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3D cadastres for densely occupied informal situations: Necessity and possibility

Charisse Griffith-Charles*, Michael Sutherland

The University of the West Indies, St. Augustine, Trinidad and Tobago

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ABSTRACT

Much of 3D cadastre research and development targets high valued urban land, including condominiums, apartment buildings, and office complexes. The value of the land and the economic activity generated from transactions in this urban space potentially support the cost and time spent on establishing and maintaining a 3D cadastre. Methods for data acquisition and for construction and maintenance of the 3D cadastre are also simpler in the regular and formally planned and surveyed structures of the high value urban environment. Low-income, urban areas of informal tenure and informal development, however, also need and can benefit from a land administration system supported by a 3D cadastre but are neglected in the 3D cadastre research. Mechanisms are required for quick and cost effective construction of a 3D cadastre in this type of area to support land management and regularisation procedures, and to provide security of tenure. Light Detection and Ranging (LiDAR) is one technology that may be examined to differentiate structures in densely occupied environments where limited information and limited resources must be able to be used for managing the land and also protecting informal rights.

This paper initially posits the need for 3D cadastres in low-income but densely structured urban settlements. It then tests the ability of an existing LiDAR dataset together with orthoimagery, derived to be low cost so therefore having limited specifications, for capturing sufficient definition of 3D occupation in the low-income, densely structured case study area of Laventille in Trinidad and Tobago.

The difficulties of manually or automatically discriminating between close and overlapping structures and boundaries are highlighted and it is found that there is still a need for adjudication and verification of boundaries on the ground, even when physical features can be discerned from the software.

1. Introduction

In most instances the 3D cadastre is directed at condominiums and apartments in urban areas where the high value of the land drives the need for, and supports the cost of precise positioning of cadastral boundaries in initial demarcation and subsequent redefinition (Oldfield et al., 2018; Griffith-Charles and Edwards, 2014; Griffith-Charles and Sutherland, 2013; Rajabifard, 2014; El-Mekawy et al., 2014; Kalantari and Rajabifard, 2014). These land units are usually regular in shape and conform to planning standards. In many of the building models, standardised forms are used since the construction is regular (Roschlaub and Batscheider, 2016). However, dense living and occupation spaces occurring in informal urban areas also require precise capture of boundaries to prevent conflict in regularisation, and land readjustment. The cost of the data acquisition for a 3D cadastre, in these instances, is high and is not justified by the value of the land but can be justified by the value to the society for reducing conflict, improving well-being, and providing for sustainable development and the achievement of the Sustainable Development Goals (SDGs) and the Urban Agenda. A few investigations discuss the potential of three dimensional cadastres to the informal urban environment. Erba and Piumetto (2012) and Griffith-Charles and Sutherland (2013) deliberate on the need for 3D cadastres in informal urban areas and conclude that there is need but realisation is some distance away because of the costs and other resource requirements. These items of research speak to informal rights but also focus on informal development where the rights may be formal but the structures do not conform to regulation but must be identified, visualised, and managed nevertheless. Where the informality is related to unrecorded customary rights, such as that found in Uganda, Papua New Guinea, Greece, Trinidad and Tobago's and the Caribbean's family

* Corresponding author at: Rm 116 Department of Geomatics Engineering and Land Management, Faculty of Engineering, The University of the West Indies, St. Augustine, Trinidad and Tobago.

E-mail address: Charisse.Griffith-Charles@sta.uwi.edu (C. Griffith-Charles).

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land, and in many other countries, the issue becomes one of transcribing tradition, and history into precise physical extents. These customary rights are most usually found in rural areas where the desire for precision of boundaries, physical or conceptual, is not as high as in the urban areas. For example, Wycliffe and Griffith-Charles. (2019) discuss customary rights in Papua New Guinea and trace its partial formalisation from a governance perspective. These areas are rural and the concern is one of defining outer limits of accepted customary rights for formalisation and governance. Three dimensional rights do become necessary to define in these instances where mining, forestry, and usufruct rights become intertwined in a complex network. Kitsakis et al., (2016) and Erba and Piumetto (2012) define the intertwined spaces of rights as Special Real Property Rights (SRPO) or Legal land objects (LLO).

The more complex the intersection of conceptual spaces defining individual homogeneous rights, and the more complex the physical spaces that relate in some way to the conceptual, the greater the need for map data for the construction of the 3D cadastre for good governance of the entire land space. Despite the value of the data capture to the state as a whole, there may still be insufficient resources to acquire data comprehensively and completely over the urban area. Procedures for data acquisition and construction of the 3D cadastre can be facilitated in the formal sector by statutory processes where the cost is borne by the applicant who supplies the parcel boundary data, such as in the building construction and facilities management, (Mekawy and Östman, 2012) building permit (Oldfield et al., 2018), land subdivision (Thompson et al., 2018), or parcel sale or mortgage transaction processes. This reduces the burden of cost on the state for construction and maintenance of the cadastre. However, informal occupants do not interface with or abide by the formal administrative processes and usually cannot afford to. If a comprehensive 3D cadastre is desired, for all its positive characteristics for land management and land administration, then other means of data acquisition, at the cost of the state, will need to be explored.

It is now accepted that the cadastral system may be comprised of various datasets of variable quality integrated together in a fit-for-purpose whole (Thompson et al., 2018). The Land Administration Domain Model (LADM) (International Standards Organization, 2012) provides a model for formal legal land objects while the related STDM provides the flexibility that can accommodate less precise physical and conceptual definition of extent of land rights (Griffith-Charles, 2011). Both datasets can be woven together to provide equitable support for tenure in a land administration system. However, in dense urban settings greater precision is required than the minimum allowable in the Social Tenure Domain Model (STDM) (International Standards Organization, 2012). In this research, the initial objective is to clarify the need for 3D cadastres in informal situations and the consequent objective is to determine the efficacy of using existing LiDAR and photo imagery data for developing as precise as possible definition of the physical extent of the individual land units of an informal settlement. These data, acquired since 2014 together with a DEM, were used to determine the possibilities for a system to be used for land management. The case study area is a hilly area in Laventille, in Trinidad and Tobago. While the use of LiDAR and other methods of data acquisition for formal registration of parcels has already been accomplished in some developed countries such as the Netherlands (Stoter et al., 2016), for the many developing countries the need for other mechanisms for data acquisition and the possibilities of use for land management in informal settings need more examination as proposed here.

2. The need for 3D Cadastres

Land administration in informal and pro-poor environments has been increasingly investigated and solutions proposed by international agencies such as the Global Land Tool Network (GLTN), The International Federation of Surveyors (FIG), and the Food and Agriculture Organization (FAO) (Hendriks et al., 2019; Zevenbergen et al., 2016). Many of these concentrate on recordation of land-rights-related information with limited focus on geospatial boundaries to those rights since this latter is usually the more expensive and time consuming aspect of recordation or title registration. In fact, the Fit for Purpose mechanism of recording of land rights, proposed by UN-Habitat/GLTN (2016), promotes dependence on physical features as boundaries in lieu of virtual fixed boundaries, and aerial photographs or other imagery in lieu of field surveys. Meanwhile, an inclusive, transparent, collaborative process should be used to ensure that the land rights of all claimants are entertained, valued, and documented precisely, regardless of the position of the right along the continuum of land tenure. This suggests that the acknowledgement of the physical boundaries in the informal area adequately supports the security of tenure but low-cost, efficient technology is necessary to establish an initial system of land units as a holder for the attribute rights information. While the Fit for Purpose mechanism supports use of imagery, LiDAR, even though more expensive, has the ability to penetrate trees and shadow to supply data where aerial photography can fail.

3. LiDAR in context

LiDAR data capture and processing are more expensive and more time consuming than photographic image capture and photogrammetric extraction of data. While the data capture itself can be quite rapid depending on the extent of the area being captured, the errors, occlusions, and magnitude of the datasets of point clouds make the entire process from data acquisition through classification of points, segmentation of discrete objects, and recognition of component features very complex whether it is manually or automatically done (Xing 2018). Virtual Geographic Environments (VGE) technologies are now more adept at extracting precise data from LiDAR point clouds and can even automate to some extent the data extraction including classifying and recognising features. In most instances, however, manual interventions are required to correct errors in classification and recognition for similar features. Xing et al. (2018) examine the complications of designing the semantic reasoning that would allow automatic differentiation of features. Specific rules for a particular environment that would define the various objects of walls, roofs of different architectural styles, and even atypical features such as outhouses, sheds, and water tanks in the informal areas of the developing world, would need to be described semantically to allow for automated extraction. This includes geometric descriptions of the dimensions of the features such as length, and breadth, geometric properties of the relationship between features such as perpendicularity, and topological relationships between features. Familiarity with the particular environment is important for constructing the semantic rules. Kada and McKinley (2009) use standard geometric shapes to which to compare the point cloud. When a sufficient number of dimensions coincide, the standard shape is put in place to visualise the real structure.

The use of UAV systems has reduced the cost of the process when small areas are targeted for acquisition at low altitudes. The cost can be lower than conventional surveying on the ground for dense data acquisition especially since the LiDAR has the advantage of remote capture of data. This is important where there may be several difficulties attached to accessing the ground for direct surveying purposes for example, in areas of conflict or resistance to intrusion by public officials. The cost also reduces with lowered specification but this also reduces the precision of the data. Roschlaub and Batscheider (2016) indicate that the density of the point cloud is significant for the possibility and precision of adequate data and that typically densities of 4 points per square metre are aimed at. This density can be increased using image matching to 25 points per square metre given high resolution imagery of 0.2 m, which can in itself be costly.

LiDAR primarily acquires height data. For 3D visualisation of condominiums, the ground level is accepted as the datum as differentiation between adjoining parcels, or land units, occur within the confines of one building. However, for densely populated areas of hillsides, conflict and overlap can occur between adjacent buildings, necessitating more careful determination of datum. For this reason, a defined datum other than ground level is required. Mean Sea Level or ellipsoidal datum or other national datum should therefore be used.

The LiDAR data presents positioning of the tangible and visible physical features on the ground. The location of the 3D legal boundaries with respect to the physical features must also be semantically defined so that the boundaries can be visualised (Griffith-Charles and Edwards, 2014; Griffith-Charles et al., 2016). The many opportunities and possibilities for visualisation in the most meaningful way for the purpose of the cadastre needs to be decided on (Pouliot et al., 2018)

4. Case Study

In Trinidad and Tobago the dual legal system of registration by either deed or title covers perhaps half of existing parcels, primarily in the urban and suburban areas. A firm figure is difficult to determine as the land administration has resource and capacity gaps (Griffith-Charles and Rajack, 2017). The land registry has no legal map of the country and is separate from the cadastral map. The map, therefore, is said to have no legal standing as opposed to the individual cadastral plans that are attached to individual deed or title certificates. 3D boundaries are reflected on these 2D cadastral plans for condominiums with a cross section drawn onto an inset on the plan. Individual units in a condominium development are treated as shares owned in a company that owns the entire parcel and not as individual parcels. As such, the construction of a 3D cadastre is only subject to the rules, regulations, and specifications of the Director of Surveys who oversees the mapping of the cadastre according to the Land Surveyors Act, from the individual legal plans. Currently, there are no rules or legislation regarding 3D cadastres as a system.

Trinidad and Tobago has several densely populated areas where both tenure and development standards are informal and where living quarters are in close juxtaposition and, especially in elevated areas, overlapping. Conflict over informally occupied, held, and developed land is frequent and often settled violently since recourse to the legal system is too costly and time consuming to be considered. What is required for land management in these areas is precise location and recordation of these intricately interwoven spaces, and their rights attributes, by cheaper methods of crowd capture by perhaps the ubiquitous cell phone or UAV image acquisition. Fig. 1 shows such a scenario where, besides horizontal and vertical positioning of boundaries above the ground, elevations above the national or at least a local community datum are required. Fig. 2 shows the same area in plan view where the densities and overlaps of adjacent rooftops are apparent and the lack of cadastral information can be observed in Fig. 3. On each originally formal parcel, owned initially by the state or private individuals as outlined in Fig. 3, dozens of actually and currently occupied dwellings exist. These would have been informally occupied and rights accrued through adverse possession or informal purchase many decades ago and never legally formalised, recorded, or acknowledged. Having been informally occupied, informal construction continued without recourse to building specifications and requirements. Trees are interspersed in the area and may relate to or be evidence of legitimate boundaries of occupation and ownership, further densifying the number of features that need to be captured using any remote sensing process. Fig. 2 also indicates how difficult capturing data using photogrammetric procedures can be since the ground is obscured over long distances. LiDAR can provide vertical differentiation, which, together with orthophoto imagery can allow for some measure of 3D visualisation.

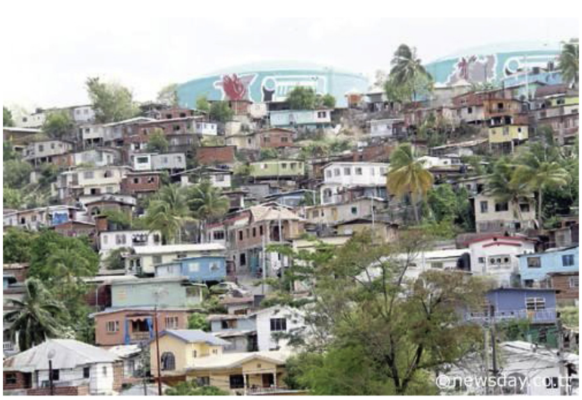

Fig. 1. Overlapping and overhanging land objects.

State funded regularisation, in these settings, is extremely expensive and more so if land readjustment is contemplated. The Land Settlement Agency (LSA) provides land management support for informal occupants on state land including monitoring, measuring, planning, regularisation, and formalisation into leaseholds from the state. The LSA has stated that it costs the institution TT$130,000 (US $19,000) to TT$160,000 (US$24,000) per lot to regularise the planning standards of informal occupants on state lands (Joint Select Committee of Parliament, 2016). This figure includes the introduction of infrastructure of roads, drains, sewers, water, and electricity but does not include the cost of regularising the tenure through provision of a Certificate of Comfort and later, a deed of lease as these latter costs are supposed to be paid by the occupant. These costs may seem excessive but State costs usually exceed private development costs in this and many countries, because of the inefficiencies and the bureaucracy of the state institutions. Private land, such as some of these parcels in the case study section in Laventille, does not have this access to state funding and the resources of this institution. In both instances, it is more economically feasible to introduce limited infrastructure without impacting structures that indicate that rights are existing. Figs. 4 and 5 show typical narrow corridors, in one informal settlement, that must accommodate access as well as utilities of water, sewer, drainage without impacting the environment, and rights.

A 3D cadastre allows for planning for introduction of the infrastructure. Regularisation, like readjustment, involves balancing areas and volumes of space taken from individual land objects with services provided while attempting to ensure that reduced development standards are met.

In some instances, occupation on state land may overlap private land and it is necessary for the state to determine how much land is encroached on so that the private owner may be compensated. These surveys are required to be accurate enough so that the calculated compensation is not overstated. Where the overlap also includes subsurface minerals or hydrocarbon deposits, as is common in parts of Trinidad and Tobago, a 3D cadastre is required to ensure that surface use is not unduly affected by access rights to the subsurface. Fig. 6 shows an area to be regularised with no clear demarcation of the boundaries.

5. Method

Datasets used in the application were the aerial imagery and LiDAR data acquired between 2013 and 2014 for the entire country by the Surveys and Mapping Division of the Ministry of Agriculture in Trinidad and Tobago at a cost of US$1 million (Ministry of Public Administration, 2015). Both datasets were acquired on the WGS 84 datum/ellipsoid but were transformed to the Naparima 1955 local datum, UTM zone 20 grid, to be compatible with most of the existing cadastral and topographic datasets. The imagery was acquired at 12 cm ground resolution primarily to obtain at least 12.5 cm orthophoto ground resolution to support cadastral mapping while the LiDAR data was acquired at 1 point per m^2 density to ensure that it met a

Fig. 2. The Laventille area on orthophoto.

requirement of 1 m vertical positional precision when averaged over hilly and flat terrain after interpolation. Classification into only ground and non-ground points was required as the stated purpose of the LiDAR data was to obtain a DEM for the country. Only four returns in the LiDAR data was requested. Precisions and density of data acquisition have implications for the cost of the process and the speed of its acquisition.

Both automated and manual methods were used in turn to compare the processes of identifying and acquiring individual features from the LiDAR data. The ESRI ArcMap software was used to perform the automated processes first. Global Mapper software was also used to perform the same procedures for purposes of comparison. The point cloud was classified into ground and non-ground points and further classified into buildings and vegetation using the built in software commands. Both software gave similar results. The proximity of the features in this settlement made it difficult to extract the positional data and discern individual building features from the LiDAR. Ground points and non-ground points are shown in Figs. 7 and 8 respectively overlaid on the orthophotos in ArcMap.

First returns from the LiDAR point cloud were used to visualise the close mass of buildings as shown in Fig. 9. The profile of the hill all the

Fig. 4. Requirement for putting in infrastructure without impacting rights.

way up to the large water tanks at the top of the hill is also shown in Fig. 9 in ArcMap. The local Naparima datum for both horizontal and vertical coordinates was used. Overlapping rooftops can be seen in the

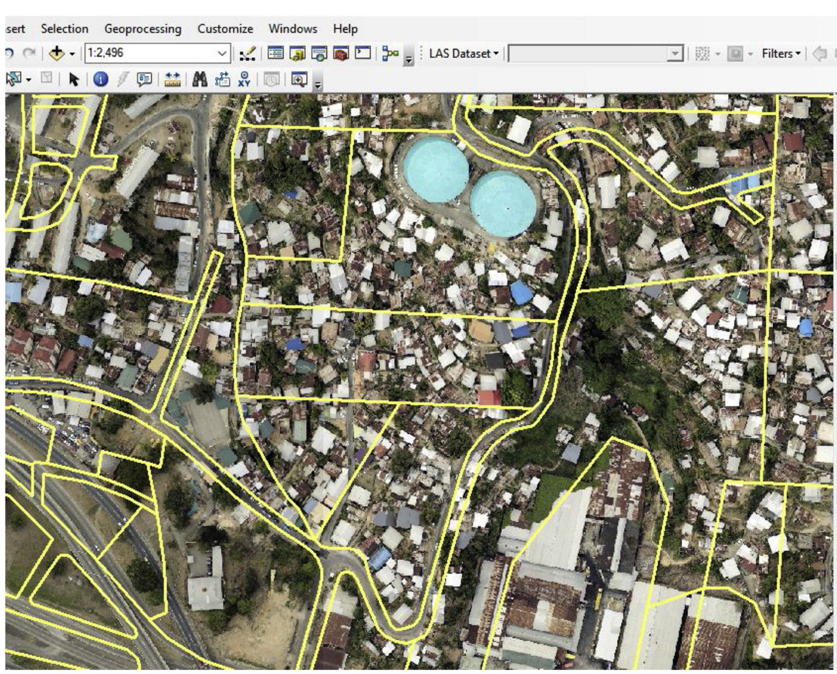

Fig. 3. Cadastral layer with only formal rights.

Fig. 5. Infrastructure must be put into tight spaces.

profile along a longitudinal line from the top to the bottom of the hill.

It was recognised that features on the ground were not possible to be seen in most instances, except where clear areas existed such as on the roadway or in the area close to the water tanks. This meant that there would be difficulty in planning of infrastructure corridors on the ground.

The digital elevation model was subtracted from the LiDAR non-ground first return points, so that the heights displayed for all points were computed from a constant (flat) surface to provide the distance above the datum of Mean Sea Level. Figs. 10 and 11 show the result.

At this point the individual property units were manually digitised. Individual roofs were manually defined with the assistance of the orthophotos. The complete land units were also defined via recourse to examination of the difference between the ground points and the roofs as established by first returns from the LiDAR. Differentiation was made between the physical features visible in the LiDAR and the legal location of the boundaries with priority placed on the boundary locations and not necessarily the physical extents of the land units. For example, even though hipped roofs could have been defined and visualised as such, a flat surface at the mean height of the highest and lowest points of the roof was deemed to be adequate for defining the upper limit of the parcel. Where roofs overlapped, an attempt was made to locate the mean distance between the building walls. In most instances this would not be possible from the data and would require further investigation on the ground. Since insufficient information can be seen from the physical features, assumptions were made regarding the legal extents of rights and these will have to be clarified on the ground as well to minimise conflicts between adjoining but both informal occupants. Unfortunately, current registration legislation may not be able to recognise communal areas where roofs overlap between houses. They may, however, be declared to be rights of way so that both parties or other parties may use the area as access routes. Fig. 12 shows a small sample of complete identified 3D land units where the extent of the rights was taken to be the vertical face from the roof edges intersecting with the ground and not the walls of the house. The heights of the roofs are averaged from the height points of the corners and apices of the roof. The height differences between the ground and non-ground or first returns were averaged for each building roof. The elevation differences cannot be discerned in Fig. 12, which is a common issue of visualising in 3D while viewing a 2D screen or 2D print.

6. Analysis

The cadastral boundaries of the occupied rights are assumed initially to follow the physical extent of the house and also include all that volume covered by the eaves of the roof and extending to the ground surface as defined by the LiDAR ground points. As a result of the density of the overlapping areas covered by the roofs, it is difficult to determine what activities are being performed on the ground that may also be establishing ownership rights. The actual use of buildings, including sheds, and outhouses, and the ownership of any fruit trees may also be evidence as to rights. It is therefore apparent that some level of ground investigation still needs to be performed to collect additional boundary and attribute information. It is acknowledged that, for any cadastre, some type of rights adjudication needs to be performed on the ground prior to recording or formalising the tenure. No ground truthing or further evidence gathering was done for the purposes of this work. The 3D land units derived from the LiDAR point clouds, however, while

Fig. 6. Determining encroachments.

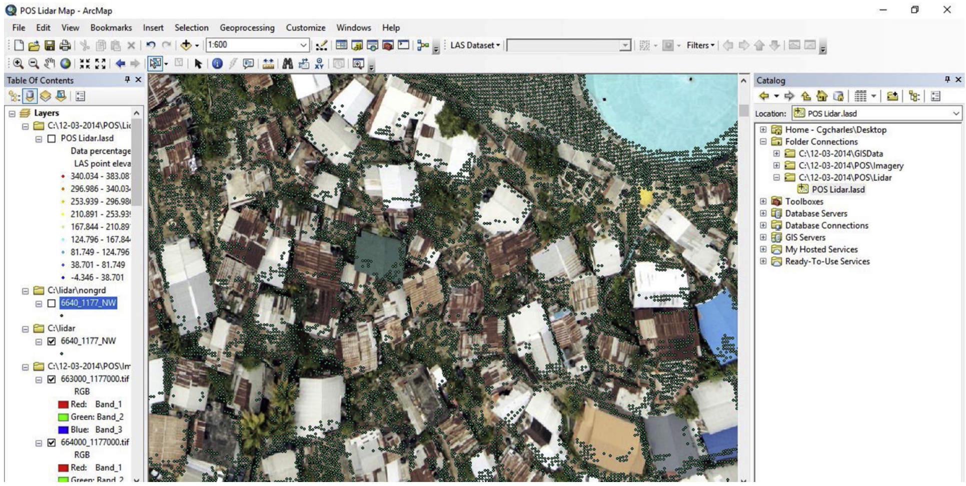

Fig. 7. Dense ground point cloud from LiDAR data.

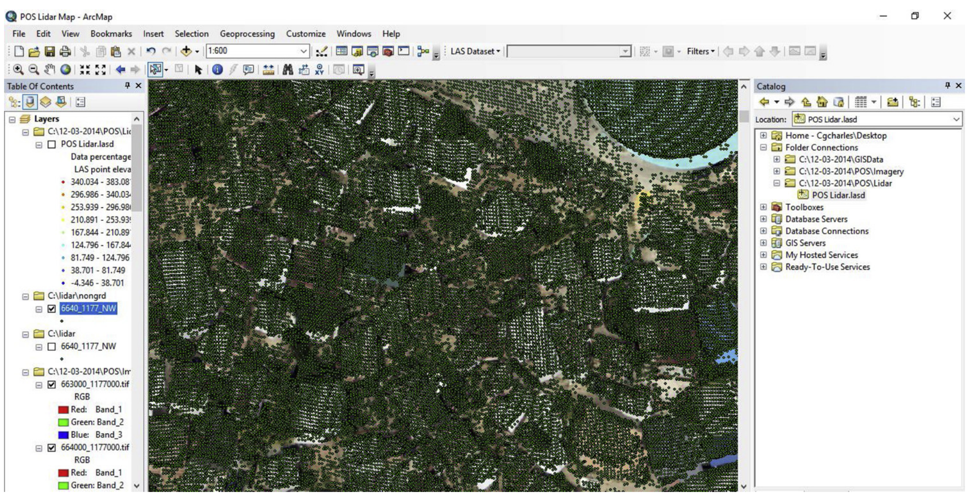

Fig. 8. Dense non-ground point cloud of LiDAR data.

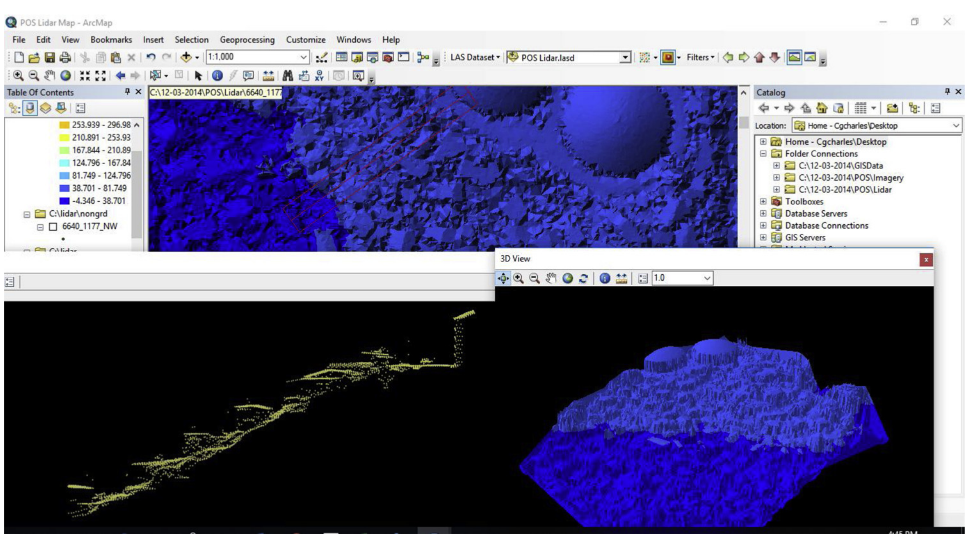

Fig. 9. Composite showing profile and 3D view of a section of the hill.

time consuming to define, go a long way towards developing a preliminary 3D cadastre graphic component for the area and can also be of assistance for areas similar to Laventille. The main advantage of this approach using LiDAR and imagery is the ability to defer the conflicts that will arise with introduction of a survey crew into a low income community such as this one. The cost of manual data acquisition on the ground may be lower than the cost of data acquisition of the LiDAR but safer from a security perspective. The need for ground surveying cannot

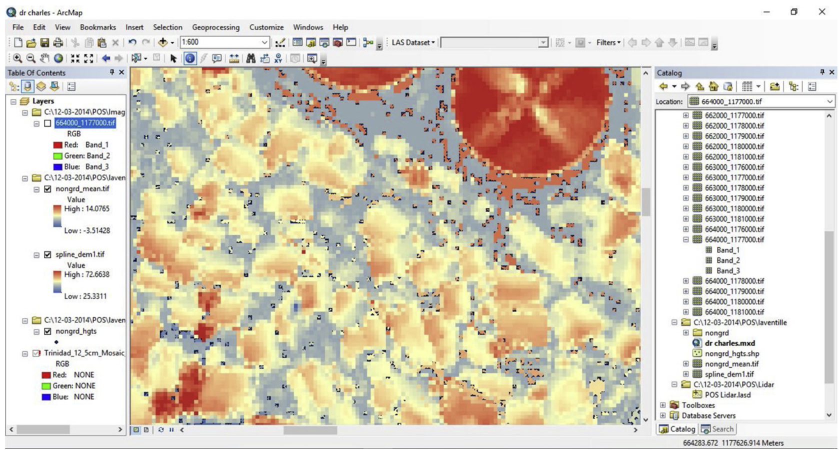

Fig. 10. Automatic identification of buildings.

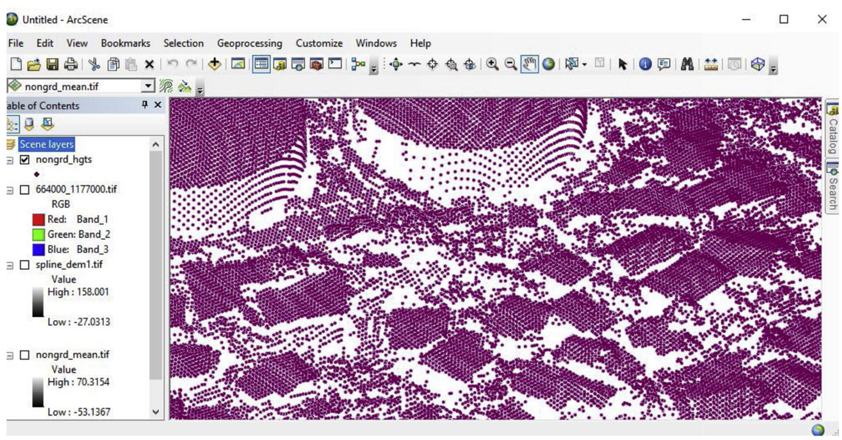

Fig. 11. Buildings identified in ArcScene.

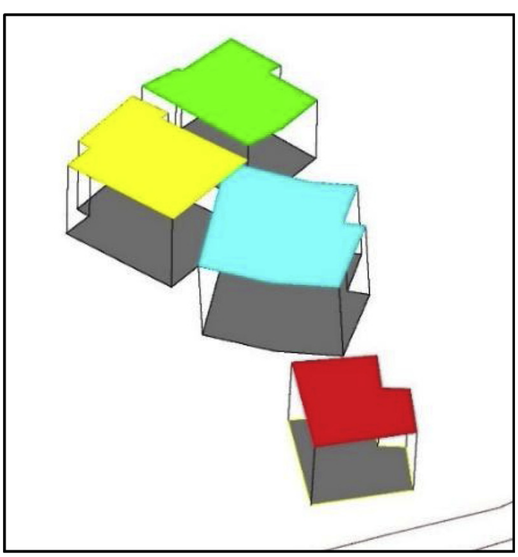

Fig. 12. Identified land units showing overlaps and intersections.

be obviated by this method.

7. Conclusion and future work

3D cadastres can be shown to not only assist land management in high valued urban areas but also provide pro-poor and fit-for-purpose land administration in dense informal urban settings. The objective of justifying the need for 3D cadastres in such low-income areas, was met. The objective of determining a method to extract as precise as possible topographic data related to tenure boundaries, given limited data, was achieved. It was determined that while the LiDAR offers many benefits for the creation of a 3D cadastre for densely populated low-income areas of the urban environment where owner-funded data is not available, there was difficulty in the digital acquisition of individual faces of the land units. The research currently being done on automated extraction of features and feature components can help to improve the process. However, owing to the relatively small size of the typical informal settlement in Trinidad and Tobago, it may not be essential for completely automatic processes to be used and manual assistance is nevertheless required to ensure that the boundaries are logical. Many obscured features in the shadow of buildings may be described by the point cloud but may not be visible on the orthophoto and would still need ground verification. The findings from this investigation are therefore that automated extraction of buildings in densely occupied informally tenured and informally planned areas is difficult using automated processes inbuilt in mapping software and data captured with less than maximum precision specifications. Manual assistance is required for the extraction. Details on the ground were also obscured by the buildings and trees, obviating the possibility of obtaining sufficient information for planning of infrastructure. Further work should include additional data gathering on the ground and the use of UAV systems for obtaining more precise LiDAR data.

References

D. Erba, M. Piumetto. (2012). 3D Cadastre in the Federal Countries of Latin America, FIG Working Week 2012, http://www. gdmc. nl/3DCadastres/literature/3Dcad_2012 _18.pdf.

El-Mekawy, Mohamed, Paasch, Jesper, Paulsson, Jenny, 2014. Integration of 3D Cadastre, 3D Property Formation and BIM in Sweden. 4th International Workshop on 3D Cadastres 9-11 November 2014, Dubai, United Arab Emirates P17–34.

Griffith-Charles, Charisse, Sutherland, Michael, Davis, Dexter, 2016. Capturing Legal and Physical Boundary Differences in 3D Space – A Case Study of Trinidad and Tobago. In Proceedings of the 5th International FIG 3D Cadastre Workshop. 18-20 October 2016, Athens, Greece 433–446.

Griffith-Charles, C., Edwards, E., 2014. Proposal for Taking the Current Cadastre to a 3D, LADM Based Cadastre in Trinidad and Tobago. 4th International FIG 3D Cadastre Workshop. 9-11 November 2014, Dubai, United Arab Emirates P363–378.

Griffith-Charles, C., Sutherland, M., 2013. Analysing the costs and benefits of 3D cadastres with reference to Trinidad and Tobago. Comput. Environ. Urban Syst. 40 (July 2013), 24–33.

Griffith-Charles, Charisse, Rajack, Robin, 2017. The challenges of Land governance assessment with limited land information. In: Proceedings of the Annual World Bank Land and Poverty. Washington D.C. March 20-24 2017.

Griffith-Charles, C., 2011. The application of the social tenure domain model (STDM) to family land in Trinidad and Tobago. Land Use Policy 28 (3), 514–522.

Hendriks, Bob, Zevenbergen, Jaap, Bennett, Rohan, Antonio, Danilo, 2019. Pro-poor land administration: towards practical, coordinated, and scalable recording systems for all. Land Use Policy 81 (February 2019), 21–38.

International Standards Organization, 2012. Geographic Information - Land Administration Data Model (LADM) ISO 19152:2012. ISO, Switzerland.

Joint Select Committee of Parliament, 2016. Joint Select Committee Report of Parliament on the Land Settlement Agency.

Kada, Martin, McKinley, Laurence, 2009. 3D building reconstruction from LIDAR based on a cell decomposition approach. In: Rottensteiner, Stilla U., Paparoditis, N. (Eds.), CMRT09 IAPRS, Vol XXXVIII Part 3W4-Paris, France 3-4 September 2009.

Kalantari, Mohsen, Rajabifard, Abbas, 2014. A Roadmap to Accomplish 3D Cadastres. 4th International Workshop on 3D Cadastres 9-11 November 2014, Dubai, United Arab Emirates 75–82.

Kitsakis, D., Apostolou, C., Dimopoulou, E., 2016. Three-dimensional cadastre modelling of customary real property rights. Surv. Rev. https://doi.org/10.1080/00396265.2016.1252518.. http://www.tandfonline.com/action/showCitFormats?.

Mekawy, M., Östman, A., 2012. Feasibility of building information models for 3D cadastre in unified city models. Int. J. E-planning Res. 1 (4), 35–58.

Ministry of Public Administration, 2015. Our journey to Diamond: enhancing the capability of the public service. Report. Government of the Republic of Trinidad and Tobago: Port of Spain, Trinidad and Tobago.

Oldfield, Jennifer, Bergs, Ronald, Oosterom, Petervan, Krijnen, Thomas Fl., Galano, Miquel Marzabal, 2018. 3D Cadastral Lifecycle: An Information Delivery Manual ISO 29481 for 3D Data Extraction from the Building Permit Application Process. Proceedings of the 7th International FIG Workshop on the Land Administration Domain Model 11-13 April 2018 Zagreb, Croatia 153–170.

Pouliot, Jacynthe, Ellul, Claire, Hubert, Frédéric, Wang, Chen, Rajabifard, Abbas, Kalantari, Mohsen, Shojaei, Davood, Atazadeh, Behnam, Van Oosterom, Peter, Vries, Marian De, Ying, Shen, 2018. 3D Cadastres Best Practices, Chapter 5: Visualization and New Opportunities Proceedings of FIG Congress 2018 Embracing Our Smart World Where the Continents Connect: Enhancing the Geospatial Maturity of Societies Istanbul, Turkey, May 6–11, 2018.

Rajabifard, Abbas., 2014. 3D Cadastres and Beyond. 4th International Workshop on 3D Cadastres 9-11 November 2014, Dubai, United Arab Emirates. P1-15.

Roschlaub, R., Batscheider, J., 2016. An INSPIRE-Konform 3D Building Model of Bavaria Using Cadastre Information, LiDAR and Image Matching. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B4, 2016 XXIII ISPRS Congress, 12-19 July 2016, Prague, Czech Republic.

Stoter, J., Ploeger, H., Roes, R., Van der Riet, E., Biljecki, F., Kedoux, H., 2016. First 3D Cadastral Registration of Multi-Level Ownerships Rights in the Netherlands. In 5th International Workshop on 3D Cadastres, 2016, Athens 491–504.

Thompson, Rod, Oosterom, Petervan, Cemellini, Barbara, de Vries, Marian, 2018. Developing and LADM compliant dissemination and visualisation system for 3D spatial units. Proceedings of the 7th International FIG Workshop on the Land Administration Domain Model 11-13 April 2018 Zagreb, Croatia 103–123.

UN-Habitat/GLTN, 2016. Fit-for-purpose Land administration. Guiding Principles for Country Implementation, Nairobi.

Wycliffe, Antonio, Griffith-Charles, Charisse, 2019. Achieving land development benefits on Customary/Communal land. Land Use Policy 83 (2019), 124–133. https://doi.org/10.1016/j.landusepol.2019.02.005.

Xing, Xu-Feng, Mostavi, Mir-Abolfazl, Chavoshi, Seyed Hossein, 2018. A knowledge base for automatic feature recognition from point clouds in an urban scene. ISPRS Int. J. Geoinf. 7 (28), 27.

Zevenbergen, J., Hendriks, B., Bennett, R., 2016. Final Report. Pro-Poor Land Recordation: A Community Based Land Tool, UN-Habitat/GLTN.