Hybrid pre-vectorization approaches to produce accurate, precise maps to scale up boundary demarcation for property rights delivery: Case study in Zambia's Systematic Land Titling Project

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Keywords: Zambia, systematic land titling. land surveying, aerial drone survey imagery, cadastral mapping, infrastructure mapping, modeling, terrain and hydrological analysis

SUMMARY

With innovative approaches to pre-vectorization, Medici Land Governance has been able to produce maps with high accuracy and precision, within a few centimeters of their location on the ground. This approach has been successful in the land surveying and mapping stages for Zambia's Systematic Land Titling Project, which MLG has participated in since 2018.

MLG's aerial imagery acquisition and post-processing service leverage cutting-edge, high-capacity drone technology with Geographic Information Systems (GIS) software and survey expertise to generate high-resolution orthoimagery and elevation surfaces with positional accuracies within a range of 10 centimeters. The orthoimagery and other data products can be used for many purposes, including cartographic base map layers, cadastral mapping, vegetation mapping (including for agriculture, forestry, or biological conservation), infrastructure mapping, hazard modeling (floods, landslides, wildfire, etc.), and solar PV potential modeling. As the national rollout (a target goal of delivering 4 million certificates of title by 2027) has expanded rapidly beyond the capital city of Lusaka and the peri-urban areas in the Lusaka province, MLG has surveyed and mapped areas in the country's Copperbelt, Central, Northwestern and Southern provinces and is now expanding into other areas of the country including the Eastern Province.

The process is a hybrid of traditional land surveying approaches with boots on the ground using a survey-grade global navigation satellite system (GNSS) in Zambia and the simultaneous use of drones that fly over areas to capture spatial data. Using the drone and survey-grade GNSS data collected from the field, images are compiled into a survey-grade map with GIS software. Drone imagery also extracts spatial information such as parcel boundaries, building footprints, building elevations, and roads. MLG utilizes machine learning to automate feature extraction and different property mapping elements to significantly increase the scale and speed of boundary demarcation for property rights delivery. When implementing these projects, MLG uses QGIS (open-source) software to share vectorized data with a GeoServer (open-source), combined with special-purpose servers for effective data distribution. MLG has cultivated significant experience utilizing terrain and hydrological analysis tools, including ESRI software, ArcGIS Pro v2.6.0, and QGIS.

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1. INTRODUCTION

One of Africa's least densely populated countries, Zambia has been frequently described as "land abundant" (de Satgé, 2022). Only 14 percent of the land available for agriculture in the country's three main agricultural-ecological regions has been used and rural areas remain relatively low in population numbers. Regarding Zambia's Systematic Land Titling Program (SLTP), the national rollout (a target goal of delivering four million certificates of title by 2027) has expanded rapidly beyond the capital city of Lusaka and the peri-urban areas in the Lusaka province. MLG has surveyed and mapped areas in the country's Copperbelt, Central, North-Western and Southern provinces and is now expanding into other areas of the country including the Eastern Province. Some of these areas encompass rich reserves and deposits of copper and other mineral resources, which could become a major catalyst and crucible for Zambia's economic development. Another major challenge that has arisen in the SLTP concerns the lack of clarified boundaries between traditional and state lands, a problem that first became prominent when MLG's field team of enumerators canvassed the Luangwa and Chongwe Districts of Lusaka Province (Sagashya & Tembo, 2022). As there had been no updated maps identifying and delineating the extent of customary land in Zambia, the MLG team discovered plenty of institutional overlaps, where over the course of many years following the achievement of Zambia's independence in 1964, traditional lands had been converted into state lands but without proper documentation (Sagashya & Tembo, 2022).

As part of its role, Medici Land Governance (MLG) has demonstrated effectively why the value of GIS as software actually extends to a comprehensive ecosystem encompassing sequential procedures, the collection and verification of data for legal purposes, the impact on communities and landowners in terms of analysis, digital terrain modeling and management of the spatial data generated. GIS has become critical as a georeferencing option for maps that are confirmed and produced, especially for linking essential qualitative data details with spatial data, which confirm claims rightly protected under the legal foundations of land rights. GIS also is a gateway for realizing land tenure security as a central goal of the national SLTP. For example, as the national rollout program extended to communities in the Kafue District, Lusaka and Copperbelt Provinces, the first wave in these areas revealed at least 774 disputes about land ownership and boundaries. As summarized, the processes leading to "land titling can bring latent disputes to the surface. Such disputes can prevent land owners from enjoying the full benefits of their property, and hinder economic development" (Phiri and Malasha, 2022).

With the participatory objective underscored in the GIS and pre-vectorization approaches to produce precise, accurate data, this has facilitated an effective channel for resolving these

disputes. The procedure, which is free for community members involved in such disputes, an adjudication committee convenes with attorneys who have expertise in land rights and governance, with representatives from MLG, Zambia's Ministry of Lands and Natural Resources and Environmental Protection and the Attorney General's Office. In Zambia, MLG has proven that certificates of titles which are verified and secured are possible because GIS technology currently can be carried out in scale and scope while meeting the objectives for accuracy, access and cost-efficiency.

MLG's aerial imagery acquisition and post-processing service leverage cutting-edge, high-capacity drone technology with Geographic Information Systems (GIS) software and survey expertise to generate high-resolution orthoimagery and elevation surfaces with positional accuracies within a range of 10 centimeters. The orthoimagery and other data products can be used for many purposes, including cartographic base map layers, cadastral mapping, vegetation mapping (including for agriculture, forestry, or biological conservation), infrastructure mapping, hazard modeling (floods, landslides, wildfire, etc.), and solar PV potential modeling.

The process is a hybrid of traditional land surveying approaches with boots on the ground using a survey-grade global navigation satellite system (GNSS) in Zambia and the simultaneous use of drones that fly over areas to capture spatial data. Using the drone and survey-grade GNSS data collected from the field, images are compiled into a survey-grade map with GIS software. Drone imagery also extracts spatial information such as parcel boundaries, building footprints, building elevations, and roads. MLG utilizes machine learning to automate feature extraction and different property mapping elements to significantly increase the scale and speed of boundary demarcation for property rights delivery. When implementing these projects, MLG uses QGIS (open-source) software to share vectorized data with a GeoServer (open-source), combined with special-purpose servers for effective data distribution. MLG has cultivated significant experience utilizing terrain and hydrological analysis tools, including ESRI software, ArcGIS Pro v2.6.0, and QGIS.

MLG's process replicates the principles outlined in the Fit for Purpose Land Administration guidelines (Enemark et al, 2014) that were developed by the World Bank and the International Federation of Surveyors (FIG). MLG's staff in Zambia have ensured that the process aligns with these principles as well as Zambia's Land Survey Act, which specifies that land slated to be verified and secured for certificates of title must be "mapped using orthorectified imagery captured using drones or aircrafts" (Sagashya, 2021). The next section outlines the process for expanding and updating Zambia's national spatial data infrastructure.

2. EXPANDING NATIONAL SPATIAL DATA INFRASTRUCTURE IN ZAMBIA

The objective has been targeted to expand and update key elements of the national spatial data infrastructure (NSDI) via modern, high-precision, and high-accuracy topographic surveys of a significant portion of the provincial territories, including urban, peri-urban, agricultural, mining and rural areas. An aerial survey using modern LiDAR technologies allows for accurate, rapid, and consistent surveying and producing subsequent derived data products. The hybrid approach MLG has taken deploys aerial photography, drone, and flight-over

photography and generates essential cadastral layers to identify land boundaries, building footprints and elevations, and others. In addition to other planning layers such as zoning, commercial areas, services areas, and others, these layers become crucial elements that will be utilized in the valuation algorithm.

Regarding its use of drones, MLG captures imagery with spatial resolution precision down to five to 10 centimeters and uses machine learning for analysis as well as for detecting boundaries of land parcels where fences and walls can make automated boundary detection possible. The tiled data products are delivered in one-square-kilometer tile formats. Tiles follow a standardized naming system that assigns a unique tile ID to each tile so that regardless of the data product, the correct data file for a given location can be identified using tile ID. These data tiles are compiled into an index of tile locations and IDs in an OGC (Open Spatial Geospatial) standard format, which allows end-users to view and query tile footprints.

The deliverables are typically presented in the following sequential formats:

1. Raw LiDAR point clouds are delivered as ASPRS LAS 1.4-R15 Point Data Record Format files. Data are organized and delivered in original swaths, with one swath per file, unless processing requires segmentation of swath files. LAS file headers of each swath will contain correct georeferenced information, properly formatted as OGC WKT. Each swath is assigned a unique File Source ID, and each point within the swath is assigned a Point Source ID equal to the File Source IR.

2. Swath index polygons and raw point clouds are accompanied by a georeferenced polygon feature class, in a standard OGC compatible format, with a polygon feature for each LiDAR swath collected. Likewise, 2-D building footprints of all permanent roofed structures with a planimetric footprint (except those partially or fully covered by vegetation canopy) are also delivered as polygon features.

3. Classified LiDAR point clouds are delivered as ASPRS LAS 1.4-R15 Point Data Record Format files. Data are organized and delivered in tiles of one square kilometer, as mentioned previously. LAS file headers of each tile contain correct georeferenced information, properly formatted as OGC WKH.

4. Tile index polygons are constructed, as based on the classified point clouds, derived terrain models, and orthoimage.

5. Digital Orthoimagery (DOI) is captured simultaneously with LiDAR points and georegistered and orthorectified. Orthoimagery are also delivered in the previously mentioned tile format. Bare-earth Digital Terrain Models (DTMs) are delivered as GeoTIFF files with pixel values, indicating elevation in meters relative to the project's vertical datum.

6. By sharing survey control data (e.g., survey control points or benchmarks used), MLG can provide the respective MLNR officials with the requisite metadata, which also

ensures alignment with the government's own network infrastructure and interfaces. The data captured is fully detailed, including transport networks including road, rail, water and port transport routes and their connecting nodes, along with road centerlines, including access roads in mining, forestry and agricultural-ecological regions as well as rivers, lakes and any present intertidal features. This includes any flooded mining pits, as well as digital imaging and hydro-flattened modeling at a 10-meter grid interval for larger ponds and lakes. Likewise, for streams and rivers with nominal width of 30 meters or greater but which also may be less than 30 meters at some points, the modeling will not be broken but flattened.

7. The standards include generating metadata to document the digital production process and no tiles are partial or contain data gaps between or edge effects. And, except in instances where ground-classified points cannot be delineated because they are located under dense forest canopy, there are no voids in the modeled images from surface features such as buildings and land cover.

3. SIGNIFICANCE OF MAPPING: ZAMBIA'S DIRECT AND INDIRECT IMPACTS

As Zambia's SLTP efforts have gained momentum, it has become clear that GIS and MLG's hybrid approaches are producing reliable, valid records in a manner that is improving efficiency and reducing the costs of land rights mapping (UN-HABITAT, IFAD and GLTN, 2016). The implications are not just for the goals of issuing certificates of titles but also for achieving the benefit of land tenure security, thanks to the advancements in machine learning, drone-based imagery and automated feature extraction. The process is essential for realizing the direct effects of user-friendly land administration reform. These benefits include transparent access to data to increase the public participation rate and eliminate redundancies, a streamlined period for property registrations and transfers, documentation of land valuations and enhanced land wealth, secured land inheritance and, most importantly, empowerment for communities and citizens.

Equally significant are the indirect impacts. The mapping and digitization. of processes unlock the capital of the property for personal investment, access to credit, and tenure security, open up channels and streams of revenue to build wealth, encourage foreign direct investment opportunities, use data roadmaps to identify and plan for economic growth and stimulation, encourage real estate investment and explore natural and mineral resources as a step toward developing this industry.

The last benefit is especially important to Zambia. In periodic statements, Hakainde Hichilema, Zambia's current president, says that only one-half of the country's mineral resources are mapped. Hichilema, following a meeting with Marisa Lago, the U.S. Under Secretary for International Trade, explained that mapping the mineral resources should reduce risks for potential investors, as they will be able to ascertain the extent and volume of resources in the ground before committing their investments.

The Zambian government has long considered mining as the critical "fulcrum" for growing the country's economy. The mining and quarrying industries are responsible for approximately 13 percent to GDP and have accounted for 70% of Zambia's foreign earnings (Mulenga, 2019). With the objective of mapping the available resources, the issue of local control becomes that much more critical to the purposes of property rights as well as environmental concerns about potential impacts of mining for the affected communities. The country's constitutional code permits licenses to be issues,

> for prospecting or mining minerals on customary or leasehold land. Small-scale mining licences receive 10-year renewable licenses and large-scale mining operations can receive a 25-year renewable license. The law requires that mining rights holders obtain consent from traditional leaders on customary land, or any other legal occupier of state land, prior to commencement of actual mining activities. However, this consent may not be unreasonably withheld, and "the failure of a landholder to allow for mineral exploration and extraction justifies the acquisition of the land" (Ministry of Lands and Natural Resources, 2017).

Likewise, the logistical infrastructure for extraction and transportation of mineral resources remains a major challenge, one that could be ameliorated through planning that is based on the hybrid approach for accurate and precise mapping. For example, Zambia's North-Western province is "at the epicenter of the copper industry. Two mines — at Kalumbila and Solwezi — produce nearly two-thirds of Zambia's annual production of 720,000 tons" (Mills, 2022).

Highlighting Zambia's prominence in the African Copperbelt, a 201 World Bank report indicated the country holds at least six percent of known copper reserves in the world and geological surveys elsewhere in the country "suggest a significant opportunity to find viable deposits of copper." Such prospects have heightened the need for a better equipped geological survey operational base in the country's ministries:

> A country that has been surveyed properly is likely to attract the right investment and, eventually, sign clearer development agreements, specifying the responsibilities of all parties involved. Such agreements would result in better outcomes for the government, the mines and Zambian people (World Bank, 2011, p. 58).

Without the maps, government ministers are unable to set the proper terms and conditions for exploration licenses. Likewise, comprehensive mapping would produce the critical data so that investors will not have to resort to speculation, given that the degree of uncertainty is typically reflected in the price they are willing to negotiate for securing an exploration license. Furthermore, the expectations of "economic viability is contingent on the price assumptions for copper, the risk premium required by financial investors and the likely cost of mining new deposits. The latter can only be determined after exploration" (World Bank, 2011, pp. 25-26).

The penultimate task of gathering and organizing information — that is, big data — for the purposes of secure land tenure is accomplished via this hybrid approach, which also

incorporates machine learning, to establish the foundation for a new database management system through blockchain technology. That is, digitization handles "the prolific provision of structured, semi-structured and unstructured data – including from social media, smart sensors and mobile devices (Bennett, Pickering & Sargent, 2018; Galić and Vuzem, 2020). Therefore, MLG, as it recognizes the need for Zambia's Ministry of Land and Natural Resources to have the optimal agile, adaptive land governance system, which means there needs to be a significant scaling up of new database and distributed ledgers technology. The main goal of digitalization is to produce data to be integrated into the Land Administration System, specifically for the following purposes: securing land titles and registration documents by converting them into digital form, preparing digital non-geographic documents for entry into the document management system, creating a spatial land information layer with topologically structured parcel polygons, linking land parcels to title register data by a unique parcel identifier, and establishing a base map for cadastral information management and a basis for land and registration information management, land allocation, land development, and planning.

The objective of the component is rehabilitation, conversion to digital format, securing and uploading to the land administration system of land records (i.e., titles, registrable instruments, land administration records, and other relevant records); cadastral maps at various scales, land survey records; physical planning records and drawings; land/property valuation/appraisal records and relevant topographic maps and other data required for land administration. In fact, the greatest challenge for Zambia and any other nation taking on the digitization of the land governance system is to do it in as timely a manner as possible. As MLG has discovered in its efforts not only with Zambia but also in Rwanda, Liberia and even stateside in the U.S. is to motivate government decision makers that systems can be agile and customized for their respective expectations of "resilience, scalability and sustainability" (Galić, 2021).

Indeed, as mentioned earlier in this section, the scalability of digitization will strengthen the tangible evidence of the indirect impacts, notably for economic development and planning in the Zambian provinces. With the support of AI and machine learning g tools, the country will benefit from streamlined and simplified urban planning, allowing the efficient identification of easements and management of construction permits, planning of housing schemas, and the validation of topographical rules for planning new settlements. The impacts for the mining sector are also transferable to the country's urban and agricultural sectors. The agricultural sector will also benefit from the spatial data infrastructure and remote sensing analysis, with land use categorization, soil identification, the measure of deforestation, and sustainable planning for agricultural industrialization, supporting food security without compromising the environmental ecosystem. This data and planned infrastructure will also aid in other areas of natural resource exploration (including forestry management), potentially expanding these industries to their maximizing output.

Based on the results of the data analytics and acquisition process, MLG subsequently can define an algorithm that can be used to establish the value of the properties. Once approved by the administration, the algorithm will ensure fair and accurate property tax rates are applied to all mapped properties, accounting for various inputs and enabling sufficient property tax revenue collection for the country. MLG's land valuation technology provides the database platform

that combines multiple data sources and variables to create formulas to calculate the property value. The land valuation system can generate various models using machine learning that can be evaluated by cross-checking with historical and current real estate data. Based on the various models proposed, the Zambian government can determine which models are best suited to ensure effective property tax collection throughout the nation for enhancing the revenue streams needed for planning and development.

4. CONCLUSION

As MLG's efforts in Zambia's SLTP rollout have expanded to more provinces, the mapping data infrastructure has expanded in parallel not only in terms of its significance for validating and securing certificates of title but also in providing community accessible data for development and planning purposes. This becomes more critical, as the national government looks toward not only mapping Zambia's mineral resources but also for developing the infrastructure logistics to turn these efforts into thriving economic sectors.

A case example in a 20222 investigative news report illustrated the complications of transportation logistics for Zambia's copper industry that must be resolved for the country to realize the full potential of its mining industry. The article noted that the roadway to the Walvis Bay port, critically located near the borders shared not just by Zambia but also by seven other African nations, might be the best solution to maximize logistic efficiencies. The problem is that in terms of port efficiency, the World Bank ranks Walvis Bay in the bottom 10 percent of global port listings. But, Mills (2022) believes a public-private partnership could be the key to resolving these inefficiencies and stimulating local economic growth, given the following:

> Regardless, the port's executive is aware of its challenges, and the imminent concessioning of the container depot (currently running at 168,000 containers per annum, compared with its capacity of 750,000) is expected to help. Walvis Bay handles 4.4 million tonnes of bulk freight annually, of which 1.4 million tonnes are cross-border regional trade. This translates into more than 400 trucks calling at the port every day, and 2,500 vessels a year.

Just as securing land tenure is critical as a basic economic driver, the purposes of GIS and mapping become the data foundations for transforming the economy driven primarily by scales of efficiency. That is, with enhanced infrastructure, the probabilities for macroeconomic stimulus and stability are also improved.

Infrastructure is improved, greater macro-economic stability achieved and better provision of healthcare and primary education lead to a more productive workforce. Frontier blockchain technologies integrate and leverage data sources, enhancing accuracy and precision of data analytics. Meanwhile, more transparent partnerships for urban, agricultural and natural resources planning become regular, which encourage constituent participation. The process strengthens the focus on sustainability in technical, financial and institutional capacities by advocating for technology that achieves: secured land tenure, cost efficiency for both governments and citizens, opportunities for collateralizing land, regularized revenue streams

and incentives to unlock dormant capital. With blockchain technology and the transparency it offers for empowering citizens, institutions are improved to streamline government bureaucracy and to accomplish the following:

1. To overcome resistance and inertia in planning and development
2. To minimize and eliminate constraints to doing business, accessing financing and facilitating trade
3. To improve the efficiency of labor and product markets, by demonstrating their technological readiness
4. To mapping land rights which fully address the need for sensitive (customary lands, for example) and innovative approaches

The outcomes are integrated and integrative. Systematic titling recognizes land property rights for ownership, tenure and security, access to capital and financing. The data infrastructure becomes the foundation for programmatic approaches in government valuation for wealth generation, sustained streams of tax collections for revenue and investment. Finally, the objectives for development and planning will materialize, for managing and securing properties, urban and resource planning, natural resources and environmental planning, climate and disaster management, and, most importantly, strengthening human capital potential in communities.

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BIOGRAPHICAL NOTES

Ali El Husseini, Ph.D., is the CEO of Medici Land Governance (MLG), a company established in 2018. MLG Inc. is a private company registered under the laws of the United States. As a public benefit corporation, MLG pledges to promote economic development and full financial inclusion by helping individuals in developing countries to establish formal ownership of their homes and land. MLG uses blockchain and other technologies (such as machine learning, cryptographic and reporting systems, verifiable claims, etc.) to support land governance, titling, mapping, and administration with a secure public record of land ownership. Using MLG products, governments can more effectively map land parcels, administer land records, enforce property rights, generate revenue, and create an enabling environment for functioning property markets. Our present activities include blockchain-based land titling and administration, land titling systems, Geographic Information Systems (GIS) mapping, and aerial imagery for land management.

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