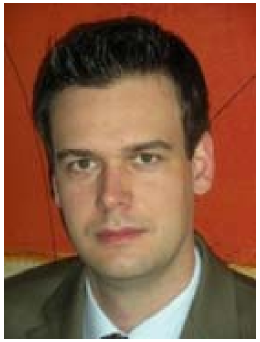
Another Step towards
Measuring the World from the Air:
Model-based 3D Real-time Simulation of Micro-UAV

Andreas Schilling - Thomas Linkugel



Cosupervisor of dissertation project:
Hanspeter Mallot, Department of Biology, University of Tübingen

Simulation of UAVs

- Why?
- How?
- What?

Why?

Applications of UAVs

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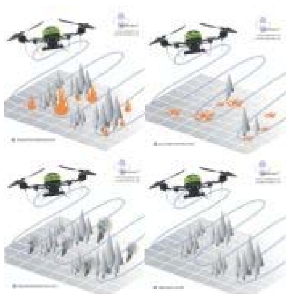
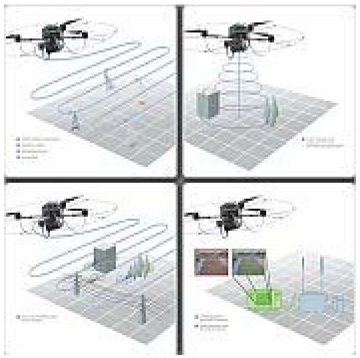
UAVs are convenient for many tasks.

Examples:



Forest Fire Fighting

Demining



Inspection of Offshore Wind Power Stations

Images from: www.airrobot.de

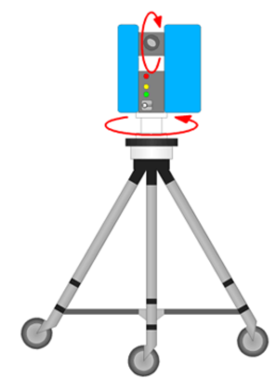
Applications

Creating models for virtual reality applications

real photograph

Model courtesy of Max-Planck-Institut für biologische Kybernetik Tübingen

realtime rendering
with RadioLab*



*Developed by Ralf Sonntag, Universität Tübingen

Applications

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- Virtual Tübingen

Applications of UAVs

- Measuring the world
- Acquisition of 3D-scenes for visualiziation
- To some extend: replace traditional surveying

Standard scenario

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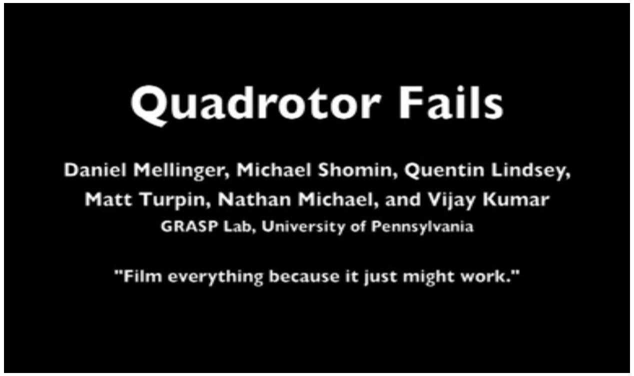
- Online manual control
- Online and offline evaluation

- A lot of research with the goal of autonomous flying

Why simulate?

Extend applications:

- Develop new hardware
- Develop new software
  - Efficient low level control
  - Automatic high level control
    (e.g autonomous flying, autonomous exploration)
  - Online and offline evaluation and measurement (high precision measurement and 3d model acquisition)



Video link

Why simulate?

- Simulation is cheaper than real experiments (time and money)
- Ground truth
- Reproducible results
- Can simulate more (24/7)
- Can simulate extreme situations
- Can simulate new, not-yet-existing hardware

How?

How simulate?

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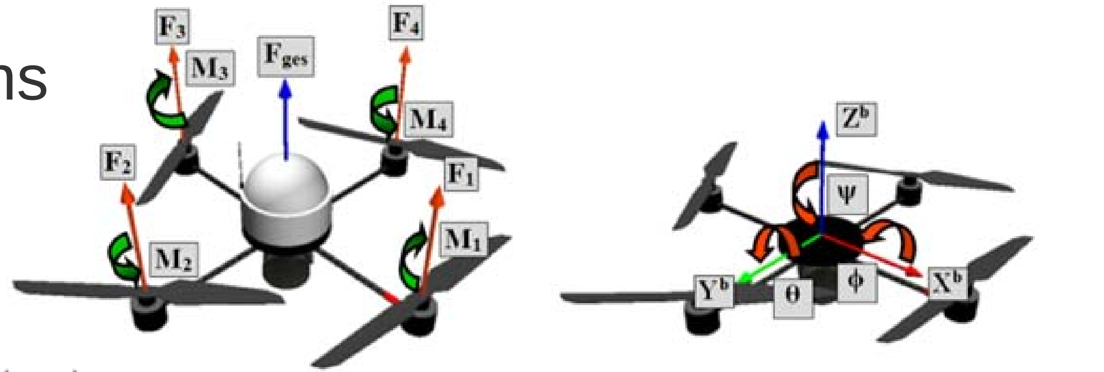
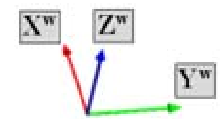
- Devise equations
- Integrate



$$C_b^w = \begin{pmatrix} c\theta c\psi & -c\phi s\psi + s\phi s\theta c\psi & s\phi s\psi + c\phi s\theta c\psi \\ c\theta s\psi & c\phi c\psi + s\phi s\theta s\psi & -s\phi c\psi + c\phi s\theta s\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{pmatrix}$$

$$\dot{\vec{v}}^w = C_b^w * \vec{a}^b + \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \qquad \dot{\vec{v}}^w = \frac{1}{m} * C_b^w * \begin{pmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} F_i \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix}$$



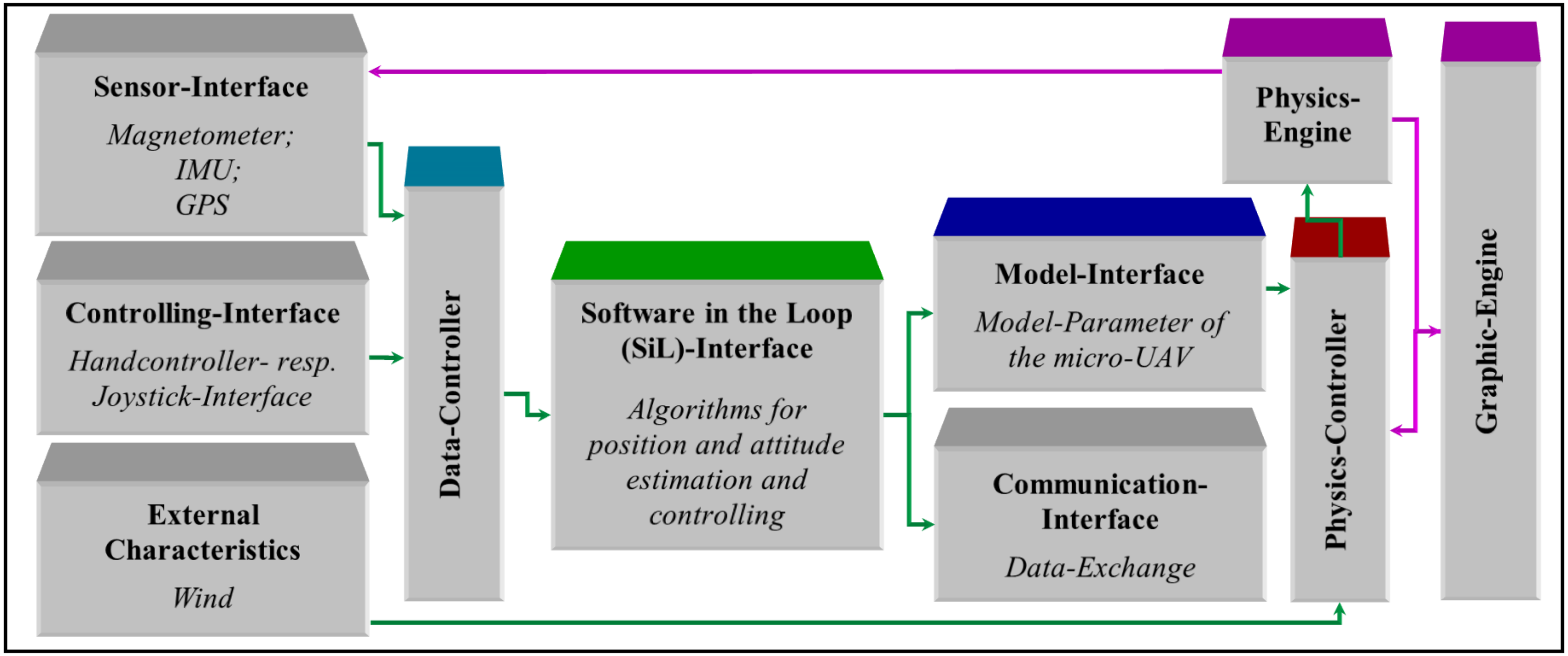
$$\overrightarrow{F_{ges}}^b = \begin{pmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} F_i \end{pmatrix} + C_b^{w\,T} * m * \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} \qquad \overrightarrow{F_{C_w}}^w = \frac{1}{2} * \rho * C_w * A * \overrightarrow{v^2}^w \qquad \vec{M}^w = \frac{d\vec{L}^w}{dt}$$

$$\vec{M}^b = \vec{\omega}^b{}_F \times \vec{L}^b + \dot{\vec{L}}^b \qquad \vec{L}^b{}_R = I^b{}_R * \vec{\omega}^b{}_R \qquad \vec{L}^b{}_F = I^b{}_F * \vec{\omega}^b{}_F \qquad \vec{L}^b = (I^b{}_F + 4 * I^b{}_R) * \vec{\omega}^b{}_F + \sum_{i=1}^{4} I^b{}_R * \vec{\omega}^b{}_{R,i}$$

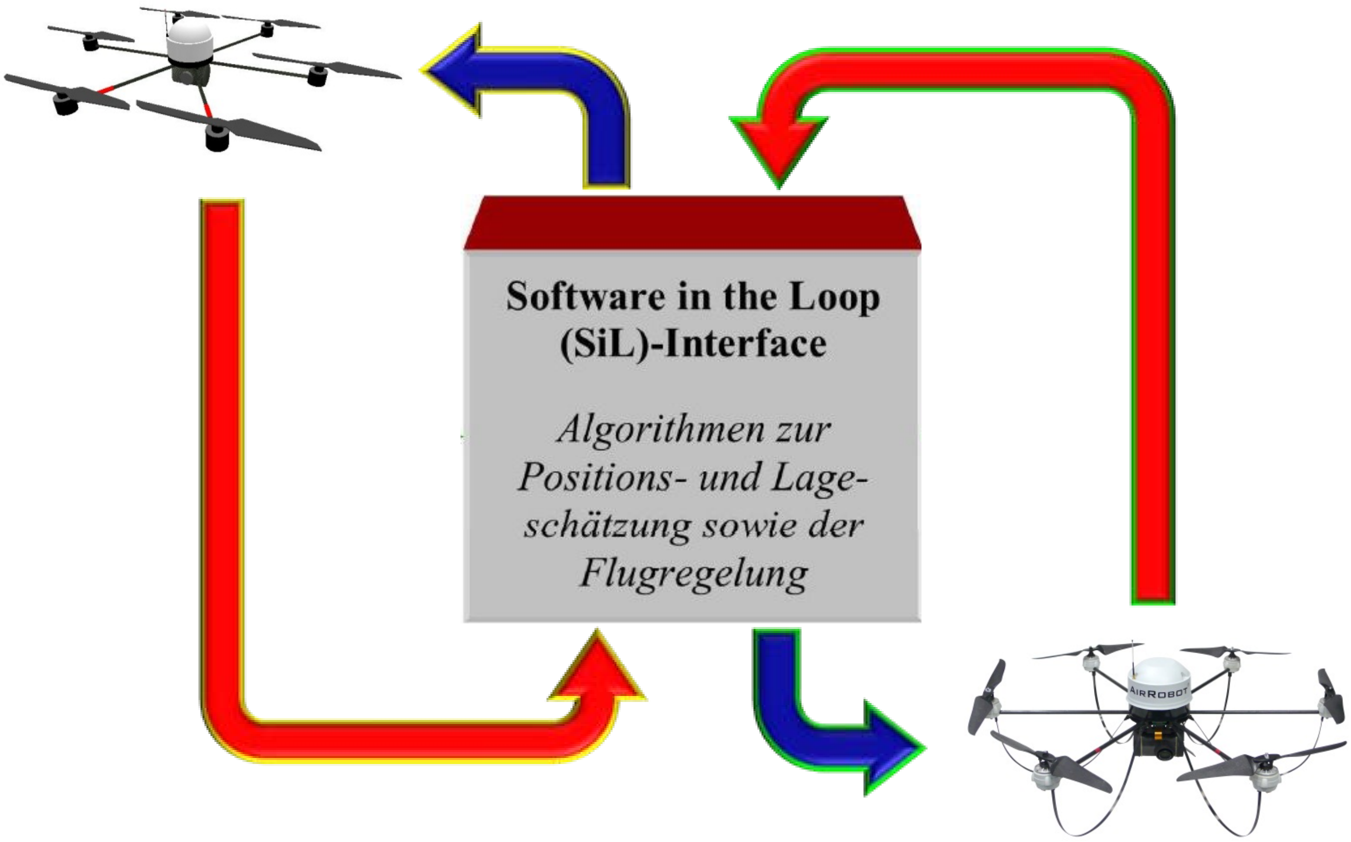
$$\vec{M}^b = \vec{\omega}^b_F \times \left[(I^b{}_F + 4 * I^b{}_R) * \vec{\omega}^b{}_F + \sum_{i=1}^{4} I^b{}_R * \vec{\omega}^b{}_{R,i} \right] + (I^b{}_F + 4 * I^b{}_R) * \dot{\vec{\omega}}^b{}_F + \sum_{i=1}^{4} I^b{}_R * \dot{\vec{\omega}}^b{}_{R,i} \qquad \vec{M}^b \approx \vec{\omega}^b_F \times I^b{}_F * \vec{\omega}^b_F + I^b{}_F * \dot{\vec{\omega}}^b_F$$

$$F_i = \alpha * n_i{}^2 + \beta * n_i \qquad M_i = \gamma * n_i$$

How simulate?



Software in the Loop



Virtual vs. Real

Fig. 4: Graphical comparison of the attitude estimation and control of the real (top, generated from video recording) and the simulated flight platform (below, rendered in the simulation). (from left to right: 1. initial position, 2. command pulse → maximum roll angle, 3. maximum roll angle reached, 4. independent return to initial position, 5. starting position reached)

A new Hexacopter - Virtual Prototype

Simulation of virtual prototype, before actual hardware was built

Video

A new Hexacopter - Real Prototype

Flight of real prototype, using the control software of the virtual prototype

Video

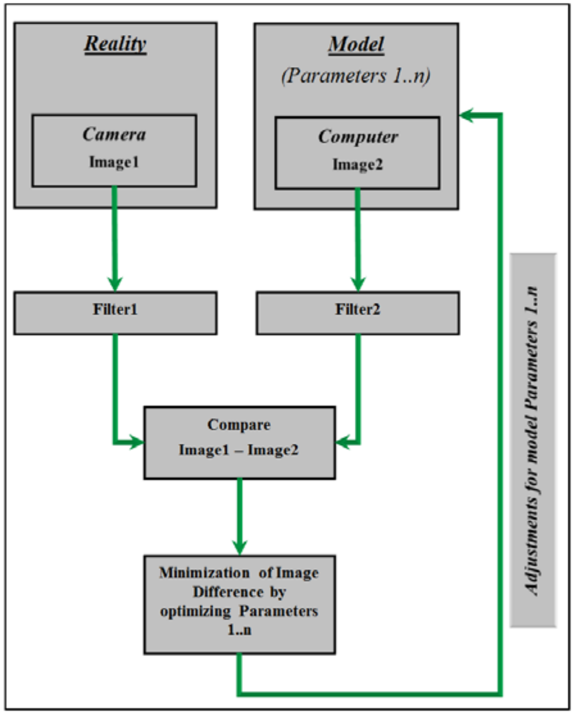
What?

What?

Devise new algorithms…

Analysis by Synthesis –

Analysis by Simulation

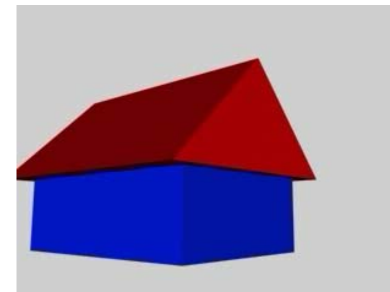


Analysis by synthesis


```
DEF Box02-FACES IndexedFaceSet {
coord DEF Box02-COORD Coordinate { point [
        -103.8 0 87.03, 103.8 0 87.03, -103.8 0 -
87.03, 103.8 0 -87.03,
        -103.8 53.56 0, 103.8 53.56 0]
      }
      coordIndex [
        0, 2, 3, -1, 3, 1, 0, -1, 0, 1, 5, -1, 5, 4, 0, -
1, 1, 3, 5, -1,
        3, 2, 4, -1, 4, 5, 3, -1, 2, 0, 4, -1]
      }
```

Synthesis

(unambiguous)



3d-model

2d-image

```
DEF Box02-FACES IndexedFaceSet {
coord DEF Box02-COORD Coordinate { point [
        -103.8 0 87.03, 103.8 0 87.03, -103.8 0 -
87.03, 103.8 0 -87.03,
        -103.8 53.56 0, 103.8 53.56 0]
      }
      coordIndex [
        0, 2, 3, -1, 3, 1, 0, -1, 0, 1, 5, -1, 5, 4, 0, -
1, 1, 3, 5, -1,
        3, 2, 4, -1, 4, 5, 3, -1, 2, 0, 4, -1]
      }
```

Analysis

(ambiguous)

Analysis by Synthesis

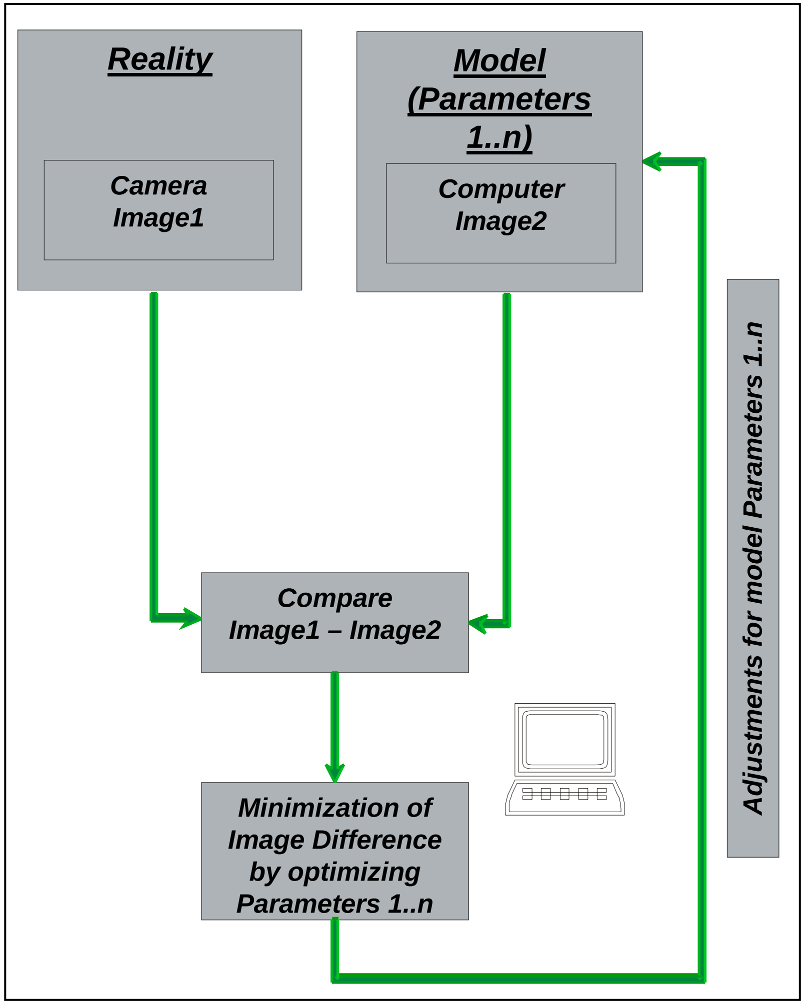
Manual analysis:

Use modelling software for analysis:

1. Devise simple model
2. Adjust camera settings
3. Adjust model
4. Render model
5. Compare photograph with synthetic image
6. Repeat steps 2 – 5 until synthetic image matches photograph

```
DEF Box02-FACES IndexedFaceSet {
coord DEF Box02-COORD Coordinate { point [
     -103.8 0 87.03, 103.8 0 87.03, -103.8 0 -87.03, 103.8 0 -87.03,
     -103.8 53.56 0, 103.8 53.56 0]
    }
    coordIndex [
     0, 2, 3, -1, 3, 1, 0, -1, 0, 1, 5, -1, 5, 4, 0, -1, 1, 3, 5, -1,
     3, 2, 4, -1, 4, 5, 3, -1, 2, 0, 4, -1]
    }
```

Analysis by Synthesis



We want automatic optimization of model

Need cost function

Optimization algorithm

Analysis by Synthesis

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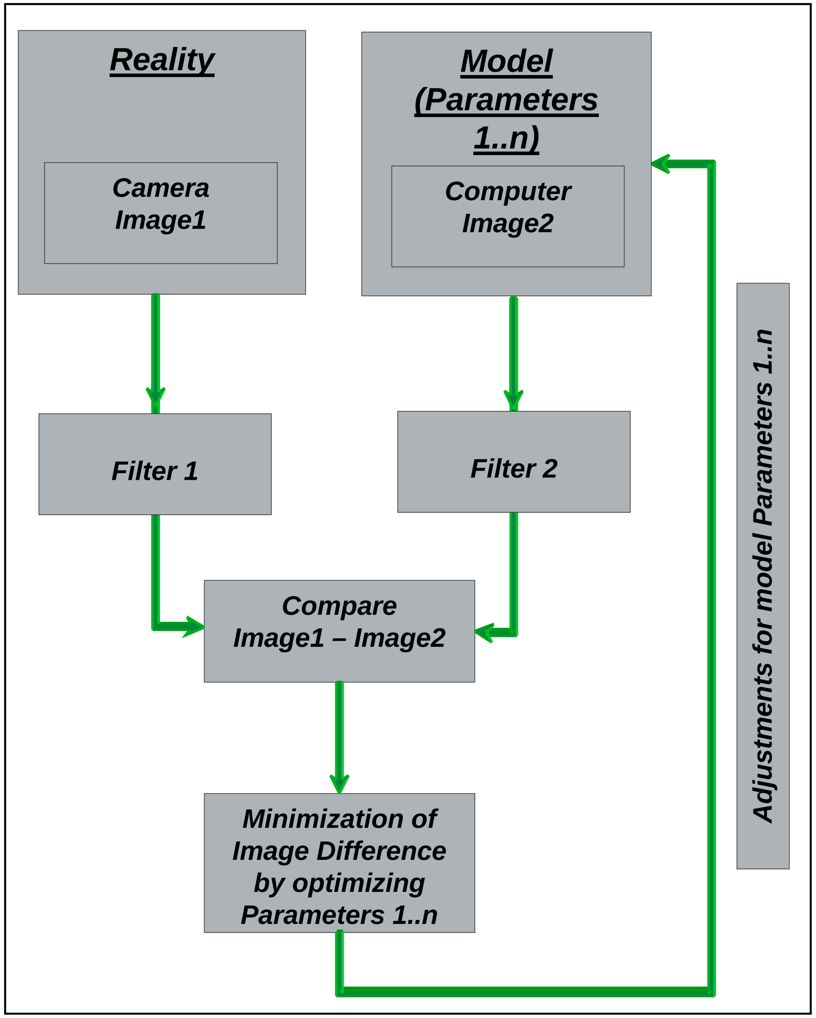

Filters to eliminate effects that are not represented by the model,

e.g. line extraction, if brightness of surfaces is unknown.

Analysis by Synthesis

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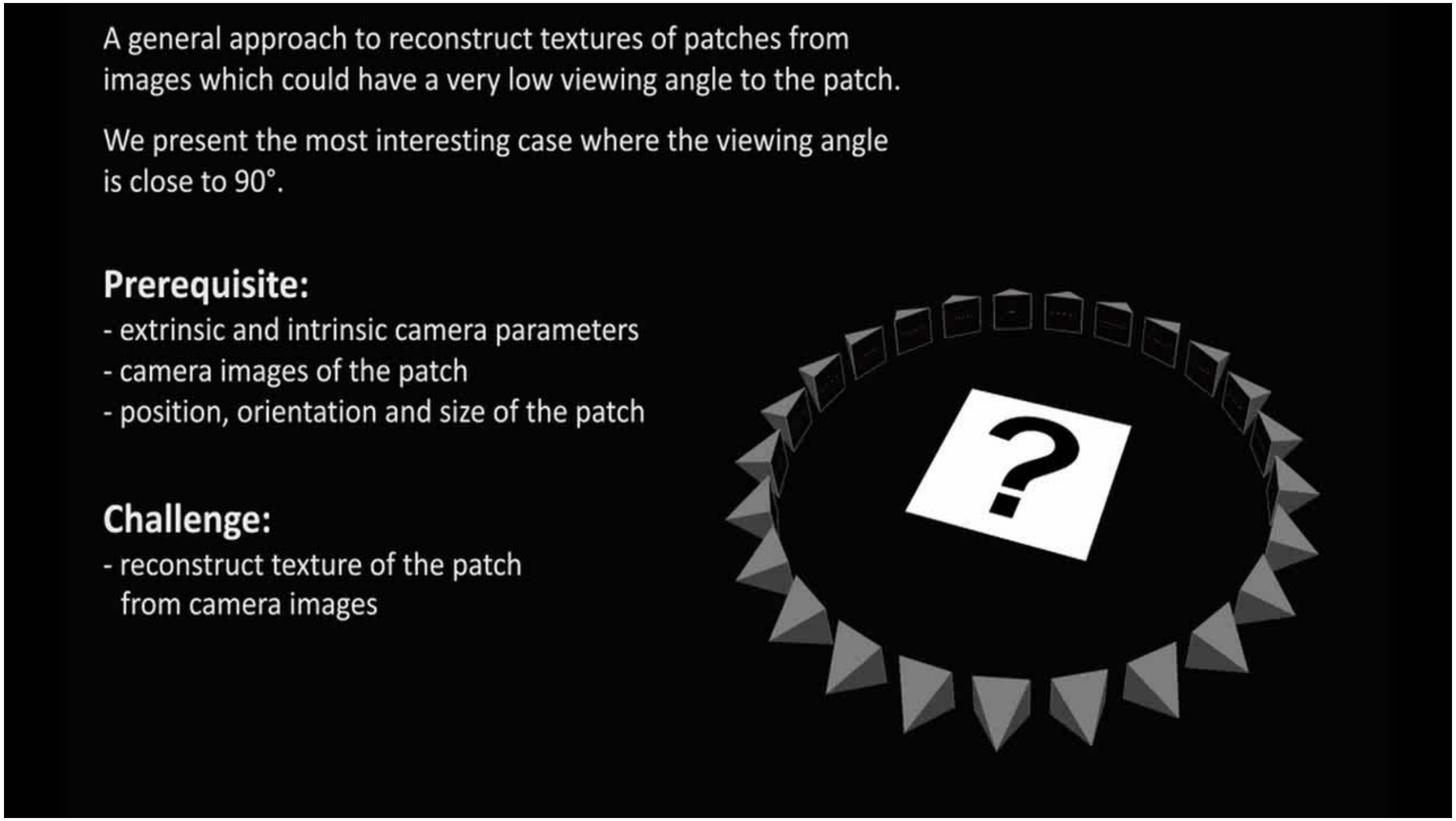

Florian Liefers, Roman Parys, Andreas Schilling, "Analysis-by-Synthesis Texture Reconstruction," 2011 International Conference on 3D Imaging, Modeling, Processing, Visualization and Transmission, pp. 571-578, 2012 Second International Conference on 3D Imaging, Modeling, Processing, Visualization & Transmission, 2012, link to paper

Video

The bigger picture – Analysis by Simulation

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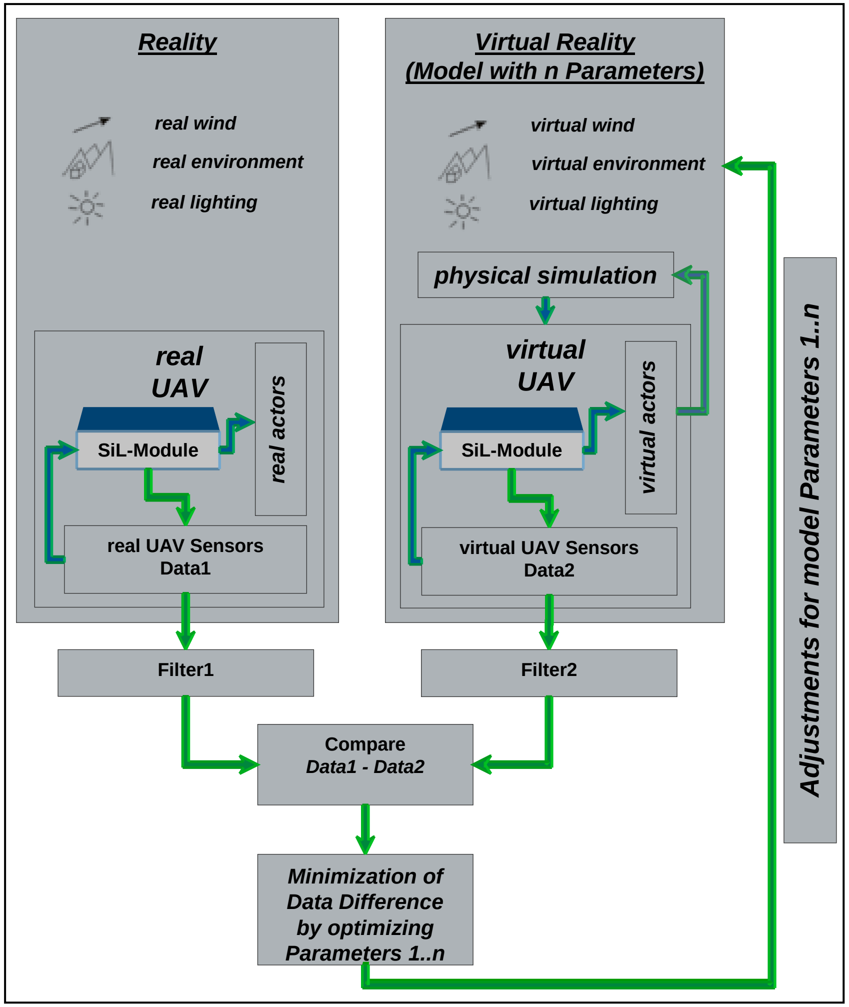

- After-simulate flight and thereby model reality
  - wind
  - scene
  - lighting
  - trajectory and orientation of UAV
- Pack prior knowledge into model and find out about unknown parameters
- Continuously adjust simulation to reality
- Can use any sensors, that can be simulated:
  - lidar, rolling shutter cams, …

Conclusion

Simulation framework allows

- Development of new hardware
- Development of new algorithms
  - low-level (firmware) and
  - high-level control and analysis software

- model flights
- model environment
- measure precisely
  with low cost sensors

} using analysis-by-simulation

AR.Drone

Video of real flight and simulation of AR.Drone