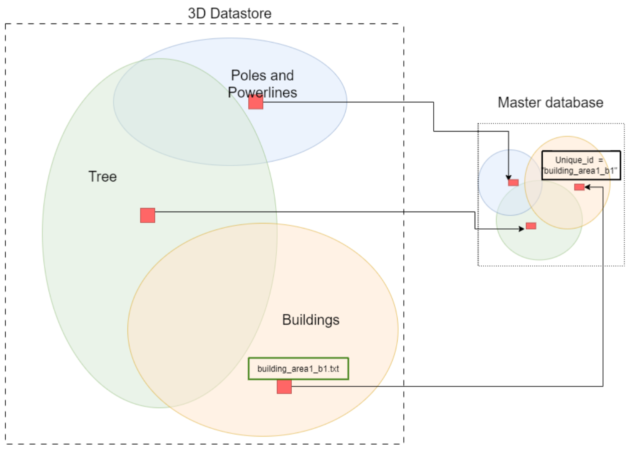

Figure 12. Ontologically linking 3D database to datastore

This approach is adaptable, to the addition of new urban object class. The two-dimensional (vector shae file) or three-dimensional data (individual point cloud of objects) of that class can be amalgamated with the existing data storage and can be used for querying. The approach, as it stores the point cloud abstraction in a database, has scope to add new objects constructed over time. The new data can be added at two different instances, at database and datastore level. To add a new object of any class like building, pole or powerline - its vector geometry with other attributes can be added to the specific database and if the point cloud of the new urban object synthetically created is available, it can be added directly to the datastore. To incorporate a new region the ALS point cloud needs to be converted to a specified data storage framework which can be added to the suitable directories of the database and datastore. The proposed approach has a decentralized data storage framework yet a centralized information extraction framework which further contributes to making it sustainable and scalable using the incremental approach in accordance with the availability of labeled point cloud. Another feature of this framework is that it allows object-based queries, for example, if an application is interested only in one of the urban class objects namely trees, then the database and the directory corresponding to trees in the data repository can only be deemed.

5. CONCLUSION

With the cities expanding, sustainable development and urban governance are key sectors where efficient planning and monitoring are required. The urban infrastructure consists of buildings and other objects like trees, powerlines, poles, etc. For holistic development and planning, it is crucial to efficiently map urban resources and also to organize the data in a way that pragmatic and useful queries and intriguing 3D visualizations can be derived.
An accurate map of the urban infrastructure can be created by using Airborne LiDAR Scanning. The data from ALS is available as a collection of point clouds which are stored in a file-based format. These point clouds are unstructured, voluminous, and not semantically linked. Because of this, the potential of this valuable data has not been fully realized in the application sector due to the limitations in retrieving information from point clouds.
In this study, we proposed an algorithmic pipeline and a bi-modular ontologically linked storage framework that facilitated point clouds to be used in a wide range of applications. It is accomplished by metamorphosing the point clouds into the proposed storage framework. In this work, we have demonstrated two of the application and furthermore applications pertaining to sustainable development and urban planning can be built on top of the suggested framework. These applications will have the potential to provide technical assistance for urban development and planning.
In future works, the concept of metamorphosing the point cloud to an application-ready point cloud can be improved, both in terms of algorithmic advancement and prospective applications. The addition of more urban objects like roads, railway infrastructure, public parks, etc. can be investigated in further study. Further, in this approach, the individual stages of object isolation, database and data repository creation, information extraction, and visualization, have scope for optimization and advancement in the future. The concept of the applications, integrated with metaverse and augment reality can further improve it as an end product to provide technology assistance for conscious decision making.

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