HIGH ACCURACY DIRECT GEOREFERENCING OF THE ALTUM MULTI-SPECTRAL UAV CAMERA AND ITS APPLICATION TO HIGH THROUGHPUT PLANT PHENOTYPING

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ABSTRACT:

Direct Georeferencing (DG) of imaging sensors using Differential GNSS and Inertial sensors to create highly efficient geospatial products without the use of Ground Control Points and traditional Aerial Triangulation has been a proven technology on manned aircraft for almost 20 years. Large area mapping is now done from the air with highly automated data collection and streamlined data processing workflows that require little if any human intervention.

With the appearance of cost effective, easy to fly Unmanned Aerial Vehicles (UAV), a new type of data collection has been enabled that cannot be done from traditional manned platforms: super high resolution multi-spectral, precisely georeferenced imagery and point clouds, collected over high value targets. The high spatial resolution and precise georeferencing accuracy makes information extraction and advanced analytics possible both in the spatial and temporal domain at scales simply not possible to collect from manned aircraft, and at much greater efficiency than can be collected from the ground. Applications include, but are not limited to, railway track survey and monitoring, construction site as-built surveying and monitoring, high-resolution inspection, and crop health/harvest monitoring and plant phenotyping.

As with manned applications, the use of Direct Gereferencing on UAV imaging payloads is proving to add a new level of efficiency to collecting these high resolution data sets, especially in the area of fast, repeatable results without the need for setting up extensive Ground Control Points and the flying of extensive side-lap required for traditional AT. The combination of this technology with new, high resolution, multi-spectral cameras built specifically for UAV applications brings a new level of automated analytics capabilities that up until now has been highly manual and inefficient.

One example of this is plant phenotyping for experimental research. Here a high-accuracy spatial reference needs to be assigned to each plot entry in an experimental layout to enable accurate and efficient plot level statistics of plant phenotypic attributes, such as leaf water content, nitrogen content, and leaf length. Repeatable, accurate knowledge of the plot boundaries must be known in the multi-spectral imagery collected from the UAV to eliminate errors in the statistics. While manual plot boundary delineation, pattern-based methods using field plans, and image based methods using computer vision are currently used, each method can be time consuming and be influenced by other limitations unique to its approach. An efficient and accurate method is to use Directly Georeferenced imagery and overlay this with high accuracy RTK GNSS plot positions from the equipment used to do the planting.

The Trimble APX-15 UAV Direct Georeferencing solution from Applanix is a highly advanced Differential GNSS – Inertial solution developed specifically for UAV mapping applications. Complete with the POSPac UAV office and cloud based post-processing software, it enables camera pixels and LIDAR points to be geolocated at the cm-level in a highly accurate and automated fashion.

The MicaSense Altum camera is a next generation high-resolution thermal, multi-spectral and RGB compact camera designed for UAV's. It integrates a radiometric thermal camera with five high-resolution narrow bands, to produce fully calibrated and synchronized thermal, multi-spectral and high-resolution RGB imagery in a single flight for performing advanced analytics.

This paper presents results from an integration of the Trimble APX-15-EI UAV Direct Geroreferencing with the Micasense Altum camera to produce a highly accurate and efficient UAV based mapping solution for advanced spatial and temporal analytics. First an overview the APX-15 Differential GNSS–inertial technology and Altum camera technology is presented. This is followed with a detailed description of how the two were integrated on a DJI M600 with Ronin stabilized mount, taking care of the precise time alignment required to enable Direct Georeferencing. Results from a series of flight tests at approximately 4 cm Ground Sample Distance (GSD) over a test range outfitted with GNSS surveyed Ground Control Points (GCP's) are then presented, showing that after boresight calibration and using a self-extracted DEM, an orthomap accuracy at the level of 3 cm RMSx,y horizontal was achieved.

Finally results are presented for the same system flown over a test field operated by researchers at the University of Guelph containing plots of soybean to generate a Directly Georeferenced orthomosaic and DEM map from the Altum camera at approximately 2.6 cm GSD. Accuracy assessment against GCP's surveyed by the University showed results at the level of 6 cm RMSx,y Horizontal, and 11 cm RMS Vertical. Cm-level plot boundaries that were previously surveyed were then overlaid on the Directly Georeferenced orthomosaic from the Altum camera showing alignment to within a few pixels.

The results prove that the MicaSense Altum multi-spectral UAV Camera integrated with the Trimble APX-15-EI UAV Direct Georeferencing solution can produce highly-accurate, repeatable large scale map products without the use of GCP's, ideal for applications such as plant phenotyping. The benefits of such a solution include:

- better plot-level geometry for machine learning of phenotyping analysis, resulting in greater accuracy and efficiency
- lower cost by removing the laborious processing of having to redefine the plot boundaries for every flight throughout the season
- more accurate height and volume information leading to better biophysical attributes of the plant canopy

1. INTRODUCTION

Direct Georeferencing (DG) of airborne imagers using GNSS-Aided Inertial systems as an alternative or complement to Aerial Triangulation (AT) has been a standard for manned applications since the early 2000's (Hutton et al., 2005). More recently it has also been adopted for use with small and medium format cameras and LiDAR on Unmanned Aerial Vehicle (UAV) platforms (Mian et al, 2015).

DG brings several advantages to airborne mapping that include eliminating the need to use Ground Control Points (GCP's) to do georeferencing, reducing sidelap and endlap (or even no sidelap or endlap) requirements, and sensor fusion of multiple imaging payloads in a single platform (such as a LiDAR with a camera). Each of these greatly reduces the cost and increases the overall efficiency of airborne mapping.

UAV platforms provide a new and powerful method of surveying using GNSS. Instead of being limited to the ground and measuring discrete points with a GNSS receiver operated by a human, a UAV with a Direct Georeferencing system moves the GNSS receiver into the sky to a vantage point where it can measure multiple points at once using an imager such as a LiDAR or a camera. With a UAV, GNSS becomes a much more viable and cost effective method to accurately georeference data, enabling activities such as temporal analysis to be conducted for applications where GNSS collected from the ground might not be practical or simply too costly.

One such application is plant phenotyping for experimental research. Plant phenotyping is generally defined as the quantitative assessment of specific characteristics and traits of plants such as: growth, yield, stress, development, maturation, tolerance, resistance and biomass. An important part of this assessment is how these characteristics and traits change over time. While there are many ways of performing plant phenotyping including destructive and non-destructive means, remote sensing using images collected from satellites or airplanes is a popular method of choice due to its productivity. However there are limitations to this approach, primarily the resolution of the imagery may not be sufficient to identify plot boundaries, and accurate georeferencing is required to perform objective temporal analysis. Data collected from UAV's can solve the issue of resolution, and the use of high accuracy georeferencing of the imagery allows for precise, repeatable alignment with pre-surveyed plot boundaries (Bruce et al. 2020). This paper investigates the use of Direct Geroeferencing on a UAV based multi-spectral imager to efficiently achieve the cm level positioning accuracy required to align the imagery with pre-surveyed plot boundaries, all without the use of GCP's.

2. DESCRIPTION OF EQUIPMENT

2.1 Trimble APX-15-EI UAV

The Trimble APX-15-EI UAV manufactured by Applanix, is a high-performance GNSS-Aided Inertial system designed specifically for Direct Georeferencing on UAV's. It is comprised of a single board GNSS-Inertial module with dual inertial measurement units (IMU) and POSPac UAV post-processing software. One IMU is embedded onto the main board (onboard IMU), while the second IMU is remote (remote IMU) and can be mounted externally onto an imaging sensor.

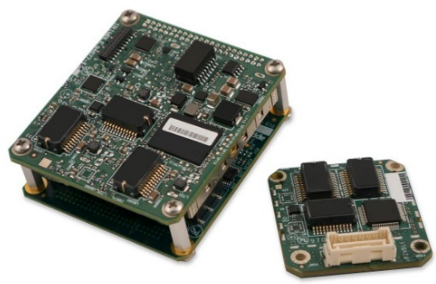

Figure 1: Trimble APX-15-EI UAV with onboard and remote IMU's

A key functionality of the APX-15-EI UAV is the computation of the position of the imaging sensor origin (ie the camera perspective centre or LiDAR origin). This is achieved by using the orientation computed by the IMU and the fixed lever arm (3D offsets) from the sensor origin to the GNSS antenna phase centre (APC) to translate the GNSS computed position to the sensor origin. However when the sensor is mounted on a gimballed mount, which performs active stabilization to keep a sensor heading along the flight path and pointed down, two sets of orientation are required to do the translation: the orientation of the airframe and the orientation of the mount itself. By mounting the APX GNSS-IMU board on the UAV airframe along with the GNSS antenna, and the remote IMU on the sensor attached to the gimbal, the APX-15-EI computes both sets orientation required to do the lever arm translation. The computed positon of the sensor origin is as follows (1):

$$p_c^M = p_G^M - \mathrm{R}_v^M l_{g-G}^v + \mathrm{R}_c^M l_{g-c}^c \qquad (1)$$

where:

p_c^M = position of sensor origin in mapping frame
p_G^M = position of GNSS APC in mapping frame
R_v^M = rotation matrix from vehicle frame to mapping frame computed by onboard IMU
l_{g-G}^v = lever arm from gimbal centre of rotation to GNSS APC in vehicle frame
R_c^M = rotation matrix from sensor frame to mapping frame computed by remote IMU
l_{g-c}^c = lever arm from center of rotation to sensor origin in sensor frame

The POSPac UAV post-processing software provides the following functions:

- Generation of centimetre accuracy combined forward and reverse GNSS-Aided Inertial position and orientation of the sensor using GNSS augmentation data
- Calibration of IMU to camera and IMU to LiDAR boresight angles
- Calibration of Camera interior orientation
- Computation of Exterior Orientation for each image or LiDAR point cloud in local mapping frame and datum.

POSPac UAV support 3 methods of GNSS augmentation:

1. Single GNSS base station
2. Applanix SmartBase post-processed Virtual Reference Station (VRS)
3. Post-processed Trimble Centerpoint RTX (PP-RTX)

For small local area collects, setting out a GNSS reference station like the Trimble SmartTarget base station is a simple way to achieve cm level accuracy.

Figure 2: Trimble SmartTarget Base Station

The Applanix SmartBase module uses existing continuously operated (CORS) networks that are automatically downloaded to generate a VRS without the need to set out a local base station.

The PP-RTX service enables cm level position without the use of base stations, and is ideal for areas that do not have CORS coverage (Mian et al, 2019)

2.2 Micasense Altum Multi-spectral Imager

The Altum is a small, high performance combined multi-spectral and thermal imager designed for UAV mapping applications. It collects imagery in 5 spectral bands (blue, green, red edge and near infrared), along with LWIR thermal, yet with a size of only 8.2 cm x 6.7 cm x 6.45 cm and weight of only 407 grams, the Altum is small enough to fit on even the smallest of UAV's.

Figure 3: Micasense Altum Combined Multispectral and Thermal Imager

With a field of view of 48 deg x 37 deg for the multispectral channels, the Altum can collect imagery with a Ground Sample Distance (GSD) of 5.2 cm at 120 m height above ground, making it ideal for supporting plant phenotyping. The Altum also uses a global shutter and supports up to a 1 second capture rate ensuring crisp and aligned imagery.

2.3 Integration on DJI M600 and Ronin Mount

The APX-15-EI UAV and Altum imager were integrated onto a DJI M600 test platform using a Ronin 3 axis stabilized mount. The APX-15-EI board set was mounted to the M600 airframe and the external IMU was attached to the Altum sensor that was then attached to the Ronin mount.

Also mounted on the airframe was the survey grade, compact GNSS antenna supplied with the APX-15-EI (AV-18 antenna). The antenna was mounted to be the highest point on the airframe, well above any sources of potential interference. The lever arm from the Ronin mount centre of rotation to the external IMU and to the GNSS antenna were measured and entered into the system, along with the lever arm from the onboard IMU to the GNSS antenna. Lever arms were measured to better than 1 cm accuracy.

A key requirement to use DG is the precise time alignment of the image exposures with the GNSS-Aided Inertial solution, in order to accurately interpolate the high rate position and orientation solution to the image times. This was achieved by connecting the mid-exposure pulse from the Altum as an event input to the APX-15-EI. For each image the APX-15-EI was then able to record the exact time of exposure in GPS time.

3. CALIBRATION TEST

3.1 Test Description

On July 31 2019, Applanix performed two flights of the M600 with Altum and APX-15 EI payload (Flight1 and Flight 2) over the Applanix test field. The test field is located approximately 60 km North-east of Toronto, and is comprised of an area of approximately 300m x 400m with 15 surveyed GCP's. The GCP's were surveyed using carrier phase differential GNSS with respect to the ITRF00 reference frame and UTM projection. Accuracy of the GCP's is estimated to be better than 2 cm in each component.

The test field contains a permanent GNSS base station that is used for POSPac post-processing. For the tests a Trimble SmartTarget Base station was also set out.

The two flights were flown at a height above ground of approximately 100 meters, producing a GSD of approximately 4 cm in the imagery. The flights were comprised of 8 East-West strips overlaid with 3 North-South strips, and were flown with 60% endlap and 40% sidelap.

Figure 4: Applanix Test Field Showing GCP Layout

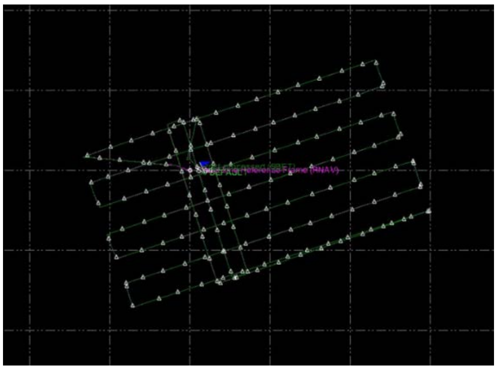
Figure 5: Trajectory Over Calibration Field

3.2 Processing Methodology

The raw data logged by the APX-15-EI for Flight 1 were processed in POSPac UAV along with the data recorded by the dedicated base station to produce a 200 Hz navigation solution with position accuracy at the cm level. This solution was then interpolated to the recoded mid-exposure times and transformed into the Exterior Orientation (EO) for each image with respect to the ITRF00 datum and UTM projection.

The EO and Altum Band 1 images were processed in the POSPac CalQC module to solve for the IMU boresight angles and to calibrate the camera. As a first step, CalQC runs point matching on the imagery to generate pass and tie points using the a-priori EO to speed up and simplify the matching process. A least squares bundle adjustment is then run using the matched points, EO, and GCP's set as control to solve for the IMU boresight and basic camera parameters such as focal length and principle point offset.

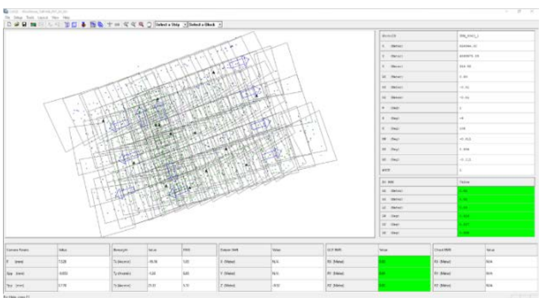
Figure 6: CalQC project for Calibration Flight1

The calibration results from Flight 1 are summarized in Table 1.

Sensor	MicaSense		
Image Size (pixel)	2,064	1,544	
Pixel Size (microns)	3.4		
GSD (m)	0.04		
Flight Height (m)	100		
Overlap / Sidelap	60%	40%	
# Strips	8 E-W	3 N-S	
Focal Length (mm)	7.528		
Principal Point Offsets Xpp (mm)	-0.054		
Principal Point Offsets Ypp (mm)	0.171		
Boresight Angles (min)	-16.16	-1.30	25.33
RMS of Photo Centre Position (m)	0.024	0.029	0.034
RMS of Photo Orientation (deg)	0.018	0.021	0.085
RMS of GCPs (m)	0.03	0.03	0.05

Table 1: Calibration Results, Flight 1

3.3 Accuracy Assessment

The data from Flight 2 were then processed in POSPac UAV using the dedicated base station to generate the EO, which was then loaded into CalQC along with the imagery. This time the IMU boresight angles and camera model computed from Flight 1 were entered and held fixed (locked), and the GCP's were used as checkpoints to validate the calibration (Table 2). The checkpoint residuals were 3.2 cm and 4.5 cm RMS horizontally (approximately 1 pixel), and 11 cm RMS vertically (approximately 3 pixels).

	Residuals (m)		
Point ID	**dE**	**dN**	**dH**
GCP01	-0.012	-0.041	-0.184
GCP02	0.008	0.103	0.035
GCP03	0.025	0.043	0.065
GCP04	0.010	0.034	0.174
GCP05	-0.039	0.029	-0.133
GCP06	-0.046	0.052	-0.088
GCP07	0.041	0.042	0.075
GCP08	-0.014	0.045	0.155
GCP11	0.015	0.057	0.080
GCP12	-0.022	0.009	-0.003
GCP13	0.064	0.033	0.007
GCP14	-0.021	0.015	0.077
Base	0.008	0.022	-0.004
ST31July19	-0.039	0.003	-0.156
Number of Points	**14**	**14**	**14**
Mean Error	**-0.002**	**0.032**	**0.007**
Standard Deviation	**0.032**	**0.032**	**0.111**
RMSE	**0.032**	**0.045**	**0.111**

Table 2: CalQC Checkpoint Residuals, Flight 2

The EO generated for Flight 2 with the IMU boresight applied was then loaded into the Agisoft Photoscan software along with the Altum images to generate a self-extract DEM and orthomosaic at full resolution.

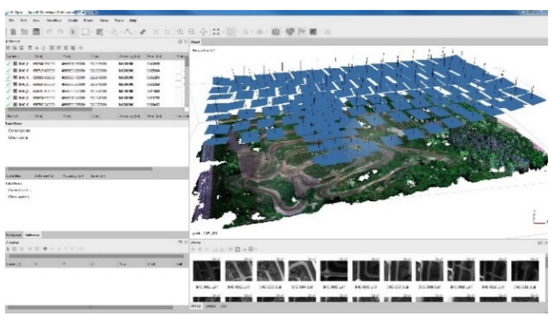
Figure 7: Agisoft Photoscan Project

The orthomosaic was then loaded into Global Mapper and the checkpoints were measured against their known values, producing residuals within 3 cm RMSx,y (Table 3, note: the number of checkpoints assessed in the orthomosaic was limited to those that could be clearly identified, resulting in fewer points being measured than in CalQC).

Point ID	Residuals (m)	
	dE	dN
GCP01	-0.014	-0.014
GCP03	-0.020	0.002
GCP04	-0.018	-0.024
GCP05	-0.013	-0.025
GCP06	-0.001	-0.022
GCP07	-0.008	-0.020
GCP11	-0.017	-0.007
GCP12	-0.008	0.023
Base	0.085	-0.002
Number of Points	**9**	**9**
Mean Error	**-0.001**	**-0.010**
Standard Deviation	**0.033**	**0.016**
RMSE	**0.033**	**0.019**

Table 3: Orthomosaic Check Point Residuals, Flight 2

4. SOYBEAN FIELD TEST

On October 23, 2019, Applanix in conjunction with the University of Guelph, performed two flights of the M600 UAV with Altum/APX-15-EI payload over a soybean research filed located near Guelph Ontario.

The field included several Ground Control Points established and surveyed in the NAD83 datum using GNSS RTK by the University. A Trimble SmartTarget Base station was deployed to act both as a base station for the POSPac UAV processing and as an additional GCP. The SmartTarget Base station coordinates were surveyed using the Trimble Post-processed Centerpoint RTX service built into POSPac UAV, with an estimated accuracy of 1 to 2 cm.

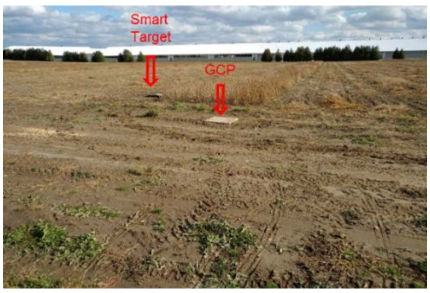

Figure 8: Location of SmartTarget and GCP Tile

The flights were flown at an above ground altitude of 60 m resulting an approximate GSD of 2.6 cm, and with an endlap and sidelap of approximately 60%.

Due to extreme wind conditions, the Ronin gimbal mount malfunctioned on the first flight preventing useful data from being collected. However for the second flight the mount functioned properly and proper data was collected.

4.1 Accuracy Evaluation Against GCP's

Using the calibration obtained from the previous flight tests over the calibration field, POSPac UAV was used to generate the EO for each image, this time in the NAD83 datum and UTM projection to be consistent with the GCP coordinates provided by the University. The EO along with the images were loaded into Agisoft Photoscan where a self extracted DEM and full resolution orthomosaic were generated without the use of the GCP's.

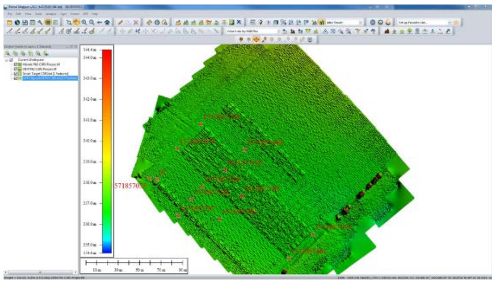

Figure 9: DEM Overlaid with GCP's

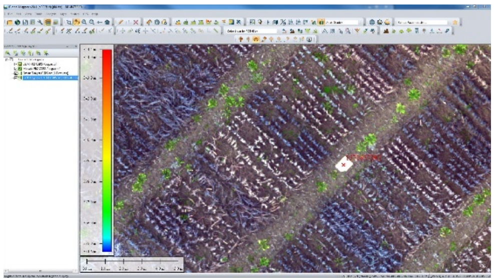

Figure 10: GCP in Orthomosaic

The DEM and orthomosaic were then loaded into Global Mapper, and the GCP's were measured to produce the accuracy statistics shown in Table 4. For this flight the RMSE of the residuals ranged from 3 cm to 6 cm horizontally (approximately 1 – 2 pixels), and 11 cm vertically (approximately 4 pixels).

Point ID	Residuals (m)		
	dE	dN	dH
SmartTarget	-0.066	-0.138	-0.060
1571857055	-0.024	-0.085	-0.154
1571857079	-0.002	-0.078	-0.092
1571857119	-0.021	-0.079	-0.085
1571857185	0.013	0.002	-0.128
1571857210	-0.005	0.027	-0.080
1571857228	-0.020	0.054	-0.141
1571857247	-0.019	-0.038	-0.163
1571857281	-0.037	-0.045	-0.088
1571857302	-0.027	-0.036	-0.127
1571857369	-0.007	0.036	-0.049
1571857401	0.021	0.019	-0.111
1571857433	0.055	0.011	-0.124
Number of Points	**13**	**13**	**13**
Mean Error	**-0.011**	**-0.027**	**-0.108**
Standard Deviation	**0.030**	**0.057**	**0.035**
RMSE	**0.031**	**0.063**	**0.113**

Table 4: Checkpoint Residuals Measured in Orthomosaic and DEM

4.2 Evaluation Against Pre-Surveyed Plot Boundaries

The Soybean field was planted into individual research plots on June 8, 2019. The plot sizes were 1.4 m in length and 5 m in width, with a 35 cm separation. During planting a Trimble TMX-2050 display with built in RTK GNSS was used to record the spatial positions of the plots to within 1 – 3 cm accuracy, from which a plot shape file was produced by researchers at the University of Guelph (Bruce et. al, 2020).

The orthomosaic produced from the Altum sensor and the APX-15-EI UAV was provided to the researchers who overlaid the plot boundaries onto the mosaic. A visual inspection showed accurate alignment of the crops identified in the orthomosaic with the plot boundaries to within a few pixels, easily allowing the plants in a given plot to be correctly identified (Figures 11 and 12).

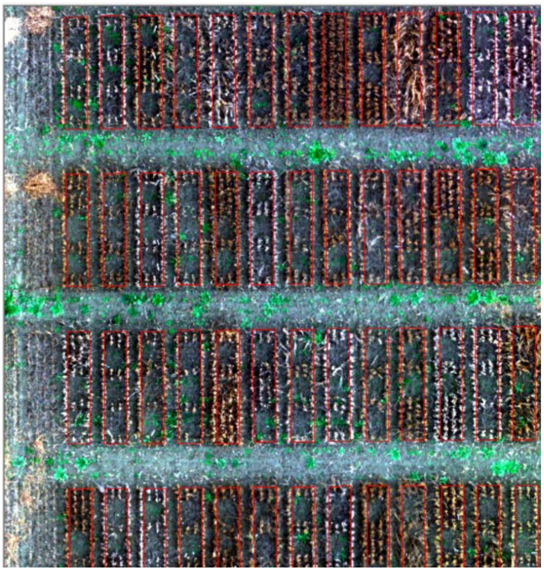

Figure 11: Altum Orthomosaic Overlaid with Plot Boundaries

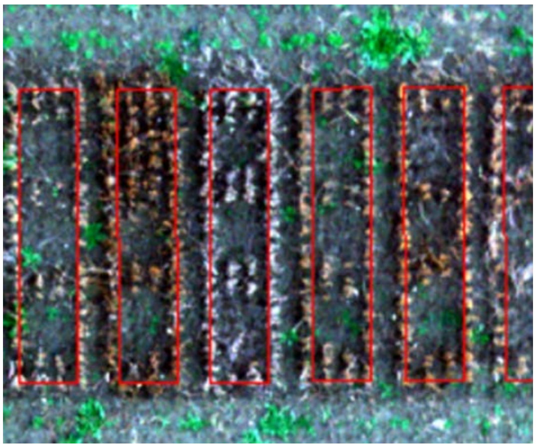

Figure 12: Zoomed View

5. CONCLUSIONS

The Micasense Altum integrated with the Trimble APX-15-EI UAV Direct Georeferencing system on a DJI M600 UAV can consistently produce georeferenced orthomosaics without the use of GPC's to an absolute accuracy level of a few pixels. Flight tests over a soybean research field showed pre-surveyed plot boundaries using RTK could be overlaid on the orthomosaic to an accuracy sufficient to identify the correct plots and plants, thus enabling more efficient plant phenotyping.

Furthermore, the accuracy of the DEM extracted from the Altum imagery was consistently found to be at the level of 11 cm RMS, which is more than adequate for many types of research requiring height information.

6. FUTURE WORK

Future work will include using the Altum and APX-15-EI payload to perform repeated flights over the research plots to investigate automatic temporal analysis.

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