GEO-REGISTRATION OF VIDEO SEQUENCES CAPTURED FROM MINI UAVs – APPROACHES AND ACCURACY ASSESSMENT

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ABSTRACT:

The goal of this project is to geo-register video streams, captured from lightweight UAV (unmanned aerial vehicle) platforms, to a digital 3D landscape model. This category of UAVs encompasses platforms with a total weight of less than 30 kilograms which are mostly equipped with flight control systems. For the determination of platform position and attitude mini UAV systems use low cost and low quality INS and GPS sensors. The challenge is to achieve optimum accuracy and reliability of the geo-referenced video sequence using the position and attitude information from the flight control system together with geometric and semantic information from a 3D landscape model. Possible applications of such integrated systems include real-time mobile mapping of arbitrary objects. Possible mission scenarios range from real-time surveillance of objects and events to the rapid disaster mapping in order to provide up-to-date decision support information.

1. INTRODUCTION

1.1 Motivation

During recent years the development of lightweight UAV systems has progressed very rapidly. Today's systems can be operated autonomously or controlled remotely by an operator. Despite their low weight of only a few kilograms or even less, such UAV systems have the capability to carry lightweight data acquisition sensors such as non-metric video cameras. The direct geo-referencing approach based on high quality INS/GPS sensors is well investigated and established in main-stream airborne photogrammetry. In contrast, mini UAVs are restricted to lightweight and low quality INS/GPS sensors with much lower exterior orientation accuracy. This lower accuracy can be compensated by calculating exterior orientation updates based on image rays to objects of the 3D landscape model.

1.2 Goals and content of the paper

The paper commences with a presentation of the UAV system and sensor configuration used of the test flights. Especially the concept of video data registration and the involved sensors and video camera will be discussed. The following part illustrates the chosen approach of time synchronisation between the video stream and the flight attitude data and the test flight missions carried out. The third chapter describes the calibration process of the video camera and the different geo-registration approaches used, whereby the direct and integrated geo-referencing approaches have been deployed and investigated in detail. In the fourth chapter, a comparison between the accuracies obtained from the different approaches is presented and an assessment of the potential of the integrated geo-referencing approach is provided. Finally, an outlook on future development steps will be given and a possible application scenario will be presented.

2. STARTING POSITION

2.1 UAV platform and sensors

For the acquisition of the test video data presented in this project, the following mini UAV system by weControl (Zurich, Switzerland) and SurveyCopter is used.

UAV category:	mini
empty weight:	8.5kg
maximum payload:	5.5kg
platform (manufacturer):	Copter 1B (Survey Copter)
flight control system:	wePilot1000 (weControl)

Figure 1: Mini UAV system Copter 1B (weControl / SurveyCopter)

The platform is equipped with an integrated flight control system which uses different sensors for determining the flight attitude data. The individual sensors and their technical details are presented in the following table.

Sensors	Type	Sensor category	Accuracy
GPS receiver	μ-blox TIM-LP	navigation grade (C/A-Code processing)	navigation: 2.5m CEP / 5.0m SEP DGPS: 2.0m CEP / 3.0m SEP
INS	Crossbow IMU400CD 100	6DOF MEMS based	bias roll, pitch, yaw <±1°/sec
barometer		air pressure	±2m (depending on air pressure change over mission time)

Table 1: Sensors for flight attitude data determination

The sensor data fusion in the wePilot1000 flight control system is realized with an EKF (Extended Kalman filter). For this purpose only low weight and low cost sensors are used, such as low quality MEMS (Micro-Electro-Mechanical System) based IMU systems and GPS navigation receivers with C/A-Code observations and the possibility for integrating differential pseudorange corrections. These sensors allow automatic platform stabilisation as well as autonomous or remotely controlled navigation. Additionally, it is also possible to use these flight attitude data as exterior orientation information for geo-registering the captured video sequence. However, the attainable geo-registration accuracy is directly dependent on the quality of the sensors used.

For video data acquisition a consumer grade non metric SONY FCB-EX780BP camera was used, which provides an analogue PAL video signal. The captured video signal was transmitted to the base control station via an analogue video data link. (see Figure 2)

2.2 Synchronisation of flight attitude data and video stream

In order to enable the geo-referencing of a video stream captured with a mobile platform, exterior orientation parameters have to be continuously available. The flight control system provides the platform position and attitude in time discrete steps (5Hz). As a result, the exterior orientation of each video frame of the stream can be determined from the corresponding flight attitude data by complementing the video stream with a time reference. This integrated time information has to be related to the time reference used in the determination of the flight attitude data. Figure 2 illustrates the deployed approach for integrating time information into the video stream.

As illustrated in Figure 2, the flight control system as well as the time code generator use GPS time, i.e. derived UTC as time reference. The time code generator integrates time stamps into the analogue video stream. The bias of time synchronisation between flight attitude data and video frame has the following two main causes:

- The actual accuracy of the time determination by both GPS receivers.
- The latency introduced by the video signal transmission from the sensor platform to the base control station.

The second bias is negligible for the targeted short range applications using analogue video transmission since the video signal transmission is roughly directed by speed of light.
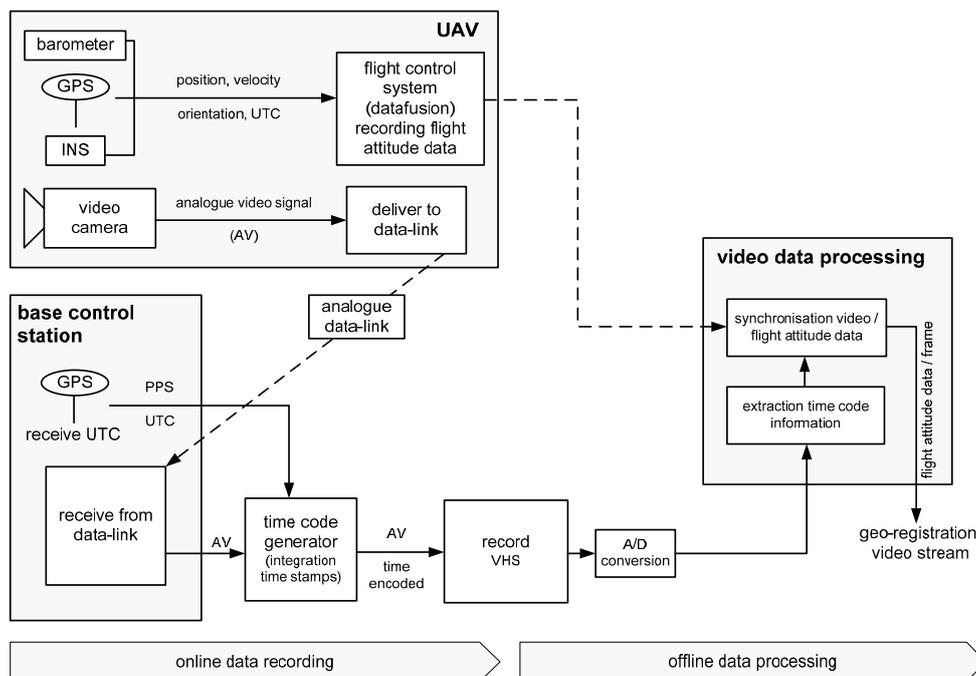

Figure 2: Data acquisition configuration and integration of time information

2.3 Data acquisition – trial project missions

The investigations presented in this paper are based on video sequences which were captured using the data acquisition configuration mentioned above. Two flight missions, one in Langenbruck (canton Basel-Landschaft) and one in Ballenberg (canton Berne) had been carried out in summer 2006. The following mission configurations were applied:

- Mission 1 (Langenbruck): Position updates of the flight control system based on a GPS navigation solution (stand-alone C/A-Code solution)

- Mission 2 (Ballenberg): Position updates of the flight control system based on a DGPS navigation solution (C/A-Code solution with pseudorange corrections provided by a so-called 'virtual reference station')

For both mission areas complete 3D landscape models were available which could be deployed as reference datasets. These landscape models contain building models, terrain data as well as orthoimage mosaics. Both 3D landscape models were acquired with aerial photogrammetry and close range photogrammetry in combination with tachymetry. The geometric accuracies of the building models in both test areas are approx. 10cm horizontally and vertically. In both missions the interior orientation parameters of the video camera as well as the camera mount on the platform were held fixed.

3. VIDEO GEO-REGISTRATION

The captured video sequences of both flight missions were to be geo-registered to the available 3D landscape model (based on WGS84 reference frame) with the direct geo-referencing as well as the integrated geo-referencing approach. Both geo-referencing approaches are discussed in detail later in this section. First, the chosen approaches for video camera calibration and camera misalignment determination of the concerned sensors are presented.

3.1 Calibration

Precondition for video geo-referencing are known interior orientation parameters of the used video camera as well as known misalignment parameters between the video camera and the INS/GPS sensors of the flight control system.

3.1.1 Interior orientation of the video camera

For the estimation of interior orientation parameters, an 'on-the-job' calibration approach was applied in the two mission areas. A test field consisting of one building from the 3D landscape model with additional ground control points was used (building surrounded by white ground control points).

Figure 3 shows the test field deployed for the Ballenberg mission. Ideally a natural object or a building is chosen, whose geometric features cover a large depth range and cover a large image section. With selected single frames out of the video sequence it is possible to estimate the interior orientation parameters, using a bundle adjustment with additional parameters. Optimal image arrangements for camera calibration are presented by Luhmann in (Luhmann, 1999).

Figure 3: Test field for camera calibration

The unknown parameters of the interior orientation were estimated using the photogrammetric software system Australis by Photometrix Pty Ltd. The following three sensor models could be solved successfully:

- Pinhole camera model (only focal length)

- Pinhole camera model with principal point

- Physical sensor model by Brown

In the data processing steps described below, the simple pinhole camera model has been applied exclusively. Especially for the direct geo-referencing approach the focal length has been estimated using a bundle adjustment configuration, in which the projection centres from of the flight attitude data were imported as additional observations with a large weight. With this configuration it is possible to approximate the focal length to fit the actual height level of the flight attitude data. In contrast to this, in the integrated geo-referencing approach the focal length estimation is based exclusively on image observations to control points of the test field.

3.1.2 Alignment between video camera and flight control sensors

In order to align the recorded flight attitude data based on GPS and INS with the projection centre of the video camera, it is necessary to know about the sensor arrangement between INS, GPS antenna and camera projection centre as well as the alignment between the body- and camera frame. The translations between the GPS antenna, barometer and INS reference point can directly be measured on the ground and are already taken into account within the flight control system. The translation between the INS reference point and the camera projection centre could also be measured directly. However, this bias may be neglected since it is strongly correlated with the camera misalignment described in the following.

The misalignment between the body frame and the camera frame is dependent on the actual gimbal orientation as well as on the misalignment between the camera frame and the gimbal frame. In the tested system configuration the actual gimbal position is also recorded by the flight control system and can be used. On the other hand, the abovementioned misalignment is not directly measurable and has to be estimated with a calibration flight mission. With the aid of a cross flight pattern over the test field, it is possible to estimate this unknown misalignment with the following concept. In selected single frames out of the cross flight video sequence control points of the test field can be measured. The three unknown angles of the misalignment ($\Delta\theta$, $\Delta\omega$, $\Delta\psi$) in Equation 2 can be estimated with

a Gauss-Newton optimisation based on the available image observations.

3.2 Direct geo-referencing

In the photogrammetric community the term direct geo-referencing is defined as the direct measurement of the exterior orientation parameters for each single frame. In this approach the exterior orientation parameters are directly determined with INS and GPS and are not estimated with a conventional aerotriangulation. This approach is documented in detail, for instance in (Cramer, 2001), and is commonly used and well-investigated in photogrammetry. In contrast to our investigations, the mentioned photogrammetric applications apply high quality sensors such as 'navigation grade' INS systems and dual-frequency phase observation-based GPS receivers (cp. Haala, 2005). The data integration strategy for computing optimum exterior orientation parameters from INS and GPS measurements are most realized with a decentralised Kalman filter. (Haala, 2005) or (Ellum and El-Sheimy, 2006) give a good overview over different Kalman filter integration strategies. Furthermore, different systematic errors exist, which have to be considered. One of these biases is caused by translations between the GPS antenna, INS reference point and camera projection centre which have not been accounted for. These translation vectors can be directly measured and applied during data processing. A second bias describes the misalignment between the camera and the body frame system. These three rotations are not directly observable and can be estimated e.g. with the approach described in section 3.1.2. (Skaloud, 1999) provides a complete overview of systematic errors in direct geo-referencing.

This paper intends to investigate the direct geo-referencing approach for the geo-registration of video sequences captured from mini UAVs. The required exterior orientation parameters of the video camera are derived by the transformations presented in Figure 4 which are obtained from the flight attitude data. By multiplying the following individual rotations it is possible to determinate the total rotation between the camera frame and the terrestrial reference frame.

$$\mathbf{R}_{cam}^{wgs84} = \mathbf{R}_{nav}^{wgs84}(\Phi,\Lambda) \cdot \mathbf{R}_{body}^{nav}(\omega,\theta,\psi) \cdot \mathbf{R}_{gimb}^{body}(\alpha,\nu) \cdot \mathbf{R}_{cam}^{gimb}(\Delta\theta,\Delta\omega,\Delta\psi) \quad (1)$$

In order to create the whole rotation matrix the following rotation angles are used:

Φ : latitude (WGS84)
Λ : longitude (WGS84)
θ : pitch (platform)
ω : roll (platform)
ψ : yaw (platform)
α : pan (gimbal)
ν : tilt (gimbal)
$\Delta\theta$: misalignment pitch
$\Delta\omega$: misalignment roll
$\Delta\psi$: misalignment yaw

With the exception of the three misalignment angles all other defined angles are available out of the flight control system. Subsequently the relation between an object point in the terrestrial reference frame and its projection in the camera frame is described with following equation.

$$\mathbf{x}_{cam} = \frac{1}{\lambda} \cdot \mathbf{R}_{cam}^{wgs84\mathbf{T}} \cdot (\mathbf{X}_{wgs84} - \mathbf{X}_0) \quad (2)$$

where

λ : scale factor
$\mathbf{x}_{cam}$: image point in the camera frame
$\mathbf{X}_{wgs84}$: object point in the terrestrial reference frame
$\mathbf{X}_0$: projection centre in terrestrial reference frame

The projection centre can also directly be derived from the position information inside the flight attitude data. The required exterior orientation of each single frame of the video sequence can be calculated with a linear interpolation between the available 5Hz flight attitude data. Due to the low sensor accuracy the established concept for direct geo-referencing without corresponding adaptations and limitations shall be assumed. Especially the camera misalignment calibration and the handling of systematic errors require new methods.
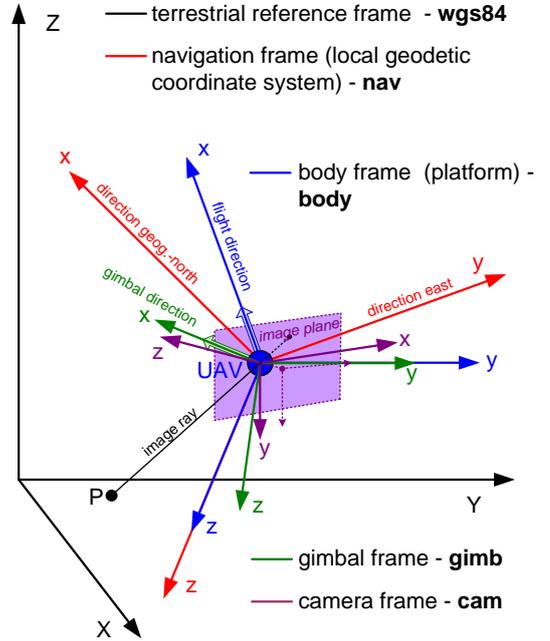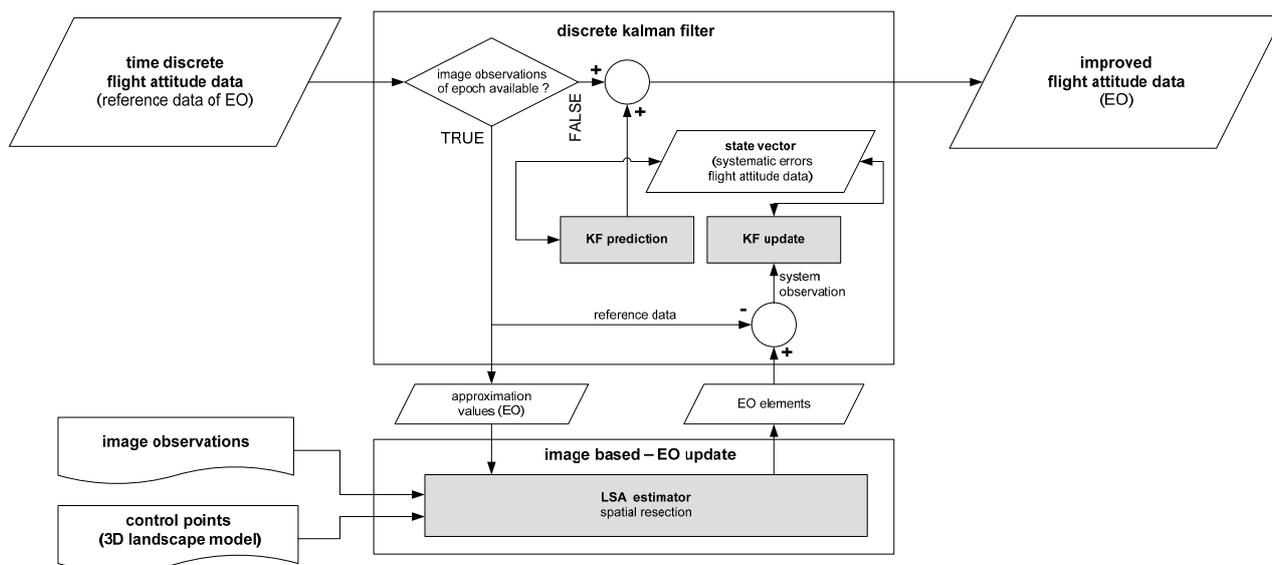

Figure 4: Used coordinate frames

Figure 5: Data integration strategy – integrated geo-referencing

3.3 Integrated geo-referencing

In contrast to the direct geo-referencing approach, this approach uses additional image observations to known control points for the optimal estimation of exterior orientation elements. While the absolute accuracy of the direct geo-referencing approach mainly depends of the GPS solution quality, the relative accuracy is mainly dependant on the INS quality. The resulting exterior orientation is superposed with systematic errors e.g. caused by failed fixed phase-ambiguities in the kinematic GPS solution. The idea of the integrated geo-referencing approach is to correct remaining systematic errors of the direct geo-referencing solution with the aid of additional image observations. In (Haala, 2005) and (Cramer, 2001) the stripe-wise approach and the orientation-image-approach for integrated geo-referencing are described. Both approaches are only partly applicable to processing the present data in our work. On the one hand the recorded flight attitude data in this work are not derived from straight flight strips which allow to model occurring drifts inside a flight strip. On the other hand, it is not possible to describe the systematic errors of the recorded flight attitude data with a simple deterministic mathematical function. The occurring biases are difficult to decompose in their single parts. Based on this, the following concept shortly explains the integrated geo-referencing approach chosen in this work.

In principle, the existing biases of the flight attitude data should be estimated as best as possible with the aid of independently estimated exterior orientation parameters. For this purpose the available flight attitude data can be corrected with the estimated biases. With spatial resections for single frames from the video sequence, it is possible to estimate independent exterior orientation parameters. The required control points for this computation are obtained from object geometry within the available 3D landscape model. With the aid of a discrete Kalman filter an adapted error model for the flight attitude data is estimated. In this filter the flight attitude data is used as high frequency reference data. The independently estimated exterior orientation elements are used as observations for state vector update estimation. Figure 5 illustrates our chosen Kalman filter

data integration strategy. The implemented filter is based on a complementary feedforward filter design.

The state vector contains the systematic errors of the flight attitude data,, their first derivatives as well as the errors of the estimated exterior orientation elements. The system observations used for a Kalman filter state update, are calculated from the difference between the parameters estimated by the resection and the reference flight attitude data. These observations are functionally associated with the state vector components through the addition of the systematic errors of the flight attitude data with the errors of the additionally estimated exterior orientations. The chosen system dynamics describe the errors of the flight attitude data using an integrated random walk. For the errors of exterior orientation update parameters a Gauss-Markov process is used. The chosen stochastic model assigns stronger weights to the system observations than to the dynamic model. The Gauss-Markov process is modelled with a strong damping, which has the consequence of a minimal time correlation between the errors of the additionally estimated exterior orientation elements. Further reading of the implemented filter design is found in (Brown and Hwang, 1983).

4. RESULTS

The results presented here are based on the flight missions mentioned in section 2.3. In order to assess the obtained geo-registration accuracy, selected check points from the 3D landscape model were used. The presented accuracies in image- and object space were derived by re-projecting check points into the image plane. The re-projection is based on Equation 2, whereby the interior and exterior orientation parameters used were estimated using the approaches presented in section 3. In order to enable the independent assessment of the accuracies obtained from the different missions and data processing configurations, independent video sequences were used which were not part of the calibration flight sections. For the accuracy assessment of the integrated geo-referencing approach, individual frames between the Kalman filter updates were used.

4.1 Accuracies reached

Table 2 below provides an overview of the accuracies obtained using the following data acquisition and processing configurations:

a Flight attitude data based on GPS navigation solution (C/A-Code solution), INS and barometer. For geo-registration the **direct geo-referencing approach** was used. (Mission Langenbruck)

b Flight attitude data based on DGPS navigation solution using a virtual reference station (correction data service: swipos/NAV swisstopo), INS and barometer. For geo-registration the **direct geo-referencing approach** was used. (Mission Ballenberg)

c Flight attitude data based on DGPS navigation solution using a virtual reference station (correction data service: swipos/NAV swisstopo), INS and barometer. For geo-registration, an **integrated geo-referencing approach** was used with ~1Hz Kalman filter updates. (Mission Ballenberg)

4.2 Assessment and potential

The following illustrations document the geo-registration accuracies reached with the direct geo-referencing and integrated geo-referencing approach respectively (configuration b and c). For comparison purposes the same epochs from of the same recorded flight mission data are presented.

Clearly visible in Figure 6 is the significantly improved accuracy of the integrated geo-referencing solution, compared to the direct geo-referencing solution. The difference vectors in the image plane between the interactively measured check point image observations and the re-projected check points nicely illustrate this dramatic improvement. This is also directly visible in Table 2. The figures of difference vectors show a remarkable systematic nature of the remaining errors in the direct geo-referencing solution, despite the compensation of the camera misalignment. Furthermore, the geo-registration accuracy is by factor two worse than the accuracy achieved in the camera misalignment calibration itself. These results lead to the assumption, that the used camera misalignment calibration approach tends to compensate primarily time correlated INS/GPS biases inside the flight attitude data rather than the actually present camera misalignment error. The strong correlation between systematic errors of exterior orientation parameters and the three misalignments angles explain this phenomenon. The difference vectors in Figure 6 also confirm this assumption. The flight attitude data of the investigated video sequence also contains a time correlated systematic error, which cannot be fully compensated with the calibrated camera misalignment angles.

Table 2 demonstrates the geo-registration accuracy of the direct geo-referencing approach, which can be achieved with flight attitude data obtained from low cost and low weight INS/GPS sensors. A comparison of the results of configurations **a** und **b** shows, that the use of pseudorange corrections increases the direct geo-referencing accuracy only marginally. With the DGPS configuration it is mainly possible to improve the absolute accuracy of the vertical component of the projection centre position. However, with an adjusted estimation of the focal length using additional weighted projection centre observations derived from flight attitude data, it is also possible to compensate this systematic vertical error, if the object distance is fairly constant during the whole mission. If the geo-registration accuracy is to be improved significantly, then new approaches must be developed like the integrated geo-referencing approach presented in this paper. Using the support of a 3D landscape model this approach enables a continuous estimation of the systematic errors of the direct geo-referencing solution. In this approach, biases of the flight attitude data and camera misalignment errors are addressed in one strong correlated error term.

5. OUTLOOK

The final goal will be to realize an integrated real-time geo-referencing solution using automatic image-based exterior orientation updates. For this purpose streamable 3D object geometry from a digital landscape model will be used. Additional automatic image processing algorithms will be developed, which are capable to detect and track objects of the 3D landscape model within the video stream.

Mini or micro UAV systems equipped by a video camera in combination with the described integrated geo-referencing solution could be used as real time mobile mapping systems. With such a system measured geo-objects could be directly integrated into interactive 3D geoinformation services. For example, so-called augmented monitoring solutions can be imagined, whereby objects (e.g. buildings or street furniture) of the 3D landscape model can be overlaid with the geo-referenced video stream. Using the known geo-registration in combination with the elevation and 3D object data of the 3D landscape model, it is possible to map points with a single image ray.

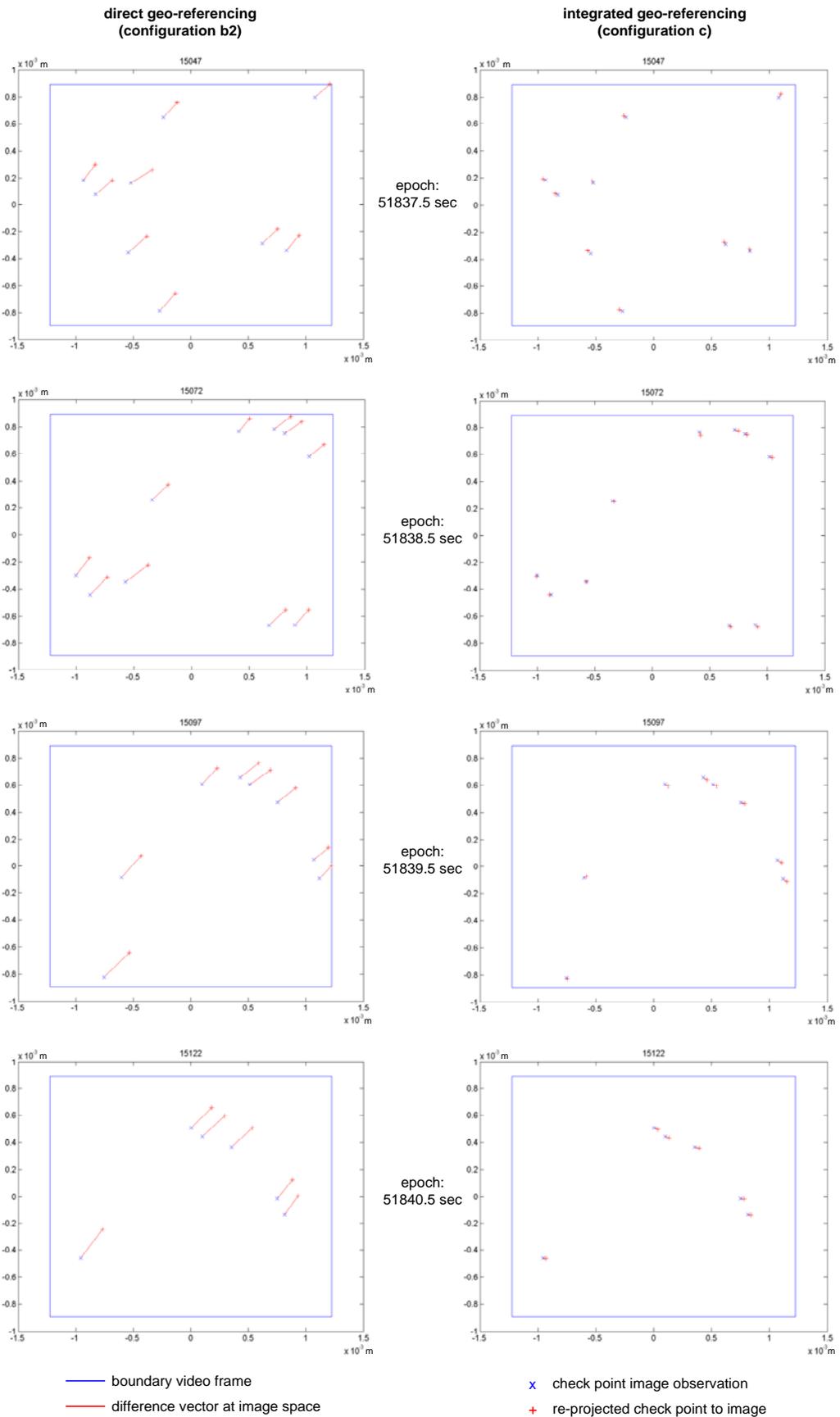|	configuration a misalignment considered	configuration b1	configuration b2 misalignment considered	configuration c
image scale	1:32'000	1:16'000	1:16'000	1:16'000
RMS image space	114.1 µm	144.12 µm	**119.4 µm**	**35.3 µm**
avg. object distance	100 m	50 m	50 m	50 m
RMS object space	3.8 m	2.4 m	2.0 m	0.59 m

Table 2: Reached geo-registration accuracy

Figure 6: Difference vectors at image plan direct- vs. integrated geo-referencing

6. CONCLUSION

This paper investigated the geo-registration of video sequences captured from mini UAV systems with low quality attitude information. For the video geo-registration, the direct geo-referencing approach as well as the integrated geo-referencing approach were used. The reachable geo-registration accuracy with the direct geo-referencing approach is directly dependent on the low quality INS, GPS and barometer sensors used in such platforms. Geo-referencing accuracies achieved using the direct approach were between 2 and 4 meters with flying heights in the range of 50 to 100 meters.

In order to significantly increase the geo-registration accuracy and reliability, new methods are required. The integrated geo-referencing approach investigated in this paper is one possible solution. This presented approach uses additional image observations to known object geometry to assist the direct measurable exterior orientation solution. First results showed a significant improvement in geo-referencing accuracy to 0.6 meters. It is expected that the final integrated geo-referencing solution using automatic image-based exterior orientation updates will yield geo-referencing and subsequent point location and mapping accuracies at the 1 meter level – despite the use of low cost and low grade on-board attitude determination of mini or micro UAVs.

7. ACKNOWLEDGEMENTS

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