A LIGHT-WEIGHT MULTISPECTRAL SENSOR FOR MICRO UAV – OPPORTUNITIES FOR VERY HIGH RESOLUTION AIRBORNE REMOTE SENSING

S. Nebiker[a, *], A. Annen[a], M. Scherrer[b], D. Oesch[c]

[a] FHNW, University of Applied Sciences Northwestern Switzerland, School of Architecture, Civil Engineering and Geomatics, Inst. of Geomatics Engineering, CH-4132 Muttenz, Switzerland – (stephan.nebiker, adrian.annen)@fhnw.ch
[b] FHNW, University of Applied Sciences Northwestern Switzerland, School of Engineering, Institute of Automation, CH-5210 Brugg-Windisch, Switzerland – marco.scherrer@fhnw.ch
[c] Syngenta Crop Protection AG, Agronomic Information Services, CH-4002 Basel, Switzerland – david.oesch@syngenta.com

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ABSTRACT:

In this paper we present the prototype of a light-weight multi-spectral sensor which can be flown on a micro UAV and we discuss the promising results from two field tests which show the excellent potential for assessing plant health in agronomical research. We start out by illustrating the gap between air- and space-based remote sensing (RS) on the one side and ground-based RS on the other. We highlight the need for (very) high resolution remote sensing offered by low altitude airborne platforms such as mini or micro UAVs (unmanned aerial vehicles). For this purpose, we first discuss the specific characteristics and requirements of typical applications requiring very high resolution RS. We then look into recent developments in light-weight UAV technologies and present the micro UAV which served as platform for the sensor development and tests at the University of Applied Sciences Northwestern Switzerland (FHNW). In the following section we provide a description and discussion of the MultiSpectralMicroSensor (MSMS), the prototype of a light-weight multispectral sensor developed at the FHNW. We further describe two field campaigns with two different types of UAV platforms and MS sensors and discuss the obtained results, which clearly demonstrate the excellent potential of very high-resolution micro UAV based remote sensing applications.

1. INTRODUCTION

Recent progress in the development of miniature flight control, propulsion and light-weight airframe technologies on the one hand and the continuing trend towards miniature imaging sensors on the other, bear the potential for creating a new generation of light-weight airborne remote sensing platforms offering very high spatial resolution and an unparalleled operational flexibility. While the development of Unmanned Aerial Vehicle (UAV) technologies was and still is driven by military applications (Bento, 2008), civilian applications are rapidly catching up and are encompassing fields such as disaster monitoring, fire detection, pipeline inspection, site inspection, real-time monitoring (Eugster & Nebiker, 2007), traffic monitoring, mapping, cultural heritage (Eisenbeiss, 2004), movie production, and increasingly forestry and agriculture.

In agronomical research new substances and products such as herbicides, pesticides, fungicides or fertilisers are tested on field test sites. Today, these field tests include labour-intensive typically weekly visual inspections of leaf properties by experienced staff. In this qualitative method the assessment of plant health is often based on number, size and condition of plant leafs. Agronomical researchers and companies are in permanent search for new methods and procedures helping them to economise their field tests while maintaining or even improving the quality and reliability of today's field test procedures. Optical satellite-based remote sensing is successfully used in supporting large scale field tests. However, the prevailing small test plots with sizes around one square metre and the need for short and reliable revisit periods require new solutions.

There is an abundance of literature on reflective optical remote sensing in agriculture, aiming at relating spectral reflectance properties of plants and soils to their agronomic and biophysical properties. Very comprehensive and valuable literature reviews include (Pinter et al., 2003) on remote sensing in crop management and (Dorigo et al., 2007) on remote sensing for agroecosystem modelling. The majority of operational procedures for estimating plant properties make use of the distinct dissimilarities in reflectance properties between the visible and NIR wavelengths. Vegetation indices (VI), computed as differences, ratios or linear combinations of reflected light in the visible and NIR wavebands, e.g. (Tucker, 1979) or (Kurz, 2003), provide a very simple and elegant method for representing these dissimilarities and are also used in this study.

* Corresponding author.

1.1 (Ultra) High-Resolution Remote Sensing in Agriculture

In the past, the majority of remote sensing applications in agriculture were either satellite- or ground-based. Over the last few years we have seen a rapid increase in airborne remote sensing due to the proliferation of multispectral digital airborne sensors (Bühler et al., 2007), (Petrie and Walker, 2007).

Table 1 gives an overview of the different remote sensing platforms with the typical spatial resolution of their multispectral channels and with their typical fields-of-view (FOV). This overview illustrates the current resolution gap at the cm to dm level which could ideally be filled by miniature UAVs.

Remote Sensing Platform	Typical Spatial Resolution (MS)	Typical Field-of-View (FOV)
Satellite	2-15 m	10-50 km
Aircraft (piloted)	0.2-2 m	2-5 km
Miniature UAV ?	*1-20 cm*	*50-500 m*
Ground-based	< 1 cm	< 2 m

Table 1: Typical spatial resolutions and fields-of-view of different remote sensing platforms – with a spatial resolution gap between 1 and 10 cm which could be filled by miniature UAVs.

The trend towards very high-resolution airborne remote sensing with spatial resolutions in the range of centimetre to decimetre is driven by agronomical research, management of speciality crops and investigations of within-field variability in general. The shift towards precision, or site-specific, crop management, and the resulting interest in within-field variability, for example, has been identified as the most significant change in agriculture over the last ten to fifteen years (Pinter et al., 2003). Further potential application areas of very high-resolution UAV-based remote sensing might be the detection and mapping of plant diseases such as fire blight or the investigation contaminated sites.

In the following we will primarily focus on the application area of agronomical research. However, most of the characteristics, requirements and conclusions also apply to the management of specialty crops. The term specialty crops includes fruits, vegetables, tree nuts, dried fruits, and nursery crops (including floriculture) (USDA, 2004) as well as grapevines, which were used in the subsequent investigations.

The characteristics and the subsequent remote sensing requirements of field tests sites can be summarised as follows:

- very small plot sizes down to one square metre resulting in a ground sampling distance (GSD) in the order of 5-10 cm in order to ensure statistically reliable results for each test plot
- regular frequent observations at weekly intervals and at short notice in order to observe different phenological developments or other rapidly evolving phenomena
- the manifold of plant species at a test site and the desire to find a single solution capable for all vegetation types
- relatively simple, robust and rapid processing procedures with a high level of automation

1.2 Miniature UAVs as Remote Sensing Platforms

Over the last few years we have seen a tremendous development of UAV technologies at all conceivable sizes, from business jet sized UAVs right down to artificial 'flying insects'. There is also an increasing number of projects with the aim of using UAVs for remote sensing purposes. These UAV platforms for civilian remote sensing purposes range from large UAVs (Coronado et al., 2003), (Herwitz et al., 2002) through mini UAVs (Johnson et al., 2003), (Eisenbeiss, 2004), (Annen et al., 2007) to micro UAVs presented in this paper (see Table 2).

Due to the rapid development and the ever increasing number of new UAV concepts and technologies, it has become a necessity to try and establish a certain classification for UAVs. The European Association of Unmanned Vehicle Systems (EUROUVS) has drawn up such classification of UAV systems, which we will adhere to in this paper. A good overview and state-of-the-art of UAV systems which is based on the EUROUVS classification can be found in (Bento, 2008).

Category	Max. Take Off Weight	Max. Flight Altitude	Endurance	Data Link Range
Micro	< 5kg	250m	1h	< 10km
Mini	< 30kg	150-300m	< 2h	< 10km

Table 2: Classification mini- and micro UAV systems

Since our UAV-based remote sensing platform is to be transportable and to be operated locally under minimal legal restrictions, candidate platforms are limited to the categories of mini and micro UAVs (see Table 2). Most mini or micro UAV systems available today integrate a flight control system, which autonomously stabilises the platform and supports remotely controlled navigation. Several systems additionally integrate an autopilot, which permits autonomous flights based on predefined waypoints – often in combination with programmable image acquisition. These flight control systems are typically based on MEMS (Micro-Electro-Mechanical System) IMU systems, navigation-grade GPS receivers, barometers, and magnetic compasses. The different sensor observations are usually integrated to an optimal flight state using an EKF (Extended Kalman Filter), which is subsequently used in the flight controller. For mapping applications, it is also possible to use this flight control data to geo-register the captured payload sensor data like still images or video streams. However, as a result of the utilisation of low weight and low cost flight control sensors, the achievable direct geo-referencing accuracy is limited to approx. 5-10 metres (Eugster and Nebiker, 2008).

1.3 Low-weight Remote Sensing Payloads

The use of mini or micro UAVs for remote sensing purposes introduces a number of constraints on the imaging payloads, namely limitations in terms of weight, power, and space. In case of micro UAVs there are also very limited possibilities for payload stabilisation or for the highly accurate direct sensor georeferencing. Typical weight limitations for imaging payloads are approx. 20-30% of total weight of the system, e.g. approximately 300g in case of 1kg micro UAVs and around 5kg in case of 25-30 kg mini UAVs. While there are an increasing number of light-weight imaging sensors for the visible spectrum and for thermal infrared, the situation is completely different in the case of multispectral sensors. In the case of imaging sensors for the *visible spectrum*, there is now a wide range of light-weight consumer cameras with weights of 150g or even less and with up to 10 MPixels or more. Unfortunately, these sensors also come with a number of features which have adverse effects on photogrammetric or remote sensing applications. These include limited optical quality, mostly zoom lenses, fully automatic focussing and image stabilisation which make the task of camera calibration very difficult. There are a number of operators providing remote sensing services for agriculture based on RGB imagery only. While this kind of imagery might provide valuable visual information to farmers, it is certainly not suitable to analytically assess vegetation properties due to the lack of information in the NIR band.

Thermal Imaging – There has been a tremendous progress in the field of miniature thermal imaging sensors over the last few years resulting in commercially available thermal imaging sensors with weights in the order of 120g (FLIR Systems, 2005). This development was influenced by miniature UAV technologies and was mainly driven by military applications such as remote reconnaissance (Kostrzewa et al., 2003) and by applications in the domain of disaster monitoring, namely forest fires (Rufino and Moccia, 2005), (Esposito et al., 2006).

Multispectral and Hyperspectral Imaging – The development of sensors for acquiring high-quality, co-registered multi-channel imagery in the visible *and* in the Near Infrared (NIR) bands poses a number of challenges in terms of optics, sensors, sensor control and calibration. In their recent overview on airborne digital imaging technologies (Petrie & Walker, 2007) identify four different concepts for producing multi-channel imagery with small-format airborne digital cameras. Among them are single lens solutions with specialised mosaic filters, multiple arrays, or beam splitters or with solutions based on multiple cameras. Among the lightest multispectral camera systems available are the DigiCAM-H39 (IGI, 2007) with a CIR option and a total weight of approx. 5 kg and Tetracam's recently released Multichannel Camera MCA4 with approx. 1.8 kg and ADC2 with approx. 500 g. The latter sensor appears promising for operations on mini or even micro UAV, however, the quoted interval of 12 seconds between two individual images would only permit stationary image acquisition.

Noteworthy investigations by (Rufino and Moccia, 2005) or (Johnson et al., 2003) create a hyperspectral line sensor by combining a monochromatic camera with a spectrograph and attempt to use it on UAVs. However, it remains questionable, if and how such line sensors can satisfactorily be used on mini or micro UAVs with their relative low attitude determination capability and the lack of payload stabilisation.

1.4 The MSMS Project

The Institute of Geomatics Engineering at the University of Applied Sciences Northwestern Switzerland (FHNW) has been active in the research of UAV-based applications on the one hand and remote sensing on the other for several years. The MSMS (MultiSpectralMicroSensor) project was launched in early 2006 for researching technologies and applications pertaining to UAV-based ultra high-resolution remote sensing in agriculture. The applied research project unites scientists and professionals from the fields of geomatics, electronics, agronomical research and UAV technologies. The goal of the first two project phases presented below, was first to investigate the feasibility of remote sensing applications based on mini or even micro UAVs including the suitability and validity of processing methods and second to develop a prototype low-weight multispectral sensor as a key component of a flexible and easy-to-operate low-cost remote sensing system for extracting *plant state variables*.

1.5 Field Tests Site

The results of each of the two project phases were evaluated by flight campaigns at the agronomical R&D plant of Syngenta Crop Protection AG in Stein (Canton AG, Switzerland). The test site is located in the northwest part of Switzerland, near the German border. At the field test site agrochemical substances and products are applied to various plant species and crop types, such as potatoes, soya or a number of specialty crops, namely grapevines. For our pilot studies, a grapevine field was selected, which consisted of 10 rows which were again subdivided into test plots of 2.5 meters in length. In total, 240 test plots were available. At the time of both test flight campaigns, these plots had been subject to a ground-based 'bonification' by specialists of Syngenta, which provided an excellent 'real-world' ground truth for the following remote sensing experiments.

Figure 1: Grapevine test field consisting of 240 test plots. Also visible are the large radiometric targets (left) and the smaller geometric ground control points (bottom).

2. MSMS – PROJECT PHASE I

In the first project phase in 2006 the feasibility and suitability of mini or micro UAV based remote sensing for agronomical research applications were to be investigated and demonstrated. The key findings of the MSMS project Phase I are summarised below. For a detailed description of the investigations and results of Phase I please refer to (Brosi, 2006) and (Annen et al., 2007).

2.1 Sensor Platform: Mini UAV

The test flight campaign of the first project phase was carried out using model helicopter based mini UAV of weControl AG (Zurich) (see Figure 2). The UAV has a rotor diameter of 1.8m, is powered by a combustion engine and can carry an imaging payload of approx. 1 kg. The mini UAV was equipped with weControl's flight control system wePilot1000, which allowed a fully automatic waypoint navigation with a verified accuracy of approx. 3 m. The system also provides a video data link which allowed a rough online verification of the acquired imagery at the ground control station.

2.2 Remote Sensing Payload

A market evaluation at the time of the study showed that there were no suitable multispectral sensors available which could have provided multi-channel imagery in the bands Red, NIR (and preferably also Green) at a total system weight of 1 kg or less. In order to proceed with the initial feasibility tests in the 2006 vegetation period, it was decided to use a combination of two different sensors for RGB and NIR, which had to be flown in two subsequent flight missions. The two imaging sensors were:

NIR sensor Sony SmartCam – 1/2" monochrome CCD with 1280x1024 pixels; onboard CPU with 400 MHz CPU, 256 MB DDR-SDRAM, and Windows XP embedded; Compact Flash on-board storage up to 4 GB; camera body weight 400g (w/o optics or power supply); precision optical lenses from Schneider Kreuznach, corrected from 400 to 1000 nm; high-pass filter with a cut-on wavelength of 780 nm (to approx. 1000 nm).

Figure 2: Mini UAV of weControl (Zurich) with the RGB sensor Canon EOS 20D.

RGB sensor Canon EOS 20D – commercial digital SLR camera; CMOS chip with 22.5 x 15.0 mm and 3504 x 2336 pixels; weight 770 g; radiometric resolution (RAW format) of 12 bits; standard lens with fixed focal length; IR blocking filter with cut-off wavelength at approx. 720 nm.

The optical lenses of the two camera systems were chosen so that they would yield the same ground sampling distances (GSDs) from identical flying heights.

2.3 Field Test Campaign

Due to the available sensor constellation, the acquisition of the RGB and NIR imagery with a GSD of approx. 7 cm had to be carried out in two separate pre-programmed flights. The flights were planned as a photogrammetric strip with 4 images and an overlap of approx. 60%. The imagery was acquired at a flying height of 100 metres above ground resulting in image scales of approx. 1:11'000 (for the RGB imagery) and 1:13'750 (for the NIR imagery). Precise ground control with an accuracy of approx. 2 cm horizontal and 3 cm vertical was established (Annen u. a., 2007).

Figure 3: Section of the generated false colour true orthoimage.

2.4 Processing and Results

The goal of the processing phase was to derive plant health figures for each plot which can directly be related to those used by the field specialists, who normally express the plant status in *percentage of damaged leaves*. The processing steps can be summarised as follows (Brosi, 2006) and (Annen u. a., 2007):

- extraction of raw imagery from both sensors
- geo-referencing of Red and NIR imagery
- co-registration of Red & NIR imagery by a true orthoimage
- radiometric corrections using radiometric field targets
- masking out of 'background' soil using a GIS-based geometric buffer for the grapevine rows
- calculation of uncalibrated or 'raw' NDVI values
- matching of raw NDVI values with leaf damage values of control plots by means of a weighted linear regression
- calculation of leaf damage values for all test plots by means of linear interpolation

The described sensor and flight constellation, namely the use of two different and radiometrically uncalibrated 'off-the-shelf' sensors and the spatially disparate exposure centres for the RGB and NIR imagery, introduced a number of challenges into the processing chain. The very special challenge of co-registering the very high-resolution RGB and NIR channels acquired in separate flights to an accuracy of 1-2 pixels at a GSD of only 7 cm was successfully met by generating a true orthoimage (see Figure 3). The underlying elevation data modelling the surface of the grapevines was derived using the GIS-based position information of the grapevine rows in combination with an average height for the grapevine cultivation.

In the subsequent investigations a number of vegetation indices were successfully used to assess the plant health within a grape vine test field. However, it is shown in (Brosi, 2006) that excellent and robust results can be achieved by using the standard NDVI. In the case our grapevine test field the percentage of damaged leaves determined with remote sensing agreed to within 10% with the comprehensive ground truth information (see Figure 1). This indicates that the remotely sensed solution roughly yields the same accuracy level as the very labour intensive ground-based bonification.

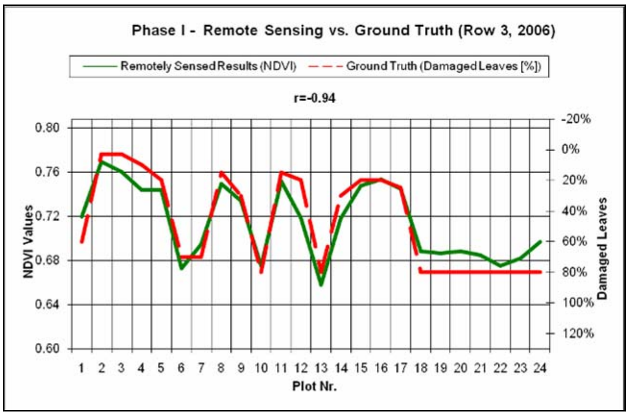

Figure 4: Percentage of damaged leaves – Remotely sensed results (solid green line) and reference data (red dashed line).

3. MSMS – PROJECT PHASE II

After project phase I had shown very encouraging and robust results, despite the use of an improvised and unfavourable sensor constellation it was decided to develop a prototype of a low-cost light-weight airborne multispectral sensor, which could ideally be flown on the latest generation of rotary or fixed wing mini or even micro UAVs.

3.1 Sensor Platforms: Micro UAV and Mini UAV

The latest generation of quadcopter micro UAVs with vertical take-off and landing (VTOL) capability and with maximum payloads currently in the range of 200g and expected to be in a range of 1kg could provide ideal remote sensing platforms for local applications such as agronomical field tests and the management of specialty crops. In our case, the micro UAV 'microdrones md4-200' (see Figure 5) served as target platform for the MSMS sensor. The md4-200 is an electrically powered, GPS/INS-equipped quadcopter with an official maximum payload of 200g, an unofficial maximum payload of approx. 350g, and a maximum flying time of approx. 20 minutes.

Figure 5: Quadcopter micro UAV 'microdrones md4-200' with the prototype MSMS multispectral sensor.

3.2 The MSMS Sensor

Based on the earlier results and on the availability of sensor hardware components at the start of the development, the design decisions for a low-cost, low-weight MSMS sensor were as follows: a modular multi-camera concept (see Introduction) with one camera per band to be sensed – initially limited to the two bands Red and NIR with the option to extend the number of channels by incorporating additional camera heads; panchromatic full frame sensor elements (with the option to upgrade to higher resolution sensor elements as they become available); identical, high-grade but low-weight lenses for all sensor heads; interference filters for the selection of the desired spectral bands; use of a programmable camera controller with support for on-board storage of the acquired imagery. The main features of the current MSMS prototype sensor are:

- two cameras with full frame CMOS sensor elements (sensor heads MT9V022m integrated into CanCam), 752 * 480 pixels per channel with global shutter (Company: Feith Sensor to Image)
- CanCam controller with CPU Motorola Coldfire MCF5272 66 MHz and µCLinux (Feith)
- Light-weight C-mount lenses, focal length 8.0mm, F1.3, interference filters with central wavelengths of 650 nm (R) and 880 nm (NIR) and a full width-half maximum (FWHM) of 80 nm and 50 nm respectively
- total weight of the MSMS prototype: 350 g (including controllers, sensor heads, and the custom-built light-weight camera frame; sensor powered by UAV battery)

3.3 Field Test Campaign

Due to supply difficulties and an approaching end of the vegetation season only one test flight campaign could be carried out so far with the described combination of the MSMS sensor and the md4-200 platform (17^{th} of August 2007). The test flight was again carried out over a grapevine field at the Syngenta test field in Stein. Since the current sensor exceeds the official payload limit and since the unofficial payload communicated by the manufacturer of the UAV turned out to be too optimistic, data acquisition was only possible in the absence of any wind and the acquired imagery was limited to a part of the field only.

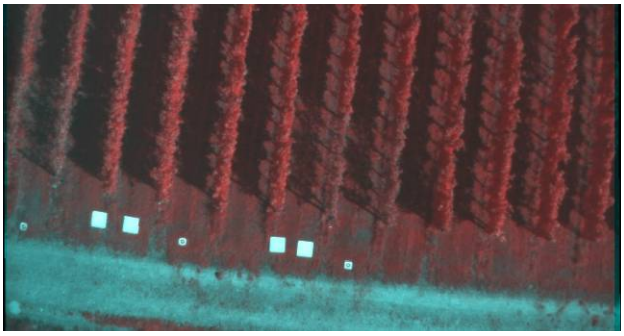

Figure 6: One of the first MSMS scenes (part) with radiometric calibration targets (large) and ground control points (small).

3.4 Preliminary Results

Due to the mentioned difficulties in acquiring the first imagery, there were again a number of challenges in processing the data. However, these challenges were mainly caused by the very irregular constellation of the acquired imagery covering only parts of the area of investigation. Due to the use of a multi-camera payload, the processing chain can principally be simplified in comparison to the processing steps used in phase I. Namely the step of a true orthoimage production will no longer be needed. Early results support the findings from phase I and again show a strong correlation between plant health status obtained via remote sensing with the MSMS prototype and the ground-truth data from the traditional bonification process.

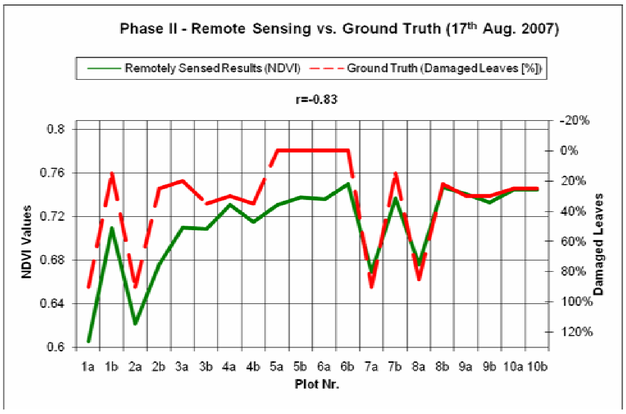

Figure 7: Percentage of damaged leaves vs. NDVI values – Results obtained with MSMS sensor (solid green line) and reference data (red dashed line) (preliminary results).

4. CONCLUSIONS AND OUTLOOK

In this paper we presented investigations using low-weight and low-cost multispectral sensors in combination with mini and micro UAVs for remote sensing applications in agronomical research. Field experiments including test flights with different UAV types and two different sensor constellations demonstrate the feasibility and a very promising potential of such very high-resolution systems. The investigated multispectral sensors consisted of a) an off-the-shelf multi-camera constellation which had to be flown in multiple flight missions and b) a prototype of a light-weight multi-channel sensor MSMS developed at FHNW. Despite the fact that both sensor constellations and the test flights were still far from ideal, an excellent agreement between the remotely sensed plant health status of grapevines with the detailed reference data provided by the agronomical specialists of Syngenta AG was found (with an overall correlation coefficient of approx. 0.9). The results also indicate that the quality of remotely sensed plant health assessment is at least equivalent to the current labour-intensive ground-based bonification. The main advantages of very high-resolution UAV-based remote sensing can be summarised as follows:

- unparalleled very high temporal and spatial resolutions
- flexible deployment and relatively simple operation of micro UAVs (no pilots required)
- potential for very rapid data acquisition and processing

Ongoing and future work includes the extension of the investigations towards speciality crops other than grapevines and towards specialty crop management in general. With respect to the MSMS sensor and the corresponding processing chain this includes the following development tasks and investigations: improvement of the current sensor, design and implementation of a robust processing chain addressing special issues such as reducing ambiguity problems in the image georeferencing process which are caused by the relatively poor direct georeferencing capabilities of micro UAVs and (Eugster 2008) and the repetitive patterns found in typical fields or orchards.

REFERENCES

Annen, A., Nebiker, S., Oesch, D., 2007. Einsatz von Mikro- und Minidrohnen für Fernerkundungsaufgaben in der agrochemischen Forschung und Entwicklung. In: *DGPF Tagungsband 16*, 16 (S.. 399-406). FHNW, Muttenz.

Bento, M. D. F., 2008. Unmanned Aerial Vehicles: An Overview. *InsideGNSS* (January/February 2008), 54-61.

Brosi, D., 2006. Modellhelikopter gestützte multispektrale Vegetationsklassifizierung. *Diploma Thesis,* FHNW, Muttenz.

Bühler, Y., Kneubühler, M., Bovet, S., & Kellenberger, T., 2007. Anwendung von ADS40 Daten im Agrarbereich. In: *DGPF Tagungsband 16*, 16. FHNW, Muttenz.

Coronado, P. L., Stetina, F., & Jacob, D., 2003. New technologies to support NASA's Mission to Planet Earth satellite remote sensing product validation: use of an unmanned autopiloted vehicle (UAV) as a platform to conduct remote sensing. *Proceedings of SPIE*, 3366, 38.

Dorigo, W., Zurita-Milla, R., de Wit, A., Brazile, J., Singh, R., & Schaepman, M., 2007. A review on reflective remote sensing and data assimilation techniques for enhanced agroecosystem modeling. *International Journal of Applied Earth Observation and Geoinformation*, 9(2), 165-193..

Eisenbeiss, H., 2004. A mini unmanned aerial vehicle (UAV): system overview and image acquisition. *International Workshop on" Processing and visualization using high-resolution imagery,* 18-20.
Esposito, F., Accardo, D., Rufino, G., & Moccia, A., 2006. 1st: A fully Autonomous UAV aimed at Monitoring ENVIRONMENTAL RISKS. .

Eugster, H., & Nebiker, S., 2007. Geo-Registration of Video Sequences Captured from Mini UAVs - Approaches and Accuracy Assessment. *Mobile Mapping Symposium MMT'07, Padova*.

Eugster, H., & Nebiker, S., 2008. UAV-based Augmented Monitoring – Real-time Georeferencing and Integration of Video Imagery with Virtual Globes. *XXIst ISPRS Congress, Beijing.*

FLIR Systems, 2005. ThermoVision™ A10 Technical Specifications. www.flirthermography.com/A10data (Last accessed: 30.4.2008).

Herwitz, S. R., Johnson, L. F., Arvesen, J. C., Higgins, R. G., Leung, J. G., & Dunagan, S. E., 2002. Precision Agriculture as a Commercial Application for Solar-Powered Unmanned Aerial Vehicles. *AIAA's 1st Technical Conference and Workshop on Unmanned Aerospace Vehicles.*

IGI mbH, 2007. DigiCAM-H/39 Product Specification. . http://www.igi-systems.com/downloads/specifications/ specifications_digicam_h39.pdf (Last accessed: 30.4.2008)

Johnson, L., Herwitz, S., Dunagan, S., Lobitz, B., Sullivan, D., & Slye, R., 2003. Collection of Ultra High Spatial and Spectral Resolution Image Data over California Vineyards with a Small UAV. *Proceedings of the International Symposium on Remote Sensing of Environment.*

Kostrzewa, J., Meyer, W. H., Laband, S., Terre, W. A., Petrovich, P., Swanson, K., et al., 2003. An Infrared Microsensor Payload for Miniature Unmanned Aerial Vehicles. Unattended Ground Sensor Technologies and Applications V. Edited by Carapezza, Edward M. *Proceedings of the SPIE*, 5090, 265-274.

Kurz, F., 2003. Schätzung von Vegetationsparametern aus multispektralen Fernerkundungsdaten. Publikation 115. Technische Universität München, Verlag der Bayerischen Akademie der Wissenschaften (Reihe C, Heft Nr. 569).

Petrie, G., & Walker, A. S., 2007. Airborne digital imaging technology: a new overview. *The Photogrammetric Record*, 22(119), 203-225.

Pinter, P. J., Hatfield, J. L., Schepers, J. S., Barnes, E. M., Moran, M. S., Daughtry, C. S. T., et al., 2003. Remote sensing for crop management. *Photogrammetric Engineering and Remote Sensing*, 69(6), 647-664.

Rufino, G., Moccia, A., 2005. Integrated VIS-NIR Hyperspectral/Thermal-IR Electro-Optical Payload System for a Mini-UAV. *Infotech@Aerospoace*, 1-9.

Tucker, C., 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8(2), 127-150.

USDA, 2004. Specialty Crops Competitiveness Act of 2004.