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# Validation of Unmanned Aerial Vehicle Photogrammetry for Landslide Mapping

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***Abstract*— Unmanned Aerial Vehicle (UAV) photogrammetry offers quick and effective landslide monitoring. UAV named Polines 01-GD has been developed for photogrammetry. The UAV is designed flexibly in its gimbal to change the camera accordingly. However, UAV validation is needed to evaluate the quality of the device. This study aims to validate the performance of UAV Polines 01-GD for photogrammetry from quantitative and qualitative analysis. The quantitative analysis was performed by RMSE and area accuracy in $m^2$ with the reference DJI Phantom 4 Pro. Meanwhile, the qualitative analysis was done using the DEM (Digital Elevation Model) result. 3D Ground Control Points (GCPs) size 2 m x 2 m were used and placed in the landslide area, UNNES park, Semarang. The camera assembled for an experiment in Polines 01-GD is GoPro Hero 3. The results show that the RMSE of Polines 01-GD is 0,0000234193, and the area accuracy to the real measurement of GCP is 97,8%. The results of landslide indicated by the data was taken in March 2022 compared to the first flight on August 2021, showing landslides in 79.4 m and 60.3 m. Even so, the DEM of DJI Phantom 4 Pro result is clearer than Polines 01-GD. In conclusion, UAV Polines 01-GD can be used for photogrammetry. However, the flight time can be a challenge for future research as Polines 01-GD can only fly in 15 minutes, which is half of DJI Phantom 4 Pro.**

***Keywords*—Validation; Polines 01-GD; mapping; landslide.**

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## I. INTRODUCTION

Natural disasters pose a major threat in various regions of the world and often cause economic losses, environmental impacts, and loss of life [1]. Factors influencing the occurrence of these natural disasters are due to extreme weather and climatic influences. Although these hazards may occur in different parts of the world, some places may be more at risk of specific hazards due to geological, morphological, and climatic factors. Humans are essential in securing natural events before they come as disasters [2]–[4].

The slopes, however, can fail at times. Understanding slope mass movement is essential for measuring landslide hazard. The measure of effective surface deformation provides an effective method for characterizing slope movement, especially in areas prone to landslides. By analyzing critical slope behavior, engineers can predict the possibility of failure [5]. The analysis of slope movement can be achieved by comparison of the Digital Elevation Model (DEM) from different dates [6], [7]. It can assess the surface of the observed area on a 3D map. The DEM was obtained from the processing point cloud of the aerial photos.

Attempts have been made to assess the landslide hazard and propose mitigation methods based on the main characteristics of the landslide, including area, volume, trigger mechanism, repeatability, and subsequent evolution. Mapping and monitoring ground movement through remote sensing is important in hazard prevention and assessment in the early stages of landslide investigations [8], especially in 3D mapping. Remote sensing techniques offer rapid measurement of surface deformation monitoring over a large area. Remote sensing on board satellite techniques have been used for monitoring the Earth's surface and local scale by providing mapping and land cover features such as vegetation, soil, water, and forests [9]–[11]. However, the resolution or repetition rate limitation to provide the landslide dynamic is not fulfilled. The technologies for extracting the information from satellite imagery is limited since no single sensor combines the optimal spectral, spatial, and temporal resolution [12], [13]. The problem of spatial resolution in satellite imagery is tried to be overcome by adopted deep learning algorithms [14]. However, the algorithms require sizeable computational power, as processing whole satellite images is considered challenging and sometimes impossible. The ESRGAN network is also presented to improve the spatial resolution of satellite imagery. Unfortunately, it is not entirely successful due to multiple errors. Even though the neural network can reduce the duration of the spatial improvement process by 10% of overlap, it still requires modification of the existing deep learning model [14].

Scientists are using UAV technology as an alternative to remote sensing with a relatively more affordable cost, relatively short time, and the ability to produce high-resolution spatial information through photogrammetry techniques. The application of remote sensing in landslide investigations is carried out through photogrammetric techniques for mapping ground shifts and surface point displacements so that differences in slope surfaces can be seen, which is the main indicator for understanding landslide development. Photogrammetry is a technique for mapping objects on the earth's surface using aerial photographs as a medium to be further processed to produce a photo map. Topographic surveys can now be carried out using the UAV by combining simple RGB aerial images to produce mappings. The use of UAV has been applied to landslide monitoring to analyze the volume of eroded slope material [15], analyze surface deformation [16]–[18] for determining landslide velocity [19], landslide characterization and mapping [20].

Repeatability analysis of landslides is a major concern for uncovering the evolution of landslides and their activities [21]. However, this repeat requires a georeferenced track record. Therefore, it is important to study landslide movements based on the previous period [22]–[25] so that an effective alternative in terms of time and cost is needed. With time and cost-effectiveness, it will be possible to repeat surveys with the time intervals needed to monitor changes by comparing the results of the digital model.

The use of the Unmanned Aerial System after 2015 has increased its application sharply, including in obtaining geospatial data through digital photogrammetry to produce high resolution [26]. Geospatial is a spatial aspect that shows the location, location, and position of an incident object that is below, on, or above the earth's surface. Resolution is related to image quality, and the camera sensor determines image quality. Up until now, UAVs were equipped with optical cameras. However, industrial-made UAVs use dedicated camera sensors with various sensor sizes, such as the DJI Phantom 4 using a 1” camera sensor [27], full-frame 35.9 x 24 mm [28]. Apart from that, there is also a photogrammetry senseFly S.O.D.A camera with a camera sensor size of 1”, but this camera is only compatible with 1 type of eBee X drone [29]. The size of this sensor will determine the quality of the image. A camera with a larger sensor size captures more light, less noise, and more detail, resulting in better image quality. Hence, there is a challenge related to the flexibility of the UAV system so that it can be integrated with different components [30]. Several studies have succeeded in developing UAVs as mapping devices, such as the UAV named Saturn [31] and the quadrotor UAV [32]. However, there is a gap where there is no validation of the mapping results using the tool. Validation is essential to ensure the quality of research tools [33].

This study aims to build a UAV named Polines 01-GD for photogrammetry and validate its mapping with industrial UAV DJI Phantom 4 Pro. This research contributes to developing a hexacopter UAV device that is designed with the flexibility of a camera that can be replaced with a gimbal to acquire geospatial data in landslide-prone areas. For this study, the hexacopter UAV was tested in its application to photogrammetry using the GoPro Hero 3 Black Edition camera.

## II. Materials and Method

### *A. Hardware*

There are two types of UAV systems used in this study, i.e., the UAV developed in this research: hexacopter UAV Polines 01-GD and DJI Phantom 4 Pro. Polines 01-GD is designed with the following specifications: the camera on the gimbal can be replaced so that the image results can be adjusted according to the camera, UAV can fly autonomously, autopilot software is programmable and configurable (open source), lightweight UAV with a classification of less than 25 kg.

Fig. 1 shows the UAV system block diagram. The UAV's components comprise the airframe's aerial platform, which uses a hexacopter with a carbon fiber frame. The flight controller uses Pixhawk, GPS M8N, LiPo battery, and a GoPro Hero 3 camera for mapping. The system on this UAV uses six propellers, so it is called a hexacopter. This system uses a brushless motor, widely used for aerial photography. This brushless motor is equipped with an Electronic Speed Controller (ESC) to connect the battery to the electric motor as a power supply. ESC was installed in every brushless motor.

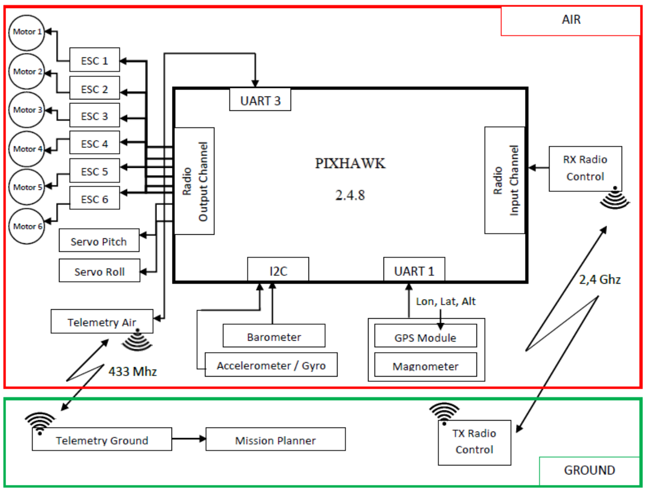


Fig. 1 UAV System Block Diagram

Fig. 2 shows the design hardware of Polines 01-GD with top view and bottom view. Meanwhile, Fig. 3 shows the design of the gimbal of Polines 01-GD. The gimbal was made from 3D Printer with PLA material.

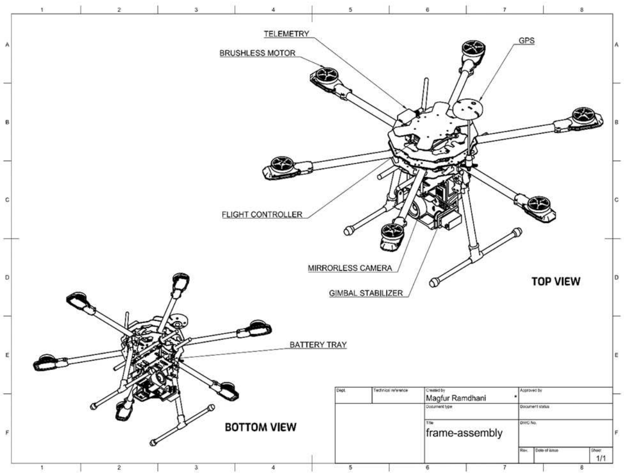


Fig. 2 Polines 01-GD Design

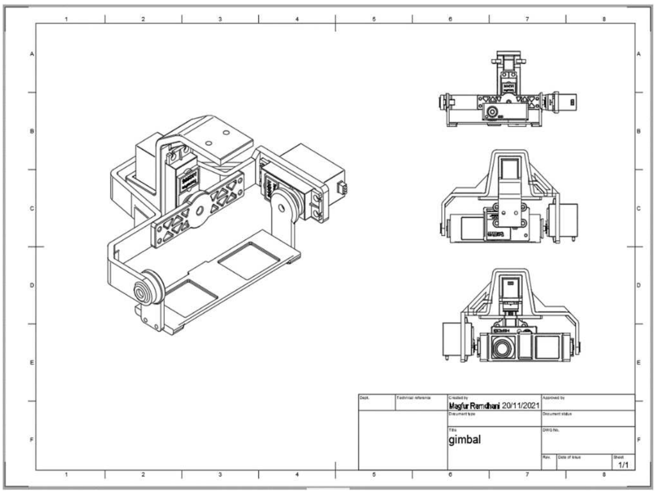


Fig. 3 Gimbal design of Polines 01-GD

*B. Software*

The software used for UAV needs is Mission Planner for GCS, while the software used for processing aerial mapping data is Agisoft. Agisoft functions to process aerial photo data which will produce point-cloud, and DEM to observe the results of mapping.

*C. Data Collection*

The GoPro Hero 3 Black Edition camera was mounted to Polines 01-GD gimbal. GoPro Hero 3 captures images with a resolution of 12 MP. This camera weighs 182 grams, and the size of the camera sensor is 6.2 x 4.65 mm. Pixel size uses a CMOS sensor with a focal length of 16 mm. Ground Control Point (GCPs) assembled as many as three units in the research location. The GCP size is 2 meters x 2 meters. The color of GCP is black and white, intended to enable the processing data with contrast colors. The use of GCP as a geo-tag can be used to determine mapping accuracy [34], because GCP serves as a real measure to calibrate image acquisition from UAVs. If the measurements from the UAV image acquisition are close to the real measurements on the GCP (2 meters x 2 meters), it can be interpreted that the data on the mapping are data close to real. Fig. 4 shows the GCP assembled in the research location.

Fig. 4 Ground Control Points assembled in the research location

The flight path was made to facilitate data retrieval orientation. This flight path is created using the Mission Planner software. The data collection scenario was carried out at the research location at points D1-D8 shown in Fig. 5. Fig. 5 shows the location of the research, situated in UNNES park, Semarang. The area is 12 ha large.

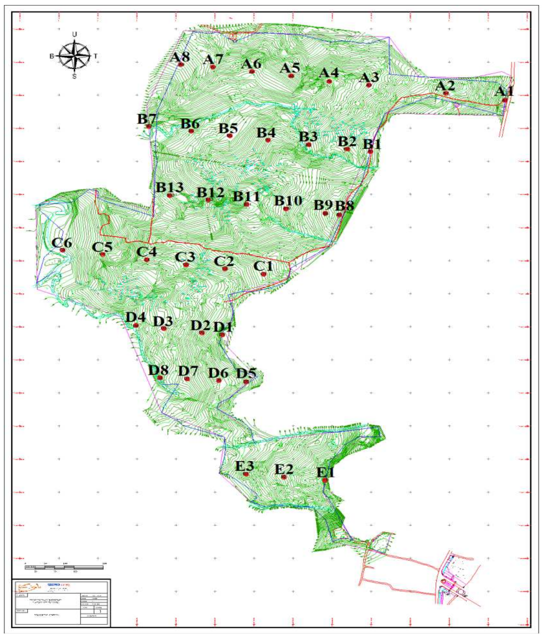


Fig. 5 Research location at UNNES park, Semarang

The data acquisition process for one map takes 12-14 minutes. The flying height of the UAV is 60 m. The aerial images were taken using Polines 01-GD and DJI Phantom 4 Pro during the day close to 12.00 to minimize the presence of shadows in the image. The data was obtained in August 2021 and March 2022 to evaluate landslides.

### *D. Validation*

The validation analysis of the results of the UAV hexacopter mapping with the GoPro Hero 3 camera is based on the results of DJI Phantom 4 Pro coordinates as the reference. This method is in accordance with [35] where the results UAV was compared to the reference tool of Laser Scanner in terms of accuracy, R square and volume. While the qualitative analysis is based on DEM results processed by Agisoft software.

## III. Results and Discussion

The UAV being developed named Polines 01-GD can carry out autonomous flights from take-off and landing. This UAV weighs less than 25 kg, so it is categorized as a light/miniature UAV or SUAV (Small UAV) [36]. Fig. 6 shows the hardware UAV hexacopter Polines-01GD and DJI Phantom 4 Pro. Table 1 shows the specifications of  DJI Phantom 4 Pro and Polines 01-GD.


Fig. 6 UAV DJI Phantom 4 Pro (left) and Polines 01-GD (right)

TABLE I
Specifications of Polines 01-GD and DJI Phantom 4 Pro

| Specification | DJI Phantom 4 Pro | Polines 01-GD |
|---|---|---|
| **Aircraft** | 1.375 gr | ±2.650 gr |
| Weight | 350 mm | 680 mm |
| Diagonal size | ±30 min | ±15 min |
| Flight time | | |
| **Gimbal** | | |
| Stabilization | 3 axes (pitch, roll, yaw) | 3 axes (pitch, roll, yaw) |
| Controllable range | Pitch -90° up to +30° | Pitch -90° up to +30° |
| **Camera** | | |
| Sensor size | 13.2 x 8.8 mm | 6.2 x 4.65 mm |
| | 20 MP | 12 MP |
| Photo | JPEG, DNG (RAW), JPEG + DNG | JPEG |
| **Remote controller** | | |
| Operating frequency | 2,400 – 2,483 GHz and 5,725 – 5,850 GHz | 2,400 – 2,483 GHz |
| Battery | 6,000 mAh LiPo 2s | 3,000 mAh LiPo 1s |
| **Flight battery** | | |
| Capacity | 5,870 mAh | 8,000 mAh |
| Voltage | 15.2 V | 15.2 V |
| Battery type | LiPo 4S | LiPo 4s |
| Weight | 468 gr | 650 gr |

### *A. Quantitative Analysis*

GCP can measure the comparison, as the object has the exact value in the field. This study used 3 GCPs. This number meets the minimum criteria for the number of GCPs, namely 3 [37]. The color of the GCP is black and white to recognize contrasting patterns easily. The coordinates of the GCP from the orthophoto resulted in X and Y coordinates, as shown in Table 2. The results of RMSE of Polines 01-GD with reference to the result from DJI Phantom 4 Pro show the value of 0,0000234193. This number fits the data perfectly as it has a value of close to 0 [38], [39].

TABLE II
Coordinate comparison between DJI Phantom 4 Pro and Polines 01-GD

| GCP | DJI Phantom 4 Pro | | Polines 01-GD | |
|---|---|---|---|---|
| | X | Y | X | Y |
| 1 | 110.3841 | 7.04193056 | 110.3841 | 7.04193333 |
| 2 | 110.3838 | 7.04138333 | 110.3838 | 7.0414 |
| 3 | 110.3831 | 7.04150833 | 110.3831 | 7.041522 |
| RMSE | | | | 0,0000234193 |

Measuring the area of the object was performed by comparing the GCP area in the orthophoto and GCP area in a real field. The real GCP size is 2 meters x 2 meters. So, the area should be 4 $m^2$ in the aerial photo. Fig. 7 shows the GCP in the orthophoto to be compared to the real area in $m^2$. The results of the area calculation are shown in Table 3. Based on the results of the calculations, it was found that the GCP value DJI Phantom 4 Pro and Polines 01-GD has a general value close to 100%. This value indicates that Polines 01-GD with Go Pro Hero 3 camera can be used as an instrument for 3D mapping. Because the minimum accuracy required for a land surface classification survey is 85% [40]. This is because the accuracy of aerial images, both Polines 01-GD and the DJI Phantom 4 Pro, meet the minimum criteria.

Fig. 7 GCP in Orthophoto

TABLE III
GCP POLINES 01-GD AND DJI PHANTOM 4 PRO

| GCP | Width of GCP in the orthophoto | | Accuracy (%) | |
|---|---|---|---|---|
| | DJI | GoPro | DJI | GoPro |
| 1 | 4.043 | 4.082 | 98.93 | 97.95 |
| 2 | 3.981 | 4.047 | 99.53 | 98.83 |
| 3 | 3.910 | 4.138 | 97.75 | 96.55 |
| Average | | | 98,7 | 97,8 |

## B. *Qualitative Analysis*

The results of DEM show the qualitative analysis. Fig. 8 shows the DEM of Polines 01-GD and DJI Phantom 4 Pro. DEM is generated from point-cloud of the images from aerial photos. The results of DEM using Agisoft visualize the differences between two UAVs. The DEM of Polines 01-GD has quite prominent differences from DJI Phantom 4 Pro. DEM of DJI Phantom 4 Pro is sharper than Polines 01-GD using GoPro Hero 3 camera. The UAVs can both detect the peaks indicated by red colors, which show the higher elevation. However, the noise from Polines 01-GD is more than DJI Phantom 4 Pro, and some edges of the texture are less clear. Meanwhile, the results of DEM from DJI Phantom 4 Pro aerial images show the sharper texture, so that parts of land and trees are easily detected. The highest peak detected in DJI Phantom 4 Pro is 149 m, while in Polines 01-GD is 134 m. The difference can be influenced by the wind while the UAV flies, which can move the leaves on the tree for instance.

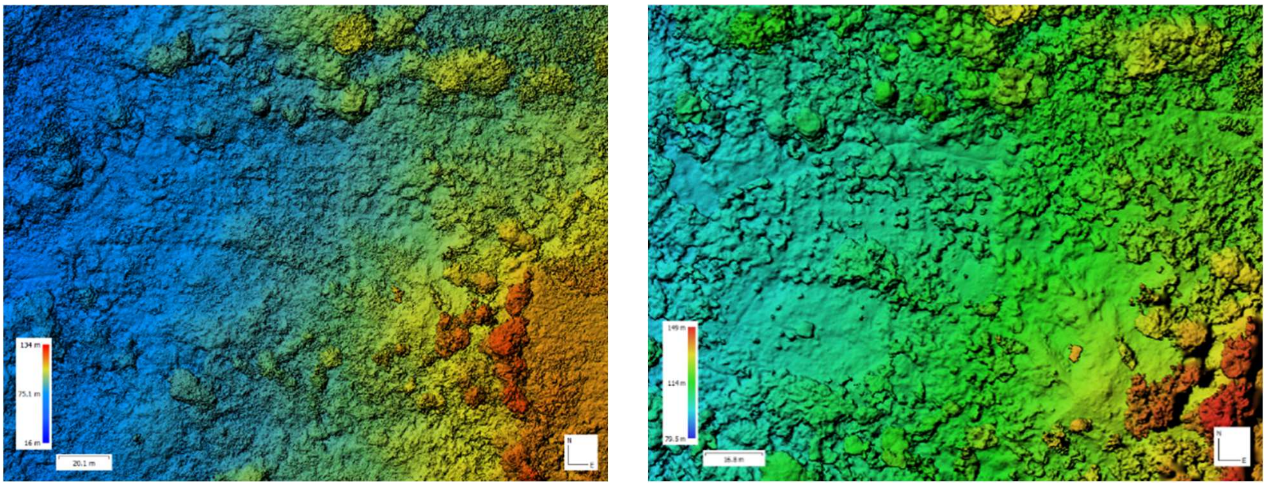
Fig. 8 DEM of Polines 01-GD (left) and DJI Phantom 4 Pro (right)

In photogrammetry applications, such as for land surveying and construction, Ground Control Points (GCPs) are proven to greatly increase the accuracy of 3D information results such as point clouds, 3D-mesh, Ortho mosaic or Digital Elevation Models (DEM). Three GCPs are sufficient for photogrammetry, as an excessive number of GCPs can be time-consuming either in the field or in computation [37]. However, this is also affected by UAV specifications such as camera focal length, flight altitude, camera orientation, and image quality [41], [42]. The resulting size of the photo with the original size has a different value. This is due to UAV is tilted, which creates distortion. An easy way to check is by measuring the dimensions of length, that is, the size of the results in the photo with the original size has different deviations. This is because there is distortion, and it is not the same in every corner of the frame area. So, the length between the photo and the original size is different. Cameras influence the quality of the image. DJI Phantom camera has 20 MP pixels while GoPro Hero 3 has 12 MP. Regarding the difference in the sensor size, DJI Phantom 4 Pro has bigger size. The sensor size on the GoPro Hero 3 is 6.2 x 4.65 mm while the sensor size on the DJI Phantom 4 Pro is 13.2 x 8.8 mm. Sensor size affects the resolution of the image. Better resolution requires a bigger sensor size.

The flight height of the UAV is 60 m. It is noted by Çelik, et al. [43] that the flight height at 30 – 50 m shows that the flight data from 30 m gave better results than 50 m. However, the consequence is the flight process took longer than a flight with height 50 m. Using lower flying height will lead to more photos were taken and file size took more space. The flight height should be considered related to terrain structure, accuracy, precision, and time-cost balance from the job. It is said in Syafuan et al. [44] that the flight altitude of 60 m is best height for the flat surface, and 100 m flight altitude is best for the hilly surface. However, the accuracy on UAV mapping in the hilly surface tends to be lower than flat surface by using 100 m flight altitude. This study used 60 flight altitude for the surface with various terrain surface in order to get better accuracy with lower flight height than 100 m. Besides, it considers the time in the field by using 60 m flight height rather than lower flight height. Because the lower height will take longer time to capture the images as said by Elhadary et al. [45] that the altitude increment can reduce flight time, processing time and cost, but still can keep the acceptable and suitable accuracy.

In a digital camera, the sensor functions like a solar panel that collects light to capture a photo. A larger camera sensor collects more light, resulting in better images with less noise, and sharper images compared to smaller camera sensors. This is because the larger the sensor size, the greater the surface area of light that can enter. The results from GoPro Hero 3 are not more detailed than those from DJI Phantom 4 Pro, as shown in Fig. 8.

Fig. 8 Results from Polines 01-GD (right) and DJI Phantom 4 Pro (left)

To analyze the landslide data, the data in August 2021 is compared to March 2022 as shown in Fig. 9 and 10.

Fig. 9 Data on August 2021

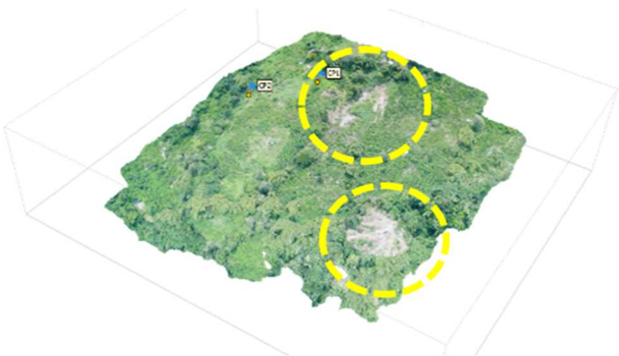

Fig. 10 Data on March 2022

The results of the first image taken on August 21, 2021, show that a landslide had just started on the ground surface, shown by the yellow circle in Fig. 10 as LS 1 (Landslide 1) and LS 2 (Landslide 2). This can be seen from the bare vegetation among the many plants around it. Based on the orthophoto on March 2022 in Fig. 10, a line can be drawn to see how far the landslide occurred as shown in Fig. 11.


Fig. 11 Landslide Indicated by Ground Movement in LS 1 and LS 2

The drawing line indicates that there is movement of 79.4 m in the LS 1 area. Meanwhile in LS 2, there is ground movement of 60.3 m. Based on the results of instrument validation using qualitative and quantitative analysis, it was concluded that Polines 01-GD with the GoPro Hero 3 camera can be used as a device for photogrammetry. That is, the results of the GoPro Hero 3 are not much different from the DJI Phantom 4 Pro. Nevertheless, the result is better image sharpness on the DJI Phantom 4 Pro. Validation is important in determining whether the resulting instrument from a development is not much different from what is commonly used. DJI Phantom 4 Pro is an enterprise-grade device and is often used in surveys. This research has developed a hexacopter UAV that can be used as a photogrammetric UAV device. The results of the hexacopter and the GoPro Hero 3 camera generally differ, especially in the results of the map visualization. A camera with a larger sensor size and more megapixels will give different results than a camera with a smaller sensor size and/or fewer megapixels.

## IV. Conclusion

The mapping results obtained from Polines 01-GD data shows RMSE in 0,0000234193 and the accuracy calculation based on GCP area has 97,8% accuracy to the real measurement. So that the UAV instrument can be used for photogrammetry. Polines 01-GD is designed flexible by its ability of interchangeable camera. This enables aerial images to get better results with better camera quality. Further research challenges can be analyzed and developed in terms of flight time, as Polines 01-GD flight time is approximately half the DJI Phantom 4 Pro's i.e. 15 minutes, which might be troublesome in the field.

## References


[1] Q. Xu, W. le Li, Y. zhen Ju, X. jun Dong, and D. lei Peng, "Multitemporal UAV-based photogrammetry for landslide detection and monitoring in a large area: a case study in the Heifangtai terrace in the Loess Plateau of China," *J Mt Sci*, vol. 17, no. 8, pp. 1826–1839, Aug. 2020, doi:10.1007/s11629-020-6064-9.

[2] M. T. Chaudhary and A. Piracha, "Natural Disasters—Origins, Impacts, Management," *Encyclopedia*, vol. 1, no. 4, pp. 1101–1131, Oct. 2021, doi:10.3390/encyclopedia1040084.

[3] M. Krichen, M. S. Abdalzaher, M. Elwekeil, and M. M. Fouda, "Managing natural disasters: An analysis of technological advancements, opportunities, and challenges," *Internet of Things and Cyber-Physical Systems*, vol. 4. KeAi Communications Co., pp. 99–109, Jan. 01, 2024. doi:10.1016/j.iotcps.2023.09.002.

[4] L. Qiu, X. Wang, and J. Wei, "Energy security and energy management: The role of extreme natural events," *Innovation and Green Development*, vol. 2, no. 2, p. 100051, Jun. 2023, doi:10.1016/j.igd.2023.100051.

[5] C. R. Song, R. L. Wood, B. Bekele, N. Glennie, A. Silvey, and M. Nasimi, "A Comparison of Surface Deformation Measurement Methods for Slopes," *Applied Sciences*, vol. 13, no. 6, p. 3417, Mar. 2023, doi:10.3390/app13063417.

[6] M. Yavuz *et al.*, "Identification of Streamside Landslides with the Use of Unmanned Aerial Vehicles (UAVs) in Greece, Romania, and Turkey," *Remote Sens (Basel)*, vol. 15, no. 4, Feb. 2023, doi:10.3390/rs15041006.

[7] C. López-Vázquez and F. J. Ariza-López, "Global Digital Elevation Model Comparison Criteria: An Evident Need to Consider Their Application," *ISPRS Int J Geoinf*, vol. 12, no. 8, Aug. 2023, doi:10.3390/ijgi12080337.

[8] M. J. Auflič *et al.*, "Landslide monitoring techniques in the Geological Surveys of Europe," *Landslides*, vol. 20, no. 5, pp. 951–965, May 2023, doi:10.1007/s10346-022-02007-1.

[9] T. S. Le, R. Harper, and B. Dell, "Application of Remote Sensing in Detecting and Monitoring Water Stress in Forests," *Remote Sensing*, vol. 15, no. 13. Multidisciplinary Digital Publishing Institute (MDPI), Jul. 01, 2023. doi:10.3390/rs15133360.

[10] B. G. Tikuye, M. Rusnak, B. R. Manjunatha, and J. Jose, "Land Use and Land Cover Change Detection Using the Random Forest Approach: The Case of The Upper Blue Nile River Basin, Ethiopia," *Global Challenges*, Oct. 2023, doi:10.1002/gch2.202300155.

[11] M. J. Mashala, T. Dube, B. T. Mudereri, K. K. Ayisi, and M. R. Ramudzuli, "A Systematic Review on Advancements in Remote Sensing for Assessing and Monitoring Land Use and Land Cover Changes Impacts on Surface Water Resources in Semi-Arid Tropical Environments," *Remote Sensing*, vol. 15, no. 16. Multidisciplinary Digital Publishing Institute (MDPI), Aug. 01, 2023. doi:10.3390/rs15163926.

[12] Z. Zhang and L. Zhu, "A Review on Unmanned Aerial Vehicle Remote Sensing: Platforms, Sensors, Data Processing Methods, and Applications," *Drones*, vol. 7, no. 6. MDPI, Jun. 01, 2023. doi:10.3390/drones7060398.

[13] A. Marzougui, R. J. McGee, S. Van Vleet, and S. Sankaran, "Remote sensing for field pea yield estimation: A study of multi-scale data fusion approaches in phenomics," *Front Plant Sci*, vol. 14, 2023, doi:10.3389/fpls.2023.1111575.

[14] K. Karwowska and D. Wierzbicki, "Improving Spatial Resolution of Satellite Imagery Using Generative Adversarial Networks and Window Functions," *Remote Sens (Basel)*, vol. 14, no. 24, Dec. 2022, doi:10.3390/rs14246285.

[15] K. G. Nikolakopoulos, A. Kyriou, I. K. Koukouvelas, N. Tomaras, and E. Lyros, "UAV, GNSS, and InSAR Data Analyses for Landslide Monitoring in a Mountainous Village in Western Greece," *Remote Sens (Basel)*, vol. 15, no. 11, Jun. 2023, doi:10.3390/rs15112870.

[16] J. Ma, X. Niu, X. Liu, Y. Wang, T. Wen, and J. Zhang, "Thermal infrared imagery integrated with terrestrial laser scanning and particle tracking velocimetry for characterization of landslide model failure," *Sensors (Switzerland)*, vol. 20, no. 1, pp. 1–12, Jan. 2020, doi:10.3390/s20010219.

[17] T. A. Teo, Y. J. Fu, K. W. Li, M. C. Weng, and C. M. Yang, "Comparison between image- and surface-derived displacement fields for landslide monitoring using an unmanned aerial vehicle," *International Journal of Applied Earth Observation and Geoinformation*, vol. 116, no. 2023, pp. 1–12, Feb. 2023, doi:10.1016/j.jag.2022.103164.

[18] Y. Hussain *et al.*, "Review on the Geophysical and UAV-Based Methods Applied to Landslides," *Remote Sens (Basel)*, vol. 14, no. 18, pp. 1–33, Sep. 2022, doi:10.3390/rs14184564.

[19] H. Thirugnanam, S. Uhlemann, R. Reghunadh, M. V. Ramesh, and V. P. Rangan, "Review of Landslide Monitoring Techniques With IoT Integration Opportunities," *IEEE J Sel Top Appl Earth Obs Remote Sens*, vol. 15, no. 2022, pp. 5317–5338, 2022, doi:10.1109/jstars.2022.3183684.

[20] R. Eker and A. Aydın, "Long-term retrospective investigation of a large, deep-seated, and slow-moving landslide using InSAR time series, historical aerial photographs, and UAV data: The case of Devrek landslide (NW Turkey)," *Catena (Amst)*, vol. 196, p. 104895, Jan. 2021, doi:10.1016/j.catena.2020.104895.

[21] L. Lin *et al.*, "Spatiotemporal Evolution Pattern and Driving Mechanisms of Landslides in the Wenchuan Earthquake-Affected Region: A Case Study in the Bailong River Basin, China," *Remote Sens (Basel)*, vol. 14, no. 10, May 2022, doi:10.3390/rs14102339.

[22] J. Cebulski, B. Pasierb, D. Wieczorek, and A. Zieliński, "Reconstruction of landslide movements using Digital Elevation Model and Electrical Resistivity Tomography analysis in the Polish Outer Carpathians," *Catena (Amst)*, vol. 195, p. 104758, Dec. 2020, doi:10.1016/j.catena.2020.104758.

[23] J. Huang, X. Zeng, L. Ding, Y. Yin, and Y. Li, "Landslide Susceptibility Evaluation Using Different Slope Units Based on BP Neural Network," *Comput Intell Neurosci*, vol. 2022, 2022, doi:10.1155/2022/9923775.

[24] Z. Luo, J. Yang, B. Huang, W. Chen, Y. Gao, and Q. Meng, "Reconstruction and Visualization of Landslide Events Based on Pre- and Post-Disaster Remote Sensing Data," *Water (Switzerland)*, vol. 15, no. 11, Jun. 2023, doi:10.3390/w15112023.

[25] W. Liu, Y. X. Hu, S. M. He, J. W. Zhou, and K. T. Chen, "A Numerical Study of the Critical Threshold for Landslide Dam Formation Considering Landslide and River Dynamics," *Front Earth Sci (Lausanne)*, vol. 9, May 2021, doi:10.3389/feart.2021.651887.

[26] S. Khanal, K. C. Kushal, J. P. Fulton, S. Shearer, and E. Ozkan, "Remote sensing in agriculture—accomplishments, limitations, and opportunities," *Remote Sens (Basel)*, vol. 12, no. 22, pp. 1–29, 2020, doi:10.3390/rs12223783.

[27] DJI, "PHANTOM 4 PROSpecs." Accessed: Mar. 30, 2022. [Online]. Available: https://www.dji.com/id/phantom-4-pro

[28] DJI, "ZENMUSE P1 Specs." Accessed: Mar. 30, 2022. [Online]. Available: https://www.dji.com/id/zenmuse-p1

[29] AgEagle, "S.O.D.A. 3D." [Online]. Available: https://ageagle.com/drone-sensors/soda-3d/

[30] F. Nex *et al.*, "UAV in the advent of the twenties: Where we stand and what is next," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 184, no. September 2021, pp. 215–242, 2022, doi:10.1016/j.isprsjprs.2021.12.006.

[31] G. Rossi, L. Tanteri, V. Tofani, P. Vannocci, S. Moretti, and N. Casagli, "Multitemporal UAV surveys for landslide mapping and

characterization," *Landslides*, vol. 15, no. 5, pp. 1045–1052, 2018, doi:10.1007/s10346-018-0978-0.

[32] U. Niethammer, M. R. James, S. Rothmund, J. Travelletti, and M. Joswig, "UAV-based remote sensing of the Super-Sauze landslide: Evaluation and results," *Eng Geol*, vol. 128, pp. 2–11, 2012, doi:10.1016/j.enggeo.2011.03.012.

[33] A.-M. Glod-Lendvai, "Validation – a brief introduction," *GeoPatterns*, vol. 3, no. 1, pp. 10–15, 2018, doi:10.5719/geop.3.1/2.

[34] J. W. Park and D. J. Yeom, "Method for establishing ground control points to realize UAV-based precision digital maps of earthwork sites," *Journal of Asian Architecture and Building Engineering*, vol. 21, no. 1, pp. 110–119, 2022, doi:10.1080/13467581.2020.1869023.

[35] S. Kurniawan and M. N. Cahyadi, "Utilization of Unmanned Aerial Vehicle (UAV) for Measurement of Surface Coal Mining Situation," *Journal of Marine-Earth Science and Technology*, vol. 3, no. 2, pp. 29–34, Jan. 2023, doi:10.12962/j27745449.v3i2.576.

[36] G. Lykou, D. Moustakas, and D. Gritzalis, "Defending airports from uas: A survey on cyber- attacks and counter-drone sensing technologies," *Sensors (Switzerland)*, vol. 20, no. 12, pp. 1–35, 2020, doi:10.3390/s20123537.

[37] V.-E. Oniga, A.-I. Breaban, and F. Statescu, "Determining the Optimum Number of Ground Control Points for Obtaining High Precision Results Based on UAS Images," *Proc West Mark Ed Assoc Conf*, vol. 2, no. 352, pp. 1–11, 2018, doi:10.3390/ecrs-2-05165.

[38] D. Chicco, M. J. Warrens, and G. Jurman, "The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation," *PeerJ Comput Sci*, vol. 7, pp. 1–24, 2021, doi:10.7717/PEERJ-CS.623.

[39] D. Hindmarsh and D. Steel, "Estimating the RMSE of Small Area Estimates without the Tears," *Stats (Basel)*, vol. 4, no. 4, pp. 931–942, Nov. 2021, doi:10.3390/stats4040054.

[40] D. Li, S. Wang, Q. He, and Y. Yang, "Cost-effective land cover classification for remote sensing images," *Journal of Cloud Computing*, vol. 11, no. 1, p. 62, Oct. 2022, doi:10.1186/s13677-022-00335-0.

[41] N. Anders, M. Smith, J. Suomalainen, E. Cammeraat, J. Valente, and S. Keesstra, "Impact of flight altitude and cover orientation on Digital Surface Model (DSM) accuracy for flood damage assessment in Murcia (Spain) using a fixed-wing UAV," *Earth Sci Inform*, vol. 13, no. 2, pp. 391–404, Jun. 2020, doi:10.1007/s12145-019-00427-7.

[42] I. Elkhrachy, "Accuracy Assessment of Low-Cost Unmanned Aerial Vehicle (UAV) Photogrammetry," *Alexandria Engineering Journal*, vol. 60, no. 6, pp. 5579–5590, Dec. 2021, doi:10.1016/j.aej.2021.04.011.

[43] M. Özgür Çelik, A. Alptekin, F. Bünyan Ünel, L. Kuşak, and E. Kanun, "The effect of different flight heights on generated digital products: Dsm and Orthophoto," *Mersin Photogrammetry Journal*, vol. 2, no. 1, pp. 1–9, 2020.

[44] W. M. Syafuan, N. Ismail, A. N. Idris, N. A. Isa, F. N. Z. Zamili, and J. Jelani, "Assessment of Photogrammetric Mapping Accuracy in Slope Area with Different Flight Altitude Using Unmanned Aerial Vehicle (UAV)," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, May 2021. doi:10.1088/1755-1315/767/1/012037.

[45] A. Elhadary, M. Rabah, E. Ghanim, R. Mohie, and A. Taha, "The influence of flight height and overlap on UAV imagery over featureless surfaces and constructing formulas predicting the geometrical accuracy," *NRIAG Journal of Astronomy and Geophysics*, vol. 11, no. 1, pp. 210–223, Dec. 2022, doi:10.1080/20909977.2022.2057148.