A direct georeferencing system for real-time position and attitude determination of lightweight UAVs

FIG Working Week 2015

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unmanned aerial vehicles

UAV…unmanned aerial vehicle

MAV…micro/mini aerial vehicle

„**lightweight UAVs**“

- size: < 1.5 m
- weight: < 5 kg (§16, Abs. 1, Nr.1, LuftVO, legal regulations in Germany)

typical MAV applications:

- precision farming
- infrastructure inspection
- surveying
- …

aerialfarmer.blogspot.com

echord.info

www.susanews.com

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direct georeferencing

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- large/heavy
- GNSS/IMU post-processing for direct georeferencing
- synchronized laser/GNSS and images
- high accuracies

?

- small/lightweight (portable and „flyable“)
- determination of absolute positions/attitudes with high accuracies (< 3 cm/1 deg) in (hard) real-time
- opportunity to trigger/synchronize extern sensors
- opportunity to include any additional sensor

- small/lightweight
- code-based GPS for waypoint flights
- offline bundle adjustment and point cloud generation
- indirect georeferencing using ground control points

direct georeferencing of aerial images

high-accurate navigation of MAVs (autonomous flight)

portable/small mobile mapping systems

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direct georeferencing system

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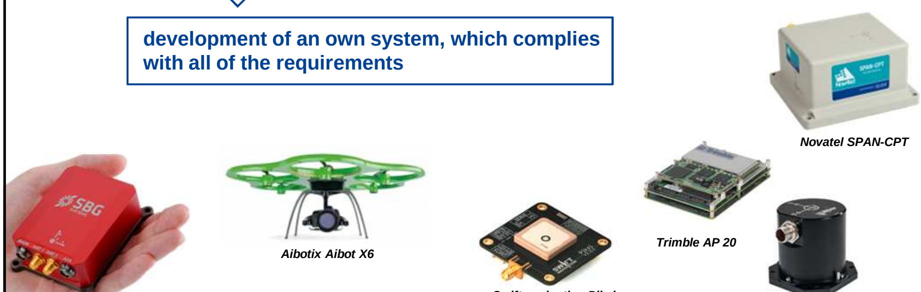
What are the system requirements?

- weight < 500 g, size < 15 x 15 x 10 cm
- real-time capability
- accuracy: σ_{pos}<5 cm, σ_{att}<1-5 deg
- sensor synchronization
- sensor outages should be bridgeable by other sensors

⇩

development of an own system, which complies with all of the requirements



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Development of a precise, small and lightweight direct georeferencing system

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direct georeferencing system

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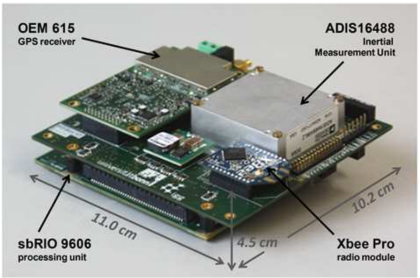

Sensors:

- dual-frequency GPS receiver
- single-frequency GPS receiver
- 3 axis gyroscopes, accelerometers and magnetometers
- barometer
- radio module (RTK GPS positioning)
- link to external sensors (cameras, laserscanner)

Characteristics:

- **small size**: 10.2 x 11.0 x 4.5 cm
- **lightweight**: < 400 g (including the GPS antennas)
- position and attitude determination in **real-time**!
- high accuracies: **< 1 cm position, < 0.5 deg attitude** (under ideal conditions)
- **in-house developed algorithms** (high robustness)
- **high flexibility** (sensor integration, algorithm adaptation)

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the UAV platform

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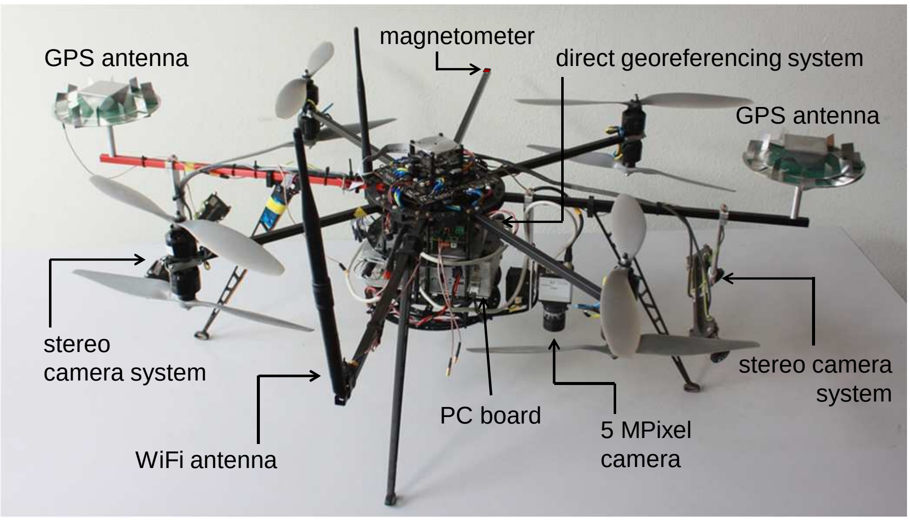

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the UAV platform

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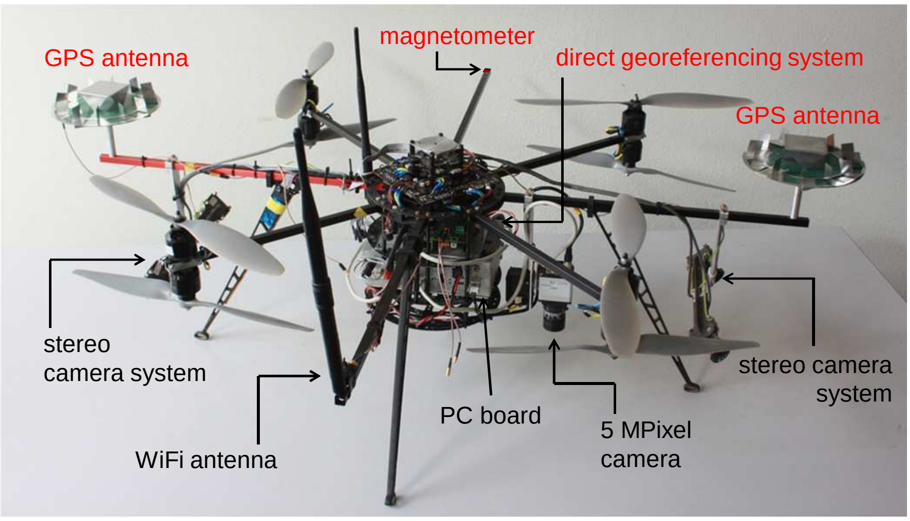

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sensors and processes

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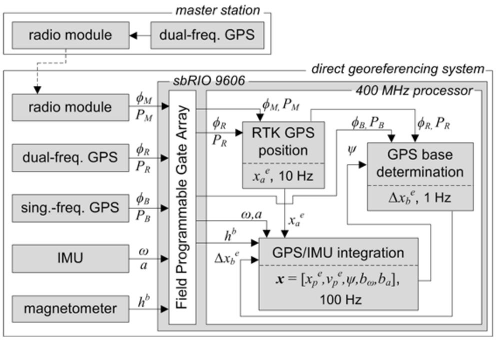

calculation steps

- dual-frequency **RTK GPS** position (10 Hz)
- single-frequency **GPS attitude** baseline (1 Hz)
- **GPS/IMU/Mag** integration (100 Hz)

challenges:

- **fast ambiguity resolution** (instantaneous if possible)
- reliable **cycle slip detection**
- only **single-frequency** GPS observations for the attitude baseline
- **real-time** position and attitude determination

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sensors and processes

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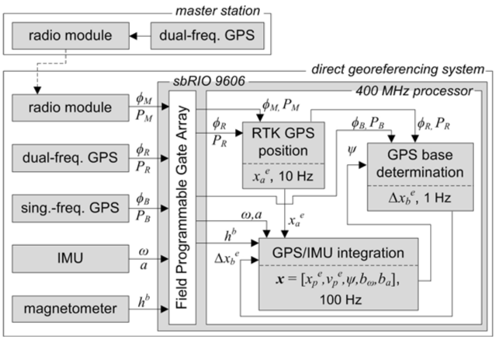

calculation steps

- dual-frequency **RTK GPS** position (10 Hz)
- single-frequency **GPS attitude** baseline (1 Hz)
- **GPS/IMU/Mag** integration (100 Hz)

all algorithms are in-house developed

challenges:

- **fast ambiguity resolution** (instantaneous if possible)
- reliable **cycle slip detection**
- only **single-frequency** GPS observations for the attitude baseline
- **real-time** position and attitude determination

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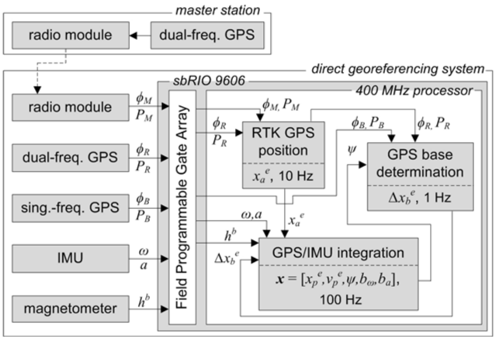
sensors and processes



data flow:

- fast sensor data reading via an **FPGA** (field programmable gate array)
- **data transfer** from the FPGA to the 400 MHz processor via **DMAs** (direct memory accesses)
- **real-time operating system** (all processes are running time deterministic)

- synchronization of the system time via the **PPS signal**
- position and attitude determination on the 400 MHz real-time processor
- software implementation in C++ and in LabView

algorithms

RTK-GPS positioning:

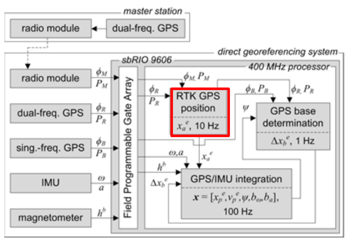
- absolute position comes from RTK-GPS algorithms
- float solution in an extended Kalman filter, fixed solution in a least squares adjustment
- dual-frequency GPS raw observations
- observation vector:

$$\boldsymbol{l} = [\underbrace{\phi_{RM,L1}^{1k} \ldots \phi_{RM,L1}^{nk}\ \phi_{RM,L2}^{1k} \ldots \phi_{RM,L2}^{nk}}_{\text{carrier phases}}\ \underbrace{P_{RM,L1}^{1k} \ldots P_{RM,L1}^{nk}\ P_{RM,L2}^{1k} \ldots P_{RM,L2}^{nk}}_{\text{pseudoranges}}]^T$$

- parameter vector

$$\boldsymbol{x}_{SD} = [\underbrace{x_{a,x}^e\ x_{a,y}^e\ x_{a,z}^e}_{\text{position}}\ \underbrace{N_{L1}^1 \ldots N_{L1}^n\ N_{L2}^1 \ldots N_{L2}^n}_{\text{single-difference ambiguities}}]^T$$

- ambiguity resolution with the MLAMBDA method
- cycle slip detection and repair with the GPS/IMU integration



algorithms

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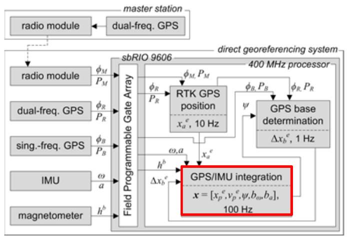
GPS/IMU/Mag integration:

- sensor integration in an error state space Kalman filter
- representation in the ECEF-frame
- **state vector:**

$$\boldsymbol{x} = \left[\boldsymbol{x}_p^{e,T} \ \boldsymbol{v}_p^{e,T} \ \boldsymbol{q}^T \ \boldsymbol{b}_a^{b,T} \ \boldsymbol{b}_\omega^{b,T}\right]^T$$

$\boldsymbol{x}_p^{e,T}$*…position* $\boldsymbol{v}_p^{e,T}$*…velocity* $\boldsymbol{q}^T$*…attitude (quaternion)*

$\boldsymbol{b}_a^{b,T}$*…accelerometer bias* $\boldsymbol{b}_\omega^{b,T}$*…gyro bias*



- **measurements:**
  - RTK GPS position of the dual-frequency RTK GPS antenna reference point, expressed in the ECEF-frame
  - single-frequency GPS attitude baseline vector, expressed in the ECEF-frame
  - magnetic field vector, expressed in the b-frame

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algorithms

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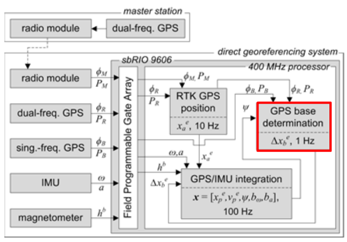
L1-GPS baseline:

- yaw angle estimation is based on a GPS heading system
- Low-cost



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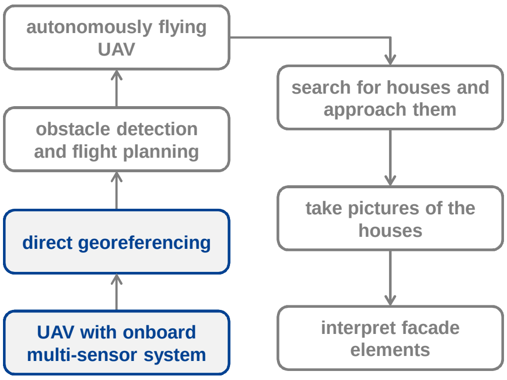
Examples for using the direct georeferencing system – different applications

"Mapping on Demand"

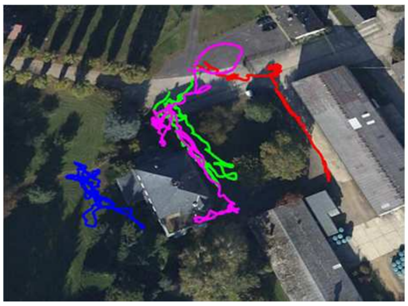
DFG Deutsche Forschungsgemeinschaft

Example scenario: Automatic generation of 3D models with interpreted details during autonomous MAV flights

modified, www.wikipedia.org



"Mapping on Demand"



Flight test:

- performance of 4 flights at one estate
- ~ 5 min per flight
- image acquisition (1 Hz)
- real-time direct georeferencing of the camera during the flights
- bundle adjustment of the images (3D point clouds as results)
- no use of ground control points

Evaluations:

- How well do the results (point clouds) of the different flights match each other?
- How is the absolute accuracy of the point clouds?

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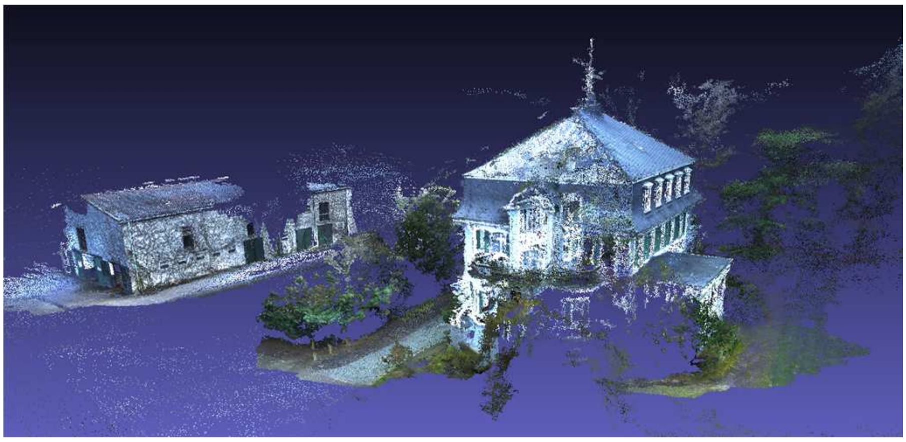
"Mapping on Demand"



Point cloud resulting from four different flights (no registration!)

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“Mapping on Demand”

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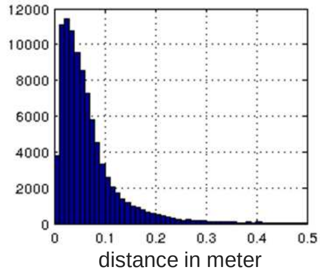

Comparison to a TLS point cloud:

- differences between the georeferenced terrestrial laserscanner (TLS) point cloud and the georeferenced MAV point cloud
- average deviations: **< 5 cm** (nearest neighbor)

Current state:

- the georeferenced images are sent to a ground station during flights
- the bundle adjustment is estimated on a ground station (on the fly) in near-real-time

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precision farming

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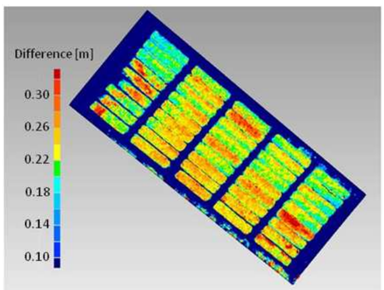
measurement of plant growth rates with directly georeferenced aerial images



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geomorphology

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Other applications for the direct georeferencing system…

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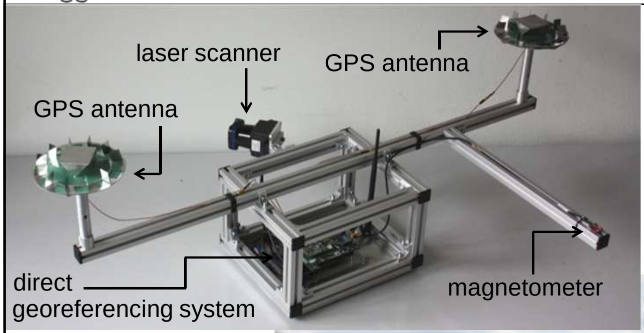
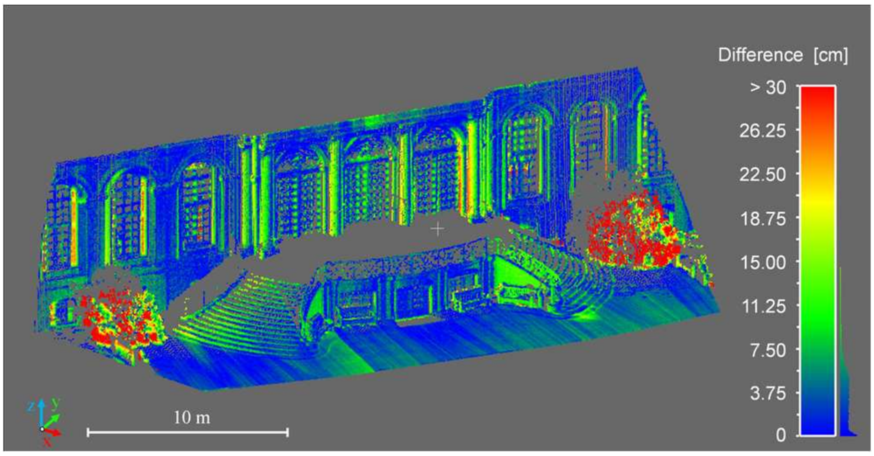
portable laserscanning system



directly georeferenced portable laserscanning system

measurement setup for the system calibration

portable laserscanning system



differences to a georeferenced TLS point cloud igg universitätbonn

Conclusion

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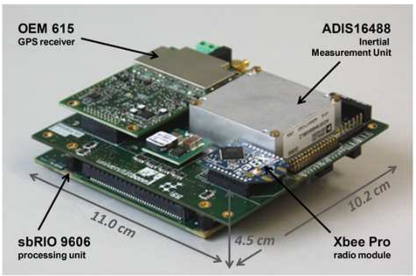
Conclusion



direct georeferencing system

- weight: < 400 g
- size: 11.0 x 10.2 x 4.5 cm
- accuracy: **< 1-3 cm** position, **< 0.5 deg** attitude

under ideal conditions

- system is **small** and **lightweight**
- system provides **georeferenced poses** (3D position and 3D attitude) with a rate of 100 Hz in **real-time**!
- **ambiguity resolution** with **in-house developed GPS algorithms** within the **first epoch** possible => important under frequent signal interruptions
- yaw angle determination is based on a **onboard multi-antenna GPS system** (low-cost) and GPS/IMU integration
- system can be used in various applications

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Thank you very much for your attention!

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