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Assessing a VTOL UAV-Based Digital Imaging System for Agricultural Monitoring using Low-Cost Digital Camera

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ABSTRACT

A vertical take-off and landing unmanned aerial vehicle (VTOL-UAV) was used to assess the possibilities of a digital image-based for agricultural surveillance system. The VTOL-UAV system has advantages in terms of efficiency, adaptability, and capacity to collect data across a variety of terrains for agricultural yield estimation, crop health monitoring, and early pest identification. The developed VTOL-UAV was constructed based on Skywalker platform with wingspan and length of 1800 mm and 1300 mm, respectively. Agricultural images were collected under various field settings using a digital camera (Canon IXUS 185 at 20 MP and 8x zoom). The study took place in an agricultural field at the University Teuku Umar, Aceh, Indonesia. The technical performance, aerodynamic and stability of the VTOL-UAV system during the hover and cruise were examined. Flight plan parameters included speeds between 10 to 20 m/s, camera angle of 90 degrees vertically looking down, altitudes between 50 m to 200 m, and flight overlap between 60 to 70 % flyaway in accordance with the chart in the flight plan that was made. The findings showed that VTOL-UAV offer viability of using imagery captured by a VTOL-UAV equipped with a low-cost camera for agricultural land mapping. Operational flexibility was increased by the capacity to switch between vertical take-off and horizontal flight, particularly in areas with restricted access. The study revealed that the system has to maintain the altitude and reference ground system within the mission planning to ensure stable flight orientation, reduce vibrations and image distortions. The agricultural ortho-photograph and digital surface model are beneficial for accurate mapping, effective monitoring, and informed decision-making in agricultural applications, particularly for smallholder farm management.

Keywords: *Agricultural monitoring, unmanned aerial vehicle, digital image system, Ortho-photograph, low cost digital camera*

INTRODUCTION

The integration of advanced technologies in satellite navigation systems and unmanned aerial vehicles (UAV) is revolutionizing in the agricultural sector. The demand for sharp, efficient and timely information in agriculture has grown significantly as driven by the merging of large agricultural production areas among of producers. Traditional methods for monitoring and measuring agricultural crops conditions are shifting to modern agricultural approach (Barnhart, et al. 2021).

UAV presents a transformative solution, leveraging the capacity to rapidly and accurately collect agricultural data over a large production area. These systems can provide sufficient imagery for monitoring crop health, detecting pest infestations, and evaluating soil conditions (Austin, et al. 2010 and Telli, et al. 2023). By merging with satellite navigation systems, UAV enables precise geospatial mapping and optimization agricultural processes. This fusion of digital technologies allows to solve the challenges of modern large-scale agriculture such as efficient resource management, reduced environmental impact and enhanced productivity (Abiri, et al. 2023; Huang et al. 2024 and Zhang, et al. 2025).

The application of UAV in agriculture has shown potential opportunities for the field digitization, monitoring agricultural land, and addressing localized agricultural challenges with speed and precision (Wang, et al. 2024). The commonly used UAV are multi-rotor UAVs and fixed-wing UAV configurations. The vertical take-off and landing (VTOL) aircraft are combination of fixed/rotary-wing that offer low requirements for landing site and flatness, stability in cruising speed, and extended flight length (Rehan, et al. 2022). Fixed-wing VTOL -UAV is known well for both purposes, that is, over and fast forward flight. Thus, it is widely used in variety of applications, including urban comprehensive patrol, geological mapping, power line inspection, and remote sensing (Osman, et al. 2025, Makhtar, et al. 2024 and Mendu, et al. 2025).

UAVs are capable of operating in manual, automatic, and semi-automatic modes, each offering distinct advantages in reference to the operational requirements (Mohsan, et al. 2023; Turk et al. 2022). In manual mode, VTOL-UAV are controlled using a remote device within the operator line of sight or guided by real-time information from a front -view camera. This mode is particularly useful for tasks requiring high levels of human oversight and flexibility.

Autonomous operation, on the other hand, involves pre-programmed flight paths with specific parameters such as altitude, speed, and orientation, managed by on board software systems. This mode ensures precision and repeatability, making it ideal for large-scale surveys or systematic data collection. Semi-automatic control serves as an intermediate approach, combining the efficiency of autopilot systems with the flexibility of operator's input. This hybrid approach enhances adaptability and responsiveness in dynamic agricultural scenarios, enabling operators to address unexpected conditions while maintaining the benefits of automation (Panigrahi, et al. 2021 and Ducard, et al. 2021).

The primary data for digital agriculture are collected using imaging systems, multispectral cameras, thermal imagers, digital cameras, and other sensors installed on VTOL-UAV. These technologies offer high-resolution, cost-effective, and timely monitoring of agricultural fields, enabling farmers to make informed decisions with greater precision (Zhang, et al. 2023; Sagan, et al. 2021 and Mohamed, et al. 2022). Multispectral cameras capture data in specific bands of the electromagnetic spectrum. Greyscale or color photos in the visible band can be obtained rapidly with a digital camera (Adão et al. 2017 and Maes, et al. 2025). Its main benefits or attributes include being low-cost, large pixel count and ease of use (Tsouros, et al. 2019 and Batchelor, et al. 2012).

Because of its requirement for extending flight duration and high cruising speed, VTOL-UAV can gather agricultural data over a wide area. Multispectral cameras are pivotal in precision agriculture, enabling the capture of images across various wavelengths beyond the visible spectrum. These cameras are primarily categorized into two types based on their spectral acquisition techniques:

single-lens and multi-lens systems (Zhou, et al. 2020). Single lens camera is used prior to conducting small-scale monitoring with budget or VTOL-UAV weight limits and need basic vegetation data.

On the other hand, multi-lens cameras are considered for high-accuracy, high-speed data for large farms, multiple crop types, or advanced crop health diagnostics (Ansari, et al., 2024). High-resolution multispectral cameras that are used in VTOL-UAV are often expensive and not feasible for small to medium scale farming field purposes (Cucho-Padin, et al. 2020). Few studies investigate the effectiveness of low-cost digital cameras for agricultural monitoring, despite their accessibility and potential benefits when paired with proper calibration and correction techniques.

In this study, low-cost camera mounted on VTOL-UAV showed that it can be effectively used for aerial photometry and generate orthophoto imaginary production. This system can also capture the images with suitable resolution for mapping and monitoring activities in agriculture. Through careful VTOL-UAV flight planning, camera calibration, and image processing, it is possible to produce fairly accurate geometric for scale and minimized distortion. There is insufficient exploration of how a hybrid VTOL-UAV collecting agriculture aerial images from low-cost cameras that can be processed to match the geometric remote sensing products. The objective this study was to assess the performance of VTOL-UAV and capturing camera system for generating orthophoto in case study research.

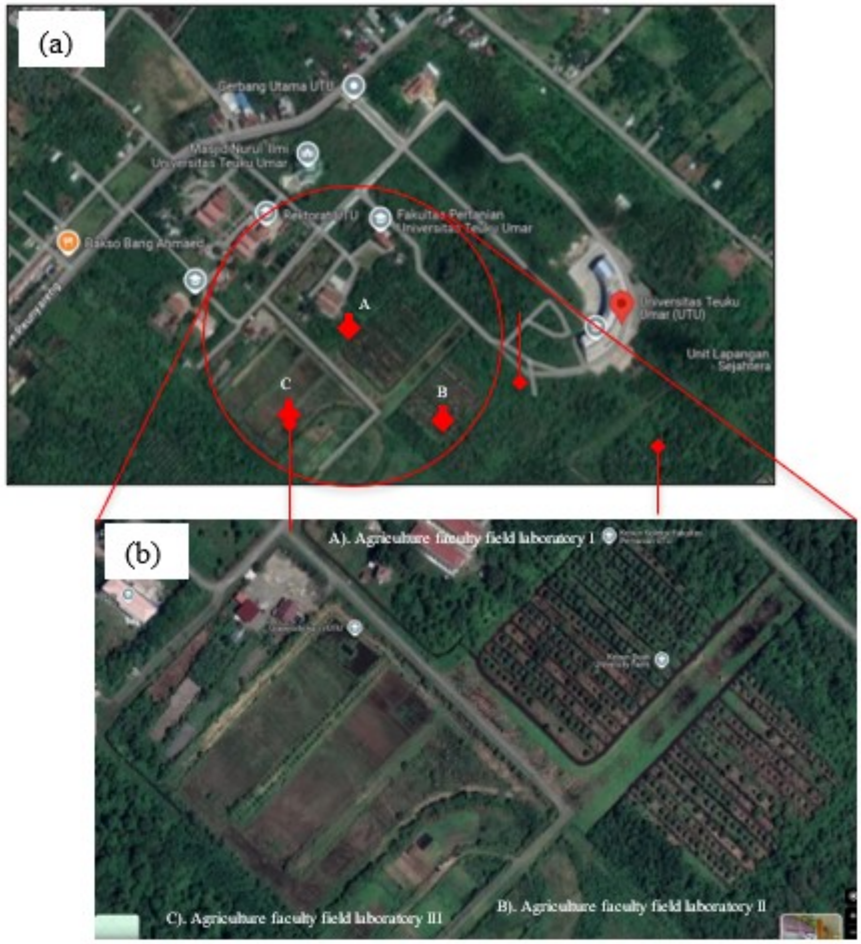


Figure 1. Research study location, Universitas Teuku Umar (UTU), Indonesia.

(Note: The red circle and lines are the planned flight area. (a) site-plan of UTU, (b) agriculture faculty field laboratory II, and (c) agriculture field laboratory III).

MATERIALS AND METHODS

Study Area

The study was conducted at the Universitas Teuku Umar (UTU) Campus, Meulaboh, West Aceh, Indonesia. The UTU campus has an area of approximately 94 hectares. Test site area including the agriculture field laboratory, was approximately (a) 0.015 km^2 (140 m x 110 m), and (b) 0.012 km^2 (120 m x 100 m) and (c) 0.0468 km^2 (260 m x 180 m) were imaged using a VTOL-UAV.

The (a) site was specified as location for image sweeping (**Figure 1**).

Table 1. VTOL UAV and camera characteristics.

FEATURE	SPECIFICATION/ DESCRIPTION
VTOL-UAV Model	Skywalker Fixed-wing
Payload Capacity	3.5 kg
Flight Time	Up to 40 minutes
Maximum Speed	65 km/h
Endurance	Flight distance up to 30 km and time fly up 40 min
Autopilot System	Full Autopilot & VTOL Pixhawk Cube Set
Multispectral Camera	20 Megapixel Canon IXUS

Table 2. A-fixed wing VTOL-UAV configuration.

PARAMETERS	SPECIFICATIONS
Wingspan	1800 mm
Wing area	45.28 dm^2
Length	1300 mm
Takeoff weight	2000-4800 g *
Center of Gravity	Backwards 90-100 mm from wing front edge
Motor	x2820 800kv prop 12x6 4s or x3520 520kv 6s
ESC	60 A, Servo 12 g x 4 pcs
Propeller	12x6
Battery	14.8 V 10000 mAh / 22.2 V 6000 mAh
Remote control:	4 CH
Engine room space	350*100*100

VTOL-UAV system

A DIY of fixed-wing VTOL-UAV 1800 wingspan was operated for aerial image acquisition. The characteristics of VTOL-UAV, sensor and digital camera used in this study are presented in **Table 1**.

The quad-X-cruise pattern configurations was implemented for fixed-wing VTOL-UAV. It used a conventional pusher and added a quadro-copter in X formation to the aircraft wings. **Table 2** and **Figure 2** illustrate the VTOL-UAV system used in this study.

METHODOLOGY

In this study, the standard procedure or workflow for capturing aerial images using a VTOL-UAV is illustrated in **Figure 3**.

The process begins with VTOL-UAV aircraft system setup. Flight planning was conducted by setting some parameters which included speed between 65 km/h, the camera angle 90 degrees (intake upright or vertical), altitude between 50-200 m, and the height of the building within the coverage area. The flight overlaps between 60-70 % flyaway in accordance with the chart in the flight plan that was generated. The flight duration was up to 40 min with a maximum flight altitude of 200 m and a maximum route length of 30 km with a minimum safe flight altitude of 150 m.

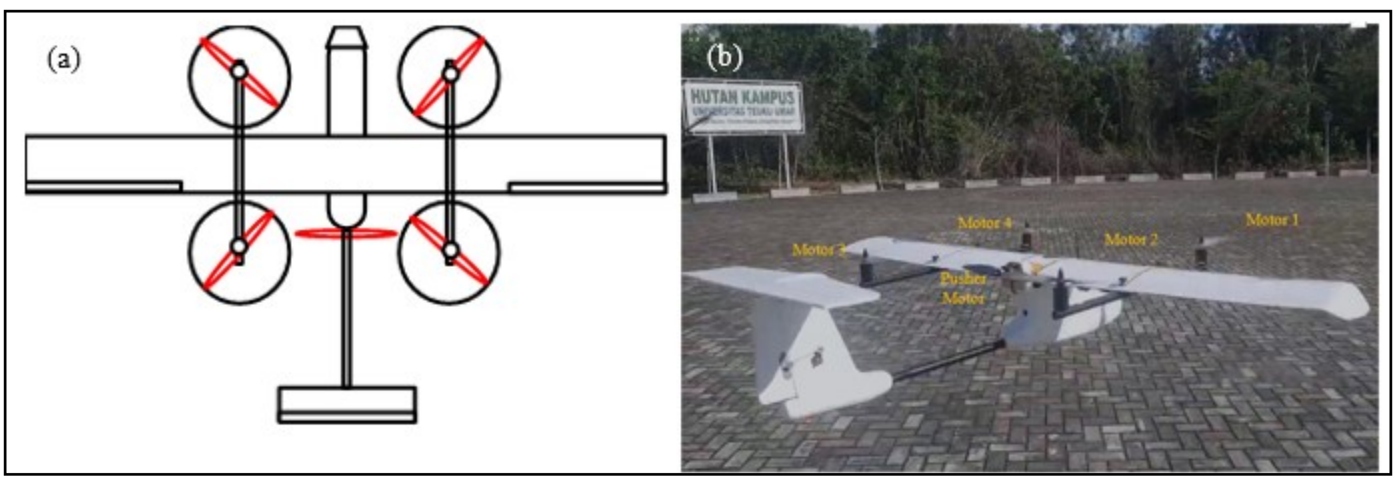


Figure 2. Illustration of the VTOL-UAV system. (a) layout a X-cruise VTOL-UAV , and (b) the developed VTOL-UAV based on Skywalker platform.

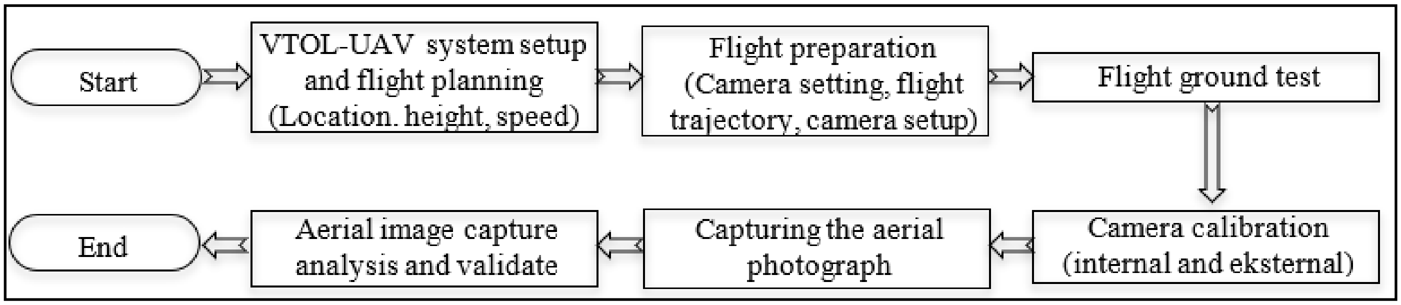


Figure 3. Workflow of VTOL-UAV capturing aerial image.

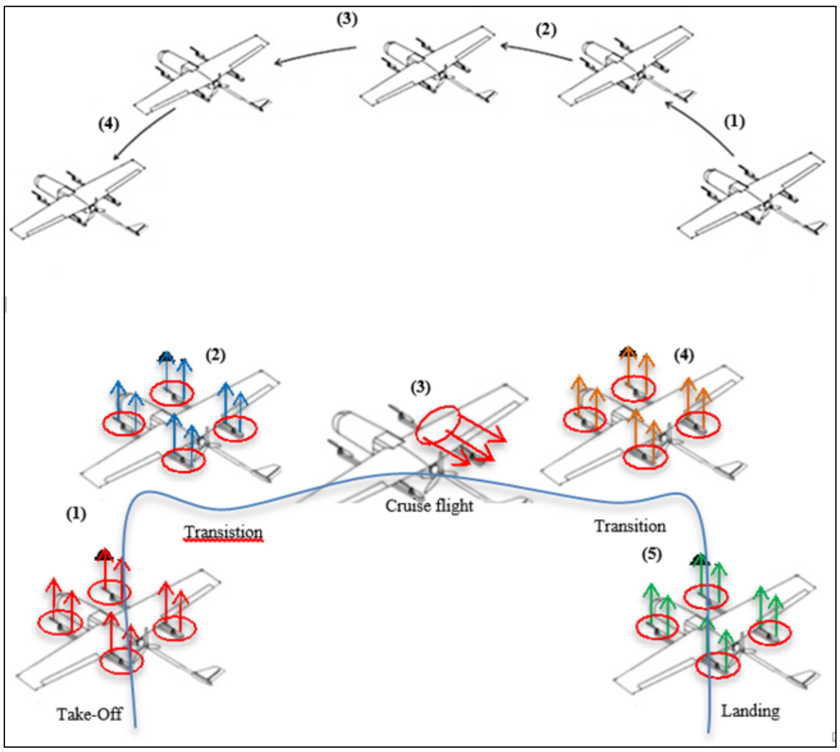


Figure 4. Mission profile and sequence of propulsion control modes during a flight mission.

The shooting area for 1 flight at a scale of 45 ms/ pixel was captured at a normal speed and a maximum take-off weight of 4,8 kg. Pixhawk autopilot system for automatic flight control and Taranis remote controller for manual operation of the UAV. **Figure 4** illustrates the flight mission profile and sequential of propulsion control modes.

Moreover, the GPS receiver for accurate positioning was set up. A Canon Digital IXUS 185 which is a non-metric digital camera with 8 x optical zoom (28-224), 20 MP was used to capture the image. It allowed the VTOL-UAV recording of the agriculture aerial images, real-time position and attitude information. The camera system was prepared for mounting and installing on VTOL-UAV and was set at the configuration components. The camera was programmed to operate automatically, allowing it to capture surface images without manual control during flight.

The VTOL-UAV system with the components of a monitoring camera, GPS and image processing software were employed for reconstructing geographical surface model, as shown in **Figure 5**. The compiled electronic maps of the fields such as contour, area, image quality were analyzed using the ArduPilot mission planner and a Geographic Information System (GIS Software). The system was connected to both an Inertial Measurement Unit (IMU) and a Global Positioning System (GPS) to ensure accurate data on the camera position and orientation.

The camera focal length was determined, and calculations on Ground Sample Distance (GSD) were made to achieve the desired image resolution and coverage. Following this, a flight trajectory was generated for the UAV to follow around the UTU campus area. Image capture points along this route were identified using tools such as Google Maps or existing location maps. Ground truth data was then collected at these points to assist with validating and geo-reference of the captured aerial imagery.

The imaging performance of the camera system was evaluated based on the quality and consistency of image capture with respect to pixel size on the ground (cm/pixel). To determine the flight altitude, the target of image should be the 5-10 times of GSD (He, et al. 2012 and Pepe, et al. 2018). For instance, the flight height below ground ranged was 0.938 km to 2 km. The GSD is expressed with respect to the flight height (H), focal length (f), and pixel size (μ), as shown in **Equation 1**.

$$GSD = \frac{H}{f}\,\mu \qquad \textit{Equation 1}$$

The pixel size can be calculated following the **Equation 2**.

$$\mu = \frac{HW}{S_w} = \frac{H}{S_H} \qquad \textit{Equation 2}$$

Where: width of CCD (W), number of pixels for W (S_W), and number of pixel for H (S_H).

Before the actual flight, a ground test was performed to ensure the system operates correctly and reliable prior to aerial deployment. This assessment included synchronizing between image capture rate and shutter speed and validating the accuracy of the georeferenced coordinates and the captured images. The data collected during this test was used to calibrate the camera system. Internal recalibration included adjusting camera settings like focal length, aperture, shutter speed, and exposure time. External recalibrations involved modifying the camera physical setup, such as its alignment and mounting on the VTOL-UAV. These adjustments are essential for optimizing the system performance before flight operations. The calculation and specifications of the camera performance were used for sweeping and capturing the images, are shown in **Table 3**. The VTOL-UAV was prepared for flight and capture aerial images after successful calibration.

Table 3. A-Ixus 185 Canon camera specification.

PARAMETERS	DESCRIPTION
Coverage area	UTU area (a) site 0,0154 km^2
Flight number and Flight trajectory	15 and 38
Camera	5152, 3864 pixel
Sensor	4,55 mm/pixel ; 0.0012 mm
Ground resolution	3.59 cm/pixel
GSD	0.027 m
Sweeping width and length	15000/swept = 185,1 m and 136.5 m
Path and Exposure of distance	74.04 and 40.95
Shutter speed	45 ms/image
Aerial photograph number	433

The aerial photograph was processed by standard image data and integrated with satellite images. During the VTOL-UAV operations, the acquired images were stored on a SD card of the camera. The positions and attitudes of the VTOL-UAV were logged and determined in real-time on board connecting to the geo-reference system. The flight planning was setup for controlling the mission planning and flight control.

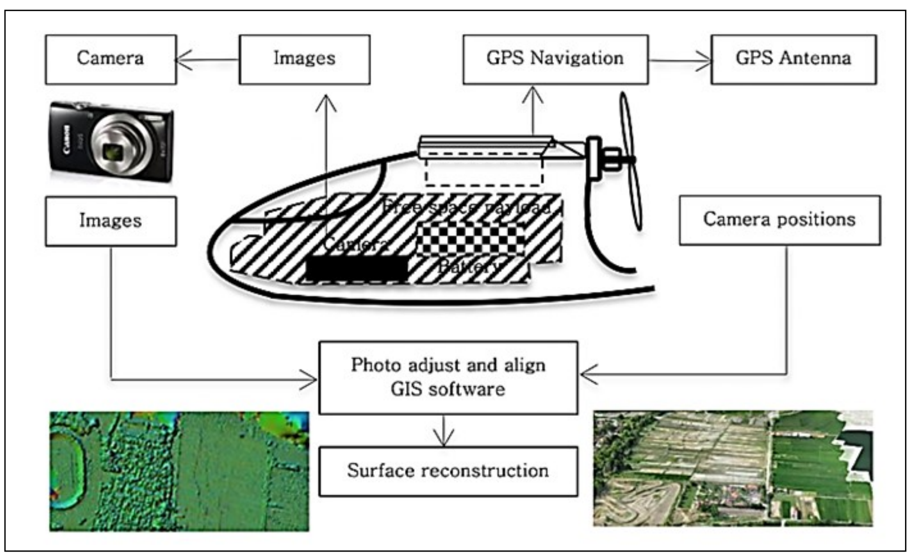
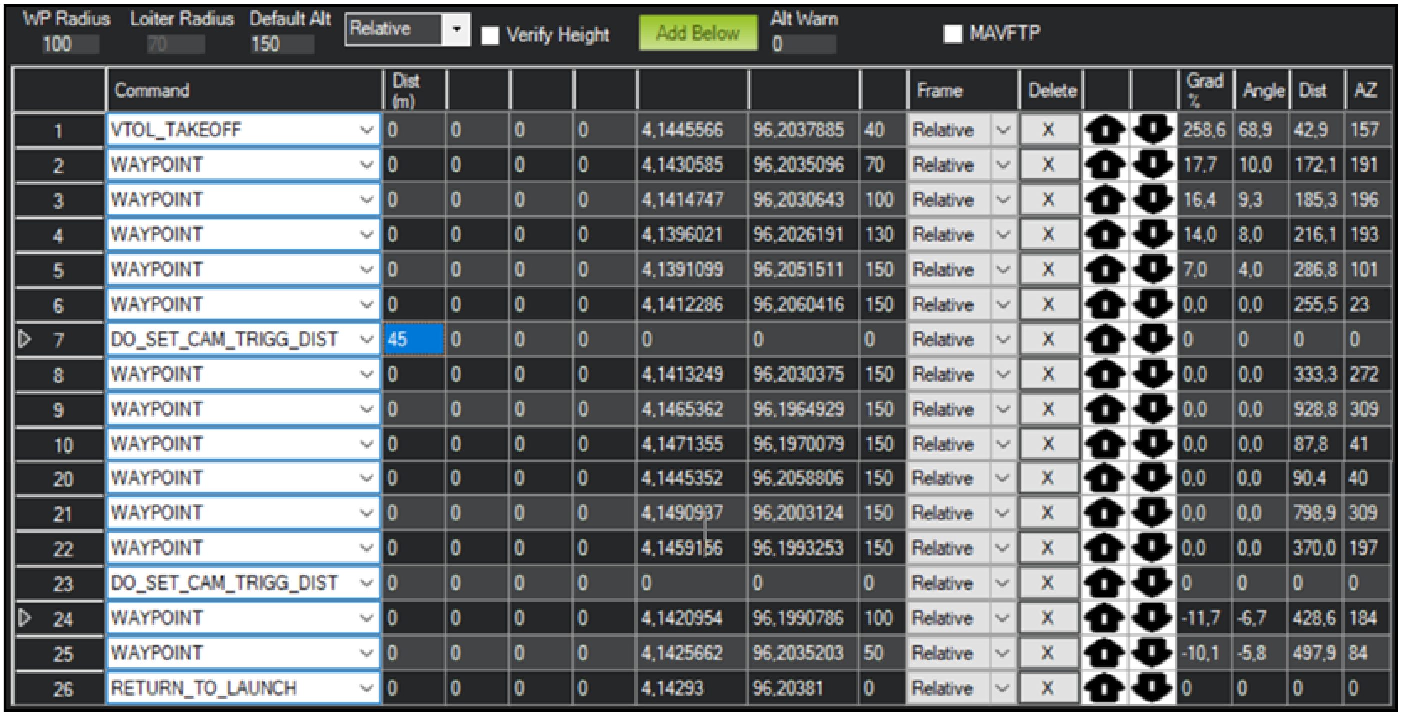


Figure 5. The platform of VTOL-UAV system and components.



WP Radius 100 | Loiter Radius 70 | Default Alt 150 | Relative | Verify Height | Add Below | Alt Warn 0 | MAVFTP

	Command	Dist (m)							Frame	Delete			Grad %	Angle	Dist	AZ
1	VTOL_TAKEOFF	0	0	0	0	4,1445566	96,2037885	40	Relative	X			258,6	68,9	42,9	157
2	WAYPOINT	0	0	0	0	4,1430585	96,2035096	70	Relative	X			17,7	10,0	172,1	191
3	WAYPOINT	0	0	0	0	4,1414747	96,2030643	100	Relative	X			16,4	9,3	185,3	196
4	WAYPOINT	0	0	0	0	4,1396021	96,2026191	130	Relative	X			14,0	8,0	216,1	193
5	WAYPOINT	0	0	0	0	4,1391099	96,2051511	150	Relative	X			7,0	4,0	286,8	101
6	WAYPOINT	0	0	0	0	4,1412286	96,2060416	150	Relative	X			0,0	0,0	255,5	23
7	DO_SET_CAM_TRIGG_DIST	45	0	0	0	0	0	0	Relative	X			0	0	0	0
8	WAYPOINT	0	0	0	0	4,1413249	96,2030375	150	Relative	X			0,0	0,0	333,3	272
9	WAYPOINT	0	0	0	0	4,1465362	96,1964929	150	Relative	X			0,0	0,0	928,8	309
10	WAYPOINT	0	0	0	0	4,1471355	96,1970079	150	Relative	X			0,0	0,0	87,8	41
20	WAYPOINT	0	0	0	0	4,1445352	96,2058806	150	Relative	X			0,0	0,0	90,4	40
21	WAYPOINT	0	0	0	0	4,1490937	96,2003124	150	Relative	X			0,0	0,0	798,9	309
22	WAYPOINT	0	0	0	0	4,1459156	96,1993253	150	Relative	X			0,0	0,0	370,0	197
23	DO_SET_CAM_TRIGG_DIST	0	0	0	0	0	0	0	Relative	X			0	0	0	0
24	WAYPOINT	0	0	0	0	4,1420954	96,1990786	100	Relative	X			-11,7	-6,7	428,6	184
25	WAYPOINT	0	0	0	0	4,1425662	96,2035203	50	Relative	X			-10,1	-5,8	497,9	84
26	RETURN_TO_LAUNCH	0	0	0	0	4,14293	96,20381	0	Relative	X			0	0	0	0

Figure 6. The flight planning setup from mission planner interface.

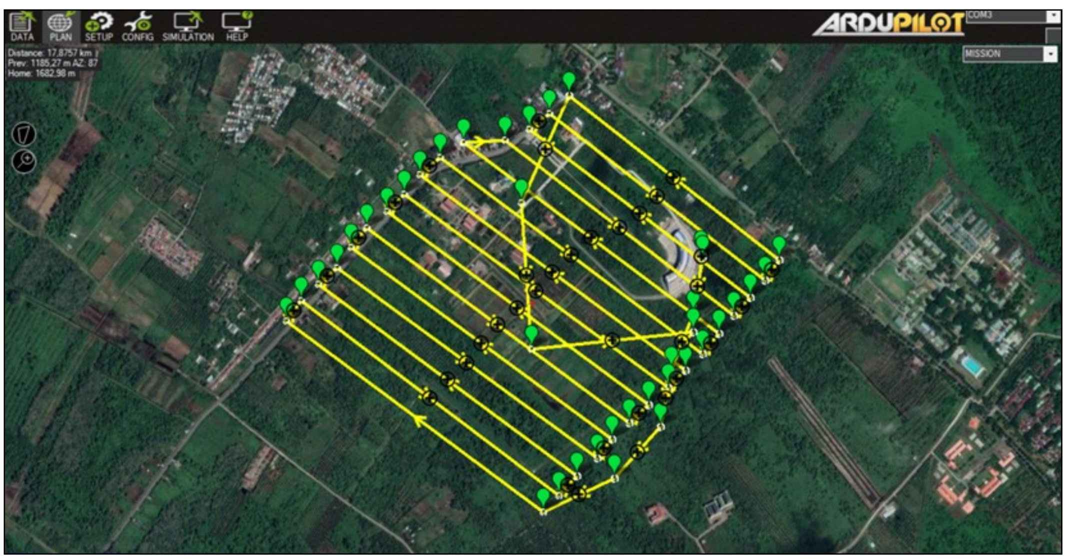


Figure 7. Predefined waypoints and flight trajectory line.

A notebook with Intel® Core™ i5 processor was used for data processing and report generation. In addition, the software used to support this study was Windows 10 Professional 64-bit operating system. For aerial photo processing, Mission Planner was the flight path planning simulator and open-source software for camera calibration and GIS software. Orthophotos were generated using Agisoft Metaphase and evaluated for geometric accuracy using 10 ground control points measured with an RTK-GPS.

RESULTS AND DISCUSSION

The VTOL-UAV aircraft flight test was conducted to automatically hover at a predefined waypoint 150 m above the ground for 30 min at the University Teuku Umar campus. Data acquisition recorded by

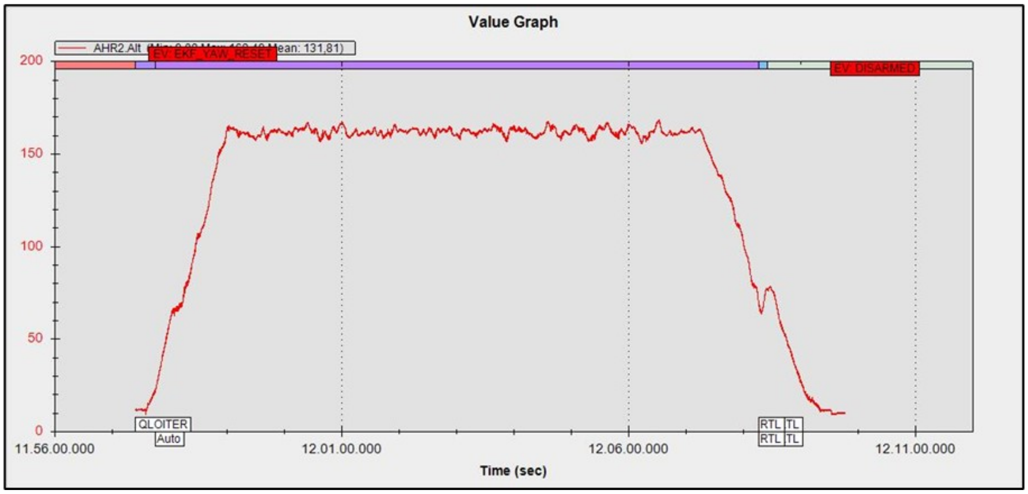


Figure 8. The altitude and heading reference flight height.

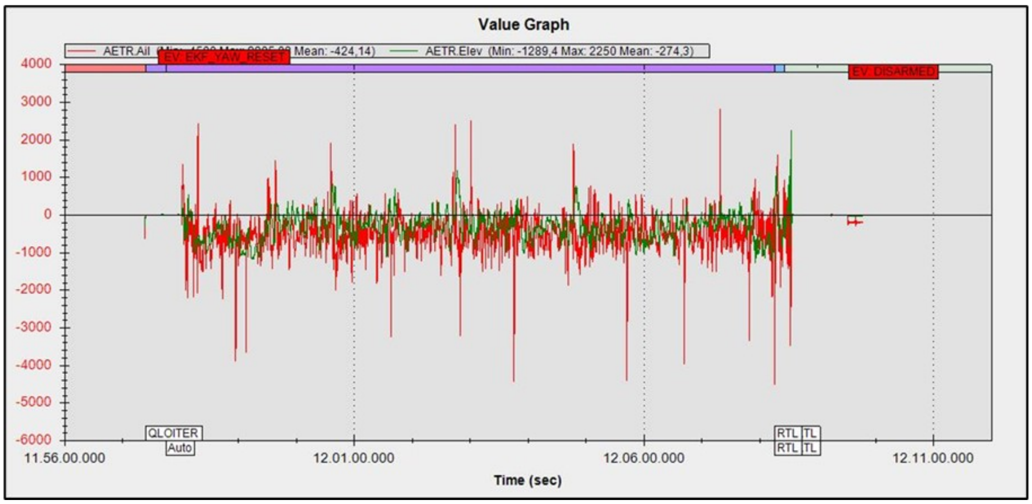


Figure 9. Aileron and elevator at flight position.

Figure 10. The angle of fuselage in the experiment at Roll, Pitch and Yaw angle.

VTOL-UAV monitoring system produced aerial photography data. A pre-planned autonomous flight was carried out by mission planning of the VTOL-UAV to simulate a typical survey mission. The VTOL-UAV followed a flight trajectory designed to fully cover UTU area (a) site measuring 15.4 km^2.

The flight planning mission allowed the VTOL-UAV flight along waypoints as presented in **Figure 6**. Flight planning mission prior to setup including the flight height (150 m), flight speed (10 - 20 m/s), and image overlap (60%, 70%) were chosen to match common standards used in agricultural mapping. This method ensured consistent data collection across the entire area (Roncella et al. 2021).

This flight pattern ensured that the aerial images had enough overlap for later processing. Flight path planning involved designing the VTOL-UAV trajectory to ensure comprehensive coverage of the target area. This study employed 18 flight lines and 38 flight trajectory numbers in a single flight session as presented in **Figure 7**.

Figure 11. A digital photogrammetric UTU captured from VTOL-UAV camera: (a) blur image, overlapped speed; (b) open exposure image; and (c) Bright captured image at 150 m.

Figure 12. Tailored aerial photo map (ortho-photograph) UTU campus.

The flight test was conducted with the objective of full flight in the mission profile setup. The results of flight test were shown in **Figure 8** to **Figure 10**. The data presented the estimation of the aircraft altitude, attitude, elevation, and ground speed.

At the initial and final stage of flight, from 0-10 seconds, power modulation value was similar for all motors used. Altitude and Heading Reference System (AHR2) in mission planner referred to the altitude estimation system (altitude mean 131.8 m) used for determining the orientation of the VTOL-UAV. Altitude, Elevation, Throttle, and Rudder (AETR) mission planner configuration ensured that the VTOL-UAV operation was correctly interpreted and executed for precise control of the aircraft as defined in a planned mission. In this flight test, a pre-defined mission was carried out by the VTOL-UAV simulation.

The mission planning was designed and tracking system pointed to the UAV during the whole mission. The maximum altitude was set at 150 m, whereas AETR altitude mean 274.3 for PWM (Pulse Width Modules) values are shown in **Figure 9**. The Roll (mean 2,91), Pitch (mean 3,92) and Yaw angle (mean 197.44) response of the tracking system and keep maintain stability during cruise flight are shown in **Figure 10**. Based on the altitude, the average in steady state was lower than a standard deviation of the Roll and Pitch controllers.

The VTOL-UAV flight in different speed resulted to a wide swept area during a mission. Flight in high-speed require vertical overlap and increase the frequency of image captured. In some situations, reducing the flight speed was necessary to maintain image quality and ensure the safety of the operation.

The aircraft pitch angle was to rise while the flight speed increased leading to inconsistency picture angles and low-quality images. The

VTOL-UAV moving at the camera exposure generated blurring image. It also reduced image sharpness, detail and photogrammetric accuracy, as presented in **Figure 11**. A swept flight camera of digital photogrammetric were a dense farm with blur image, 378 pixels and 73 dpi (**Figure 11a**).

The overlapped speed during swept at farm field whereas the open exposure, 186 pixels and 35 dpi (**Figure 11b**). For bright captured image at 150 m, 951 pixels and 75 dpi (**Figure 11c**). Motion blur is typically measured as a percentage of the ground sampling distance, which is permitted for blur levels up to 150% GSD VTOL-UAV flight at 2 m/s with a shutter speed of 1/500 s, and travels 4 mm shutter was open enough to produce visible blur. Modern camera has included built-in stabilization in their sensors or lenses, which helps greatly in minimizing motion blur.

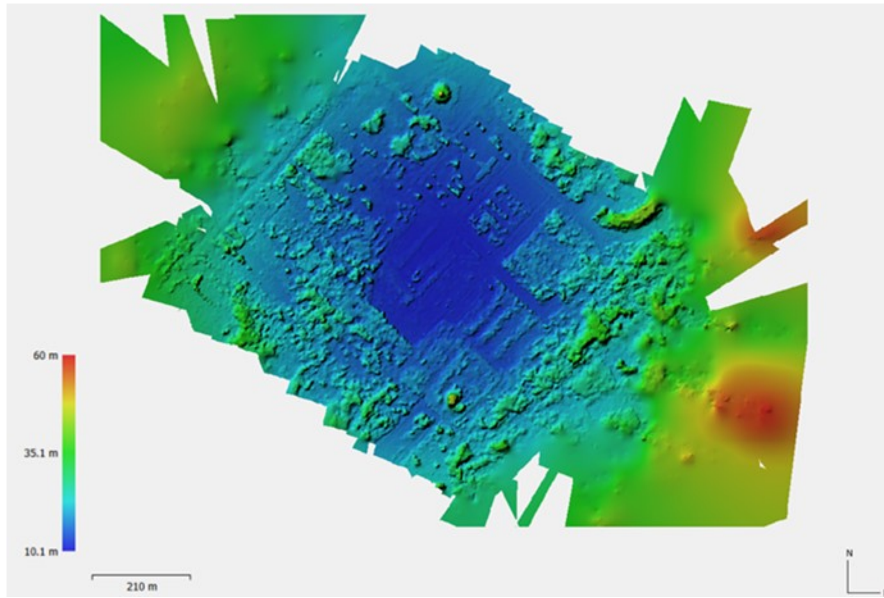


Figure 13. Digital model of the UTU agriculture field.

The digital agriculture field model requires informative and basis for the rational use of agricultural land analysis. During the agriculture ortho-photograph maps generation, the area calculations of each field were taken into account. A digital model of UTU agricultural fields was generated using GIS image processing as presented in **Figure 12**. The result of generating ortho-photograph uses the same principle as traditional photographs. The approaches results were in 3D structures obtained from several overlapping images due to geometry and location, as shown in **Figure 13**.

The photogrammetric method showed poor performance in areas with uniform texture, often producing gaps, or low-density point clouds. Elevation errors were also found in complex terrain and buildings (10 to 60 m) that are located near hills. In these cases, the elevation at the building base was incorrectly blended with the slope, causing some pixels to be assigned higher values than they should. These issues are mainly due to inaccuracies in generating process of the digital surface model.

CONCLUSION

In this study, a VTOL-UAV with low-cost camera was developed for agricultural land mapping. The aerial captured images were tailored a map of the University Teuku Umar agricultural field and the photogrammetry with a total of 433 photos. The test flight at 150 m in height, approximate flight speed 16 m/s, and image overlap 70% present the fairly accurate images.

This indicated that the images taken were mostly correct with minor deviations from the true images of the area. The blurring image was found to be the cause by overlapping the speed and open exposure as well as the experienced machine vibrations during flight. By maintaining the altitude, reference system and flight speed, it stabilized the orientation and reduced the vibration fixing any distortions from the VTOL-UAV system. Tailoring of agricultural map (ortho-photograph) and surface model presented the geo-references images for monitoring and decision-making in agriculture application particularly for smallholder farms.

RECOMMENDATIONS

The VTOL UAV system using a low-cost digital camera has shown good potential for agricultural monitoring. However, to improve image quality, it is recommended to add a camera gimbal. This would help reduce vibration and keep the camera steady and pointed straight down during flight.

The UAV's speed during turns should also be studied further as slowing down in turns can affect how the images are captured. Creating accurate orthophotos and mosaics still requires a lot of work, especially in checking for errors and making sure the results are precise. In addition, image quality checks should not only focus on resolution (GSD), but also look at issues on blurry images and incorrect exposure.

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