Course Teachers

Michael Cramer
michael.cramer@ifp.uni-stuttgart.de

Görres Grenzdörffer
goerres.grenzdoerffer@uni-rostock.de
Online Course Phase – March 14-25

• Module 1 – Introduction & Principles of RPAS
• Module 2 – RPAS project design and flight planning
  • Lab 1 – Flight planning
  • Lab 2 – Camera quality
• Module 3 – RPAS data processing
  • Lab 3 – Real data processing using Pix4Dmapper
• Module 4 – Legal aspects
RPAS in land survey
Introduction to the course

Görres Grenzdörffer
Professur für Geodäsie und Geoinformatik
Universität Rostock

Michael Cramer
Institut für Photogrammetrie
Universität Stuttgart

www.eurosdr.net
Content – Course Introduction

- RPAS Motivation & Introduction (10“)
- Systems & Sensors (15“)
- Data Acquisition & Processing Concepts (20“)
- Legal Aspects (15“)
RPAS in land survey
Course Introduction – Section 1

RPAS Motivation & Introduction

Görres Grenzdörffer
Professur für Geodäsie und Geoinformatik
Universität Rostock

www.eurosdr.net
Potential of RPAS

- RPAS activities will translate into new jobs.
- US study\(^1\) forecasts in the first three years of RPAS integration in the national airspace more than 70,000 jobs will worth more than $13.6 billion.
- More than 100,000 RPAS related Jobs by 2025 in the US
- For Europe\(^2\), about 150,000 jobs by 2050 are forecasted.

- Growth potential can only be unleashed if a legal framework is established at EU level.

\(^2\) Estimate provided by ASD, the AeroSpace and Defence Industries Association of Europe.
Motivation

• Demand of temporally and spatially high resolution aerial images is growing

• conventional (manned aircraft) systems are too expensive and too weather dependent for small areas (individual objects - some 100 ha)

• The development of miniaturized autonomous control systems (GPS / INS) for Unmanned Aircraft Vehicles (UAV) allows systematic aerial surveys → interesting alternative to traditional surveying aircrafts

• Use of RPAS offers cost savings and greater flexibility (weather independence)

• RPAS close the large gap between terrestrial and airborne or spaceborne spatial data collection
Advantages of Geo data acquisition with RPAS

Scalability
Details – Overview, Depending on question

Endurance
Minutes – Days, Depending on the problem

Flexibility
Where and when it is necessary to survey - flight planning possible on site

New possibilities
Applications, impossible or too expensive in the past

Ideal for aerial surveys of individual properties and small areas
Use of RPAS in Mapping / Photogrammetry

Part I - Introduction & Motivation

© Luhmann et al., 2006
• Current Status:
  – Hottest issue in photogrammetry
  – Highly automated workflow
  – Open and public domain products are available (e.g. Bundler, PMVS, MicMac, Apero etc.)
  – Commercial products available (Pix4D, Agisoft, etc.)
  – Ground control points are necessary for high accuracy
  – Image processing of large blocks requires much time
  – Excellent results: (True) Orthos, DOM, 3D-point cloud

• Open Issues
  – Direct georeferencing
  – Orthophotos of difficult surfaces
  – …
Use of RPAS in Mapping / Photogrammetry

Are there any RPAS-applications in (national) mapping?

Will RPAS-mapping provide sufficient accuracy?
RPAS (Geo)Applications

- Photography & Videography – for TV, cinema, press, advertising and corporate publicity.
- Surveying – Mapping, measuring, building inspection, crop monitoring, wind turbines inspection. Potential for local councils to use as part of planning applications.
- Emergency Services – monitoring, spotting, hazardous air testing, search and rescue, rapid disaster resonance.
- Agriculture – Mapping, harvest monitoring, soil analysis, spraying
- Forestry – Inventory and management of pests & diseases
- Environmental and ecological change monitoring
- Entertainment – Disney has already filed applications for their use
- Communications – Portable emergency relay stations in remote locations
- Short range delivery (?)
RPAS Projects / Applications

- Real estate
- Fire scene inspections
- Monitoring catastrophes
- Plane crash scenes
- Volcanic eruptions
- Spreading of algae
- Monitoring aerosol parameters
- Forestry management
- Monitoring of marine mammals
- Mapping of sandbank movements
- Counting animal populations
- Forestry monitoring
- Tree diseases
- Anti-pirate operations
- Border controls
- Road accident analysis
- Detecting forest firefighting
- Burial grounds
- Mapping in coastal areas
- Geophysical surveys
- Meteorological research
- Mapping of sandbanks
- Identification of plants
- Perimeter monitoring
- Power line inspections
- Railway line inspections
- Project documentation
- Supporting forest firefighting
- Mapping flooding
- Volcanic eruptions – monitoring & ash clouds
- Agriculture – harvesting
- Study of coastal regions
- Iceberg monitoring
- Monitoring earthquakes
- Monitoring & ship collisions
- Monitoring nuclear accidents
- Tool for forest firefighting
- Mapping of industrial zones
- Power cable inspections
- Oil pipeline inspections
- Police operations
- Iceberg monitoring
- Post tsunami mapping
- Agriculture – plant growth
- Agriculture – harvest management
- Arctic research
- Environmental surveillance
- Saltwater infiltration detection
- Surveillance of volcanoes
- Forestry – monitoring tree growth
- Historical building inspections
- Critical infrastructure inspections
- Gas pipeline inspections
- Wind turbine inspections
- Surveillance of coastal regions
- and much more …
Content – Course Introduction

- RPAS Motivation & Introduction (10"
- Systems & Sensors (15"
- Data Acquisition & Processing Concepts (20"
- Legal Aspects (15"

www.eurosdr.net
Terminology

- **Aircraft**: any machine that can derive support in the atmosphere from the reactions of the air other than the reaction of the air earth’s surface (ICAO Annexes).

- **Autonomous Aircraft**: an unmanned aircraft, *that does not allow pilot intervention* in the management of flight (Amend. 43, ICAO Annex 2)

- **Remotely piloted aircraft**: RPAS – an unmanned aircraft which is *piloted from a remote pilot* station (Amend. 43, ICAO Annex 2)

- **Unmanned aircraft**: UA – an aircraft which is intended to operate with *no pilot in board*; note: RPA is considered a subset of UA (ICAO Circular 328)
Terminology

- **Unmanned aircraft system**: UAS – an unmanned aircraft system comprises individual system elements consisting of the UA and any other system element necessary to enable flight, such as remote pilot station, communication link and launch and recovery elements (CAP722, CAA, UK)

- **Unmanned aircraft system**: UAS – An aircraft and its associated elements which are operated with no pilot on board. (ICAO Circular 328)

Not recommended for further use

- **Unmanned aerial vehicle** (UAV) – see RPAS
- **Unmanned aerial system** (UAS) – see RPAS
- **Drone** – see RPAS
RPAS is not a flying object, but a complex system of many individual components.

Relevance for photogrammetry incl. calibration and orientation.
# RPAS-Classification

<table>
<thead>
<tr>
<th>Category</th>
<th>Acronym</th>
<th>Range (km)</th>
<th>Flight Altitude (m)</th>
<th>Endurance (h)</th>
<th>MTOW (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano</td>
<td>η</td>
<td>&lt; 1</td>
<td>100</td>
<td>&lt;1</td>
<td>&lt; 0,025</td>
</tr>
<tr>
<td>Micro</td>
<td>µ</td>
<td>&lt;10</td>
<td>250</td>
<td>1</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Mini</td>
<td>Mini</td>
<td>&lt;10</td>
<td>150-300</td>
<td>&lt;2</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Close Range</td>
<td>CR</td>
<td>10-30</td>
<td>3000</td>
<td>2-4</td>
<td>150</td>
</tr>
<tr>
<td>Short Range</td>
<td>SR</td>
<td>30-70</td>
<td>3000</td>
<td>3-6</td>
<td>200</td>
</tr>
<tr>
<td>Low Altitude Long Endurance</td>
<td>LALE</td>
<td>&gt;500</td>
<td>3000</td>
<td>&gt;24</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Medium Altitude Long Endurance</td>
<td>MALE</td>
<td>&gt;500</td>
<td>14000</td>
<td>24-48</td>
<td>1500</td>
</tr>
<tr>
<td>High Altitude Long Endurance</td>
<td>HALE</td>
<td>&gt;2000</td>
<td>20000</td>
<td>24-48</td>
<td>4500-12000</td>
</tr>
<tr>
<td>Stratospheric</td>
<td>STRATO</td>
<td>&gt;2000</td>
<td>20000-30000</td>
<td>&gt;48</td>
<td>30-?</td>
</tr>
</tbody>
</table>

- Orange: Platform for image-based spatial data
- Light Blue: Indoor-platform for image-based spatial data

van Blyenburg, 2008
Micro and Mini-RPAS

Multicopter

Helicopter

Fixed wing

Blimp
## Comparison RPAS platforms for geomatics applications

<table>
<thead>
<tr>
<th></th>
<th>Fixed wing UAS</th>
<th>UAS Model helicopter</th>
<th>Multicopter</th>
<th>Ballon / Blimp</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handling</td>
<td>Simple</td>
<td>Complex</td>
<td>Simple</td>
<td>Simple</td>
</tr>
<tr>
<td>Navigation</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>Wind suspectability</td>
<td>O</td>
<td>-</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Robustness</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Noise</td>
<td>quiet</td>
<td>noisy (fuel)</td>
<td>quiet</td>
<td>quiet</td>
</tr>
<tr>
<td>Transport</td>
<td>Car / trunk</td>
<td>Car / trunk</td>
<td>Car / trunk</td>
<td>separate unit</td>
</tr>
<tr>
<td>Endurance</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Rolling costs</td>
<td>O</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Mapping Application</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed / coverage</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Pointing</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Payload</td>
<td>O</td>
<td>++</td>
<td>+</td>
<td>O</td>
</tr>
<tr>
<td>Start- u. Landing</td>
<td>runway</td>
<td>everywhere</td>
<td>everywhere</td>
<td>runway</td>
</tr>
</tbody>
</table>

- -- very low
- - low
- 0 medium
- + high
- ++ very high
Model planes Challenges: Start

- **Hand start**
  - Only possible for RPAS < 6 kg
  - Requires experience

- **Start Catapult**
  - heavy
  - complex
  - dangerous
Model planes Challenges: Landing

- **Net**
  - complex, not easy to hit,
  - frame can be damaged

- **Parachute**
  - wind dependent
  - dragged on ground
„Standard“ Cameras on RPAS

„GoPro“-Class
- small
- light weight (< 100g)
- fixed lens (stable IO)
- Image quality (low light)
- Fish eye lens

„Consumer Camera“
- small
- light weight (< 250g)
- external exposure control
- lens (instable IO)
- Image quality (low light)

„DSLR“
- Image quality
- Image size (>20 MP)
- fixed lens (stable IO)
- external exposure control
- heavy (> 500 g)
Image motion – a crucial parameter for RPAS flights

- In airborne applications image motion $u$ should be below 0.5 pixel
- Using a surveying aircraft high airspeeds limit the minimum GSD or demand for forward motion compensation (FMC)

$$u = \frac{c \ast \omega \ast \Delta t}{CCD[\mu m]}$$

- Multirotor RPAS fly at low speeds, exposure times have to be kept short, why ??
  - Vibrations of the RPAS
  - Necessary acceleration and rotation to keep the RPAS stable in windy conditions
  - Accelerations and rotations of the stabilization mount, incl. latency
Image motion – a crucial parameter for RPAS flights

Acceptable rotational speed to keep image motion below 0.5 pixel in relation to the exposure time

Example:
exposure time of 1/800 sec
\[ c = 9 \text{ mm} \]
allows for rotation speed of 11.8°/sec.

(common max. rotation speed of RPAS during flights at 2 - 3 Bft).
Stabilized mounts

• State of the art
  – 2-axis / 3-axis stabilized brushless gimbal
  – Built in independent IMU module
  – Multiple Control Modes (Photo / Video)
  – Gimbals for GoPro (weight > 200g)
  – Gimbals for DSLR (weight > 1.500g)
Current Trends and Innovations

- Multicopter and fixed wing grow together

- **SONGBIRD / Aerolution**
  - Combination of multi copter and fixed wing aircraft
  - perpendicular starting and landing
  - does not require a runway
  - fast > 110 km / h
  - Flight time: up to 1 h
  - About 1.5 kg payload
  - Powerful autopilot
Current Trends and Innovations

- RPAS become "intelligent" and autonomous in which they recognize their environment

Example: eXom – Inspection-RPAS from Sensefly for indoor and outdoor

https://www.sensefly.com/drones/exom.html
Current Trends and Innovations

- RTK-GNSS for navigation and orientation

- High-precision GNSS allows:
  - More precise Flights / navigation
  - Accurate image capture
  - Direct georeferencing

- Problems
  - Ambiguities in the vicinity of buildings
  - “Metric” camera required
  - Expensive
  - ...

Mavinci „Sirius Pro“

Javad „Triumph F1“
Current Trends and Innovations

- Full exterior orientation information from integrated GNSS/inertial systems for direct georeferencing, i.e.
  - Corridor surveys
  - reduced image overlaps

<table>
<thead>
<tr>
<th>PERFORMANCE SPECIFICATIONS² (RMS ERROR)</th>
<th>SPS</th>
<th>DGPS</th>
<th>RTK⁴</th>
<th>Post-Processed⁵</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (m)</td>
<td>1.5 - 3.0</td>
<td>0.5 - 2.0</td>
<td>0.02 - 0.05</td>
<td>0.02 - 0.05</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
<td>0.015</td>
</tr>
<tr>
<td>Roll &amp; Pitch (deg)</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.025</td>
</tr>
<tr>
<td>True Heading³ (deg)</td>
<td>0.30</td>
<td>0.28</td>
<td>0.18</td>
<td>0.080</td>
</tr>
</tbody>
</table>

From Applanix product information

Applanix APX15 – UAV board
Current Trends and Innovations

- Cheap RPAS become better and Open Source Projects

  - Example DJI Phantom 3
    - Flight time: ca. 20 min.
    - Payload: 200 g
    - Automatic flight
    - Flight planning software
    - Cost: ca. 1.200 €

- Example ArduPilot
  - Hard- and Software for Auto pilot and Gimbal
  - Flight planning software
Current Trends and Innovations

• Miniaturized Multi / hyperspectral and laser sensors for RPAS (examples)

  • Rikola Hyperspectral Scanner
    – Weight: ca. 600g
    – Spectral Range: 500-900 nm
    – Frame camera, d.h. simple Geo referencing

  • Yellow Scan Laserscanner
    – Weight: ca. 2.2 kg
    – Range: ca. 100 m
    – FOV: 100°
RPAS-laser scanning

• **RIEGL VUX-1** system
  - 10 mm survey-grade accuracy
  - scan speed up to 200 scans / second
  - measurement rate up to 500,000 meas./sec @ 550 kHz PRR & 330° FOV
  - operating flight altitude up to more than 1,000 ft
  - field of view up to 330° for practically unrestricted data acquisition
  - regular point pattern, perfectly parallel scan lines
  - compact (227x180x125 mm), lightweight (3.6 kg) and rugged

Tetracam Multispectral cameras

- Tetracam Agriculture Digital Camera (ADC) Serie

- Tetracam Multiple Camera Array (MiniMCA) Serie
Sample Data - Tetracam Multispectral camera
Challenges - Radiometry

\[ \rho(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{L(\theta_i, \phi_i, \theta_r, \phi_r)}{E(\theta_i, \phi_i)} \]

\( \theta_i, \phi_i \) Zenith and azimuth angles of incident light
\( \theta_r, \phi_r \) Zenith and azimuth angles of reflected light

Reflected radiance
Irradiance

---

Honkavaara, 2014

European Spatial Data Research – www.eurosdr.net
RPAS in land survey
Course Introduction – Section 3

Data Acquisition & Processing Concepts

Michael Cramer
Institut für Photogrammetrie
Universität Stuttgart
Content – Course Introduction

- RPAS Motivation & Introduction (10"
- Systems & Sensors (15"
- Data Acquisition & Processing Concepts (20"
- Legal Aspects (15"
Data Acquisition

Land survey

Terrestrial Photogrammetry

RPAS Photogrammetry = Terrestrial Photogrammetry from airborne „Tripods“
Concept of (stereo) photogrammetry

Photogrammetric stereo reconstruction

\[ p'(x', y') \]

\[ p''(x'', y'') \]

Accuracy parameters
- Imaging geometry
  - Base
  - Distance / height

Measurement accuracy in image space
- Camera geometry
  (interior orientation)
- Exterior orientation quality
- Mathematical model

Base
Distance
\[ \sigma_{X,Y} \]
\[ \sigma_Z \]
Concept of (stereo) photogrammetry

**Photogrammetric stereo reconstruction**

\[ x' = \frac{X}{c} - \frac{Z}{c}, \quad y' = \frac{Y}{c} - \frac{Z}{c}, \]
\[ x'' = \frac{X - B}{c} - \frac{Z}{c}, \quad y'' = \frac{Y}{c} - \frac{Z}{c}, \]
\[ Z = \frac{c \cdot B}{x' - x''} = \frac{c \cdot B}{p_x}, \]
\[ Y = -Z \frac{y'}{c} = -Z \frac{y''}{c}, \]
\[ X = -Z \frac{x'}{c}. \]
Concept of (stereo) photogrammetry

Photogrammetric stereo reconstruction

\[ \mathbf{p}'(x',y') \]

\[ \mathbf{p}''(x'',y'') \]

Distance \( Z \) Base \( B \)

Accuracy

\[ \sigma_x, \sigma_y, \sigma_z \]

\[ \sigma_x = m_b \cdot \frac{Z}{B} \cdot \sigma_x \]

\[ \sigma_y = \sigma_x = m_b \cdot \sigma_x \]

\[ Z \uparrow \Rightarrow \sigma_z \uparrow \]

\[ B \uparrow \Rightarrow \sigma_z \downarrow \]

\[ \sigma_x \uparrow \Rightarrow \sigma_z \uparrow \left( m_b = \frac{Z}{c} \right) \uparrow \Rightarrow \sigma_z \uparrow \]

stereo normal case used for accuracy estimation
Concept of (multiple stereo) photogrammetry

Photogrammetric stereo reconstruction

The stereo model was the traditional working unit in (analog) airborne photogrammetry, with digital imaging this changed to the multiple stereo model / ray processing. This also is the case in terrestrial and RPAS projects.
Photogrammetric blocks
Factors influencing accuracy

- Accuracy of image measurements
- Image scale
- Configuration (base-to-height/distance ratio)
- **Design factor** for close-range blocks

\[
\sigma_Z = m_b \cdot \frac{Z}{B} \cdot \sigma_{x'}
\]

\[
\sigma_Y = \sigma_X = m_b \cdot \sigma_{x'}
\]

\[
\sigma_{XYZ} = q \cdot m_b \cdot \sigma_{x'}
\]

Airborne blocks
Close-range blocks
Aerial Triangulation
Collinearity equation

- **Transformation Image ➔ Object**

\[
\Delta X = \Delta Z \frac{r_{11} x + r_{12} y + r_{13} z}{r_{31} x + r_{32} y + r_{33} z}
\]

\[
\Delta Y = \Delta Z \frac{r_{21} x + r_{22} y - r_{23} c}{r_{31} x + r_{32} y - r_{33} c}
\]

- **Transformation Object ➔ Image**

\[
\bar{x} = \bar{z} \frac{r_{11} \Delta X + r_{21} \Delta Y + r_{31} \Delta Z}{r_{13} \Delta X + r_{23} \Delta Y + r_{33} \Delta Z}
\]

\[
\bar{y} = \bar{z} \frac{r_{12} \Delta X + r_{22} \Delta Y + r_{32} \Delta Z}{r_{13} \Delta X + r_{23} \Delta Y + r_{33} \Delta Z}
\]

with

\[
\Delta X = X - X_0 \quad \bar{x} = x - x_0
\]

\[
\Delta Y = Y - Y_0 \quad \bar{y} = y - y_0
\]

\[
\Delta Z = Z - Z_0 \quad \bar{z} = z - z_0 = -c
\]

- **Note**: model assumes cartesian coordinate frames
  - stringent approach: **pre-transformation** of object coordinates
  - alternative: **correction of earth curvature** at object or image coordinates (note: no error in image space in its closer sense)
Extended collinearity equations

- Transformation from Object → Image

\[ \bar{x} = \frac{r_{11}\Delta X + r_{21}\Delta Y + r_{31}\Delta Z}{r_{13}\Delta X + r_{23}\Delta Y + r_{33}\Delta Z} + \Delta x \]

\[ \bar{y} = \frac{r_{12}\Delta X + r_{22}\Delta Y + r_{32}\Delta Z}{r_{13}\Delta X + r_{23}\Delta Y + r_{33}\Delta Z} + \Delta y \]

with

\[ \Delta X = X - X_0 \]
\[ \Delta Y = Y - Y_0 \]
\[ \Delta Z = Z - Z_0 \]
\[ \bar{z} = z - z_0 = -c \]

- typically the standard model is amended by additional parameters (AP) \[ \Delta x, \Delta y \]
- allow for compensation of **systematic errors** in image space and estimation **camera calibration parameters** (dependent on block geometry)
- models are functions of reduced image coordinates
- **classification** of AP sets
  - **physical models**, obtained from physical interpretable params (D. Brown)
  - pure **mathematical models** without physical meanings
  - **combined/mixed models** (combination of former two)
Camera Calibration

- Most often camera calibration is done in a so-called **self-calibration approach** (camera calibrated in the block itself)
- For a priori calibration (to get approx. values) a **mobile test field** (possibly with coded targets) might be used.
Extended collinearity equations

*Indirect georeferencing*

\[
X^l = X_0^l + \lambda R_{Cam}^l p^{Cam}
\]

---

**Part I-3 – Data Acquisition & Processing Concepts**

European Spatial Data Research – www.eurosdr.net
Extended collinearity equations

GNSS/inertial EO parameters

Modified geometry used in **direct** georeferencing

Inertial Measurement Unit

Object coordinate system

Part I-3 – Data Acquisition & Processing Concepts
Extended collinearity equations

**GNSS/inertial EO parameters**

- Coordinate transformation **Image ➜ Object**
  - **frame sensor**
    \[
    \mathbf{X} = \mathbf{X}_0^l + \mathbf{R}_b^l \left[ \lambda \mathbf{R}_\text{Cam}^b \cdot \mathbf{x}_P^{Cam} + \Delta \mathbf{X}_\text{Cam}^b - \Delta \mathbf{X}_\text{GPS}^b \right]
    \]
  - Note: for rolling shutter cameras the **change of EO parameters during exposure** might be modelled.

► Keep in mind:
- **Navigation angles** from GPS/inertial are **non identical** with the typically used photogrammetric angles
  \[
  \mathbf{R}_b^l(\omega, \varphi, \kappa) \neq \mathbf{R}_b^n(\Phi, \Theta, \Psi)
  \]
- GPS/inertial data have to be related to the imaging sensor to be oriented, so-called **boresight alignment corrections**
  - Translation offsets \(\Delta X_{\text{Cam}}^b, \Delta X_{\text{GPS}}^b\)
  - Misalignment matrix \(\Delta \mathbf{R}_{\text{Cam}}^b(\Delta \omega, \Delta \varphi, \Delta \kappa)\)
Photogrammetric block layouts

(c古典) airborne

close-range
Aerial Triangulation

Standard-AT

- GNSS/inertial data „levelled“ camera
- AAT (tie points from FBM/LSM)
- GNSS supported AT few control points
- Calibrated cams + self-calibration (math. models)

Process chain

- Initial Orientation / Set-up of Image Block
- Orientation of image block
- Transformation into object coordinate frame
- Camera calibration
- Product generation DTM/DSM (Dense Matching) & Ortho

RPAS

- GNSS (code) Attitudes > 0…20deg
- Structure from Motion (SIFT key points)
- Few control points
- Full in-situ camera calibration (physical models)
**CV – Multiple View Geometry Structure from Motion SfM**

- **Scene geometry** (structure): Given 2D point matches in two or more images, where are the corresponding points in 3D?

- **Correspondence** (stereo matching): Given a point in just one image, how does it constrain the position of the corresponding point in another image?

- **Camera geometry** (motion): Given a set of corresponding points in two or more images, what are the camera matrices for these views?
CV – Multiple View Geometry
Structure from Motion

• **Given**: $m$ images of $n$ fixed 3D points

\[ x_{ij} = P_i X_j, \quad i = 1, \ldots, m, \quad j = 1, \ldots, n \]

• **Problem**: estimate $m$ projection matrices $P_i$ and $n$ 3D points $X_j$ from the $mn$ correspondences $x_{ij}$
Feature detection using SIFT / ASIFT / SURF
CV – Multiple View Geometry Structure from Motion

Incremental SfM
Matching features in stereo-pairs
Structure from Motion Algorithm

• Initialize 3D model by selecting suitable stereo pair from all available images

• Expand 3D model
  – If there are connected images add that image which contains the largest number of existing 3D points
  – Compute orientation of corresponding camera station (DLT)
  – Spatial intersection of additional stereo points
  – Compute bundle block adjustment (global best estimate)
Structure from Motion Algorithm

- Initialize motion from two images using fundamental matrix and SIFT matching
  - Initialize structure

- For each additional view:
  - Determine projection matrix of new camera using all the known 3D points that are visible in its image – calibration
  - Refine and extend structure: compute new 3D points, re-optimize existing points that are also seen by this camera – triangulation

- Refine structure and motion: bundle adjustment
Structure from Motion Algorithm

• Initialize motion from two images using fundamental matrix and SIFT matching
  – Initialize structure

• For each additional view:
  – Determine projection matrix of new camera using all the known 3D points that are visible in its image – calibration
  – Refine and extend structure: compute new 3D points, re-optimize existing points that are also seen by this camera – triangulation

• Refine structure and motion: bundle adjustment
Structure from Motion Algorithm

Example: VisualSfM [http://ccwu.me/vsfm/](http://ccwu.me/vsfm/)
Image Matching

• Basic assumption: Corresponding points in images usually have similar gray values

• Problems from matching ambiguity due to
  – Similar grey values depict different points i.e. surface patches
  – Homogenous texture

• Identical points appear different
  – Changes in illumination, different look angle, noise

• Strategies to overcome ambiguities
  – Use of robust similarity measures

• Match windows instead of single pixels
  – Constrain correspondence with additional information

• Epipolar geometry to restrict matching to 1D problem
Dense Image Matching
Semi global matching

• Match single pixels with global algorithms such that a global energy function is minimized
• Additional assumptions / constraints to overcome ambiguity
• Semi-global matching
  – Matching: dense, intensity-based
  – Global: optimization approach using a global model
  – Semi: approximation ▶ fast numerical solution

Intensity image
Disparity image using a correlation matching method
Disparity image using Semi Global Matching

Hirschmüller (2005)
Course **High density image matching**

Prof. Dr. Norbert Haala
University of Stuttgart, Germany

see [http://www.eurosdr.net/education/past](http://www.eurosdr.net/education/past)

---

**High density image matching**

**Tutor:** Norbert Haala (Stuttgart University, Germany)

**Dates:** 10 - 21 March 2014

**Instructor:** Prof. Norbert Haala, Institute for Photogrammetry, University of Stuttgart; e-mail: norbert.haala@ifp.uni-stuttgart.de

**Target audience:** PhD and Master students involved in geomatics and photogrammetry, staff from national mapping agencies, public authorities and third parties in charge of 3D databases like DTM and urban model.

The course provides an overview of recent developments in photogrammetric image processing, which considerably improved the automatic image-matching and reconstruction of 3D models and 3D point clouds. Course participants will become familiar with state-of-the-art techniques for pixel-wise stereo image matching like the Semi-Global Matching approach. They will also learn how dense surface reconstruction profits from the redundancy of stereo and multi-view matching. The course will demonstrate how techniques and concepts from computer vision can be used to increase the efficiency of photogrammetric image processing.

**Course outline:** The introductory course during the kick-off seminar provides the participants with the basic knowledge for a successful course. The course will provide an overview on the relevant photogrammetric processing chain. The individual work and exercises as well as hands-on demonstrations during the following online study phase use real-world data e.g. from the EuroSDR benchmark on image matching for DSM computation. Potential applications are demonstrated, while additional sample calculations will exemplify the relevant processing steps and enable the required feedback.

**Module 1. Structure-from-motion and image pre-processing**

The module briefly reviews the standard photogrammetric processing chain including automatic image orientation, rectification of stereo pairs and point determination from estimated parallaxes. Main emphasis is put on the efficient computation of such photogrammetric tasks based on projective geometry as it is commonly used in computer vision within open source libraries and available software tools – **8 hours**

**Module 2. Pixel-based stereo matching for dense surface reconstruction**

The module discusses state-of-the-art algorithms and optimization criteria for dense stereo image matching.
RPAS in land survey
Course Introduction – Section 4

Legal Aspects

Görres Grenzdörffer
Professur für Geodäsie und Geoinformatik
Universität Rostock

www.eurosdr.net
Content – Course Introduction

- RPAS Motivation & Introduction (10“)
- Systems & Sensors (15“)
- Data Acquisition & Processing Concepts (20“)
- **Legal Aspects** (15“)
RPAS and legal issues

- **Scenario 1**: A farmer with a 2000 ha farm throws a RPAS into the air in the morning and a little later he gets fully automatically up to date information about all of its fields.

- **Scenario 2**: After an emergency call, the fire fighters starts an RPAS flying a few miles ahead and once they arrive at the fire, valuable information is already available at the scene.

- **Scenario 3**: After an emergency call the police launches an RPAS and scans generously the whole scenery to acquire all possible data for subsequent use.

*Are these scenarios possible or legal today?*

- No, because of legal restrictions and privacy issues.
Where can I fly at all?
Structure of the lower airspace

- RPAS <25 kg may operate only in uncontrolled airspace (G), < 1,000 ft, (2,500 ft) above ground
- Flights in airspace D and F requires a special permission from air traffic control (ATC)
Airspace Usage - Airspace Maps

http://maps.openaip.net/
Privacy

• No separate RPAS-privacy laws. Normal laws apply

• It is forbidden to take images AND distribute them IF people can be identified WITHOUT permission UNLESS there is a justified reason
What is the state of play in Europe?

- 14 countries have regulation (not harmonised)
- 5 countries are developing rules
- 6 allow operations under strict conditions
- 2800+ civil approved commercial companies and growing
- Most operators and manufacturers have no aviation background
- Economic potential estimated at several billions before end 2020
- Pragmatic European approach …
Legal framework - current status, Germany

- RPAS > 25 kg, and flights beyond line of sight (BLOS) are generally prohibited, exceptions are possible (Repressive prohibition)
- Distinction between permit free and subject to authorization flights is the purpose of the flight
  - Sports and Leisure = RC, i.e. permit free
  - Commercial or science, etc. = RPAS, i.e. subject to authorization (Permit required)
- Permits issued by state authorities
- Permits require proof of insurance, no pilot licence, no certification of UAS, no ID-plate
**Austrian RPAS Regulations**

The extent of the technical investigation is determined by the category and ranges from self declaration to a sample inspection.

<table>
<thead>
<tr>
<th>Category</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airworthiness Requirements</td>
<td>no compliance with CS needed</td>
<td>≤25kg: Model aircraft certification &gt;25kg: CS for model aircraft (self declaration)</td>
<td>Case-by-Case basis (CS-LURS, CS-LUAS, ...)</td>
<td>Case-by-Case basis (CS-LURS, CS-LUAS, ...)</td>
</tr>
<tr>
<td>Continuing Airworthiness</td>
<td>Pre-flight check</td>
<td>Pre-flight check</td>
<td>Maintenance by check list</td>
<td>Maintenance by check list</td>
</tr>
<tr>
<td>Control System</td>
<td>Non complex manual control</td>
<td>Non complex with stabilization</td>
<td>Complex with stabilization and automation</td>
<td>Complex with stabilization and automation and navigation</td>
</tr>
<tr>
<td>Record Keeping</td>
<td>Date, time, duration, pilot...</td>
<td>Date, time, duration, pilot...</td>
<td>Date, time, duration, pilot...</td>
<td>Date, time, duration, pilot...</td>
</tr>
<tr>
<td>Failure Tolerance</td>
<td>none</td>
<td>FMEA</td>
<td>FMEA</td>
<td>FMEA</td>
</tr>
</tbody>
</table>
Experiences up to now

- Civil UAS certification and operation for VLOS in Austria legally possible from 1st January 2014
- Over 250 VLOS applications and ~150 permits – certification needs 4 - 6 months
  - Category A + B: ~120
  - Category C: ~20, permanently, general constraints
  - Category D: few, single permit, specific constraints for each flight
- Many „illegal“ flight operations due to strict regulations and delays
- BVLOS not possible due to missing regulations
- Uncertainty about European regulation is a problem
- Further legal questions:
  - Data Protection/Privacy, further Civil Law (landlord permission), Insurance, Regional Laws (Lands), Radio Frequencies, etc.
**Spain**

ES - Ratings being considered: MTOM < 2 kg, 2-25 kg, 25-50 kg, 50-150 kg
No airworthiness approval to be required below 25 kg.
National registration marks: >25 kg
Use of QE under discussion.

**Sweden**

SE - 4 Categories:
1: VLOS - MTOM <1,5 kg (kinetic energy <150 Joule)
2: VLOS - MTOM 1,5-7kg (kinetic energy 1000 Joule)
   - Technical, operation & maintenance manual required.
   - Theoretical pilot knowledge: commercial pilot licence
   - Practical pilot skill: Completed approved training
3: VLOS – MTOM >7 kg
   - Technical, operation & maintenance manual required.
   - Theoretical pilot knowledge: commercial pilot licence
   - Practical pilot skill: Completed approved training
4: BLOS
   - Distance aircraft/persons, animals, property: >50m
   - Flight altitude: <120m (400 ft) AGL
   - Fail-safe system: Required

---

**SE**

Daylight activities only, automatic/programmed flight possible if manual take-over possible at all times.
Accident & incident reporting: Obligatory
Flight logs must be kept.
NAA approval required for design, manufacture, modification, maintenance & operation of RPAS.
Operator approval validity: Category 1 & 2: 2 years
   Category 2 & 3: 1 year
National registration marking: Required
Insurance: EC 785/2004
European Regulation

- European Aviation Safety Agency (EASA) is responsible for civilian RPAS > 150 kg
- 6. March 215 – Riga Declaration
- By 2016 EASA plans to finalize a corresponding framework.
- In addition to the mandatory task, the EU wants to harmonize national regulations for all RPAS <150 kg
- EASA Regulation will come in 2017–2018 (after approval of basic regulation (EASA-VO (EG) Nr. 216/2008)

EU vision of the integration of UAS in the civilian airspace

Aviation safety rules: impact on areas of public concern

- Privacy rules and data protection
- Security
- Environment
- Liability/Insurance

- Open operations: No aviation specific rules, Enforcement by police
- Specific operations: Aviation specific rules, Enforcement of rules by aviation authorities
- Certificated operations: Aviation specific rules, Enforcement of rules by aviation authorities
### EASA Technical Opinion – 3 Categories

<table>
<thead>
<tr>
<th><strong>Open Category</strong></th>
<th><strong>Specific Category</strong></th>
<th><strong>Certified Category</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>– Equal rules for model planes and UAS</td>
<td>• Mostly for commercial UAS-users</td>
<td>• Specific for large UAS &gt; 25 kg</td>
</tr>
<tr>
<td>– Geofencing</td>
<td>• „small“ licence</td>
<td>• Certification similar to manned aviation</td>
</tr>
<tr>
<td>– Subcategories in relation to potential harm</td>
<td>• Requirements depend on use of operation</td>
<td>• Pilot licence (PPL)</td>
</tr>
<tr>
<td>– Exemption for toys</td>
<td>• Certification of Flight Operation through „Certified Entities“</td>
<td>• Certification of Flight Operation through Certified Entities</td>
</tr>
<tr>
<td>– Control thru police</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EASA Technical Opinion - Geofencing

Restricted zone

- Geo-fencing
- Identification
- Mass
- Product requirements

Aeromodel Zone

No-fly zones

City Centre

Airport

Natural Park
Conclusions for civil / commercial RPAS segments

• RPAS with < 5 - 30 kg* (no integration in general aviation (max. 150 m altitude and easy flights within visual line of sight (VLOS))

• Small RPAS - good value for money and well suited to carry a (photogrammetric) camera

• Potential for commercially successful applications

* Max. take off weight differs from country to country
Conclusions for civil / commercial RPAS segments

- RPAS with > 30 kg (primarily military use, possible future integration into general airspace)
- Requirements for payload, telemetry, TCAS, security systems (redundancy) lead to large and therefore expensive systems, thus commercial civil usage appears very difficult
- Regulation issues for beyond line of sight (BLOS)-flights will remain critical for the upcoming 5 – 15 years
- EU has decided on a common list of minimums in order to enable cross border work in the future