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Cost minimization of UAV-based workflows

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Abstract:

Technical report for cost minimization of UAV-based workflows for land tenure recording

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Executive Summary

Before jumping headlong into the implementation of innovative technologies, a critical evaluation of costs plays a significant role for funding agencies and stakeholders during decision-making processes. Thus, this deliverable encompasses a technical report for cost minimization of UAV-based workflows for land tenure recording. At that, costs are analyzed from different perspectives: labour costs, time, costs for software and processing but also implementation efforts and values such as reliability, openness and transparency. The focus of the report is put on three main topics: minimizing need for ground truth measurements, minimizing costs and computational capacity for image processing and lastly evaluation of strengths of UAV-based workflows compared to other established data acquisition methods.

Firstly, a comparative analysis of eight different UAV datasets captured during the its4land project provides valuable insights into the trend of the overall horizontal accuracy of the final orthomosaic in relation to a varying number of Ground Control Points (GCPs). Results of this investigation suggest that six well-distributed and well-marked GCPs are sufficient to georeference the image block regardless of the context, size of the area, or camera specifications of the UAV dataset. This is argued by the fact, that after six GCPs, the horizontal RMSE does not decrease significantly and the trendline keeps one level with a range of maximum 1.5 Ground Sampling Distance.

Secondly, this deliverable reports on the modifications of Open Drone Map (ODM) – an open-source image processing tool – to customize it for user needs and to allow the implementation on the Publish and Share platform. The use of ODM on the Publish and Share platform minimizes two costs at the same time: license costs for commercial-off-the-shelf software and purchase costs for powerful laptops that can process large sets of UAV images. Additionally, processing and storage of image datasets will be handled in the cloud environment of the Publish and Share platform. Thus, only internet access will be required to upload the UAV dataset and initialize the image processing.

Thirdly, the UAV-based data acquisition workflow was compared to established workflows, namely ground surveying, aerial images or satellite images. The qualitative and quantitative data for this comparison was captured during an interactive workshop with more than 40 participants from governmental and non-governmental organisations in Kenya. Results suggest that UAV-based workflows stand out for their independency of data collection and cost-effectiveness for small to medium-scale areas. Overall, UAV-based workflows were rated as the most promising data collection technology as they are able to produce up-to-date orthoimages with a high resolution and at moderate costs. The most considerable drawback was perceived in current legislative frameworks.

Keywords: UAV, Open Drone Map, ground-truthing, geometric accuracy, qualitative research, cost minimization

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1. Introduction

Sub-Saharan African countries have an immense challenge to map millions of unrecognized land rights in the region. Land administration systems, the technologies, and processes that maintain information about the relationship of people to land are recognized as a crucial tool to achieve sustainable economies, environments, and social cohesion: land tenure recording helps to deliver tenure security, dispute reduction, investment opportunities, and contributes to good governance. Seeking for sustainable development, the four land administration functions – namely land tenure, land value, land use and land development - are facilitated by appropriate land information infrastructures. These ideally combine cadastral and topographic datasets to link the built environment (including legal and social land rights) with the natural environment (including topographical, environmental, and natural resource information) (Enemark, 2004). Therefore, land information and geospatial data serve as reliable base data and thus are crucial to the successful implementation of land policies and strategies. Existing literature proves that spatial data collection is *the* key challenge of an effective land administration system (Zevenbergen *et al.*, 2013; Bennett and Alemie, 2016). Establishing and maintaining the spatial database is the most expensive and time-consuming but also the most essential task in land administration.

its4land aims to deliver an innovative suite of land tenure recording tools that respond to Sub-Saharan Africa’s immense challenge to rapidly and cheaply map millions of unrecognized land rights in the region. its4land is a European Commission Horizon 2020 project funded under its Industrial Leadership program, specifically the ‘Leadership in enabling and industrial technologies – Information and Communication Technologies ICT (H2020-EU.2.1.1.)’, under the call H2020-ICT-2015. ICT innovation is intended to play a crucial role. Many existing ICT-based approaches to land tenure recording in the region have not been highly successful: disputes abound, investment is impeded, and the communities poorest lose out. its4land seeks to reinforce strategic collaboration between the EU and East Africa via a scalable and transferable ICT solution. Established local, national, and international partnerships seek to drive the project results beyond research and design (R&D) into the commercial realm. its4land combines an innovation process with emerging geospatial technologies, including smart sketchmaps, UAVs, automated feature extraction, and geocloud services, to deliver land recording services that are end-user responsive, market-driven, and fit-for-purpose. The transdisciplinary work also develops supportive models for governance, capacity development, and business capitalization.

A UAV-based mapping mission in the context of land tenure data acquisition ultimately aims to truly reflect the real situation of the area that was captured with UAV images. Additionally, data collection should be efficient and cost-effective. Whilst main issues with radiometry and the quality of images were already discussed in deliverable 4.2, this report builds upon those results and focusses on different means to minimize the overall costs of a UAV-based workflow. There is a general consensus that the spatial distribution of GCPs actively controls the final geometric accuracy and literature provides insightful information on GCP settings, number, distribution and size. However, the synergy between GCP settings, flight planning is not fully understood as most study setups are limited to one ideal study area that covers a small area. To expand the existing knowledge base to small to medium scale mapping applications, section 2 of this report investigates the relationship between the horizontal geometric accuracy and a varying number of GCPs.

Next to the costs during the data collection, costs also incur during the data processing, namely license costs of commercial-off-the-shelf software and purchase costs for hardware with large computational capacities. This topic is addressed in section 3, which elaborates on different software for image processing as well as the modification of an open-source tool called Open Drone Map (ODM), which is modified and customized for the integration on the its4land Publish and Share platform. This will allow low-cost and user-friendly image processing in the cloud.

Section 4 of this report focuses on the overall evaluation of UAV-based workflows in comparison to established data collection methods, namely ground surveying, aerial images or satellite images. The qualitative and quantitative data for this comparison was captured during an interactive workshop with more than 40 participants from governmental and non-governmental organisations in Kenya. The analysis of the qualitative and quantitative data provides deep insights into the perception of stakeholders, as well as realistic perspectives on the strengths and weaknesses of UAV-based workflows.

The content of this deliverable is based on the following (planned) publications:

[2019] Stöcker, C., Ho, S., Nkerabigwi, P., Schmidt, C., Koeva, M., Bennett, R., Zevenbergen, J.: Unmanned Aerial System Imagery, Land Data and User Needs: A Socio-Technical Assessment in Rwanda. Remote Sensing, 11, 9, 1035.

[2019] Stöcker, C., Nex, F., Koeva, M., Gerke, M.: UAV-based cadastral mapping: an assessment of the impact of flight parameters and ground truth measurements on the absolute accuracy of derived orthoimages. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 2/W13

[2019] Stöcker, C., Koeva, M., Bennett, R., Zevenbergen, J.: Evaluation of UAV-based technology to capture land rights in Kenya: Displaying stakeholder perspectives through interactive gaming. *Proceedings of the 20th Annual World Bank Conference on Land and Poverty 2019.*

[under preparation] Stöcker, C., Nex, F., Koeva, M., Gerke, M.: High-quality UAS-based orthophotos for land administration: guidelines for optimal data collection workflows. International Journal of Geo-Information.

The data of the presented results is archived on the its4land server (restricted access): https://share4land.itc.utwente.nl:5566 in /data/WP4/UAV_data/7_Deliverable/DATA

2. Cost minimization of Ground Measurements

Geometric accuracy describes the gap between the actual location of a point of interest and the location derived from the dataset. Particularly in the domain of land tenure data acquisition, geometric accuracy refers to a crucial characteristic as the location of a spatial object shall unequivocally be recorded in the cadastral database. However, most UAVs are not able to provide accurate angular and positional measurements which are sufficient for direct georeferencing. Thus, the images need to be georeferenced by means of integrated sensor orientation or indirect georeferencing (Benassi *et al.*, 2017), which involves the manual collection of Ground Control Points. At the same time, the measurement of GCPs is a costly and time-consuming procedure. Some areas might not even allow the deployment of GCPs as they are inaccessible or covered by trees and dense vegetation. Our experiences also showed that it can be tricky to place reliable GCPs in densely populated urban areas as local people might remove or cover the placed marker (Stöcker *et al.*, 2019).

RTK and PPK systems and their potential for Africa

Currently, many UAV companies offer real-time kinematic (RTK) or post-processing kinematic (PPK) solutions to obtain high geometric accuracy. Here, the GNSS observations of the UAV and geotag information of the images are corrected for range errors with a static measurement on the ground or data from a continuously operating reference station (CORS). As shown in Figure 1, the RTK system continuously corrects GNSS observations for any anomalies of the actual location during the flight, the PPK system does not require a real-time connection as the log-files are stored and post-processed after the flight mission. Both options sound promising but come with their own disadvantages.

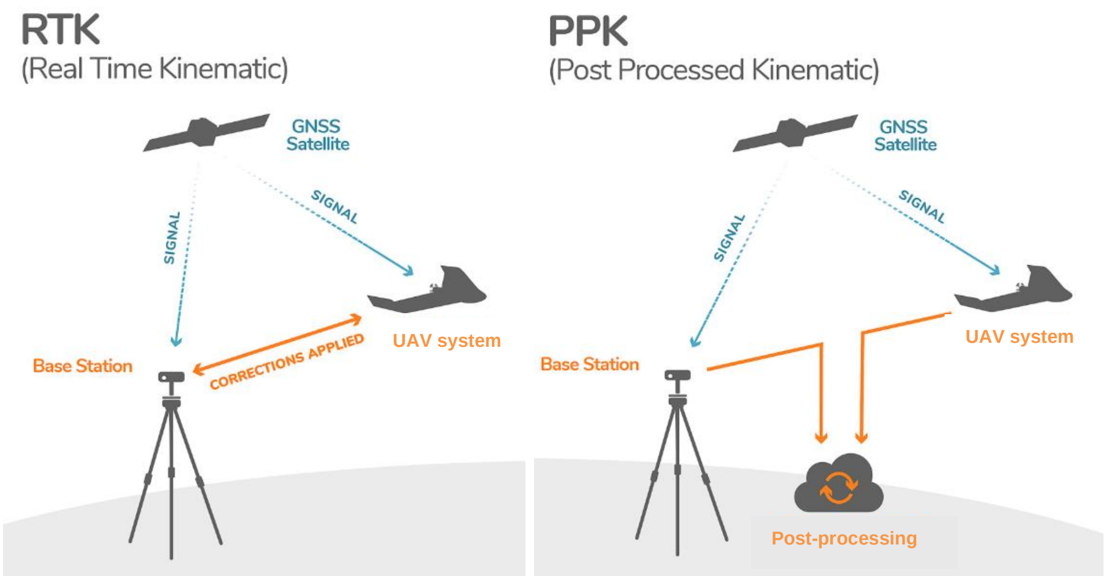


Figure 1: RTK and PPK systems, adapted from Delair Aerial Intelligence (2019)

Table 1: Overview of the advantages and disadvantages of RTK and PPK systems

RTK	PPK
Advantages: • Real-time geotags with an error range of a few pixels • No post-processing of images required	Advantages: • Independent of range of the UAV flight mission • Consistent results • Forward and backward processing
Disadvantages: • Constant radio connectivity required • Additional hardware on the UAV required • Reliable GNSS observations that are compatible with real-time	Disadvantages: • Special hardware required for post-processing • Reliable GNSS observations that are compatible with post-processing software

Looking at advantages and disadvantages (Table 1), both approaches seem to be very interesting and highly applicable to the its4land target countries. However, during WP4 field missions in the past three years, many obstacles were encountered which led to the decision that, for the time being, a classical approach with GCP observations is the most reliable mapping approach. Problems included missing transformation parameters from Arc1960 to WGS84 in Zanzibar, unreliable CORS observations in Rwanda, and incompatible observation formats for a PPK workflow in Kenya. Table 2 summarizes the specifications of available GNSS equipment and CORS networks.

Table 2: Specifications of available GNSS equipment and CORS networks in its4land target countries (WP4)

Country	GNSS survey providers	Condition of the equipment	Datum of reference points	CORS available
Tanzania - Zanzibar	Commission of Lands Zanzibar has two GNSS receiver Sokkia STRATUS (L1)	Poor	Local Arc1960 without transformation parameters to WGS84	no
Kenya	Several private and governmental institutions, University of Nairobi	Good	Arc 1960	Yes, but only a few stations that large cities, countrywide CORS planned for the future
Rwanda	INES Ruhengeri has several survey-grade GNSS devices, private surveyors, Land offices	Good	ITRF 2005	Countrywide, but not reliable (very often under maintenance)

Other limiting factors for ground measurements are the availability and the costs of survey-grade GNSS equipment in the its4land target countries. The costs to hire a professional surveyor and survey-grade equipment amount to approximately 100 $, which is the same rate as you can hire a semi-professional UAV. Given a small scale mapping project of one day, the costs for ground measurements can have a 50% share of the total UAV mapping costs.

The following subsections will provide guidelines on how to minimize the need for ground measurements whilst maintaining an absolute geometric accuracy. The focus is put on in impact of a varying number of GCPs as well as the effects of the survey area on the geometric accuracy. The outcomes will help to plan and implement an efficient mapping project with minimal surveying costs.

Study setup and data collection specifications

A vast number of scholars already investigated the topic of geometric accuracy and different types of georeferencing (James *et al.*, 2016; Agüera-Vega, Carvajal-Ramírez and Martínez-Carricondo, 2017; Benassi *et al.*, 2017; Manfreda *et al.*, 2019). However, test datasets of those studies are limited to one or two, which makes it difficult to generalise the results to provide transferable guidelines and recommendations. The its4land project offered the opportunity to collect data in different contexts, with various equipment and with different areal coverages (Amtsvenn, Bentelo, Ruhengeri, Mukingo, Kibonde, Muhoza, Gerleve, Kajiado). As shown in Figure 2, this includes various sizes and shapes of the study areas, as well as diverse landuses representing rural, peri-urban, and urban contexts. In total, more than 100 separate flight missions were needed to collect the images for the eight study areas with areal coverages ranging from 0.14 km² to maximum 8.70 km² (see Figure 2 and Table 3).

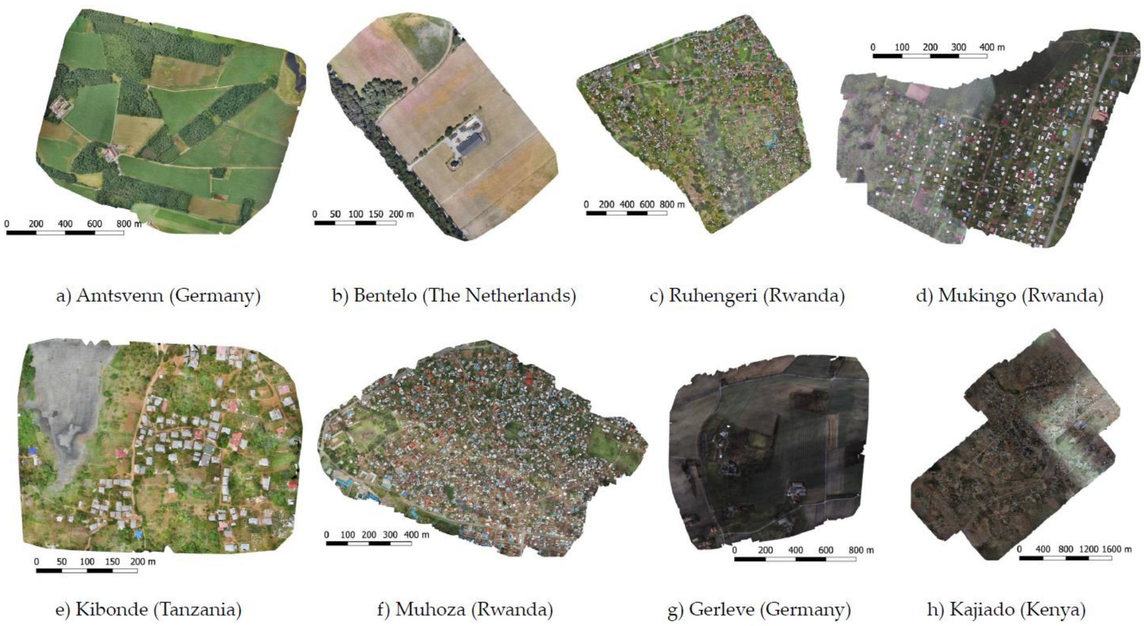


Figure 2: Overview of all datasets

According to the environmental context, national policies, regulations, and flight conditions, various UAV equipment have been applied including rotary-wing UAVs, fixed-wing UAVs and hybrid UAVs. Except for the FireFLY6 and the Germap G180, in-build camera systems were used. The UAV used in Gerleve and Bentelo were equipped with a PPK system. The Ground Sampling Distance (GSD) was chosen according to regulations (maximum flight height) and the overall objective of the flight mission. For that reason, we decided to fly Kajiado with 5.8 cm GSD as the flight mission had the aim to capture the entire city.

Table 3: Technical specifications of UAV systems and flight mission

Dataset	**Area [km²]**	**GSD [cm]**	**UAV**	**Camera**	**Sensor size [mm]**
Muhoza	0.98	2.1	BirdEyeView FireFLY6	SONY ILCE-6000	13.50 x 15.60
Mukingo	0.50	2.2	DJI Inspire 2	DJI FC652	13.00 x 17.30
Ruhengeri	3.12	2.3	DJI Inspire 2	DJI FC652	13.00 x 17.30
Kajiado	8.70	5.8	DJI Phantom 4	DJI FC330	06.20 x 04.65
Kibonde	0.30	3.0	SenseFly Ebee Plus	SenseFly S.O.D.A.	12.70 x 08.50
Amtsvenn	0.98	4.8	Germap G180	RicohGR	23.50 x 15.70
Gerleve	1.10	2.8	DelairTech DT18	DT 3Bands	08.45 x 07.07
Bentelo	0.14	2.7	DJI Phantom 4	DJI FC330	06.20 x 04.65

To allow the comparability of the datasets, GCPs were placed according to a specific pattern (see Figure 3). The pattern was designed based on standards for traditional aerial surveys which ensures that the GCPs are equally distributed and if possible, all corners of the image block are captured.

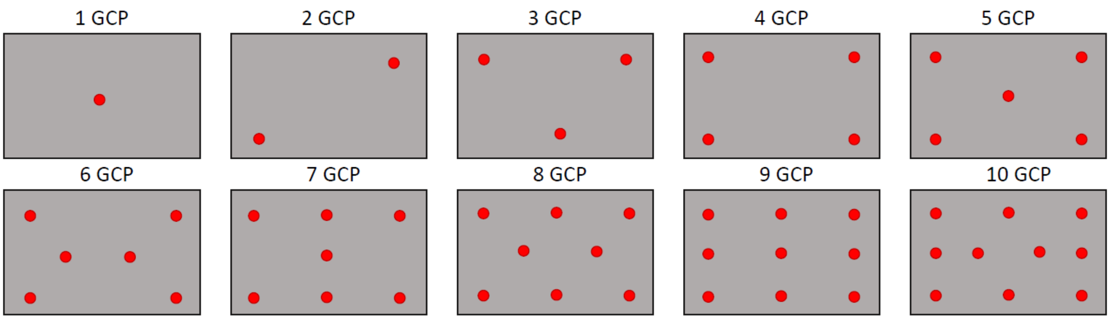


Figure 3: Distribution of GCPs for the experimental setup

For all study sites, GCPs were measured with survey-grade GNSS-receivers with a base-rover setting to guarantee a 2cm measurement accuracy. Here, the Kibonde dataset is slightly exceptional as the GCPs were measured in the local datum (Arc1960) which did not allow a proper transformation to WGS84. As the UAV mission was flown with high-quality PPK setup, we could obtain ground coordinates of the marked GCPs from an independent low altitude flight with a high overlap and cross-flight pattern. Afterwards, the point pairs of the Arc1960 observations and the derived GCP coordinates from the UAV flight were used to apply a 6 parameter Helmert Transformation. With applying the transformation parameters, we could eliminate the systematic shift between the Arc1960 and WGS84 observations.

Results of analytical tests

All datasets were processed with the same parameter settings in Pix4D. To compare the final geometric accuracies, all datasets were normalized according to the ground sampling distance. The overall horizontal error was calculated using the Euclidian distance between the Root Mean Square Error of the X and Y residuals of all independent checkpoint observations.

Impact of different sources to derive GCP coordinates

As a first analysis, we investigated the effect of various sources to acquire GCP coordinates. The Muhoza dataset was chosen for this comparison, as Rwanda was the only its4land target country with a reliable high-resolution base data with a ground sampling distance of 25cm. Even though the aerial images in Rwanda were captured in 2009, sufficient places with no changes were discovered to extract clearly distinguishable GCPs. Suitable locations were found on roof ridges, courtyards, corner of houses or rooftops (examples are displayed in Figure 4).

Figure 4: Examples of extracted clearly visible points (green dot) from Rwandan aerial image 2009

The chart of the horizontal RMSE shows a similar trend for both datasets – a steep decline until two to three GCPs and relatively constant values after five to seven GCPs (Figure 5). The dataset in which GCP observations are based on aerial images does not reach a better horizontal accuracy than 45 cm. The dataset in which GCP observations are based on GNSS measurements level at a horizontal accuracy below 10 cm.

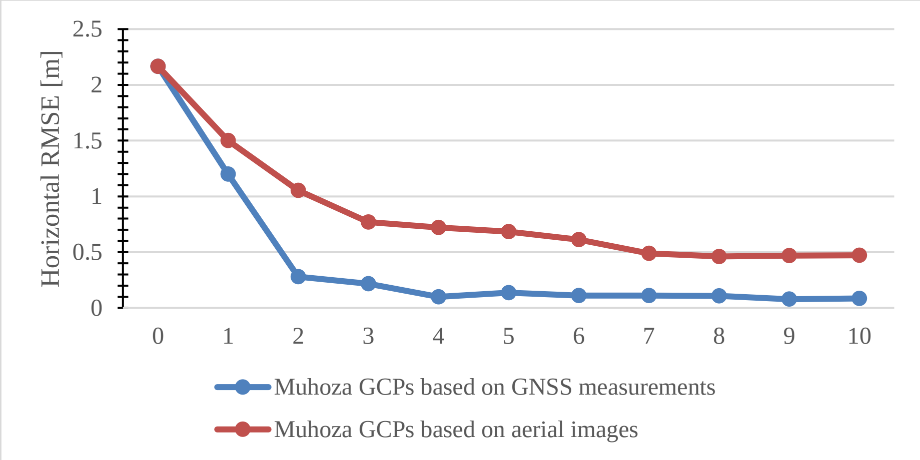


Figure 5: Horizontal RMSE of Muhoza dataset using different sources for GCP coordinates

Impact of the number of GCPs

Being one of the most time-consuming activities during a UAV flight mission, the amount of GCPs that need to be placed and measured has a significant impact on the overall economic efficiency of a flight mission. Thus, a clear guideline on the crucial question about how many GCPs need to be placed facilitates the design of effective UAV-based workflows. The comparative analysis of seven datasets shows clear commonalities but also some differences.

The horizontal RMSE with 0 GCPs demonstrates significant discrepancies. Here, the two datasets with PPK already obtain very low residuals. The high residuals of Kajiado are likely to be explained by the size of the image block. Due to the large area, flight missions were carried out during three consecutive days. This condition in combination with a low-grade GNSS unit on-board the Phantom 4 leads to a large horizontal RMSE. Amtsvenn could not be processed with less than three GCPs as the images were not geotagged. If this is the case, it requires at least three GCPs to transform the photogrammetric model to real object space, where positions and measurements can be reconstructed. This mathematical condition explains the congruence of the horizontal RMSE with three GCPs, where all horizontal RMSE reach a value below 10 GSD. The results suggest that fixing the image block with four GCPs in four corners minimizes the horizontal RMSE of all almost all datasets. This trend does not continue at five GCPs as Bentelo and Muhoza record an increase of the final residuals. However, after six GCPs the trendline of the horizontal RMSE of all datasets stays constant within a maximum change of 1.5 GSD (Muhoza).

The results of our tests suggest that a number of six well-distributed GCPs are sufficient for a UAV mapping mission. Adding more GCPs does not significantly increase the final horizontal geometric accuracy of a dataset. Even though the conclusion can be drawn independent from land use and areal coverage, it should be noted that this result can only be transferred to datasets with:

1) At least 70% forward overlap and 70% side lap
2) Professionally surveyed and well-marked GCPs.

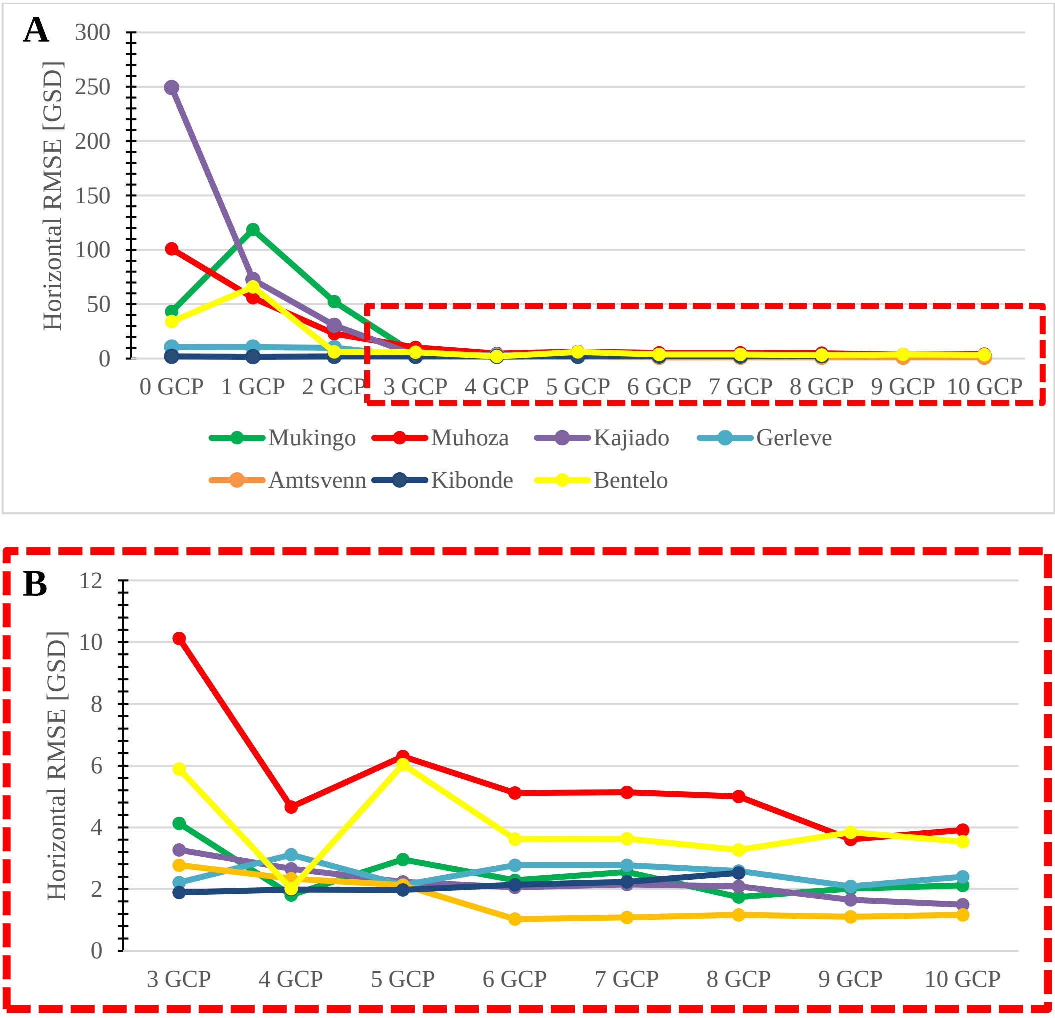


Figure 6a and b: Comparson of horizontal RMSE of various datasets. A: 0-10 GCPs; B: 3-10 GCPs

Given the ideal number of 6 GCPs, all datasets show a different range of horizontal RMSE. Looking at the results, it seems that land use plays a minor role than image quality as Amtsvenn (rural) and Kibonde (per-urban) present high horizontal accuracies whilst Muhoza (urban) and Bentelo (rural) show lower horizontal accuracies. However, the sample size of the available datasets is too small to draw meaningful conclusions about the impact of land use and sensor specifications.

Alternative approaches

Another rather new approach is the co-registration of UAV images with already existing datasets (Aicardi *et al.*, 2016). In this method, anchor images that show no changes are automatically selected from a reference dataset and are included in the photogrammetric processing to constrain the orientation of the other datasets. However, this approach is only of limited applicability for the its4land use cases as only very few datasets are already existing for the study areas in Kenya, Rwanda or Zanzibar.

The most promising dataset is the aerial images from 2009 in Rwanda. However, differences in geometric accuracy (1m of the aerial image vs requirement of 10 cm for UAV orthomosaic) and differences in resolution/radiometry (25cm of aerial images vs 3cm of UAV orthomosaic) are too large to be beneficial for the co-registration of UAV images based on aerial images. Additionally, numerous changes in the image scenes as shown in Figure 7 would prevent the successful implementation of such a workflow.

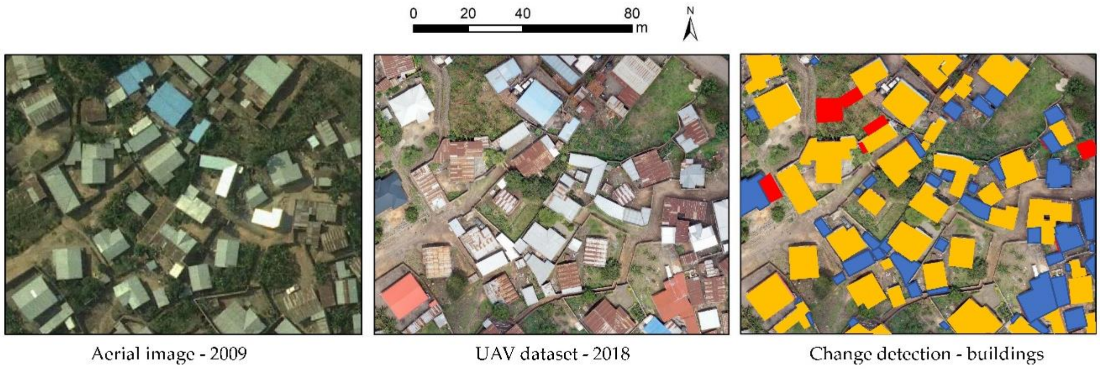


Figure 7: Categorization of land-use changes (2009-2018). Left: Orthomosaic based on aerial images from 2009; centre: Orthomosaic based on UAV images from 2018; right: Change detection of buildings (orange: buildings remained the same, red: buildings got demolished, blue: new building constructions).

3. Cost minimization of image processing

Input datasets for image processing

Even though the image overlap was kept similar for all datasets, one of the first investigations is the difference in the ratio of the number of images and the total size of the reconstructed scene. The comparison excludes Kajiado and Amtsvenn as these datasets were captured with a considerably lower resolution as the other datasets.

Especially cameras with a large sensor and a lens with a wide field of view (e.g. S.O.D.A. camera) allow very efficient mapping and image processing. As an example, the Bentelo dataset includes 299 UAV images to reconstruct a scene of 0,14 km². In contrast, the Kibonde dataset includes approximately one-half of the number of images of the Bentelo dataset whereas the reconstructed area of Kibonde is twice the size of Bentelo (see Figure 8). Advantageous camera specifications not only increase the efficiency of the flight execution (i.e. less flight time) but also the efficiency of image processing.

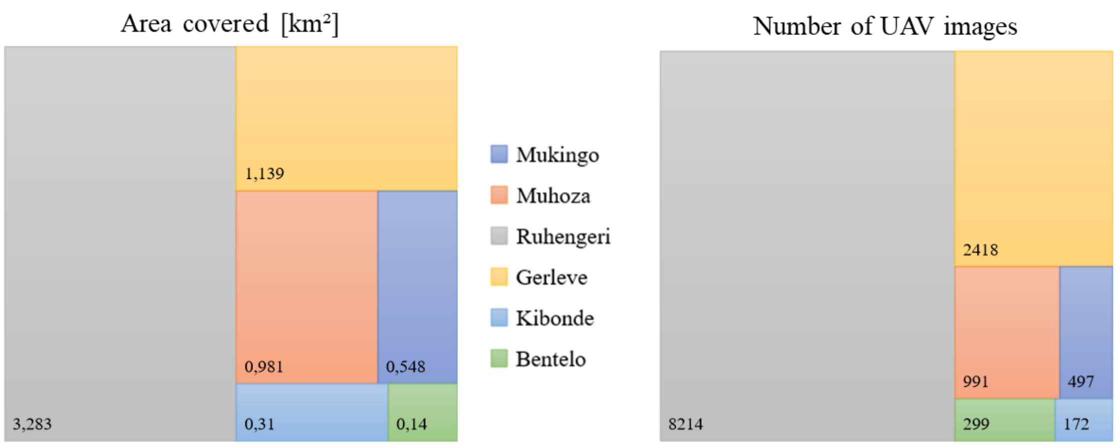


Figure 8: Comparison of areal coverage and number of UAV images of the datasets

Software for image processing

The incredible diffusion of UAVs has pushed many companies and research groups to implement dedicated software for the processing of data. The number and the completeness of these software solutions have increased continuously with the aim to satisfy a growing and heterogonous market. Depending on the scope of the UAV acquisitions, the experience and technical skills of the operator as well as the available budget, there are several affordable solutions already available on the market. The holistic software probably does not exist, but some features and options should be, however, considered when we approach these instruments in order to find the optimal solution for our needs.

The software should be able to upload and process images and videos acquired with different sensors. The image processing is usually performed according to "modern" and automated photogrammetry and computer vision algorithms that accomplish highly automated efficient feature extraction, detection and matching procedures. Depending on the user expertise, turn-key solutions (with reduced options) can be preferred to more technical and rigorous approaches. Default parameters can give quite good solutions in most of the practical cases. However, the possibility to modify the parameters and their weights can be preferable to improve the results, especially in the most challenging situations. Tunable parameters can be beneficial both in the image orientation and dense point cloud generation phases. Even if the automation is a priority, small tools for adding tie-points in critical image orientations or removing mismatches in the generated dense point clouds can also be crucial for effective processing. The same is valid for true-orthoimages and meshes generated from these datasets: simple manual or semi-automated editing tools to "polish" the results allow the faster delivery of these products without the need for external software like image and 3D models editors.

UAV applications are increasing in complexity, and the delivery of products beyond the classical photogrammetric workflow is becoming more common. Automated DTM extraction, scene classification exploiting both images and point clouds as well as detection and tracking of features of interest are necessary for many applications. In this regard, software capable to automatically or semi-automatically generate such kind of information can be beneficial in terms of productivity.

The battery endurance and the productivity of UAVs have increased, with the consequence that more significant amounts of data are collected and more substantial computations are needed to process these images. Luckily, most of the photogrammetric algorithms can be parallelized and software exploiting multi-core and graphical computing can, therefore, mitigate this problem. Recent software able to support the processing on clusters or on the cloud can represent another efficient solution to reduce the computational time and increase productivity.

When it comes to costs, we observe a large diversity on the market. During the past years, the growing demand for image processing software also stipulated the open-source community to develop user-friendly processing tools that offer ready-to-use applications but also large ranges of customizable solutions.

Open Drone Map

Open Drone Map (ODM) refers to an open-source toolkit that allows processing aerial drone imagery. In 2014, the development of ODM was initiated by the Open Source Geospatial Foundation. The software follows modern photogrammetry approaches and includes fully automated matching, generation of dense 3D point clouds, the extraction of digital elevation models, as well as the generation of orthomosaics. The developer-community strives for an open ecosystem:

> *"Our goals are to support the development of an open ecosystem of solutions for collecting, processing, analyzing and displaying aerial data and to build strong, self-sustaining communities around them."*
> (https://www.opendronemap.org)

At this time, ODM has seven applications to accommodate various levels of software integration and user cases:

1) Native ODM: A command-line toolkit to process aerial images. Since its creation in 2014, it has become the de-facto standard of open-source drone image processing
2) WebODM: A user-friendly, extendable application and API for drone image processing. It provides a web interface to ODM with visualization, storage and data analysis functionality
3) NodeODM: A lightweight REST API to access ODM. It also provides a minimal web interface to access its functions
4) LiveODM: A bootable DVD/USB ISO with ODM, node-ODM and WebODM pre-installed
5) CloudODM: A command-line tool to process aerial imagery in the cloud
6) PyODM: A Python SDK for adding aerial image processing capabilities to applications
7) ClusterODM: A NodeODM API compatible reverse proxy, load balancer and task tracker for easy horizontal scaling

In general, the image processing pipeline of ODM follows the principle of modern photogrammetry. In the first step, ODM initializes and executes a structure from motion tool that is based on OpenSFM, an algorithm developed and utilized by Mapillary. During this process, OpenSFM reconstructs a sparse 3D point cloud of a set of images with 2D point correspondences. Here, the first set of images and respective calculated 3D points and cameras serve as baseline 3D reconstruction. Subsequently, all images are added one-by-one to the existing reconstruction. Finally, rotation and positional parameters of the images are optimized. Compared to traditional photogrammetric approaches, structure-from-motion allows reconstructing a 3D scene even if neither intrinsic nor extrinsic parameter of the images are known.

The information of camera positions is used in the next step which densifies the existing sparse 3D point cloud according to the image scale which is set as a processing parameter. The dense 3D point cloud is the basis for the generation of the digital surface model (raster dataset in the desired resolution that represents the height of all surface points including vegetation and structures) and the digital terrain model (raster dataset in the desired resolution that represents all ground-points). In the next step, the digital surface model is used for the orthorectification process. Here, For each pixel of the orthophoto the corresponding height in the digital surface model is considered. The point in the digital surface model is back-projected to the image, using the photogrammetric equations (collinearity equations). Finally, the corresponding value of the image is used to colour the pixel of the orthophoto. The Graphical User Interface of WebODM with dense 3D point cloud of sample dataset from Muhoza is presented in Figure 9.

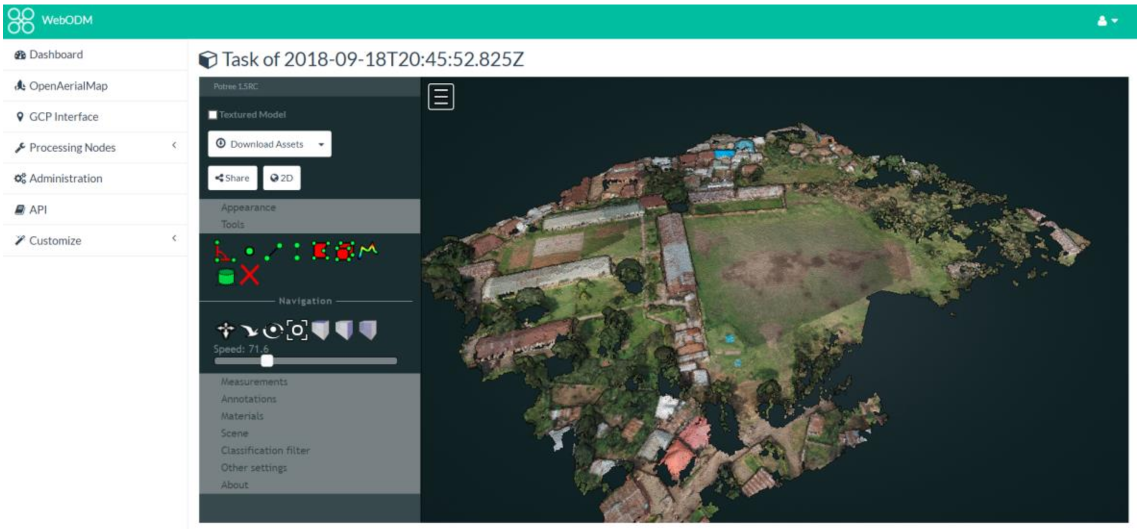


Figure 9: Graphical User Interface of WebODM with dense 3D point cloud of sample dataset from Muhoza

Integration of Open Drone Map on Publish and Share platform

As ODM provides a state-of-the-art open-source image processing supplication with various opportunities of implementation, it was selected as an image processing tool for the its4land Publish and Share Platform. During fieldwork activities in Kenya and Rwanda, we investigated that limited processing capacities (i.e. software availability, processing power (RAM), storage capacity) are one of the significant challenges implementing UAV-based workflows. Thus, we were searching for a solution that combines an easy to use, open-source software embedded in a cloud-processing environment. With this, we can reduce costs to purchase image processing software as well as costs to buy hardware with sufficient RAM and storage capacity. Additionally, cloud computing allows to speed-up the image processing if needed. Those requirements can be met by integrating the ODM image processing tool in the Publish and Share platform by following the tool-integration-usage model (cf. Deliverable 6.1 and Deliverable 6.4).

WP4 Image

To successfully integrate ODM processing capabilities on the its4land Publish and Share platform and to utilize the Publish and Share runtime environment, several adjustments and additions to the native ODM Docker image were needed (cf. Figure 10). First of all, a custom entry script for WP4 docker image was developed which is integrated with the Publish and Share Wrapper (provided by WP6). This allows for communication between the Publish and Share API and the Wrapper. Furthermore, a specific command line script ODM_WP4 had to be coded to make the tool compatible with the environment of Publish and Share and to convert optional custom arguments from the user into standard ODM arguments. ODM, ODM_WP4 and the Wrapper are combined in a docker image and executed as a container in the PaS runtime environment as documented in Deliverable 6.1.

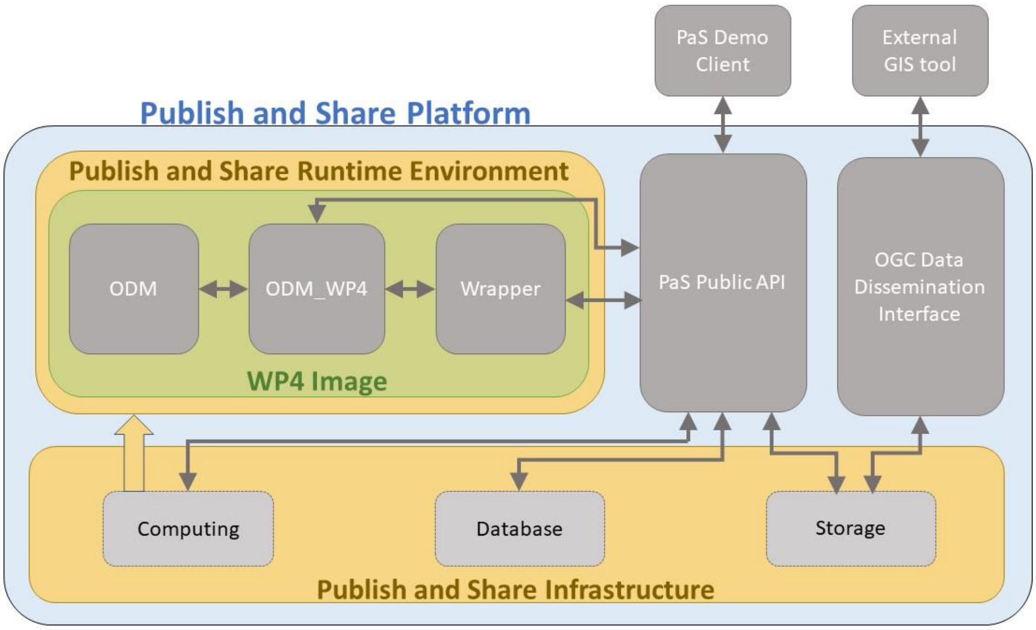


Figure 10: Schematic structure of ODM_WP4 tool integration on its4land Publish and Share Platform

Looking at ODM_WP4 more closely, a logical approach is followed, as shown by the extract of the source code in Figure 11. The raw images of a UAV mission are stored as Spatial Source in a Project on the Publish and Share platform. Firstly, the desired dataset stored as .zip-file is being downloaded and unzipped by ODM_WP4. Subsequently, image properties are derived (width and height) and stored as variables. During the next steps, the custom arguments are converted to standard ODM arguments. Afterwards, the ODM application is initialized and executed. Once the processing is done, the results such as the orthomosaic, the digital surface model or the 3D point cloud are uploaded and registered on the Publish and Share platform. Results can be retrieved via WMS services and a be visualized in standard GIS software.

```
def start(args: Dict) -> None:
    """Run orthophoto creation."""
    try:
        download_file = os.path.join(WORK_VOLUME, 'download', 'files.zip')
        extracted_dir = os.path.join(WORK_VOLUME, 'extracted')

        download(DOWNLOAD_URL, download_file)
        unzip(download_file, extracted_dir)

        image_props = get_image_properties(download_file)
        image_max_side_size = max(image_props['width'], image_props['height'])

        odm_args = to_odm_args(args, image_max_side_size=image_max_side_size)

        app = ODMApp(odm_args)
        app.execute()

        upload_results(RESULT_DIR)

    except Exception as err:
        handle_error(err)
```

Figure 11: Extract from ODM_WP4 source code representing the main steps of ODM_WP4 docker image

Custom arguments for ODM_WP4

Table 4 outlines all custom arguments which were selected for a user-specific and reliable image processing. Most of the arguments are public and need to be defined by the user on the frontend of the Publish and Share platform.

Table 4: Custom arguments for ODM_WP4 image processing

GUI prompt	Parameter	Type	Public/non-public	Selection criteria GUI	Associated arguments input ODM
Image scale for reconstruction	`--resize-to`	Integer	Public	Full image resolution	-1
				1/2 image resolution	$\frac{largest\ side\ of\ the\ image\ [pixel]}{2}$
				1/4 image resolution	$\frac{largest\ side\ of\ the\ image\ [pixel]}{4}$
				1/8 image resolution	$\frac{largest\ side\ of\ the\ image\ [pixel]}{8}$
Image overlap	`--opensfm-depthmap-min-consistent-views`	Integer	Public	Forward overlap and sidelap ≥ 70%	6
				Forward overlap and sidelap < 70%	3
Context of the scene	`--texturing-nadir-weight`	Integer	Public	Urban context	24
	`--texturing-nadir-weight`	Integer	Public	Rural context	16
Mode of Georeferencing	`--gcp`	Path string	Public	Ground Control Points	
	`--use-exif`		Public	Exif-data	
Optional outputs and specifications	`--pc-las`		Public	Check if you want to export a point cloud	True/False
	`--dsm`			Check if you want to export a Digital Surface Model	True/False
	`--dem-resolution`	Float	Public	Specifies the resolution of the DSM [cm]	<Any float number>
	`--orthophoto-resolution`	Float	Public	Specifies the resolution of the orthophoto [cm]	<Any float number>

NO PROMPT	`--opensfm-depthmap-method`	String	Non-public	BRUTE_FORCE
NO PROMPT	`--min-num-features`	Integer	Non-public	10000

Image scale refers to a crucial parameter when it comes to processing time and processing capacities. At full image resolution, the dense matching process will try to use every pixel for the 3D reconstruction. The better the image resolution, the better and more detailed the 3D reconstruction but also the more time is needed to finish the processing. For scenes in an urban environment with many small-scale features, a full resolution reconstruction is recommended to preserve those small features and structures. To processing scenes with rather normal structures or with images of very high resolution, an image scale of ½ or ¼ image resolution is recommended. If one only wants to see a first rough result to check for consistency and completeness, the option of 1/8 image resolution should be used as it provides fast results with less computational effort.

Image overlap refers to an argument which is related to different perspectives of the raw images. The smaller the image overlap, the less perspective consistency is observed in the image dataset. Thus a number of at least three consistent views should be acknowledged during the structure from motion process. However, with a higher overlap, this number can be increased to six. As a result, the 3D reconstruction entails less noise and can be considered as more reliable.

Context of the scene plays an important role in the generation of the orthomosaic. A high weight on nadir images for the texturing process results in sharper corners of structures. An image dataset representing urban contexts should be processed with a higher weight on nadir images (i.e. 32) whereas rural and peri-urban contexts should be treated with a lower weight on nadir images (i.e. 16).

The mode of georeferencing refers to another vital parameter during image processing. This argument tells ODM tool whether the geolocation should be taken from the EXIF-file of each image, or if GCPs are included in the image processing. In the latter case, a textfile that related image coordinates with ground coordinates should be included in the compressed .zip folder of all raw images. The textfile should be generated using the interactive Ground Control Point tool for ODM which can be derived from GitHub: https://github.com/posm/posm-gcpi.

Finally, the user can make a decision on the additional output files, which include a 3D point cloud in .las format or digital surface model in .tif format. An orthomosaic will be generated by default. However, the user can determine a final resolution of all output raster datasets.

The last two arguments in Table 4 refer to non-public arguments and cannot be changed by the user. The first one sets the brute-force method as default for the reconstruction of the depth map, with the reason that it produces denser reconstructions than the patch-based method, which refers to the default by ODM. The other custom argument increases the minimum number of required features per image. Similarly to the brute-force method, this change increases the reliability of the reconstructions as more features are extracted ultimately used to determine the interior and exterior orientation parameters.

Download the Dockerfile ODM_WP4

The docker image ODM_WP4 has been uploaded to the its4land GitHub repository and can be accessed via the following link:

https://github.com/its4land/wp4_odm.git

The full integration of the image processing tool ODM_WP4 in the its4land Publish and Share platform is planned for October/November 2019.

4. Overall evaluation of UAV-based workflows

Besides the cost minimization of specific UAV-data collection missions, an assessment of the overall strengths and advantages of UAV-based workflows compared to other data acquisition techniques is a crucial factor for the sustainable implementation of UAV technology. In this regard, UAV-based data acquisition was compared with field surveying, aerial images and satellite images. Whereas field surveying is a direct data collection technique, aerial images and satellite images are categorized as indirect data collection techniques (Fig.12).

Figure 12: Examples of data derived from different data acquisition techniques. These examples were printed on A3 paper and used during the workshop

Study setup and data collection specifications

To obtain quantifiable insights about the perception of UAV-bassed workflows compared to other data collection methods, various Kenyan stakeholders from the national government, local government from Kajiado County, the private sector, academia, and NGOs were invited to attend an interactive boardgame dealing with different data acquisition techniques for cadastral surveying. In total eight groups were formed acknowledging a similar background and affiliation to ensure that people can speak openly. The groups were represented by participants from the national government, local government, private sector, surveyors, NGOs, and academia.

The set-up of this workshop was intuitive and easy. A blanc radar chart with six axes served as a board game and is presented at the centre of the table (see Figure 12). During the workshop, stakeholders were asked to rank four different methods of data acquisition, namely satellite images, aerial images, UAV images and ground surveying according to six parameters derived from state-of-the-art frameworks for selecting fit-for-purpose data collection methods in land administration (Rahmazitadeh 2018). Both, the different data acquisition technologies as well as the chosen parameters, are sufficiently explained to the participants before the group discussion started. Once a consensus was found, the group placed the chip on the board game with each data collection technology being represented with one colour — the closer the chip was positioned towards the centre, the better the ranking. The conversational process to reach consensus facilitated the group members to engage in a constructive dialogue and share experiences with other practitioners. Hence, the workshop served not only as a means for the collection of qualitative and quantitative data but also to exchange information and generate knowledge among the group members. Results of this paper were obtained from a survey about the familiarity of the workshop participants with the data collection methods, the outcomes of the board game (i.e. placement of the chips), as well as voice recordings during the group conversation. The workshop was completed under ethically sound conditions, and informed consent was obtained beforehand.

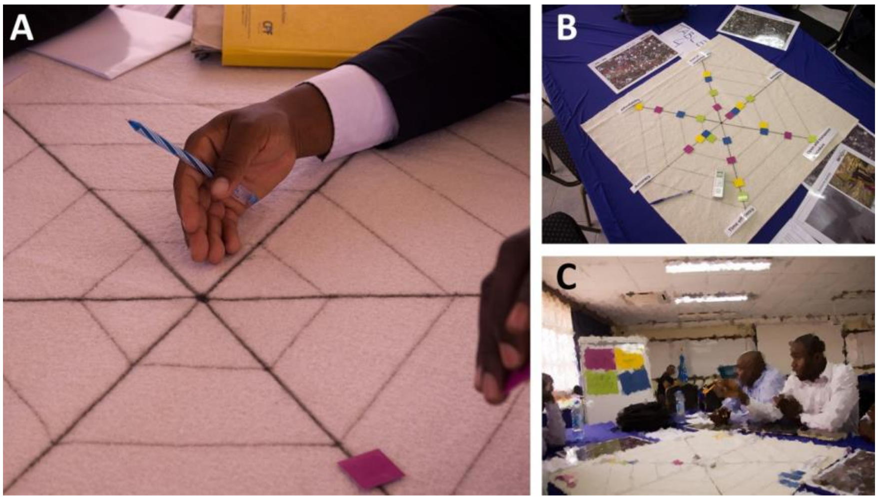


Figure 13: Impressions from the interactive workshop. A) Starting the game with a blanc radar chart; B) Final result of the board game; C) Active discussion to find consensus among the group members

For the board game, six parameters were derived from state-of-the-art frameworks for selecting fit-for-purpose data collection methods in land administration (Rahmazidadeh 2018). This amount of parameters had proven to allow enough room for discussion in the given time frame of one hour and fitted nicely to the layout and design of the board game. Four out of six parameters characterize the data collection method, namely *time efficiency*, *affordability*, *ease of implementation*, as well as *open and transparent procedure*. The remaining two parameters *accuracy* and *reliability* mainly refer to the data quality itself (see Table 5).

Table 5: Definition of parameters for the board game

Parameter	**Definition**
Accuracy	Geometric accuracy of the data product
Time efficiency	Time aspect of data collection

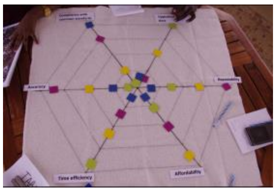
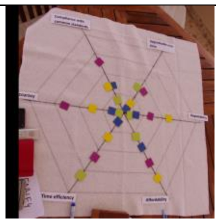
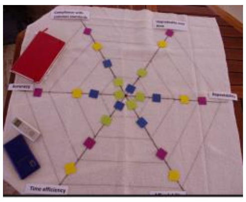
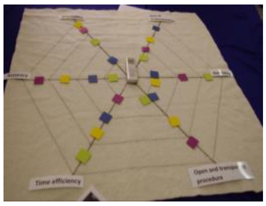
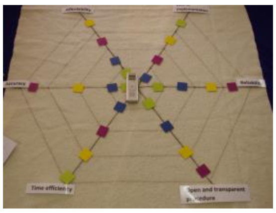
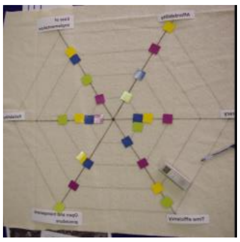
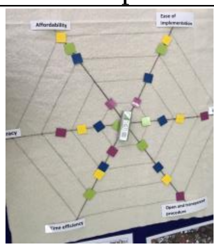
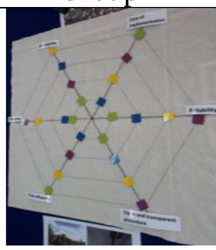
Affordability	The available budget for the data collection
Reliability	Trustworthiness and reproducibility of data product
Open and transparent procedure	Extend to which the procedure of data collection is transparent
Ease of implementation	Ease of access and availability of the data collection method

Evaluation results

The results of the board game visually unveiled opportunities and drawbacks of each data acquisition technology from the perspective of the stakeholder group while the continuous group discussion provided valuable insights into existing workflows and different perceptions (Table 6). Although the interactive workshop equally weights all four data acquisition technologies, results were derived with a focus on UAV-based images.

The parameters *accuracy* and *time efficiency* show lowest variances among the statistical analysis as shown in Figure 14. This means that all eight stakeholder groups have ranked the various data acquisition technologies similarly. In contrast, the other parameters *open and transparent procedure*, *ease of implementation*, and *reliability* show high variances in their rankings and thus reveal different perspectives, especially between data provider (i.e. practitioners) and data user (i.e. national and local government and NGOs). The following subsections will provide more insights into the group discussions and driving arguments for the individual ranking.

Table 6: Radar charts with results of individual group discussions

 Group 1	 Group 2	 Group 3	 Group 4
 Group 5	 Group 6	 Group 7	 Group 8

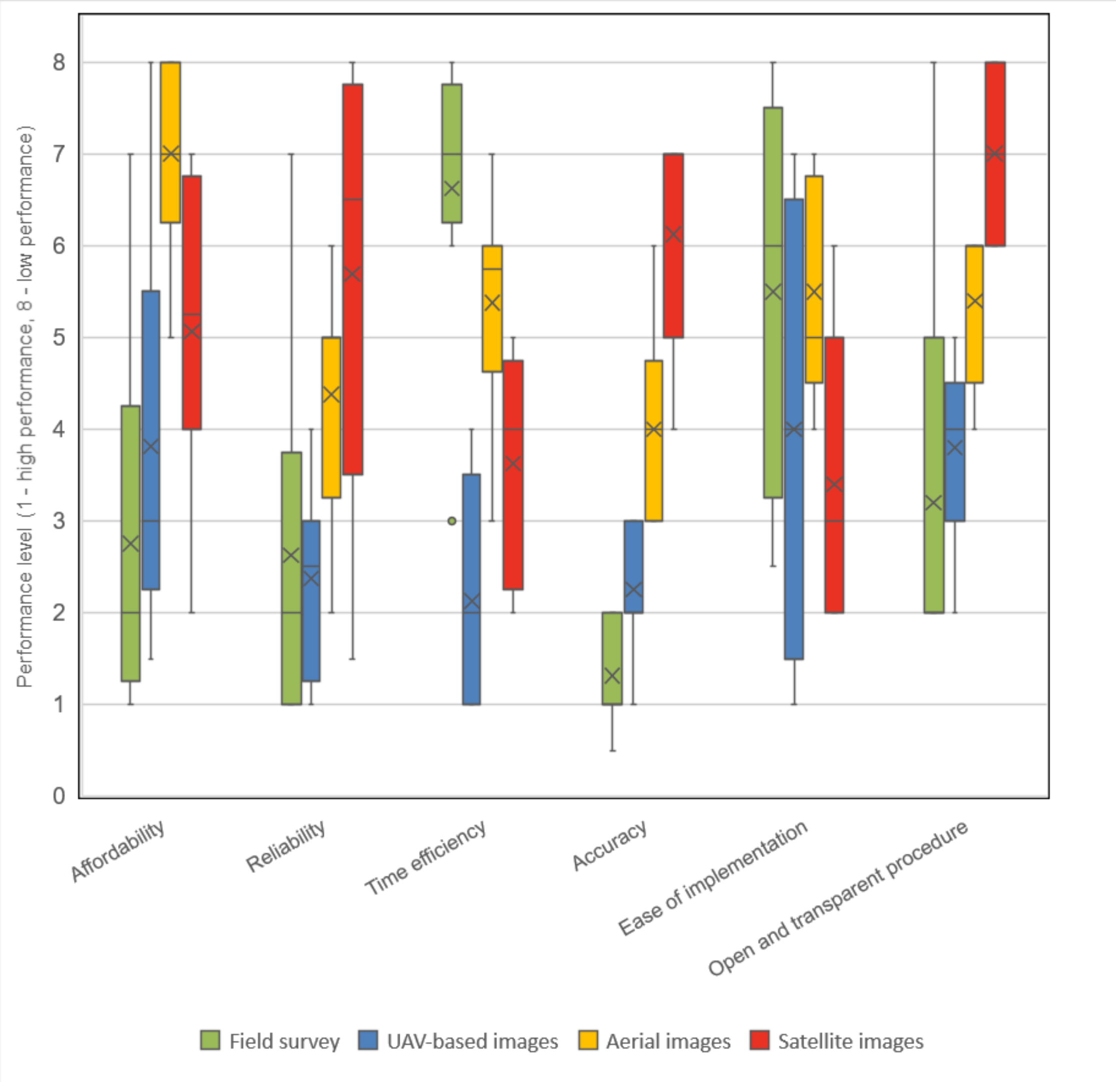


Figure 14: Statistical distribution of responses presented in a Box-Whisker plot (n=8 groups)

Affordability

Although the parameter *affordability* was ranked differently among the various stakeholder groups, a general trend can be observed. On average aerial images were ranked with the lowest performance, followed by satellite images. The respondents identified that recurring costs for each data request characterize both data collection methods, i.e. hiring a company to capture aerial images or requesting satellite images. In contrast, field surveying and UAV data collection involve only one-time purchases of the professional equipment and recurring staff rates. The highest variance in the ranking of the performance level can be observed with UAV-based images, ranging from 1.5 to 8, a result of the broad range of purchasing costs.

Moreover, costs for airworthiness certification and legal registration were perceived to have a large share of the total expenses as well. Field surveys perform the best, especially when using general boundaries where measurement accuracies of a few meters are acceptable. Besides the costs of the data itself, the majority of the groups raised the economies of scale about the indirect surveying techniques. The more parcels are captured in one orthoimage; the cheaper and more cost-effective the image-based data collection will become.

Reliability

Two different discourses emerged during the discussion of *reliability*. The first discourse referred to the *reliability* of the data collection technique itself and the second to the *reliability* of the person who collects and processes the data. In this aspect, we observed a large variance in the responses for field surveying and satellite images. Although a professional GNSS device can determine cm-accurate boundary coordinates, the majority of groups raised concerns regarding the trustworthiness of the surveyor.
Furthermore, beacons or monuments of geodetic reference points can be found as demolished, moved or even removed. Looking at satellite images, most doubts were mentioned about post-processing (i.e. correct rectification) and image quality (i.e. cloud cover).
In contrast, post-processing of UAV and aerial images was considered reliable among the groups with the only drawback of weather-dependency setting its operational limitations (i.e. cloud-free sky, no strong wind and decent lighting conditions). The highest performance was achieved by UAV images which can be captured in post-processing kinematic or a real-time kinematic mode and thus do not necessitate the collection of ground control points which was perceived as a processing step which could lower the performance of UAV images. Some groups indicated the problem of vegetation cover which can obstruct the view from above and hinder the correct identification of parcel boundaries and thus have an adverse effect on the *reliability* of the data.

Time efficiency

All groups reached a consensus that the parameter of *time efficiency* highly depends on the scale and availability of existing data. However, the results on average suggest a general trend with UAV images showing the best performance, followed by satellite images, aerial images, and field survey with the lowest performance. A critical point which caused the low ranking of UAV images refers to the legislation and flight authorization, a component which was found unpredictable as it can range from a few days to a few months. However, compared to to the timely processes of tendering and procuring a flight mission with a regular airplane, the immediate realisation of UAV missions – with given authorization – was identified as most promising about time efficiency. Next, to this, the opportunity to directly download satellite images enthused the workshop participants. However, it was observed that this argument provoked an intense discussion as most satellite data providers restrict access to up-to-date pictures or charge additional fees for this service. Another weak aspect of satellite images was the fact that satellite data can hardly be tailored to the requirements as the satellite usually has a fixed orbit with determined revisit times. The parameter *time efficiency* showed the only statistical outlier from this study. Here, one group ranked field surveying with a high performance whereas all other groups decided to rank it with low performance.

Accuracy

Similar to the parameter of *time efficiency*, *accuracy* shows a clear ranking and consensus among the groups. According to the statistical analysis, field surveying demonstrates the best performance followed by UAV images, aerial images, and satellite images. This parameter was found to be easy to rank as it highly correlates with the spatial resolution for indirect surveying techniques and the measurement accuracy for field surveying. The group discussions revealed that for both aerial and UAV image-based techniques ground measurements are still required to achieve geometric accuracies below 0.5m.

Ease of implementation

The assessment of this parameter showed the most substantial variance in group responses among the six parameters. Responses for UAV images have a range of 1 – 7, field surveying 2.5 – 8, and satellite images 2 – 6. Only aerial images showed more consensus with a range of only three performance levels. On average, satellite images were ranked with the highest performance due to the simplicity of downloading and using the images right away. Main reasons to rank UAV images with high performance were identified in the little amount of training for UAV mapping as many processes such as flight planning, image capture, and processing are automated.

In contrast, the rectification of aerial images, as well as field surveying with GNSS equipment, requires a high level of training which lowers the ease of implementation as the staff has to be trained. At the same time, responses revealed that field surveying is the only data acquisition technique which is defined in a standard (Act of Surveying) and thus the only legally accepted surveying method. Current UAV legislation in Kenya was identified as a hindering factor with a negative impact on the ease of implementation. However, most groups found that the fast deployment and data collection in the field can compensate for this aspect.

Open and transparent procedure

The ranking of this parameter was quite clear for the indirect surveying methods but showed a large variance in the responses for field surveying. Main reasons to rank UAV images better than aerial or satellite images are that the data collection takes place on the ground and people can participate in this process. Furthermore, delineation on top of a UAV/aerial/satellite image scores better in terms of transparency compared to field surveying where the surveyor collects measurements while people are present but processes the data when he/she is back in the office. With an overlay of cadastral boundaries on top of an orthomosaic, people can prove that the cadastral boundary corresponds to the real situation on the ground. However, some groups also indicated that local people are mainly used to “traditional” surveying maps and might not accept orthoimages as a source for the delineation of their parcel boundaries.

Reflection on evaluation results

The interactive workshop was designed to assess the potential of direct and indirect surveying methods from the perspective of various stakeholders in Kenya. In some instances, perceptions differed widely which can be explained by the different levels of familiarity but also different interpretations of the parameters. Further difficulties were observed in the singular ranking of parameters as most of them show interdependences among each other, such as *reliability* and *accuracy* or *affordability* and *time efficiency*. Overall, the most obvious finding to emerge from this study is the compatibility of UAV images with field surveying. Particularly about *open and transparent procedures*, a parameter which was considered as most important for choosing a fit-for-purpose data collection method (Rahmazitadeh 2018), UAV images were perceived to outperform the other techniques. It was somewhat surprising to see how much emphasis was drawn on the opportunity of public participation during the data collection whereas aerial and satellite images were ranked with a low-performance level as they are captured without the awareness of the people. One reason for the low average performance of aerial images can be seen in the experiences in Kenya with poorly rectified aerial images from the 1960s.

Reflecting on the workshop design, it was observed that the immediate visualization of the ranking through the placement of the chips on the boardgame had the positive consequence that the chip was only placed once the group came up with a consensus. This approach strongly encouraged workshop attendees to contribute to the co-production of information through the exchange of practical experiences. Furthermore, the gamification of the discussion accelerated the social interaction and allowed to break silos and think out of the box. The strategy to discuss one parameter with regard to all four technologies instead of all parameters for one technology minimized a potential bias of ranking one technology per se with high performance. However, the presence of high-level politicians or professionals introduced bias as those attendees have tended to take over as a team leader with a notion of pushing their perspectives and perceptions in the ranking. Nevertheless, based on this experience it was found that the approach of this interactive workshop can facilitate a constructive discussion to rank various (technological) solutions according to a set of parameters that should be considered in the process of tackling a real-world problem. In this regards, it can be said that the method of this interactive workshop can be transferred to various domains to supports decision making processes, especially if different stakeholder groups are involved.

5. Conclusion

The results of the interactive workshop as well as the exemplified opportunities for cost minimization, both in terms of ground measurements as well as image processing were elaborated in this report.

More than 100 UAV orthomosaics based on eight different UAV flight mission across Europe and Africa provided a representative basis in this report to analyse resulting horizontal accuracies which are of vital importance to meet existing cadastral surveying standards and to propel the uptake of UAV technology in land administration processes. The focus was put on the minimization of ground measurements. We could show, that with a PPK workflow, the need for time-consuming GCP measurements can be eliminated. However, the experiences of WP4 in Rwanda, Kenya and Tanzania also showed, that PPK workflows are not always possible due to missing CORS, local datum transformation problems or GNSS equipment which is not compatible with the PPK UAV system. Thus, GCP measurements were found to be the more reliable data collection setup. Results of this investigation suggest that six well-distributed and well-marked GCPs are sufficient to georeference the image block regardless of the context, size of the area, or camera specifications of the UAV dataset. This is argued by the fact, that after six GCPs, the horizontal RMSE does not decrease significantly and the trendline keeps one level with a range of maximum 1.5 Ground Sampling Distance.

ODM_WP4, which will be implemented on the its4land Publish and Share platform during the upcoming months provides a user-friendly environment to process UAV image datasets. The use of ODM on the Publish and Share platform minimizes two costs at the same time: costs to purchase COTS software and costs for powerful laptops that can process large sets of UAV images. Additionally, processing and storage of image datasets will be handled in the cloud environment of the Publish and Share platform.

Evaluating UAV-based workflows as a whole, the analysis of quantitative and qualitative data revealed the largest advantage in the independence of the UAV data capture; independence from an extended training program and large companies or donors who can afford satellite images or aerial flight missions. Local authorities, private companies as well as government agencies saw UAV technology capable of providing long-desired up-to-date raw data at a medium-scale such as towns or municipalities where cadastral plans can be updated using accurate and reliable UAV images. This procedure reflects the expressed wish of local authorities to opt for time-efficient and modern geospatial technologies. Looking at future developments, the results suggest that most stakeholders already perceive UAV technology as a viable method for land data capture. Given that legal issues will UAV regulations will be cleared in the near future, this investigation shows the benefits of UAV technology compared to other surveying techniques and can be considered as a starting point for a successful technology uptake.

Overall, it can be concluded that efficient UAV-based data collection workflows are available and ready to be implemented for cost-effective land tenure mapping. It is now the turn of politicians and stakeholder to take up those opportunities and to evoke policy transfer and to pave the way for the sustainable implementation of UAV technology.

References

Agüera-Vega, F., Carvajal-Ramírez, F. and Martínez-Carricondo, P. (2017) ‘Assessment of photogrammetric mapping accuracy based on variation ground control points number using unmanned aerial vehicle’, *Measurement*, 98, pp. 221–227. doi: 10.1016/j.measurement.2016.12.002.

Aicardi, I. *et al.* (2016) ‘An Image-Based Approach for the Co-Registration of Multi-Temporal UAV Image Datasets’, *Remote Sensing*, 8(9), p. 779. doi: 10.3390/rs8090779.

Benassi, F. *et al.* (2017) ‘Testing accuracy and repeatability of UAV blocks oriented with gnss-supported aerial triangulation’, *Remote Sensing*, 9(2). doi: 10.3390/rs9020172.

Bennett, R. M. and Alemie, B. K. (2016) ‘Fit-for-purpose land administration: lessons from urban and rural Ethiopia’, *Survey Review*, 000(000), p. 1752270614Y.000. doi: 10.1179/1752270614Y.0000000149.

Enemark, S. (2004) ‘Building Land Information Policies’, *UN, FIG, PC IDEA Inter-regional Special Forum on The Building of Land Information Policies in the Americas*, (October), pp. 1–20.

James, M. R. *et al.* (2016) ‘Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment’, *Geomorphology*. doi: 10.1016/j.geomorph.2016.11.021.

Manfreda, S. *et al.* (2019) ‘Assessing the Accuracy of Digital Surface Models Derived from Optical Imagery Acquired with Unmanned Aerial Systems’, *Drones*, 3(1), pp. 1–14. doi: 10.3390/drones3010015.

Stöcker, C. *et al.* (2019) ‘UAV Imagery , Land Data and User Needs : A Socio-Technical Assessment in Rwanda’, pp. 1–17.

Zevenbergen, J. *et al.* (2013) ‘Pro-poor land administration: Principles for recording the land rights of the underrepresented’, *Land Use Policy*. Elsevier Ltd, 31, pp. 595–604. doi: 10.1016/j.landusepol.2012.09.005.