Towards UAV-based Land Tenure Data Acquisition in Rwanda: Needs Assessment and Technology Response

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SUMMARY:

As a response to the urgent need to record the millions of unregistered land parcels, governments and the international development community seek to design appropriate policies and leverage innovative technologies. Amongst others, Unmanned Aerial Vehicles (UAVs) are emerging as a tool for alternative land tenure data acquisition. The advent of low cost, reliable and lightweight UAVs have created new opportunities for collecting timely, tailored and high-quality geospatial information. Even though UAVs appear a promising technology, it is not clear to what extent they meet the needs of communities and governments in the land sector. Furthermore, major bottlenecks are evident: cumbersome regulatory frameworks and undeveloped ground truthing strategies, amongst others, are issues currently impeding scaled application. Thus, the question remains whether the application of UAVs can meet contemporary land administration requirements in developing countries.

This question creates the motivation of this paper and is considered in the context of Rwanda. A multi-disciplinary approach is employed. A comprehensive needs assessment with various stakeholders across different levels in Rwanda is undertaken. The outcomes of the needs assessment, as well as a number of UAV test flight missions, provide the profound pre-requisites for the design of UAV workflows. This study sheds light on the needs assessment and design process of UAV-based data acquisition workflows and reveals results of data collection activities and initial UAV test flights in Rwanda. Insights into operational challenges and data quality measures are presented. The paper concludes that the tool of UAV-based data collection seems to offer an answer to the majority of the expressed needs which were assessed with the NGT method. However, the realization of the test flights also reveals three specific challenges that have to be addressed before UAVs can be used for large scale mapping in Rwanda.

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1. INTRODUCTION

The realm of land administration is currently being challenged: conventional western-oriented land administration systems have mostly failed to supply their expected results. As a response to the urgent need to record millions of unrecorded land parcels, land policies as well as innovative technologies are now seeking for appropriate concepts and tools which are able to address this task. *Its4land* is a research project funded by the European Commission Horizon 2020 program. It aims to deliver a pioneering suite of land tenure recording tools that respond to this immense challenge. To carry out this task, *its4land* combines an innovation process with emerging geospatial technologies, including smart sketchmaps, unmanned aerial vehicles (UAVs), automated feature extraction, and geo-cloud services, to deliver land recording services that are end-user responsive, market driven, and fit-for-purpose. A strategic collaboration between the EU and East Africa is being reinforced during the project lifetime via scalable and transferrable ICT solutions. Established local, national, and international partnerships in Rwanda, Kenya and Ethiopia are driving the project results.

Within the last decade UAVs became a genuine gain for scientific as well as commercial applications. The advent of low cost, reliable, user-friendly and lightweight UAVs and recent developments in digital photogrammetry and structure from motion (SfM) image processing software solutions have created new opportunities for collecting timely, tailored, detailed and high-quality geospatial information. Due to their flexible operational setups, UAVs are able to bridge the gap between time-consuming but high accuracy field surveys and the timeless fashion of classical aerial surveys. Resulting data products include true orthoimages, digital elevation models and 3D point clouds which can all serve as a basis for cadastral mapping applications. Experiences in western European cadastral systems, as well as in developing countries with customary land tenure systems prevail. Manyoky et al. (2012) showed that UAVs can reach the required sub-decimetre-level of accuracy for cadastral surveying in Switzerland.

However, the geometrical accuracy of UAV-based data products can vary enormously: they are influenced by multiple factors including the flight parameter, the quality of the camera, the camera calibration and ground truthing strategies. Widening the focus from a solely high-tech and cm-level of accuracy perspective to a more holistic point of view, UAVs may have the ability to revolutionize land administration tools (Rubinov et al. 2015). This is argued by the fact that spatial information can rapidly and precisely be acquired at low costs which allows for just in time supply of geospatial products.

Another advantage of UAV data acquisition procedures involves the independency of this technique. With due regard to the limitations considered within current regulations, the ease-of-use workflows of UAV image capturing allow for data acquisition at a time of choosing, and nearly all places without any dependence on aerial or satellite imagery provider. Hence, these simple characteristics promise a favourable option for non-conventional bottom-up land administration mapping actors.

Even though UAVs appear a promising technology, it is not clear to what extent they meet the needs of communities and governments in the land sector. Furthermore, major bottlenecks are evident: cumbersome regulatory frameworks and undeveloped ground truthing strategies, amongst others, are issues currently impeding large-scale implementation. Thus, the question remains whether the application of UAVs can meet contemporary land administration requirements in developing countries. This question creates the motivation of this paper and is considered in the context of Rwanda. The research is conducted in a multi-disciplinary approach. A comprehensive needs assessment with various stakeholders across different levels in Rwanda is undertaken. The outcomes of the needs assessment, as well as UAV test flight missions, provide profound pre-requisites for future design of UAV-based land tenure data acquisition workflows.

2. STUDY AREA

Rwanda, with an area of over 26,000km2 and a population of almost 12m people, is the most densely populated country in Africa (more than 470 per km^2) (NISR 2014; The World Bank Group 2016). The population of Rwanda is still largely rural, with 83% living in rural areas (NISR 2014):it is not a surprise that land is of vital importance to Rwanda. Despite its scarcity, the country continues to be highly reliant on agriculture as a form of employment and subsistence, and an increasing population exerts a growing demand for housing and infrastructure. Land ownership in the country has evolved from customary law to a system of state ownership. Recently, a country-wide land tenure regularisation program (LTRP) was completed where more than 11 million parcels were demarcated and almost 9 million parcels titled to offer Rwandan citizens a range of social, legal and economic benefits perceived to be derived from holding titles to land. The LTRP used 96% aerial and 4% satellite imagery as base data to demarcate and adjudicate parcel boundaries in a community-mapping exercise (Gillingham and Buckle 2014). Geo-information derived from this exercise has also enabled the development of a national cadastral map (or land information system), which now underpins a range of purposes.

Land will continue to feature prominently in Rwanda's future development. Its role is emphasised in its key long-term national policy, Vision 2020, which is realised through shorter-term national Economic Development and Poverty Reduction Strategies (EDPRS) and district development plans. In the context of *its4land*, the problem is expressed as one of an almost absent ability to collect relevant land and property information at a certain frequency and scale to implement and enforce the district plan to achieve policy objectives around sustainable urbanisation. Such data is important not only as an updating mechanism and input into the land information system, but also missing are general topographic information, such as buildings, parcel boundaries and visible infrastructure, etc., that is fundamental for planning and development. Likely ramifications at a local level are increasingly out-of-date cadastral data and the lack of a sound evidence base to develop subsequent district plans; at a national level, it is likely to impede the realisation of Vision 2020's objectives regarding sustainable urbanisation.

When it comes to UAVs, Rwanda can be seen as very progressive in comparison to other East African countries. At the recent World Economic Forum in Davos, high level delegates from the Government of Rwanda promoted Rwanda as the first country to adopt a performance based UAV regulations[1]. They further outline that development of infrastructure and policy frameworks will spur business growth and social impact. Current UAV projects in Rwanda tell a story of success. In October of 2016, Zipline and the Government of Rwanda launched the world's first national drone delivery service to make on-demand emergency blood deliveries to transfusion clinics across the country. Since then, Zipline UAVs have flown more than 100,000 km in Rwanda, delivering 2,600 units of blood during more than 1,400 flights (Zipline 2018). Besides foreign businesses, local UAV companies such as Charis UAS Ltd.[2] who provide professional services in various UAV industries are emerging as well. These developments seem to create a robust foundation for UAV innovation growth in Rwanda.

3. METHODS

3.1 Needs assessment

Needs assessment for Rwanda was conducted in two main ways. At the district and national levels, a form of group interview known as the Nominal Group Technique (NGT) was used. NGT is a form of group interview that enables structured problem-solving or idea-generation that aims to reach consensus (Delbecq and Van de Ven 1971). In this technique, ideas are initially generated individually, but these are then gathered and combined as a group, and consensus is reached through two rounds of individual voting. NGT offers advantages over other qualitative data collection methods like focus group discussions as it facilitates a balanced input from all participants and takes advantage of each person's knowledge and experience to provide deep and meaningful results ranked by importance to the topic of interest (Lloyd 2011). This also provides insight into the extent to which individual participants agree or disagree with the consensus vote. Additionally, the voting/ranking aspect of this process provides a quantitative aspect to the data.

NGT workshops were held in Kigali and Musanze with experts identified through purposive sampling by local partners, as well as snowballing (through delegation and recommendations

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[1] http://www.newtimes.co.rw/section/read/228255/ accessed on 12.02.2018

[2] http://charisuas.com accessed on 12.02.2018

from those initially contacted). 38 organisations across six stakeholder classes were contacted; of these, 22 participated (58% response rate). Three NGT workshops were held at sector and national levels with each workshop meeting the NGT requirement of having between five to nine participants. One nominal question was posed at each workshop: "***What land and land-related information is still needed?"***. This was followed by a discussion on which of the *its4land* tools participants felt had the most potential to meet their needs.

At the local level, the workshop format was deemed to be inappropriate for practical reasons. An adapted version of the NGT was used as an interview guide with cell officials (see Table 1). The aim was to gain an understanding of current practices regarding the implementation and/or enforcement of the district land use plan, as well as information needs related to this.

Table 1 Interview guide for cell officials.

Area of inquiry	Questions
Current context	1. What do you know about the District Land Use Plan (DLUP)? *(If they say no, record answer and conclude interview)* 2. Are people using their land according to the land use plan?
Community land information needs	3. What kind of land information do you use to ensure the DLUP is being followed? • Are people using their land based on the DLUP? • How do you know if this is the case? • How do people know (what they can use their land for)? What information does the community use?
Local government land information needs	4. Do you need other types of information? If so, what are they? 5. Of these you have mentioned, how would you rank them in order of importance? Can you please explain why you have ranked them in this order?

Six cell officials were interviewed with no significantly different insights gained after four interviews. To minimise the burden on these participants, the research team tried to limit interviews to 30 minutes. Table 2 shows the respondents' characteristics, as well as the land use characteristics of their respective cells.

Table 2 Characteristics of respondents and land use types of their respective cells.

Respondent ID	Respondent's experience	Cell land use characteristics
C1	Less than 6 months	Purely rural with some informal residential development discernible.
C2	Between 2 and 5 years	Mainly rural. Plots along the main road are moving towards residential land use types.
C3	Btw. 6-12 months	Mixed urban-rural. Land use here is mostly for residential and agricultural use. Some parts of the cell have become purely urban.
C4	Between 2 and 5 years	Mixed urban-rural. Land use here is mostly for residential and agricultural use. Some parts of the cell have become purely urban.
C5	Approx. 10 years (across different cells)	Mixed urban-rural. Under the DLUP, this cell is zoned as fully urban (residential) but some parts have yet to change over from traditional agricultural land uses.

Respondent ID	Respondent's experience	Cell land use characteristics
C6	Less than 6 months	Purely urban. Has been zoned for urban land use (residential) for some time. Services provided mainly relate to construction or renovation permits.

3.2. UAV data collection

The subject of UAV in general and UAV data acquisition in particular refers to a wide variety of different platforms, instruments and sensors, data acquisition procedures, calibration and image processing methodologies. Next to technical aspects, also non-technical concerns need attention since they can considerably influence the whole UAV mission. As shown in Figure 1, certain requirements as well as parts of the UAV data collection workflow can be distinguished. Here, the UAV itself, the UAV pilots as well as the legal permission to conduct UAV flights refer to necessary requirements to proceed with the data collection. The UAV workflow itself consist of three major phases: flight planning, data acquisition and data processing. Whereas the flight planning and the data processing are completed in the computer lab, the UAV flight for the image data acquisition is conducted in the field.

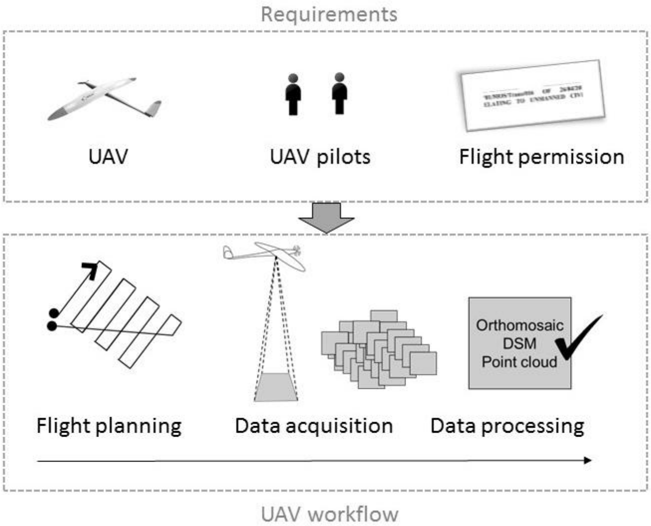

Figure 1: UAV data collection – requirements and workflow

3.2.1 Requirements for UAV flights

The data acquisition flights were carried out with three different UAVs; one rotary-wing UAV, one hybrid UAV and one fixed-wing UAV which was especially purchased for the its4land project. Type and sensor specifications are presented in Table 3. The Inspire2 from DJI refers to semi-professional UAV with a focus for filmmaking. Both, the FireFLY6 and the DT18 PPK are survey-grade UAVs whereof the FireFLY6 presents a lower cost solution and the DT18 PPK refers to a professional UAV with high-end components. With regard to the DT18 PPK, especially the combined IMU/GNSS solution from Applanix (APX15) needs to be emphasized. Recent improvements of such highly accurate positional devices allow for the use of direct georeferencing methods and thus minimize the need for ground control measurements.

Table 3: Specifications of UAVs

Name	Inspire 2 (DJI)	FireFLY6 (BIRDSEYEVIEW)	DT18 PPK (Delair Tech)
			
Type	Rotary wing UAV	Hybrid UAV	Fixed-wing UAV
Sensor	Zenmuse X5S	SONY A6000	DT18 3Bands PPK
Area	Busogo (50 ha) – 2 flights	Muhoza (94 ha) – 2 flights	Gahanga (14 ha) – 1 flight

In April 2016, the Ministerial Regulations N°01/MOS/Trans/016 relating to UAVs were officially gazetted (RCAA 2016). Respective regulations are very prescriptive (Stöcker et al. 2017) and contain subparts dealing with UAV registration and marking, privacy and safety, airworthiness certification, operating rules and pilot licensing. Before any commencement of activities, the UAV needs to be registered and marked with a unique identifier. Furthermore, pilots as well as the operating institution need to hold specific licenses issued by Rwanda Civil Aviation Authority. These requirements demand a high standard of UAV professionality and make it a challenge for new companies and institutions to obtain legal flight permissions. With the regulations as recent as they are, the authorities seem to be learning on the go with early applications as the one by the *its4land* team. For over a year, the Rwandan its4land project partners have been working on obtaining all necessary documents and clearance for the start of their UAV flights, but this has not yet been completed. Due to these circumstances, all flights presented in this paper were piloted and operated by Charis UAS Ltd.

3.2.2 UAV workflow

The creation of a flight plan is the first step for the UAV data collection. During the flight planning areas for take-off and landing, the UAV trajectory and the flying height are specified. Typical features to create the flight trajectory are 80% longitudinal and 40-80% transversal overlap (Colomina and Molina 2014) since redundancy can compensate aircraft instabilities. The large amount of overlap also tackles differences between estimated and actual image footprints which can be significant within undulating terrains as it is the case in Rwanda. Following this recommendation, all flights of this study were carried out with 80% longitudinal and 80% transversal overlap. For each mission, the flight height was set to 100m above the surface. Resulting ground sampling distances varied between 2-3cm depending on the sensor specification of the employed UAV.

Suitable places for take-off and landing are determined by two factors. Firstly, the space which is needed for take-off and landing. At this, UAVs with vertical take-off capabilities are preferably used in densely populated areas where open space for large landing strips – as required by many fixed wing UAVs – is missing. Secondly, Rwandan UAV regulations decree to operate the UAV in 300m visual line of sight. Thus, the radius for one flight mission is by default limited to 300m and the point to set the ground control station should be as central as possible.

For this study, three setups were chosen. The FireFLY6 collected data of an urban environment in Musanze Sector, whereas the Inspire6 was flown over a peri-urban area in Busogo Sector. The DT18 PPK captured images over a cricket stadium embedded in a rural environment in Gahanga Sector. Both, the Inspire2 and the FireFLY6 are equipped with a consumer-grade GNSS antenna which allows to geotag all images. However, resulting spatial accuracy is limited to approximately 10m making additional measurements of ground control points (GCPs) indispensable. In both cases the classical workflow of an integrated sensor orientation (Rehak and Skaloud 2016) is applied. In contrast, the DT18 PPK stands out for precise attitude logs including both: angular observations as well as camera positions. Here, the need for additional ground control measurements can be minimized tremendously (Stöcker et al. 2017). To include known point coordinates for georeferencing as well as a means for quality control, artificial ground reference points were deployed and measured in all three case locations. The ground reference points that were used have a quadratic shape with an edge length of 30cm showing a black and white chess pattern (cf. Fig.2). Points were measured with two different GNSS devices. The first was a Leica CS10 set as base and rover with a final RTK measurement accuracy of 2cm. The second device was a handheld Trimble GeoXH which received RTK corrections via the Rwanda CORS GeoNet which allowed for final measurement accuracies of 10cm.

Figure 2: Measurement of ground reference points

4. RESULTS

4.1 What do Rwandan stakeholders need?

The outcomes of the needs assessment pertaining to each stakeholder group are shown in Tables 4 (sub-national stakeholders), 5 (national government stakeholders) and 6 (national non-government stakeholders).

4.1.1 Sub-national government stakeholders

Table 4. NGT outcomes from sub-national government stakeholders.

Land tenure or land info need	P1	P2	P3	P4	P5	P6	P7	P8	P9	SoC	Rel. Impt.	Popl.	Priority
Highly accurate data - image and GIS data	1	5	4	5	5	5	5	5	5	40	29.63	1.00	#1
More mobile tools	5	3				2	3		3	16	11.85	0.56	#2
Physical characteristics of land						4	4	4	4	16	11.85	0.44	#3
Access to information	4	2	2		4			2		14	10.37	0.56	#4
Geological data	3	4		4						11	8.15	0.33	#5

Table 4 shows the top five prioritised land tenure or land-related information needs (out of a priority list of 10 needs) amongst sub-national government stakeholders. Stakeholders clearly prioritized the need for high accuracy land-related data, both in terms of imagery and GIS data, which was rated to have a relative importance of almost 30%. Thereafter, various types of land-related information were prioritized, but not as strongly. These included information types, e.g. physical characteristics of land, geological data and land use type, but also capacity aspects including the need for mobile tools and greater access to data. Amongst other land information needs identified but not shown here are: parcel boundaries; location of underground infrastructure; and all transactions made on a parcel. There were also other needs of secondary relation including efficient implementation of development plans (Master Plan and Land Use Plan); providing information to stakeholders (about forthcoming developments) and the need for wireless infrastructure.

4.1.2 National government stakeholders

Table 5. NGT outcomes from national government stakeholders.

Land tenure and/or land info need	P1	P2	P3	P4	P5	SoC	Rel. Impt.	Popl.	Priority
High accuracy satellite/aerial imagery	5	2		5	2	14	18.7	0.8	#1

Land tenure and/or land info need	P1	P2	P3	P4	P5	SoC	Rel. Impt.	Popl.	Priority
To know what spatial data is available and held by who		1	1	4	5	11	14.7	0.8	#2
Current land use information				3	4	7	9.3	0.4	#3
3D cadastral data	4		2			6	8.0	0.4	#4
Utility supply data	1	4				5	6.7	0.6	#5

Table 5 shows the top five prioritised land tenure or land-related information needs (out of a priority list of 14 information needs) amongst national government stakeholders. Similar to the sub-national government stakeholders, there was a clear need expressed for higher accuracy data, but in this case, only relating to aerial or satellite imagery. The second priority included the need to know what spatial data is available, and who holds this (data discovery and accessibility). This was followed by a cluster of needs of similar relative importance (between 6-9%): current land use information, 3D cadastral data, utility supply data, aligning parcel boundaries with administrative boundaries. There were also capacity needs such as moving towards open source technologies, importance of monitoring infrastructure projects (e.g. utilities). Less prioritised land information needs to include existing developments (at parcel level), climate data, topographic data and greater community access to information about land rights.

4.1.3 National non-government stakeholders

Table 6. NGT outcomes from national non-government (industry and academia) stakeholders.

Land tenure and/or land info need	P1	P2	P3	P4	P5	SoC	Popl.	Rel. Impt.	Priority
Value of land (valuation process)	3		5	4	5	17	0.8	22.67	#1
Accessible open data	5	5			4	14	0.6	18.67	#2
Consultative process around land use planning	4			5		9	0.4	12.00	#3
More detailed (sub-use) land use planning in Master Plan			4	1	3	8	0.6	10.67	#4
Actual land use information		2	2	3		7	0.6	9.33	= #5
History of land Information to resolve conflict between infrastructure development and arable land	1	3	3			7	0.6	9.33	= #5

Table 6 shows the top five prioritised land tenure or land-related information needs (out of a priority list of 10 information needs) amongst national non-government stakeholders. These stakeholders prioritised information about the value of land, followed closely by accessible open data (related to land). The next cluster of priorities included information needs such as more detailed (sub-use) land use planning in Master Plan, actual land use information, and the history of land Information (to resolve conflict between development and arable land). Less prioritised information needs included demographic data integrated with land data, more accurate (sub-metre) parcel boundaries in urban and peri-urban areas, information about proposed developments and associated risks, as maintained web-based master plans.

4.1.3 Cell-level land information needs

Cell officials were generally consistent in the types of land information they were using, and how they were using these to support plan implementation. Nonetheless, challenges remain such as:

- **lack of information, or lack of access to information, about the Master Plan** (i.e. information about proposed new development): inhibits cell officers' ability from effectively playing a role in plan implementation (C5)
- **lack of title information:** although most of the land in Rwanda has been demarcated and titled during the land tenure regularisation (LTR) program, some plots (or owners who occupy the plots) remain untitled due to information gaps at the time of the LTR, e.g. lack of identification, family disputes, etc. (C1)
- **lack of updated land use information post LTR:** evident in two different use types in one parcel which are not indicated on the land title (C1)
- **lack of accuracy in plot sizes:** general boundaries used in the LTR are not being updated accurately due to resolution of GPS receivers (3 metres) or lack of GPS receivers (pacing by foot is used instead).

Table 7. Land information needs identified by cell-level stakeholders.

Land information needs	C1	C2	C3	C4	C5	C6
Soft copy of the master plan	X			X	X	
Soft copy of the DLUP				X	X	
Spatial dataset (shapefiles) of master plan and land parcels	X	X	X	X		
GIS software	X	X	X	X		
Information about planned infrastructure				X		
Integration of land use map with land information database				X	X	

4.1.4 Community land information needs

Cell officers reported that the community generally use their land as indicated on title. There are some instances of informal building but these are not significant. In those cells transitioning to more urban land use types, a greater issue was the community not using their land as zoned. The main source of land information for communities are their land title, and the cell office; however, whether information on title actually reflects reality is predicated on the individual community member, and not on a systematic process. For example, in one of the cells, despite the whole cell now being zoned for urban land use (residential), some land titles still reflect (the previous) agricultural land use. In these instances, land records are only updated if the land owner formally seeks a building permit or other land related service; otherwise, the land title remains unharmonised with the Master Plan. In addition, given that the Master Plan plays a key role in setting out future development, it appears that local community consultation is fairly ad hoc. For example, in some cells, local communities do not participate in the establishment of the master plan/LUP; in others, only cell officers are contacted, whereby it then falls onto them to inform the community; and yet others, local consultation has been undertaken.

4.2 Which its4land technology could potentially meet stakeholders' needs?

In the workshops, stakeholders were asked to provide an opinion on which its4land technologies were best suited to meet their identified land information needs. Only two stakeholder groups could do this and Table 8 provides an overview of the distribution of 'yes' votes.

Table 8. Distribution of yes votes across Rwandan stakeholder groups who voted.

Stakeholder group	Smart Sketchmaps	UAV	Automated Feature Extraction	Geocloud Services
Nat_Gov	2	7	1	6
Nat_NonGov	4	5	2	2
Dist_Gov		✓		✓
Total no. of 'yes' votes	**6**	**12**	**3**	**8**

Even though the number of 'yes' votes is not representative of the views of all stakeholders, the highly centralised governance structure in Rwanda suggests that the perspectives of national government stakeholders may carry more weight as they are likely to be the technology owners. Stakeholders show clear preferences for UAVs and geocloud services – indicating a need for high resolution terrestrial aerial imagery data capture (for both cadastral and non-cadastral purposes) and corresponding potential of processed data outputs, and a desire for greater land information sharing across government (horizontally and vertically) and to support data analysis. Government stakeholders supported the potential of UAVs for meeting Rwanda's land information needs. In contrast, non-government stakeholders felt that smart sketchmaps was an innovative technology of greater potential primarily because it offered a mechanism for collecting other types of land information that requires community input. In addition, the tool employed a participatory approach to data acquisition, which was considered important for supporting transparency and facilitating stakeholder consultation. The sub-national stakeholder group refrained from voting as they did not feel sufficiently familiar with the technologies to form an opinion. However after input from the research team and a discussion, the group felt that both UAVs and geocloud services held potential for meeting the needs.

4.2 UAV data collection results

All data collection activities were completed as planned and resulting orthomosaics are presented in Figure 3. Two main challenges were observed during the field work activities: 1) meteorological conditions and 2) the deployment of ground reference points. Due to the mountainous terrain of Rwanda and especially for the UAV flights Muhoza and Busogo in the

Northern Province, weather conditions change very fast and can require spontaneous changes in the flight plan. When the UAV data collection necessitates two or more flights, different illumination conditions can lead to differences in image quality (cf. Busogo dataset).

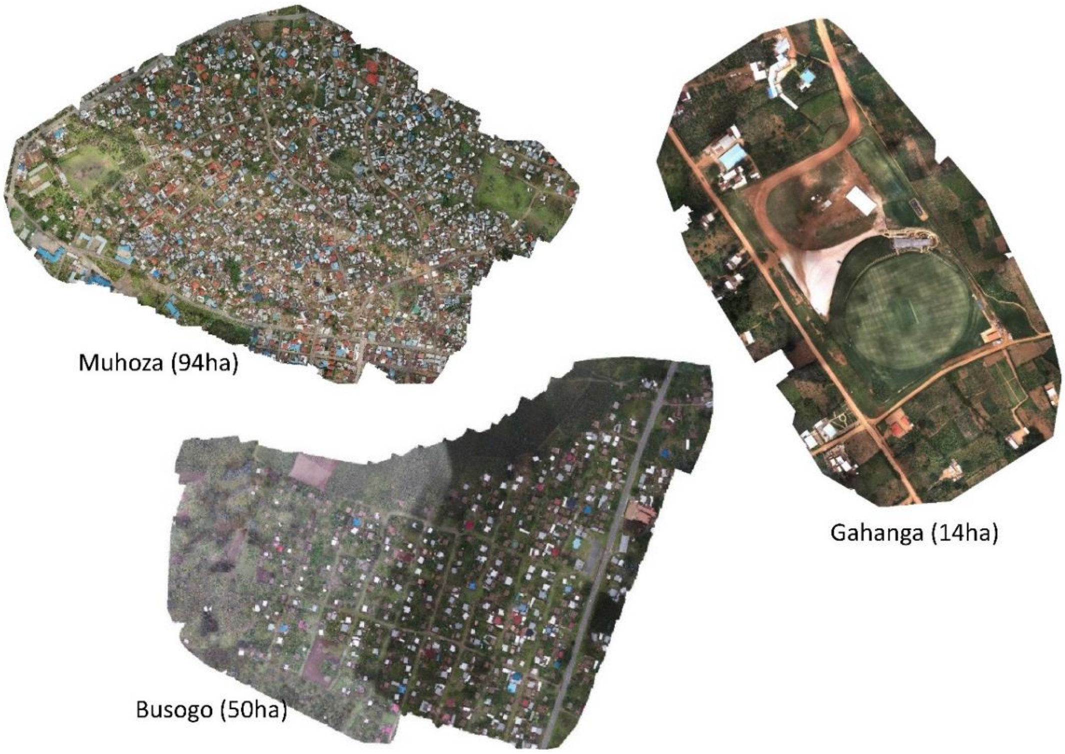

Figure 3: Overview of generated orthomosaics of areas of interest (scales vary).

The second challenge refers to the deployment and measurement of ground reference points. First of all, this task is very time-consuming and needs to be completed before the flight mission can be executed which in turn limits the number of potential flights during one day. Although less than ten ground reference points are sufficient to achieve high geometric accuracies, redundancy in deployed points has proven to be the preferable option as local people – and especially kids – show a high interest in the ground marker and the U-shaped metal pegs that were used to fix the points. Due to unforeseen administrative problems, the time between the deployment of the ground marker and the UAV flight itself was almost 5h. This can explain the fact that almost 25% of all deployed points in area of Muhoza were taken away. As summarized in Table 9, the peri-urban and rural areas Busogo and Gahanga show both: less time delay as well as less losses of ground reference points. Next to the aspect of the time delay, the involvement of more than one team for the measurement of ground reference points is also seen critically. Here, the strategy to choose a place to deploy points as well as the quality of measurements can vary substantially.

Table 9. Number of deployed ground reference points - count before and after the UAV flight

	Teams deployed	GCPs measured pre-flight	GCPs remained post-flight	Time between measurement and final collection of ground marker
Muhoza	2	39	30	5 h
Busogo	1	22	18	3 h
Gahanga	1	13	13	2 h

However, all cases showed sufficient ground reference points to be used either as Ground Control Point (GCP) or Check Point (CP). Whereas GCPs are included as weighted observation during the least-square bundle block adjustment, CPs are not taken into account during image processing and present as classical way to evaluate the geometric accuracy.

Although the DT18 PPK allows for direct georeferencing, the necessary RINEX file for post-processing could not be retrieved from the Rwanda GeoNet Service. Thus, all datasets were processed using the classical photogrammetric approach with 9 equally distributed GCPs and remaining ground reference points as CPs. Final residuals of CPs are outlined in Table 10. Almost pixel-level of geometric accuracy was achieved with the Busogo dataset. Both, Gahanga and Busogo show more than 10cm RMS error of horizontal residuals. Differences in terms of final geometric accuracy can be attributed to the UAV equipment and sensor as well as to the device and conditions for the measurements of ground reference points.

Table 10. Final residuals of CPs.

	GNSS device	Count GCPs	Count CPs	RMS error of CP residuals (X/Y/Z)
Muhoza	Leica CS10 and Trimble GeoXH	9	21	0.122m / 0.086m / 0.467m
Busogo	Leica CS10	9	9	0.033m / 0.031m / 0.349m
Gahanga	Trimble GeoXH	9	4	0.127m / 0.170m / 0.244m

5. DISCUSSION AND CONCLUSION

5.1 How can the technology of UAVs respond to the needs expressed by different stakeholders?

A comparison of the obtained UAV-based orthomosaic of Busogo and the corresponding orthomosaic which is based on classical aerial images from 2009 shows a high number of clearly visible changes (Fig.4). Knowing that the government as well as non-government entities are using the base map from 2009 the need for for an update of base data for cadastral and non-cadastral purposes becomes even more apparent. To meet this need, UAV-based data acquisition workflows allow to gradually upgrade existing base-maps whenever needed.

Figure 4: Left: Orthomosaic based on aerial images from 2009; right: Orthomosaic based on UAV images from 2018

More specifically, the expressed need by government stakeholders for higher accuracy data can be completely met by UAV imagery. Ground resolution of less than 10cm provides a high level of detail to extract actual land use information and geospatial information to directly demarcate the parcel boundary in the orthomosaic. Furthermore, the high level of absolute accuracy achieved by a UAV-based orthomosaic can support the calculation of plot sizes – a need which was prioritized by the cell-level stakeholders. Moreover, the flexibility of UAV data collection supports the collection of timely base data for on-going and current tasks such as the revision of the Master Plan in secondary cities or development plans for urban and peri-urban settlements. Frequent changes in land use can be tracked and monitored by means of repetitive UAV data collection activities. Additionally, disputes about former land ownership and land use can be solved more easily with the existence of a multi-temporal database.

5.2 Opportunities and remaining challenges for UAV data collection in Rwanda

Technically speaking, the tool of UAV-based data collection seems to offer an answer to the majority of the expressed needs which were assessed with the NGT method. Fixed wing UAVs equipped with a RTK or PPK option especially stand out for long endurance and time-effective mapping. However, from an operational point of view, three large hurdles are challenging the realization of an up-scaled implementation. Firstly, it needs to be noted that the terrain in Rwanda – the country of the thousand hills – is a very challenging testbed. Fixed wing drones have only limited climbing rates and flight planning must to be aligned with the physical environment. The availability of sufficient open space for appropriate landing strips is an essential precondition which can hardly be fulfilled. Hybrid UAVs – fixed wing UAVs that can take off vertically – can be the answer to this aspect. However, current UAV technology does not yet provide a professional hybrid UAV with PPK option.

The second hurdle refers to the UAV regulations in Rwanda. With an operational limitation to fly only in 300m visual line of sight, scaled application of UAV-mapping activities remains aspirational. Acknowledging the plans of the Government of Rwanda, legislation with a more performance based orientation may soon be redrafted. This development could pave the way for broader use of UAV-based data acquisition techniques that support land tenure recording, as well as extensive land information collection for development purposes.

The third hurdle includes the topic of ground truthing. It has been shown that especially in an urban environment, the collection and measurement of ground reference points is very challenging. PPK and RTK capable UAVs can provide an answer to this challenge as they minimize or even eliminate the need for ground control measurements tremendously. However, the availability of professional GNSS equipment or a national network of existing GNSS reference stations are essential preconditions for RTK or PPK-based workflows. This aspect entail its own challenges with respect to the provision of accurate and reliable data products.

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BIOGRAPHICAL NOTES:

Since 2012, Claudia Stöcker is working with unmanned aerial vehicles (UAVs) and UAV data. As a physical geographer by training, she first focused on high resolution surface reconstruction to study soil erosion. Fascinated by the almost unlimited capabilities of UAVs for data capture, she is pursuing a PhD which is associated with the EU H2020 project its4land (www.its4land.com) at ITC, University of Twente. Her PhD research aims to design, test and verify UAV-based data acquisition workflows as a tool for responsible land administration. For more information on her publications, see https://www.researchgate.net/profile/Claudia_Stoecker.

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