Article

Towards a 3D Data Model of Underground Utilities for Land Administration

Jingya YAN [1,†*] https://orcid.org/0000-0001-8321-1329, Siow Wei JAW [1,2,3], Kean Huat SOON [4], Andreas WIESER [5] and Gerhard SCHROTTER [6]

1 ETH Zurich, Future Cities Laboratory, Singapore-ETH Centre; Jingya.yan@arch.ethz.ch
2 Geoscience & Digital Eaeth Centre (INSTeG), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia, Malaysia; swjaw@utm.my
3 Department of Geoinformation, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia
4 Singapore Land Authority, Singapore – SOON_Kean_Huat@sla.gov.sg
5 ETH Zurich, Institute of Geodesy and Photogrammetry – andreas.wieser@geod.baug.ethz.ch
6 Geomatik + Vermessung Stadt Zurich, Zurich, Switzerland – Gerhard.Schrotter@zuerich.ch
* Correspondence: Jingya.yan@arch.ethz.ch

Abstract: Cities around the world face an increasing need for land as density in urban areas increases rapidly. The pressure to expand a city's space is especially acute for a city-state like Singapore. In the big data era, a data-driven approach of underground spaces is necessary for the sustainable development of a city along with rapid urbanization. A reliable three dimensional (3D) digital map of utility networks is crucial for urban planners to understand one of the most impactful aspects of underground space planning. How to map reliable 3D underground utility networks and use it in the land administration? This is a challenging issue, especially for cities with limited land resources, congested underground spaces, and a lack of uniform existing practices. First, this paper proposes a framework for utility data governance from the underground utility data survey to data usage. This is the backbone to support coordination of different roles in the utility data management and usage. Then, an initial design of the 3D utility cadastral data model is introduced, which aims to support the 3D modelling of utility networks and connect it to the cadastral parcel. It is expected that reliable and accurate information on underground utility networks can lead to a better understanding and management of underground space, which eventually contributes to better city planning, making the unseen structures visible.

Keywords: 3D Data Model, Underground Utility Networks, Underground Space Planning, Underground Mapping, Utility Cadastre, Land Administration

1. Introduction

Rapid urbanization creates a strong need to optimize land use in densely populated cities. Attention is thus shifting from the very limited available space above ground to generation and increased use of underground spaces. A prerequisite for including the underground in urban planning is the availability of sufficiently complete, accurate and up-to-date 3D maps of the underground. However, such maps are not yet widely available, if at all, and the required data acquisition is much more challenging than for spaces above ground. Some countries and institutions have implemented or at least conceptualized the 3D mapping of underground utility network and their management in a related cadastral system. For instance, the Canton of Zurich started to establish a comprehensive

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 April 2019 doi:10.20944/preprints201904.0223.v1

Canton-wide utility cadastre map based on the Cantonal Act on Geoinformation of 2011[1], derived from the Federal Act on Geoinformation of 2007[2] and the Cantonal Regulation on Utility Cadastre of 2012[3]). The municipalities of the Canton of Zurich have time till 2021 to implement the requirements. The City of Zurich has an own utility cadaster since 1999 and has set up a governance framework with the corresponding utility providers[4]. Figure 1 shows an example of utility map of City of Zurich. Additionally, the United States of America, the United Kingdom, Malaysia, and Canada have developed 3D maps of underground utility networks [1,2].

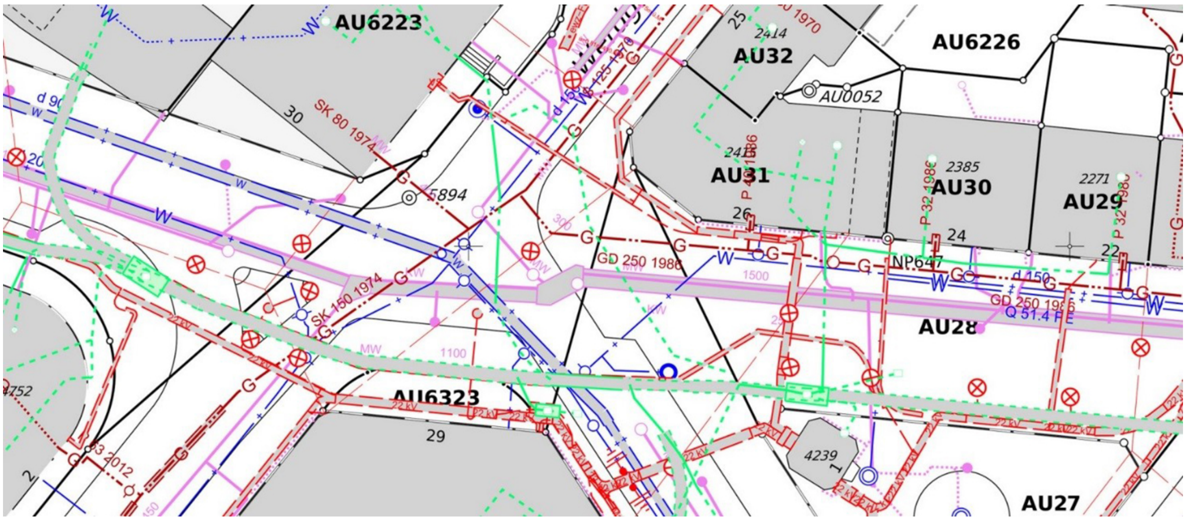


Figure 1. Utility map of City of Zurich[5](Source: Geomatik + Vermessung Stadt Zurich).

With a population of more than five million living in an area of 720 square kilometres, Singapore has revealed a plan for placing infrastructure underground. To establish a map of the Singapore underground including utility services, government agencies (e.g. utility owners, land developers, and land owners) have already started sharing their data using Singapore Land Authority (SLA)'s GeoSpace platform. Figure 2 shows an example in Marina Bay region of Singapore. All the existing data are 2D. Obviously, all of them overlay each other make the chaotic visualization. In order to observe the existing data, we zoom in to a corner of Marina Bay region. Figure 3a presents five layers of different power grid networks. But the geospatial information of different layers are totally the same. These data are unreliable and so difficult to be visualized in 2D. From figure 3b, the limited attributes are provided from current database. Only the main water pipes have diameter. Most of them have 2D geospatial information. In addition, data owners have more details of existing utility data. But most of them are 2D data as well. Depending on the requirement of application, some data owners try to collect 3D data. There are some issues during the data capture to usage. Without the utility survey standard, some of them only use traditional survey method to get the 3D points data of piplines and overlay on the existing data. Nobody can guaranty the quality of these data. Meanwhile, because of limitation of existing data model, 3D data have trouble to integrate with the existing 2D data. The update is once per six months. In general, a number of issues prevent these data from being sufficient for urban planning, land administration, and on-site work. In fact, many existing

---

1 http://www2.zhlex.zh.ch/appl/zhlex_r.nsf/0/84FC05FF03048541C12581DE00372667/$file/704.1_24.10.11_99.pdf
2 www.admin.ch/opc/en/classified-compilation/20050726/index.html
3 http://www2.zhlex.zh.ch/appl/zhlex_r.nsf/0/2177E9F8B5B576A1C1257A99002C2307/$file/704.14_27.6.12_78.pdf
4 www.stadt-zuerich.ch/ted/de/index/geoz/geodaten_u_plaene/leitungskataster.html
5 www.stadt-zuerich.ch/content/dam/stzh/ted/Deutsch/geoz/Geodaten_und_Plaene/Formulare_und_%20Merkblaetter/Adressliste_Leitungserhebungen.pdf

 doi:10.20944/preprints201904.0223.v1

databases, not only the ones in Singapore, contribute incompletely to the spatial understanding of the underground because of similar restrictions. In particular:

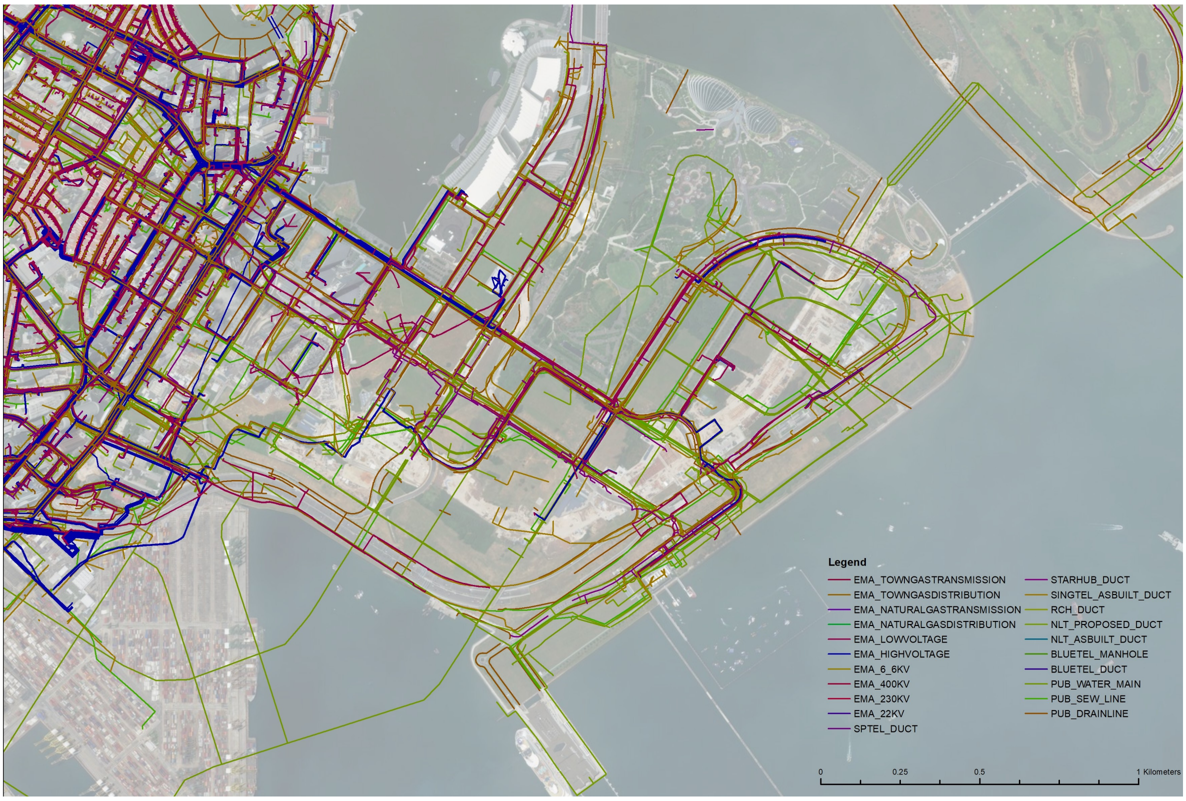
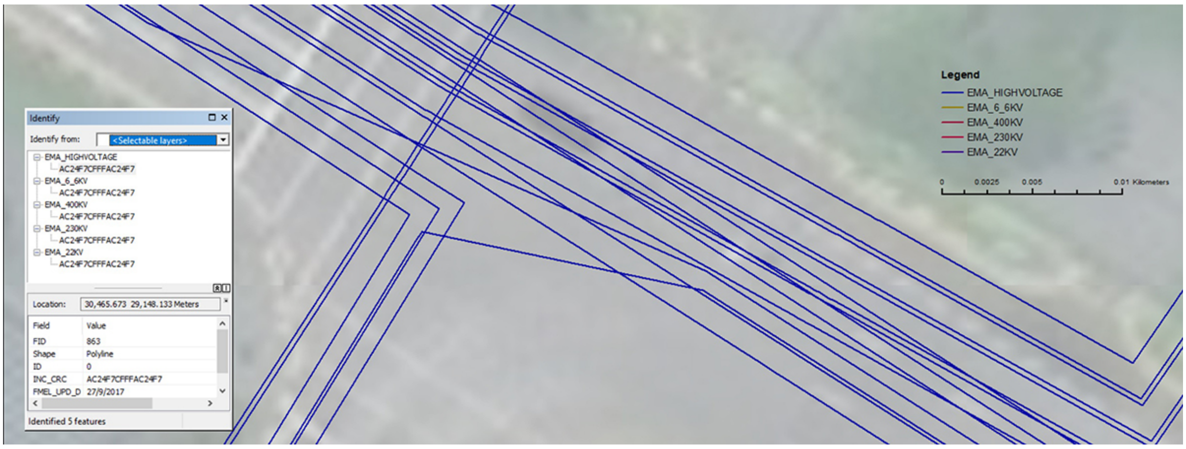


Figure 2. An example of utility data in Singapore (Source: Singapore Land Authority, 2018).

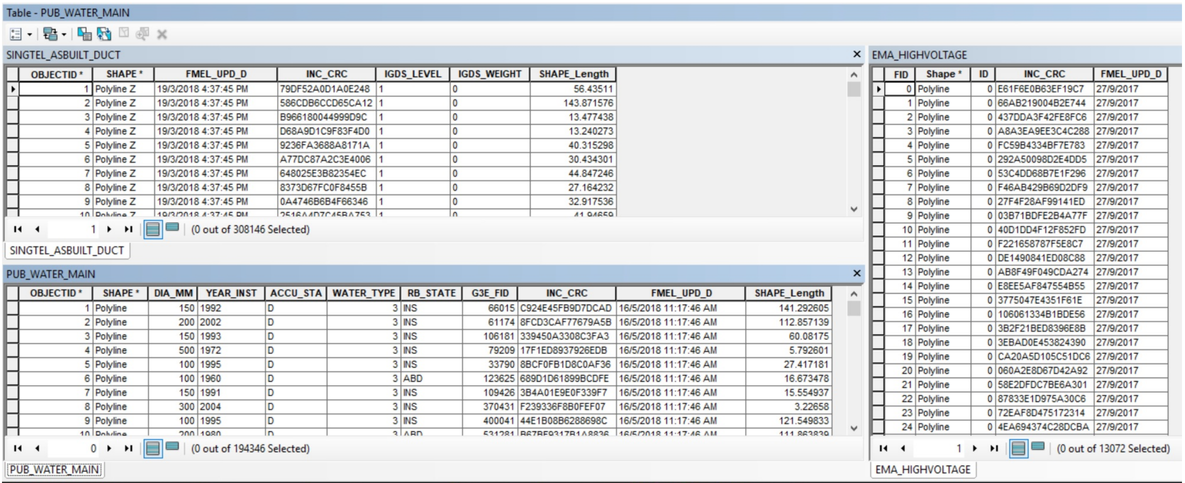
- The data are often only 2D i.e., lacking depth information entirely, or 2.5D (i.e. featuring depth as an attribute to horizontal position rather than as an independent coordinate. Furthermore, the depth information may be sparse with depths measured at few locations only, e.g. at accessible manholes, and it may be ambiguous because it is not always clear whether the values represent depth relative to a specific surface with unknown elevation or height relative to an established height datum.
- It is unknown whether the data represents the current situation, the possibly different as-built state, or just the as-designed state. Furthermore, the geometric accuracy and the completeness of the are often unknown.
- Much of the attribute information (e.g. diameter, material, installation date) required to support specific applications is not available or not represented the appropriate level of detail.
- There is a lacks of standards for organizing the data and semantic information of underground utilities, impairing data sharing and use of the shared data.

Overall, the reliable and accurate 3D data of utility networks is sorely demanded. Therefore, the Singapore-ETH Centre together with the SLA and the Geomatics Department of the City of Zurich have started a related project under the name "Digital Underground". The initial goals of this project are to develop a road map, a data model and a concept for deriving a unified and complete 3D map of the relevant underground structures (in particular of utilities and spaces like corridors or tunnels). Collecting best practices for underground utility mapping is a special focus within the project. Figure 4 describes the work process of 3D underground utility mapping. In the data capture, different types of survey techniques are explored and compared in order to find the optimal underground utility survey approach. After the data processing, the new collected data should be integrated to

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 April 2019 doi:10.20944/preprints201904.0223.v1



(a) An example of power grid data



(b) The attributes of existing utility data

Figure 3. The issues of existing utility data (Source: Singapore Land Authority, 2018).

the existing database aiming to improve the information of underground utility. As the backbone of 3D underground utility map, the 3D consolidated database of underground utilities should be developed for data management. Additionally, a 3D map of utility networks could shed light on the management of utility networks such as their ownership and operation in order to ensure legal compliance, efficiency, and resilience of these utility networks. Then, the underground utility data can be used in various applications. However, securing reliable data for a consolidated database with sufficient and consistently accurate information is a challenging task. A gap exists between engineering practices and mapping disciplines for underground utilities. Meanwhile, we need to find the solution of how to use the existing data and integrate it with new collected data.

Here we focus on underground utilities, ignoring other underground structures which eventually need to be represented in the same 3D data base as the utilities. We propose an approach to data governance for underground utility data and a 3D underground utility data model, which aims at bridging the gap between underground utility surveying and data management for land administration. Our proposal addresses the following:

- The organization of different roles for the sharing of data. It is necessary to make clear the governance of different roles. During data sharing, the communication between different roles (e.g. data producers, regulatory bodies and users) is very important.
- Different roles require different permissions to access, change, delete or add data. These permissions must be defined and maintained administratively.

 doi:10.20944/preprints201904.0223.v1

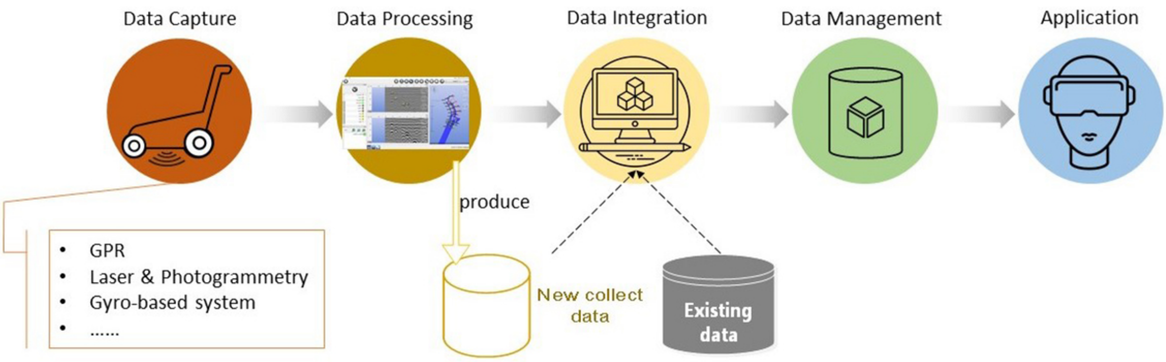


Figure 4. Workflow of underground utility mapping.

- Building and updating the 3D map of the underground requires integration of datasets of different type, quality and source. Data may originate from recent surveying e.g., using Ground Penetrating Radar (GPR) or self-contained sensors tracking their own movement through a pipe. Data for building a map may also be derived from other databases. This integration requires handling various data formats, and quantifying and properly taking into account the respective data quality.
- The underground data need to be convertible into the data formats required by a variety of different applications and end users without loss of relevant information.

Subsequently, we first introduce related works on 3D underground utility data acquisition and reviews existing data models for utility networks. In section 3 we propose a framework to resolve the above issues about data governance and explain the design of a 3D underground utility data model. In section 4 we briefly summarize a Singapore case study covering the work process from large scale GPR-based data acquisition to 3D visualization. We conclude with a summary and an outlook on future work.

2. Related Works

2.1. The technologies for 3D underground utility data acquisition

The information of the buried utility networks can be retrieve without any physical contact through underground utility mapping. However, underground utility mapping is more challenging as compare to above ground mapping as most of the utility networks are invisible to the naked eyes. In this context, underground utility mapping is adopted to scan, detect, mark and locate utility networks, in collaboration with different subsurface geophysical technologies [3,4]. These subsurface geophysical technologies are considered as the trenchless technologies, where the inspection can be done without proving excavation [5,6]. These subsurface geophysical technologies, such as Ground Penetrating Radar, Electromagnetic Locator, are recommended for capturing the information of the buried utility networks [4,7]. However, optical (e.g. using photogrammetry, or laser scanning) and physical (e.g. total station or global positioning system) measurement are recommended for capturing the information of the utility network while it is still expose through the trenching pits as shown in Table 1.

As the numbers of utility networks increases, the urban underground is now a spider web of utility networks. The adoption of the above-mentioned technologies at such congested cities has become limited. It is hard to measure the exact location of the utility network. A gyroscope-based system [8] was developed to measure the trajectory of the newly laid pipeline in offline mode. In this paper, our data capturing was using GPR due to its popularity in underground utility mapping [4] and the gyroscope-based system as it is not limit by depth measurement or susceptible to any electromagnetic disturbances [8].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 April 2019 doi:10.20944/preprints201904.0223.v1

Table 1. Data capture methods for underground utility services.

Method	Use case	Typical (primary) data
Conventional surveying	Open pit	Sparse point trajectory
Laser scanning & photogrammetry	Open pit	Dense point cloud
GPR	Buried utilities	Radargram
IMU-based system	Buried, newly built	Dense point trajectory
Marker tagging	Buried	Sparse set of points

2.1.1. Ground Penetrating Radar (GPR)

GPR is a widely used technology for characterizing structures in the underground. It is based on recording the delay and power of electromagnetic (EM) signals scattered and reflected at discontinuities of the permittivity. Such discontinuities are associated with differences in materials or differences in material properties allowing to detect e.g. man-made objects, holes, and layers of different composition or water content in the underground [9,10]. GPR is used for a variety of applications, among them geophysical exploration, archeology, and the buried utility networks [11,12]. Depending on the type of transmitted signals, Impulse radar systems and Continuous wave radar systems are distinguished, with the former being more common [13]. The penetration depth, i.e., the maximum depth at which discontinuities can be detected using GPR is on the order of a few meters to a few tens of meters, depending on the soil characteristics, transmission power, signal stacking time and the frequency which typically range from 10 MHz to 4 GHZ. Lower frequencies require bigger antennas but facilitate higher penetration depths. Higher frequencies on the other hand yield better spatial resolution and thus allow correctly locating smaller objects or distinguishing objects at smaller distances [11]. 3D information is obtained by moving the radar antennas along the ground surface, recording data quasi-continuously, and subsequently analyzing the data tomographically. Figure 5a shows two examples of GPR instruments, one being integrated with a mobile mapping trailer, and the other one a manually pushed cart.

As opposed to optical techniques used for mapping above ground, the (relatively) low-frequency GPR signals cannot be bundled well, and the radar images (radargrams) obtained from the measurements, see (Figure 5b) for an example, are thus typically difficult to interpret. So far, both the data capturing processes (selection of frequencies and data recording parameters) and the extraction of 3D information of underground utilities from the raw data require an operator with significant expertise . Along with unavoidably physical limitations the factors impede the application operation of the GPR as a sole means for mapping the underground.

(a) **(b)**

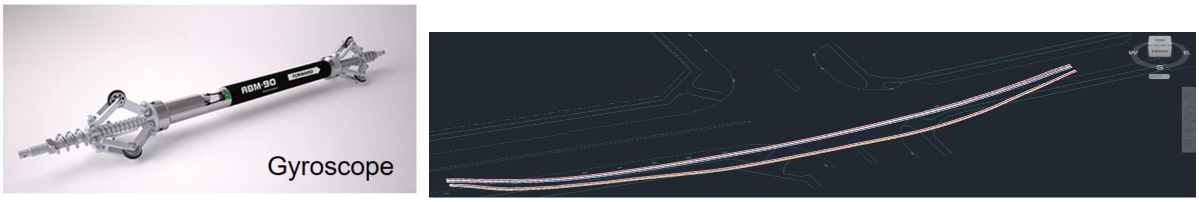
Figure 5. Examples of GPR instruments (a) and GPR data (b); the data show a radargram of a longitudinal cross section of the top-most about 2.85 m along an asphalt paved road (bottom), a perpendicular cross section of one lane (top right) and the top view of the scanning tracks covered by GPR measurements (top left).

 doi:10.20944/preprints201904.0223.v1

2.1.2. Gyroscope-based systems

Utilities with a diameter of more than about 5 cm through which a probe can travel may be accessible to mapping with an inertial measurement unit (IMU). Such a unit measures 3-axis acceleration and 3-axis rotation rates which can be integrated over time yielding position and orientation changes of the unit. If the unit is mounted within a probe and the probe travels through the utility (typically a pipe), the trajectory of the probe – and thus the 3D coordinates of points along the axis of the utility [8].

The potential benefits of such a measurement system are that (i) it can acquire the as-built information of the suitable utilities even if they are buried at a depth exceeding the penetration depth of GPR, (ii) the location can be geometrically more accurate than using above-ground measuring technologies for location of underground structures, (iii) it can acquire data irrespective of the properties of the surrounding underground (e.g. soil composition, water content) and of electromagnetic fields, and (iv) that the probe can be equipped with additional sensors capturing more information than just the coordinates (e.g. diameter, radius of curvature, corrosion). Major disadvantages are that (i) only pipes with sufficient diameter, sufficient minimum radius or curvature and accessibility can be measured, (ii) depending on the measurement system, the pipe needs to be empty during the measurement i.e., the service of the utility is interrupted, (iii) the accuracy of the 3D coordinates degrades rapidly with time such that only short parts of the utility, with known coordinates of the start and end point can be measured if high accuracy is needed, and (iv) additional provisions may be required, e.g. short periods through which the probe remains stationary while moving fast at others. Figure 6b shows an example of such a probe and a 3D map of utilities mapped using it.



(a) (b)

Figure 6. An example of a Gyroscope-based pipeline measurement system (a) and the 3D map of the measured pipes (b).

It can be concluded that each technology has its advantages and limitations. The selection of using the right instrument depends on its application. A comprehensive collection of utility network mapping technologies may be required to acquire reliable 3D utility network data. The data that is obtained by different instruments needs to be integrated with utility networks attributes before storing in a geospatial database to support 3D visualization, utility data management, urban planning and others application.

2.2. The review of data model for underground utility networks

A range of utility data models has been developed for storage, visualization, exchange, analysis in the geospatial domain. Obviously, the general data model is not enough to reach all the requirements from different users. In order to develop the 3D data model for the land administration of underground utilities, this work reviews the existing data models that are related to underground utility networks and land administration.

2.2.1. 3D data model for underground utility networks

The CityGML utility network ADE [14] focuses mainly on the representation of topographical, graph structural and functional information across the multi-utility networks in 3D space [14,15]. This data model not only represents a utility network component by its 3D topography and complementary graph structure [14], but also considers interdependencies between utility network features and city objects [16]. Because this data model is an extension of GityGML [17], which is the popular standard for 3D city modelling (e.g. building), is beneficial to integrate information of utility network to the infrastructures to support urban planning and the other city studies. However, it does not consider the accuracy of the data. Some works begin to extend the existing data model to consider much more details about utility networks, such as Scholtenhuis *et al.* represent geographical uncertainties of utility locations based on CityGML Utility Network ADE. The Industry Foundation Classes (IFC) utility model [19], which is an ISO standard for data exchange, pays more attention to the supply service of buildings in the civil engineering and architecture domain. It describes 2D and 3D geometry of utilities within the building and the logical or physical connection between building service components. However, the IFC utility model lacks spatial information. The INSPIRE Utility Networks [20] organize the basic information of utility network and administrative service of utility networks in a city or country range. It is a part of INSPIRE, which is a standard of European Union to describe the spatial information of infrastructures. However, the INSPIRE Utility networks lacks of definition of 3D geometric information of utility networks. ESRI developed the ArcGIS utility model [21] that provides a GIS-based utility solution to represent the underlying logical and physical relations of utility networks. The ArcGIS utility model is a general utility data model to represent the 2D geometric information and connections of the utility networks.

Until now, there is not a widely accepted international standard for an underground utility data model [22]. Even though the standardized data models, such as CityGML and IFC have been developed to integrate multi-layer utility network data, these data models do not guarantee the information to be reliable, and there is currently no integration with above-ground urban features. Moreover, in order to provide utility data for 3D visualization and other applications, it is necessary to integrate different types of utility datasets from multiple surveying methods. Table 2 compares four popular utility data model relevant to the objectives of this work. Obviously, most of the existing utility data models are to focus on the 3D representation, include 3D geometric and topological information. The existing data models provide a good reference to describe the geometric and spatial information of utility networks in 3D. Nevertheless, none of them consider the accuracy of data of underground utility networks. Industry service providers are often not aware of these extensive standards that should ideally guide mapping procedures and accuracy requirements for underground utility network mapping. The surveying method is related to data accuracy and data management directly. Hence, we need a 3D utility data model to fill the gap between underground survey and land administration applications.

Table 2. Comparison of model characteristics.

	CityGML Utility Network ADE	ArcGIS Utility Networks	INSPIRE Utility Networks	IFC
3D representation modelling				
-3D geometries	+	-	-	++
-Topological aspects	++	++	++	++
-Hierarchical modelling	++	.	++	+
Land Administration	-	-	-	-
Data quality management	-	-	-	-

-: no support, .: basic support, +: sophisticated support, ++: comprehensive support.

2.2.2. Underground utility in land administration

The rapid urbanization and increasing complexity of urban spaces worldwide presents an urgent need to provide much more and precise information for land usage. Obviously, 2D cadastral information and visualization are not enough for current land administration. During the past decade, a number of works research on the 3D cadastre from various aspects, such as legal, organization and technique [1,23,24]. The Land Administration Domain Model (LADM) [25] is an important legal framework to define and integrate concepts and terminology of Land Administration for 3D representations. As an international standard, the LADM provides a flexible conceptual schema from three main aspects: organizations, rights and spatial in formations [24]. The integration of 2D and 3D information in the LADM can provide solutions for 3D cadastre. However, the LADM still lacks of information about underground utility services.

In recent years, some researchers or government agencies begin to consider the cadstre for underground infrastructures. Pouliot and Girard provided a discussion about the integration of underground utility networks in the land administration system. Based on the case study of Quebec, they discussed three key questions in the following:

- Do we need to register underground objects?
- Should underground networks be registered in the Land Register, with the same specifications as land parcels?
- Which information should be part of the registration process?

On the basis of their discussion and the situation of Singapore, it is necessary to register the utility segments as the legal objects in the land administration system, which helps to identify the ownership of underground utility. Moreover, land parcel, as an important role in the land administration, should be connected to the underground utility [1,26].

3. Design of the 3D Data model for Underground Utility Networks

3.1. A Framework for Utility Data Governance

From data capture to usage, the whole work process includes several participants in different stages. Hence, this work proposes a framework for underground utility data governance at a top level (Figure 7), which aims to resolve issues about communication between different organizations, data integration, and data sharing during 3D mapping of underground utility networks. This framework consists of five roles that are listed in the following:

- A data producer, who can be a contractor and/or part of the data regulatory bodies' organization, will submit data to the utility network database after utility survey.
- Data owner manages their collected data. This role could be companies or data regulatory bodies.
- Data regulatory bodies, which are government agencies, will collect data and manage them based on their utility network data model. The data regulatory bodies should provide a clear permission to use and predefined subset of utility data, which will be used by data integrator.
- The data integrator integrates all utility data and manages the utility cadastre of all the utility networks in a city or country. The data integrator should provide the required information for the application of utility cadastre management to users. This role is vital in this framework, connecting the data regulatory bodies and users.
- Data users can use utility data for utility cadastre management applications.

In this work process, the surveyor as data producer to capture data during the field work. After that, the data will be submitted to data owner (e.g. Public Utilities Board (PUB) of Singapore) who needs to manage the data of their own utility networks. According to the requirements of government, the utility data will be submitted to data regulatory bodies (e.g. PUB and SLA), which include two options. If the data regulatory body has the utility data model, they can continue to use it. Otherwise, a general utility network data model will be designed as a standard to manage underground utility data for data regulatory bodies. A consolidated 3D utility data model will be designed to support utility cadastre management. The data integrator (e.g. SLA) needs to integrate data of different kinds of utility networks. The LADM plays as a connection component to build relationship between the general utility network data model and utility cadastre data model in the utility cadastre management.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 April 2019 doi:10.20944/preprints201904.0223.v1

Meanwhile, the LADM will connect underground utility network to the land administration of above ground. At last, the utility cadastre data model should support applications in the land administrative management.

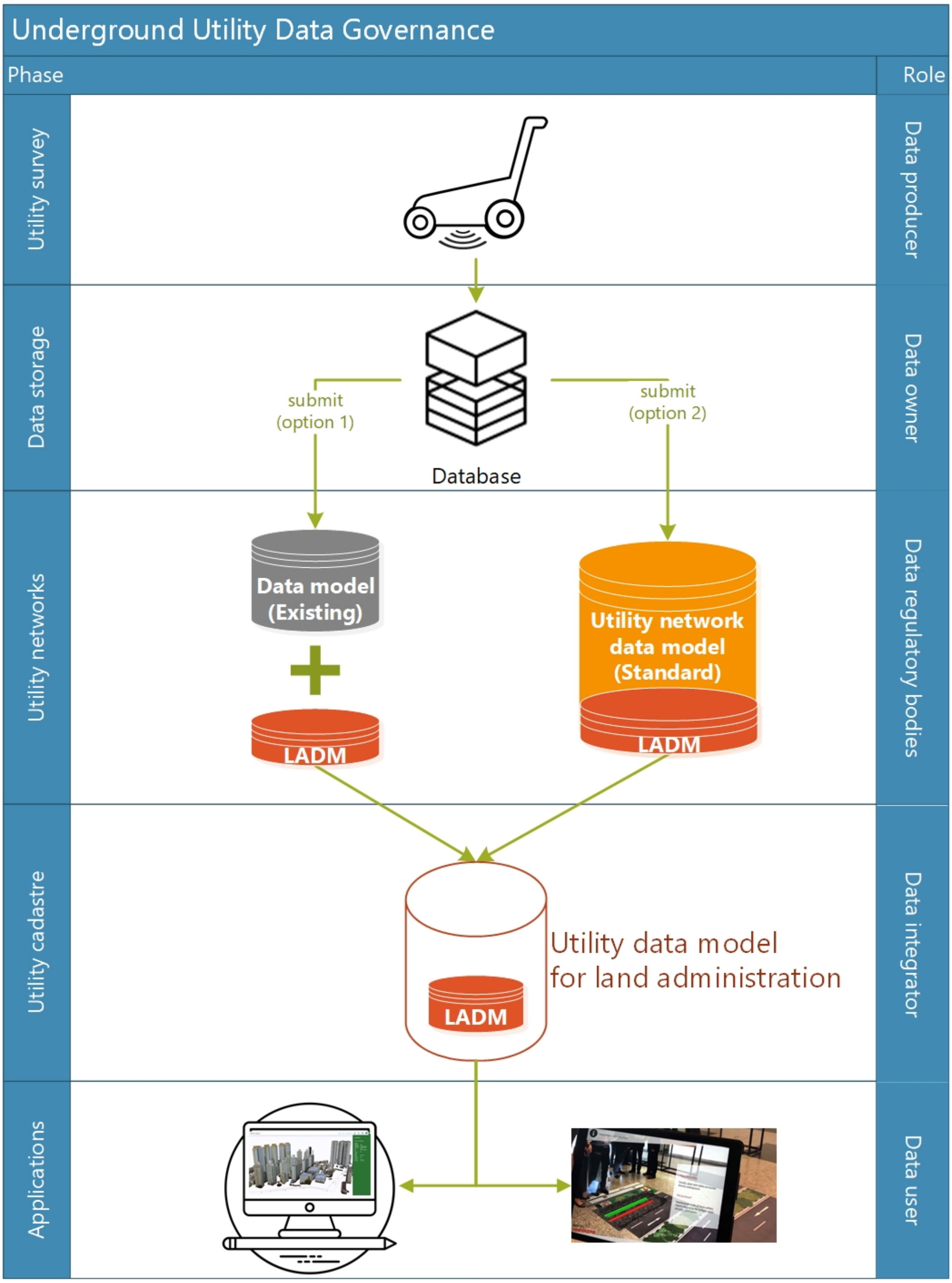


Figure 7. The framework of underground utility network data governance.

3.2. 3D Utility Cadastre Data Model

Current work focuses on the design of 3D utility cadastre data model. In order to understand the demands of underground utility data users, a workshop was organized to learn the work process and needs of land administration in Singapore. This studying includes four application domains,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 April 2019 doi:10.20944/preprints201904.0223.v1

land acquisition and purchase, planning and coordination, land transfer and sale, and land leasing. Currently, the existing data sources are hardcopy of utility network, 2D CAD and 2D geospatial information. There is an urgent demand of 3D geospatial information of underground utility and space to evaluate underground environment and support reallocation, land sales and the other applications. Therefore, the 3D utility cadastre data model includes three packages to organize the basic information and structure of utility networks, utility survey information, and the land administration information (Figure 8). In order to connect 3D utility cadastre data model to the information of land administration, these three packages inherit from Singapore cadastral data model and LADM (ISO 19152). Meanwhile, the geometric and spatial definition are inherited from Spatial schema data model ([27]).

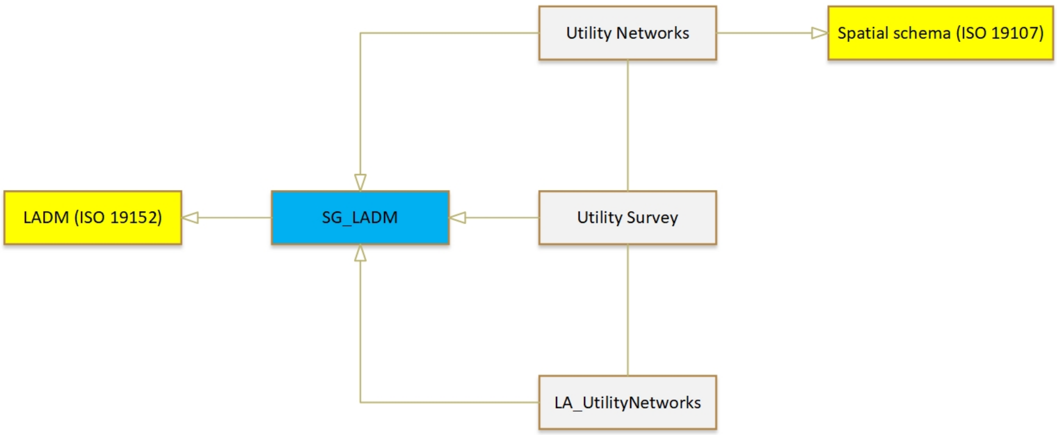


Figure 8. The overview of packages of 3D utility cadastre data model.

The **Utility Networks** package describes the basic information of utility networks, includes geometric, spatial and physical information. Based on the partonomy (part–whole) relationships, this work defines the hierarchy of utility networks in three levels (Figure 9). The macro-level is the whole utility networks, which is described by *UtilityNetwork* class with the basic information of utility networks, such as the type, material of utility networks. The meso-level is the surface of the utility networks, which is the part of the utility networks. The surface could be the tunnel, duck, manhole and the other types of space in the utility networks. Hence, the aims of *UtilityNetworkSurface* class are to describe the types and 3D geometric information (e.g. diameter) of surface. The micro-level is the basic elements of utility networks, includes nodes and segments of utilities. The node is a connection point in the network, which is defined by *UtilityNetworkNode* class. The segment is the line segment of the utility, which is defined by *UtilityNetworkSegment* class. The relationship between micro and meso level helps to transform 2D to 3D data as well. Figure 10 shows the relationships of different classes in the **Utility Network** package and basic attributes of each class. The values of utility networks type inherit from LA_LegalSpaceUtilityNetwork in the LADM (ISO 19152) [25].

The *LA_UtilityNetworks* class (Figure 11) aims to describe the land administration information of utilities. On one side, it connects to the utility network surface in order to identify the land administration information of different parts of utility networks. On the other side, it connects to the cadastral parcel from Singapore cadastral data model and LADM ([25]). The spatial relationship is used to describe the relationship of cadastral parcels and utilities, includes contain, cross and touch. This class could support ownership management of utilities and the land administration management.

The *Utility Survey* class (Figure 12) aims to organize utility survey information. It could help to manage survey status and accuracy of data. The *Utility Survey* class inherits attributes of the survey from Singapore cadastral data model. Furthermore, the ground conditions and survey methods are related to accuracy of data directly. Hence, the *Utility Survey* class integrates information from Standard and Specification for Utility Survey in Singapore ([28]). The *Evaluate* attribute describes the method to check the accuracy of surveying data. If the accuracy of data is unknown, the value of *Evaluate* is null.

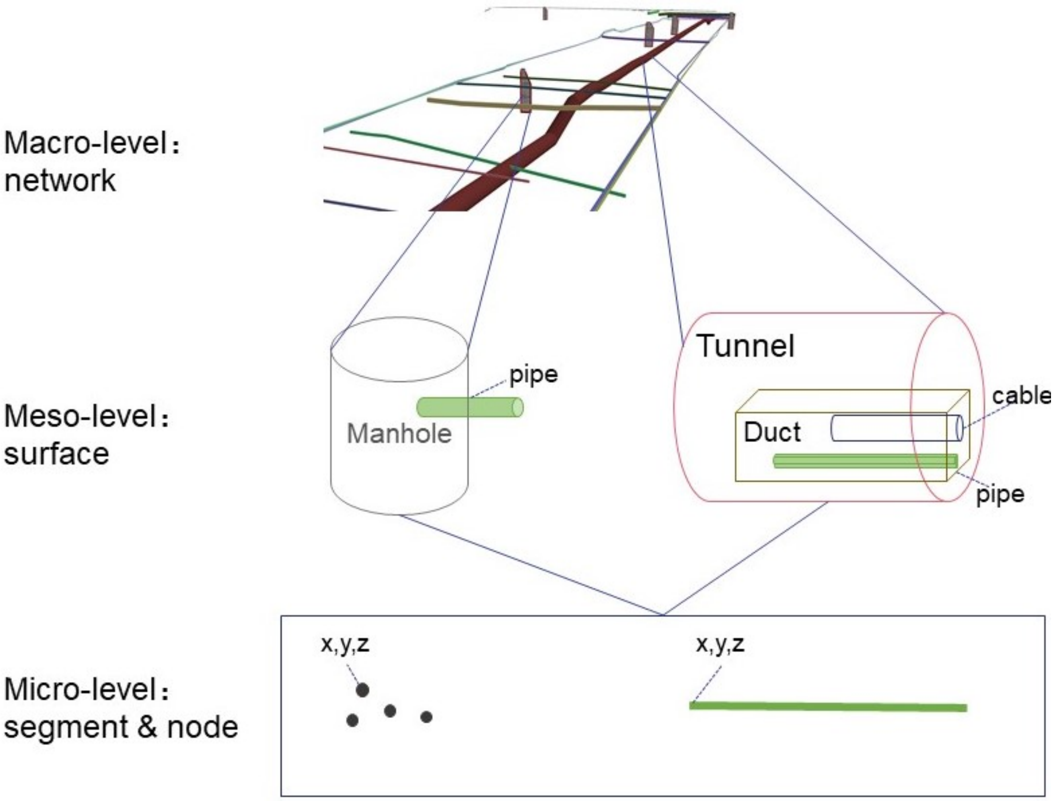


Figure 9. Multilevel structure of utility network.

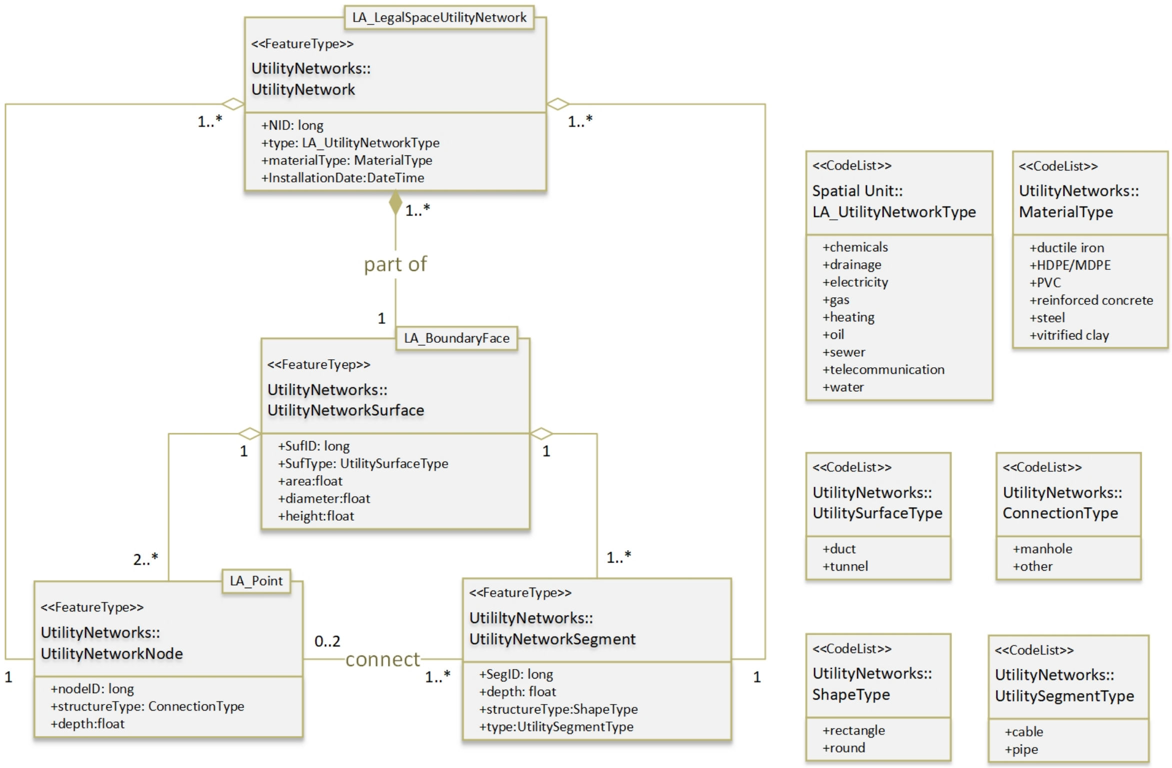


Figure 10. The classes diagram of utility networks.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 April 2019 doi:10.20944/preprints201904.0223.v1

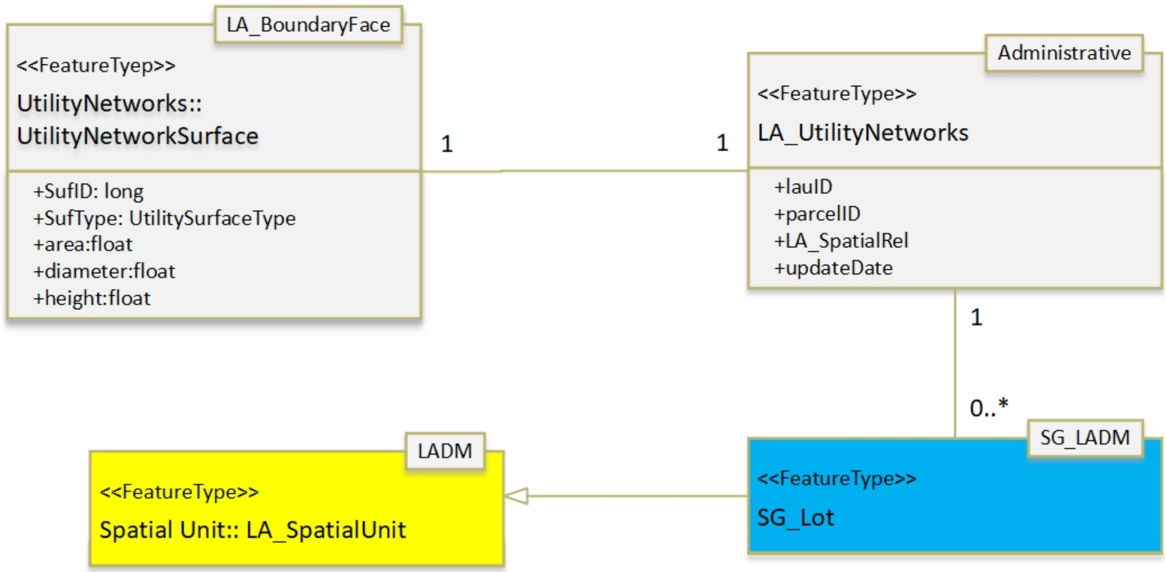


Figure 11. The classes of land administration.

In future work, the accuracy level should be defined to be based on the depth level, soil condition and survey method.

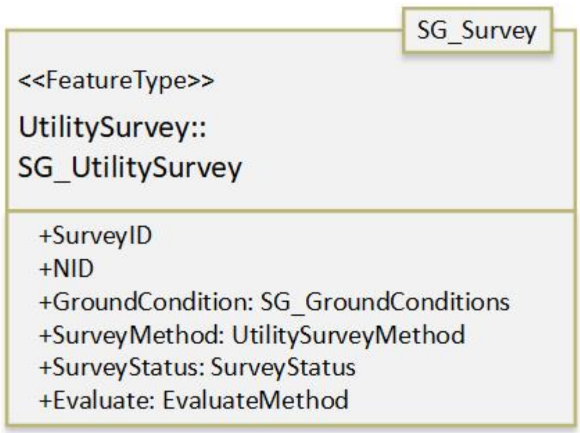


Figure 12. The classes of utility survey.

4. Case study

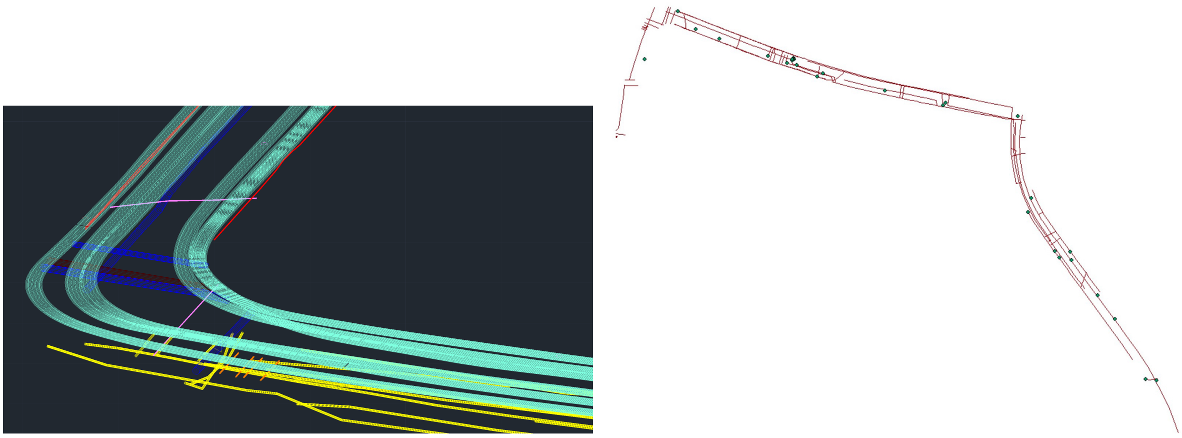
This initial study aims to integrate of GPR data and the existing underground utility data and land cadastral data in the form of geospatial database. It aims to find a reasonable work process to bridge the gap between data capture and application. Moreover, this implementation can help to improve the design of 3D data model for underground utility.

4.1. Study area and datasets

This initial study was conducted at around Lorong 2, 3 and 4 at Toa Payoh, which is located in the northern part of Singapore. This is one of pilot study sites in our project to deploy mobile GPR platform, Pegasus: Stream for 3D mapping of above and underground. The scan site is a 1.8 km long bi-directional 4-lane asphalt road in an inland area of Singapore that has seen development since the 1960s. This study was conducted to investigate the feasibility of GPR for large scale underground utility

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 April 2019 doi:10.20944/preprints201904.0223.v1

mapping for the purpose of improving the quality of existing utility map information. Pegasus:Stream integrating photogrammetry, laser scanning and ground penetrating radar to capture above and underground environment in one scan. The data were collected at a driving speed of about 15 km/h. The data were then post-processed in order to obtain digital 3d models of both the environment above ground environment and underground utilities in different format. After data processing, the GPR data needs to export to CAD format or GIS format with x, y, z value as points and lines for 3D data modelling and visualization. Figure 13 shows an example of GPR data in CAD (Figure 13a) and GIS (Figure 13b) format.



(a) CAD **(b)** GIS

Figure 13. GPR data in CAD and GIS format.

The existing datasets from Geospace and cadastral data from Singapore Land Authority were used as secondary data to obtain or improve the attributes of utilities that were extracted from the radargram and to explore the relationship between the above land administration information and underground utilities. These existing utility data are as-build data from utility services (e.g.: power, water, gas, telecommunication and sewerage) and cadastral information in 2D form. Of these datasets, it contains only a small portion of information that has diameter with updated time and type. It possess challenges for land planning with such limited information.

4.2. 3D Visualisation

To develop the 3D utility data model for land administration, the underground utilities need to be connected to the land parcels. Figure 14 explains the work process in this case study. The data model is designed in UML and exported to XML format, which can be imported into ArcGIS as a geodatabase schema. Based the database schema, the GPR data can be loaded as utility network components in polyline and point. According to the information from the existing utility data and GPR data, the utilities can be modelled in 3D (multipatch). The 3D modelling is realized manually in the ArcSence and CityEngine.

In order to get the related land administration information, the utility networks data can be integrated with cadastral parcel through their spatial relationships. Because the existing cadastral data is in 2D, the current work only considers the pipe line within the cadastral parcel in 2D. In order to improve the accuracy of data in 3D, the current cadastral data has to be extended to 3D so as to support more spatial relationships (e.g. cross and touch). Figure 15 shows an example of 3D visualization of utilities with objects above ground. As shown in the figure, the selected pipe line is highlighted in pink. The information shown in the pop window includes spatial data from GPR and other attributes about underground utility survey and land cadastral information above ground.

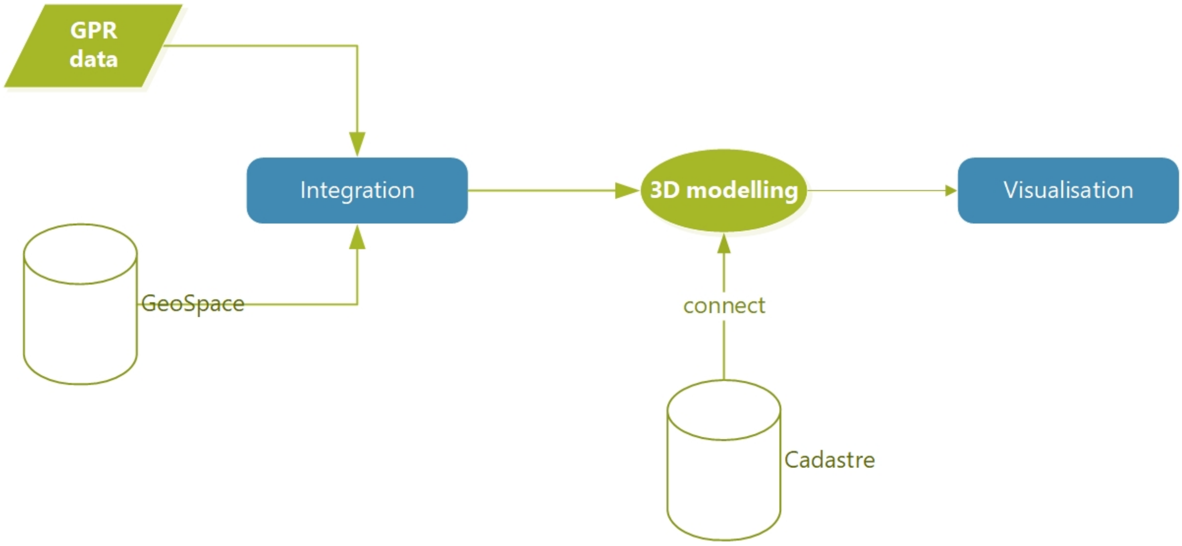


Figure 14. Implementation process.

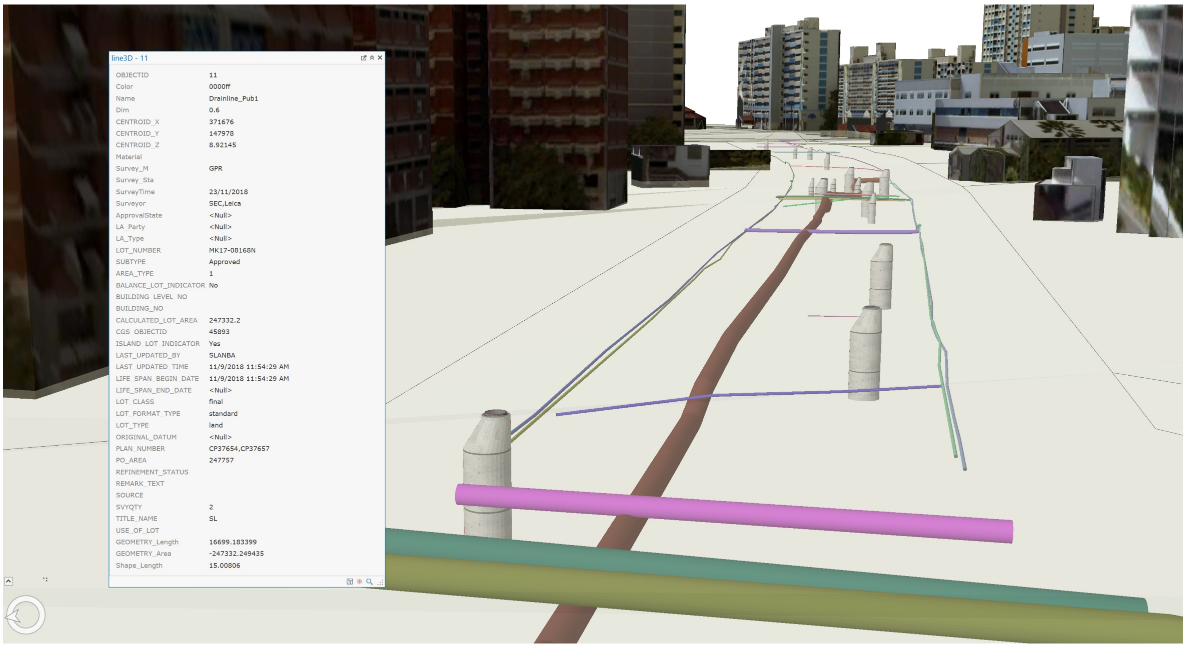


Figure 15. A result example of 3D visualization with land administration information.

4.3. Discussion

This is a simple implementation to explore the work process of 3D modelling of underground utility from the GPR data and existing 2D data. Because GPR cannot capture the diameters, material and some attributes of utilities, it is necessary to extract these information from GeoSpace database for 3D modelling. Depending on the spatial relationship (e.g. overlap, within) of the GPR data and existing utility data, some of the utilities from GPR data can be connect to the existing utility data. Because of two main limitations, there is a big challenge to improve the accuracy of data. First, the existing utility data is as-build data which may not be reliable enough for updating work. Second, the existing utility data is in 2D data, which is difficult to identify utilities accurately. Hence, the future work needs to find the solution to detect much more attributes of utilities from GPR data. In addition, the tentative integration of underground utility and land cadastral data helps to improve the development of data model for land administration.

5. Conclusions

This work proposes to develop a consolidated 3D data model of underground utilities for land administration. The work includes two parts. On one hand, a framework for data governance is designed to organize the workflow of utility data survey, management and application. This framework is made up of four roles and two kinds of the data model. Through the understanding of current workflow in the utility data usage, this work needs to clearly define different roles, including their operations and rights for 3D underground utility mapping. On the other hand, a 3D data model of underground utilities is designed with 3D spatial information, i.e. utility survey information, and land administration information of underground utilities. In order to fill the gap between data capture and usage, this data model has the following main tasks:

- Integrating utility networks data of varying formats, which were acquired using a variety of non-destructive surveying technologies. This data model is a first step towards bridging the gap between data acquisition and data management for underground utility mapping.
- Integrating the existing data and GPR data. As mentioned earlier, GPR data cannot get the diameters and types of utilities. This way helps to improve the attributes of utilities from GPR data. Moreover, it is also a process to transform utility data from 2D to 3D.
- A crucial part of the utility network data model is to connect the utility network data model with the Land Administrative Domain Model for 3D cadastral management of underground space in Singapore. It is useful to support ownership management applications and build the relationship of utilities and land parcels. Such a reliable and complete centralized repository of underground utility data will provide a crucial basis for planning and administering underground spaces.

A case study is implemented based on the GPR data from the large scale mobile underground utility mapping. The initial implementation transform GPR data from CAD to GIS format and 3D visualization of utilities based on 3D utility data model. In order to get land administration information, the utility networks have been connecting to cadastral parcel. The accuracy and details of utility networks need to be improved in future work, such as the spatial relationship between utilities and cadastral parcels. To fully support underground space planning, the cadastral data model should eventually be extended to include other underground features in the future, such as underground substations, pedestrian links, common services tunnels, road and rail networks, etc.

This is a work in progress and is in its initial stages. Two main aspects of limitations need to be improved in future work. First, for the accuracy of utilities data. Obviously, the GPR data is not enough to provide the comprehensive 3D underground utility networks. The other kinds of data (e.g. Gyroscope) should be integrated to provide more precise attributes for underground utilities. Moreover, the details of shapes and structures of utilities need to be improved. Second, the next step of data model development will improve the definition of land administration for underground utilities. A pilot study will be conducted to implement the entire process from data capture to data integration and application, working with a selection of agencies and the preferred data integrator. It aims to evaluate and improve the framework. After that, recommendations from this study can be used for the implementation of the platform in Singapore with government agencies. Also, this work will not limit itself to underground utilities. In future work, it will be extended to include other underground structures such as underground indoor spaces, and support urban planning applications.

Author Contributions: Conceptualization, Jingya YAN and Kean Huat SOON; methodology, Jingya YAN and Kean Huat SOON; implementation, Jingya YAN; Data curation, Jingya YAN and Siow Wei JAW; writing—original draft preparation, Jingya YAN; writing—review and editing, Siow Wei JAW, Kean Huat SOON, Gerhard SCHROTTER and Andreas WIESER; visualization, Jingya YAN; supervision, Gerhard SCHROTTER and Andreas WIESER.

Funding: UNDERGROUND-RELATED STUDIES AND PROJECTS FUND (USPF), Ministry of National Development and is sponsored by Singapore Land Authority.

Acknowledgments: This publication has been realised as part of the project "Digital Underground: 3D Mapping of Utility Networks" at the Future Cities Laboratory, established by ETH-Zurich and Singapore's National Research Foundation (NRF), and operating under the auspices of the Singapore-ETH Centre.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pouliot, J.; Girard, P. 3D Cadastre: With or Without Subsurface Utility Network?; International Federation of Surveyors (FIG): Athens, Greece, 2016. OCLC: 831214525.
2. Tan, L.C.; Looi, K.S. Towards a Malaysian multipurpose 3D cadastre based on the Land Administration Domain Model (LADM)–an empirical study. Proceedings of the 5th FIG Land Administration Domain Model Workshop, 2013, pp. 24–25.
3. Hao, T.; Rogers, C.; Metje, N.; Chapman, D.; Muggleton, J.; Foo, K.; Wang, P.; Pennock, S.; Atkins, P.; Swingler, S.; Parker, J.; Costello, S.; Burrow, M.; Anspach, J.; Armitage, R.; Cohn, A.; Goddard, K.; Lewin, P.; Orlando, G.; Redfern, M.; Royal, A.; Saul, A. Condition assessment of the buried utility service infrastructure. *Tunnelling and Underground Space Technology* **2012**, *28*, 331–344. doi:10.1016/j.tust.2011.10.011.
4. Lai, W.W.L.; Dérobert, X.; Annan, P. A review of ground penetrating radar application in civil engineering: a 30-year journey from locating and testing to imaging and diagnosis. *NDT & E International* **2018**, *96*, 58–78.
5. Ni, S.H.; Huang, Y.H.; Lo, K.F.; Lin, D.C. Buried pipe detection by ground penetrating radar using the discrete wavelet transform. *Computers and Geotechnics* **2010**, *37*, 440–448. doi:10.1016/j.compgeo.2010.01.003.
6. Rogers, C.; Hao, T.; Costello, S.; Burrow, M.; Metje, N.; Chapman, D.; Parker, J.; Armitage, R.; Anspach, J.; Muggleton, J.; Foo, K.; Wang, P.; Pennock, S.; Atkins, P.; Swingler, S.; Cohn, A.; Goddard, K.; Lewin, P.; Orlando, G.; Redfern, M.; Royal, A.; Saul, A. Condition assessment of the surface and buried infrastructure – A proposal for integration. *Tunnelling and Underground Space Technology* **2012**, *28*, 202–211. doi:10.1016/j.tust.2011.10.012.
7. Lagüela, S.; Solla, M.; Puente, I.; Prego, F.J. Joint use of GPR, IRT and TLS techniques for the integral damage detection in paving. *Construction and Building Materials* **2018**, *174*, 749–760. doi:10.1016/j.conbuildmat.2018.04.159.
8. van Disseldorp, R. Unique Autonomous Pipeline Mapping System. 2nd Pipeline Technology Conference, 2007.
9. Sato, M. GPR and Its Application to Environmental Study **2001**.
10. Lunt, I.A.; Hubbard, S.S.; Rubin, Y. Soil moisture content estimation using ground-penetrating radar reflection data. *Journal of hydrology* **2005**, *307*, 254–269.
11. Lai, W.W.L.; Chang, R.K.W.; Sham, J.F.C. A blind test of nondestructive underground void detection by ground penetrating radar (GPR). *Journal of Applied Geophysics* **2018**, *149*, 10–17. doi:10.1016/j.jappgeo.2017.12.010.
12. Desai, L. Underground Utility Survey **2016**. *2*, 4.
13. Yelf, R.J. Application of ground penetrating radar to civil and geotechnical engineering. *Electromagnetic Phenomena* **2007**, *7*, 18.
14. Becker, T.; Nagel, C.; Kolbe, T.H. Integrated 3D Modeling of Multi-Utility Networks and Their Interdependencies for Critical Infrastructure Analysis. In *Advances in 3D Geo-Information Sciences*; Springer, 2011; pp. 1–20. bibtex: becker_integrated_2011.
15. Becker, T.; Nagel, C.; Kolbe, T.H. Semantic 3D modeling of multi-utility networks in cities for analysis and 3D visualization. In *Progress and New Trends in 3D Geoinformation Sciences*; Springer, 2013; pp. 41–62.
16. Hijazi, I.; Kutzner, T.; Kolbe, T.H. Use Cases and their Requirements on the Semantic Modeling of 3D Supply and Disposal Networks. Kulturelles Erbe erfassen und bewahren-Von der Dokumentation zum virtuellen Rundgang, 37. Wissenschaftlich-Technische Jahrestagung der DGPF, 2017, pp. 288–301.
17. Gröger, G.; Kolbe, T.H.; Nagel, C.; Häfele, K.H. OGC city geography markup language (CityGML) encoding standard, Version 2.0, OGC doc no. 12-019. *Open Geospatial Consortium* **2012**.

18. Scholtenhuis, L.L.o.; Duijn, X.d.; Zlatanova, S. Representing geographical uncertainties of utility location data in 3D. *Automation in Construction* **2018**, *96*, 483–493. doi:10.1016/j.autcon.2018.09.012.
19. Liebich, T. IFC 2x Edition 3. In *Model implementation guide. version 2.0*; AEC3 Ltd., 2009.
20. JRC. D2.8.III.6 INSPIRE Data Specification on Utility and Government Services – Technical Guidelines. *European Commission Joint Research Centre* **2013**.
21. ESRI. What are geometric networks?, 2017.
22. Lieberman, J.; Ryan, A. OGC Underground Infrastructure Concept Study Engineering Report. OGC Engineering Report, Open Geospatial Consortium, 2017.
23. van Oosterom, P. Research and development in 3D cadastres. *Computers, Environment and Urban Systems* **2013**, *40*, 1–6. doi:10.1016/j.compenvurbsys.2013.01.002.
24. van Oosterom, P.; Lemmen, C. The Land Administration Domain Model (LADM): Motivation, standardisation, application and further development. *Land Use Policy* **2015**, *49*, 527–534. doi:10.1016/j.landusepol.2015.09.032.
25. International Standards Organization. ISO 19152: Geographic information — Land Administration Domain Model (LADM), 2012.
26. Döner, F.; Thompson, R.; Stoter, J.; Lemmen, C.; Ploeger, H.; Oosterom, P.v.; Zlatanova, S. Solutions for 4D cadastre – with a case study on utility networks. *International Journal of Geographical Information Science* **2011**, *25*, 1173–1189. doi:10.1080/13658816.2010.520272.
27. International Standards Organization. ISO 19107:2003(en), Geographic information — Spatial schema, 2003.
28. Singapore Land Authority. Standard and Specifications for Utility Survey in Singapore, 2017.