Technische Universität Braunschweig

Institute of Aerospace Systems

UAS design aspects for intelligent flight control, positioning and attitude determination

Peter Vörsmann

Journées du GDR Robotique

09. November 2010

Overview

1. Introduction

    - CAROLO P200 and spline-based flight path control

2. Positioning and Attitude Determination

3. Intelligent Flight Control

    - Neural network topology and control loop architecture

    - Statistical approach and results

    - Online learning results

4. Review and outlook

The CAROLO P200 UAV

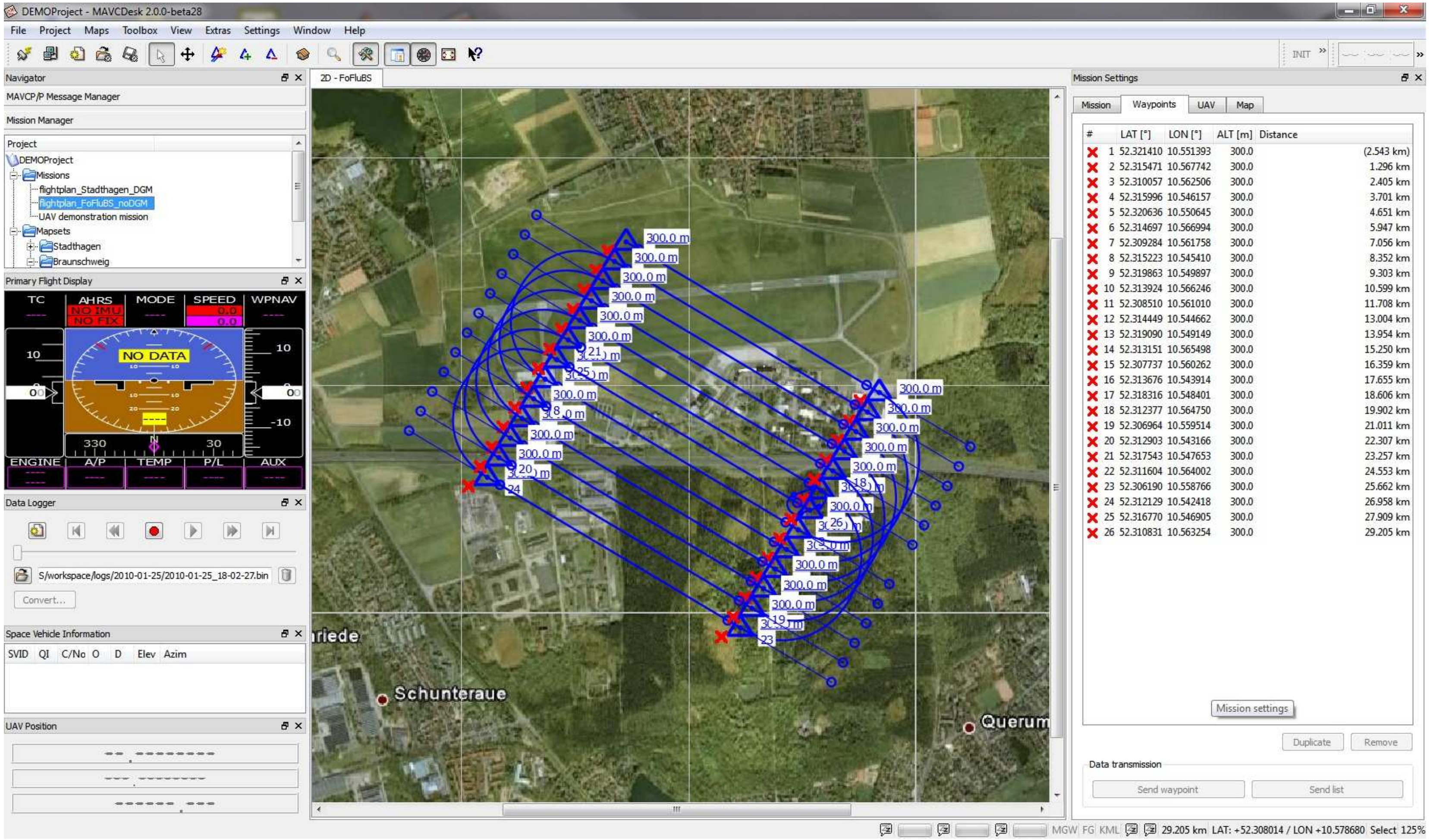
Aircraft specifications:

- take-off weight – 6 kg (1 kg payload)
- wing span – 200 cm
- cruising speed – 20 m/s
- flight time – 60 min
- fully automatic flight control

Simulation specifications:

- nonlinear simulation environment
- simplified atmosphere
  Dryden turbulence model
- actuator and sensor models

Aerial Photography Mission



Mission Profile

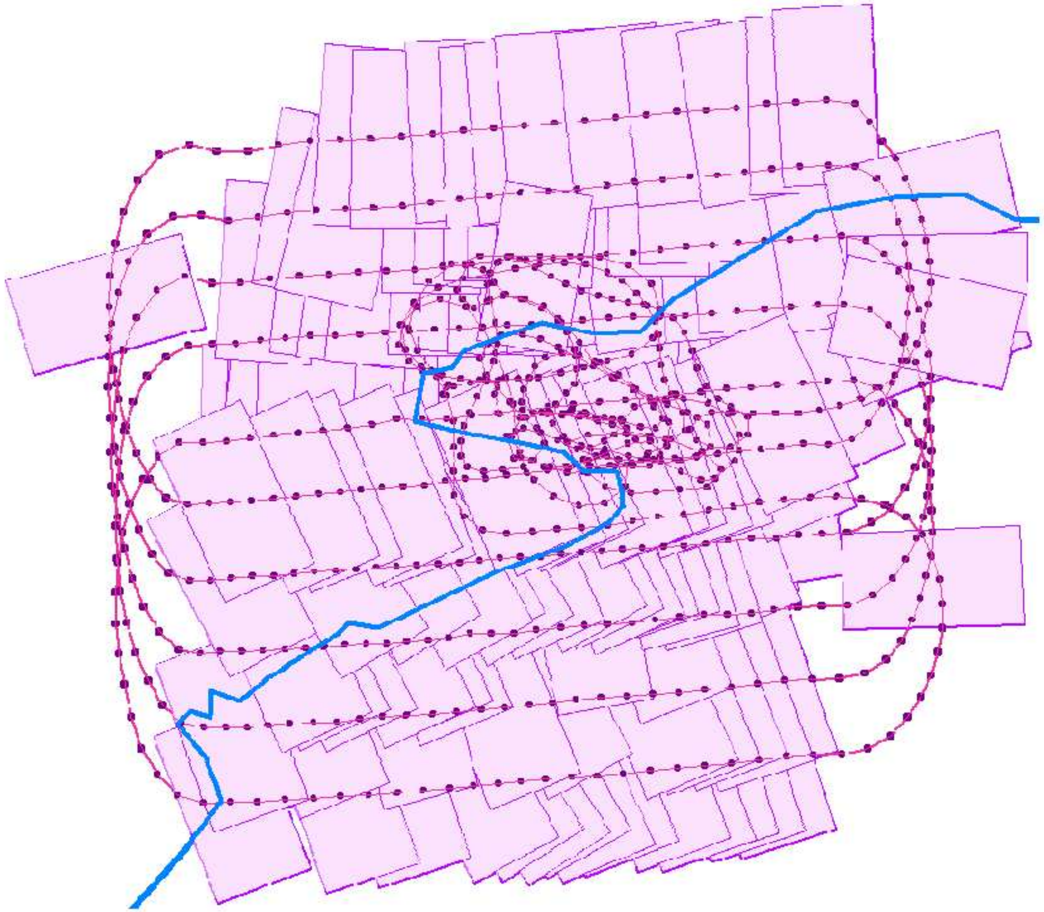
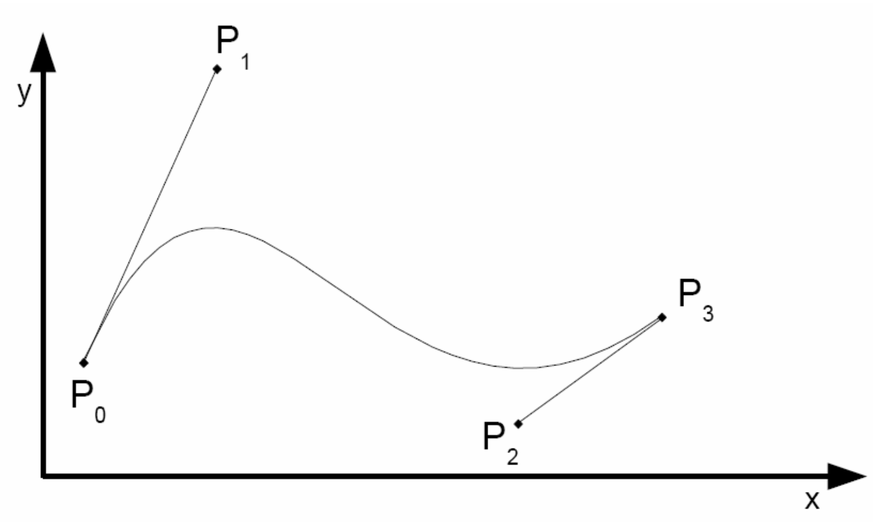


Photo Mission of the Leina Canal near Gotha, Germany

Aerial Photo

Joining of 200 Pictures

Spline-Based Trajectories



defined by:

$$x(t) = a_3 \cdot t^3 + a_2 \cdot t^2 + a_1 \cdot t + x_0$$

$$y(t) = b_3 \cdot t^3 + b_2 \cdot t^2 + b_1 \cdot t + y_0$$

t = spline parameter

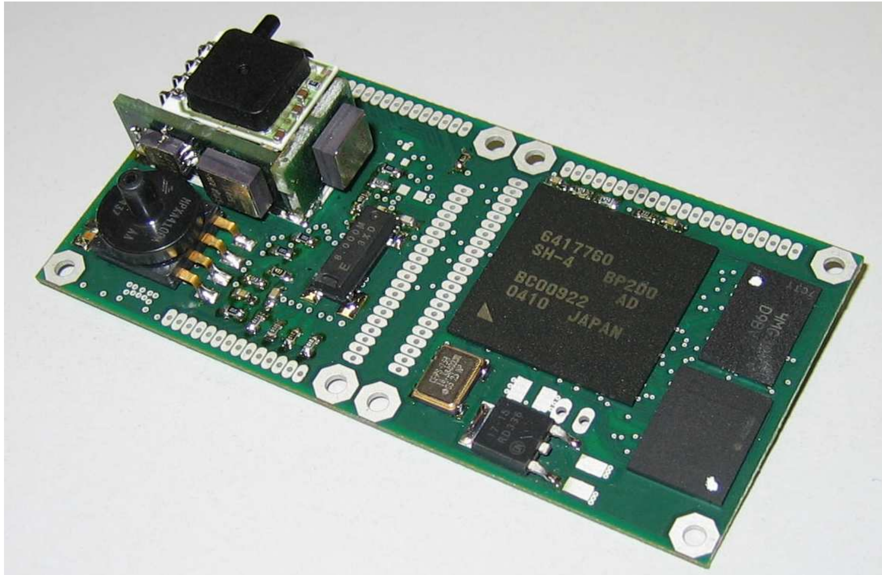
a / b = coefficients from geodetic x-y coordinates

The known geometry of the flight path allows the calculation of important flight mechanical variables.

Positioning and Attitude Determiniation, the MINC Solution

<u>M</u>iniature <u>I</u>ntegrated <u>N</u>avigation & <u>C</u>ontrol System:

- <u>I</u>ntegrated <u>N</u>avigation <u>S</u>ystem
  - MEMS-based inertial sensors
  - GPS/INS data fusion on board
  - ➔ precise attitude determination at 100 Hz using low-cost sensors
- complete autopilot
  - flight path setting using splines, not just simple waypoints
  - fully automatic operation, from takeoff to landing (option)



The MINC – System: Sensor Block and Navigation Core (single PCB version)

dimensions: 80 x 40 x 16 mm³ **Mass 25g**

GPS/INS Integration – Kalman Filter

- discrete error state Kalman Filter:

<u>state vector</u>

$$\mathbf{x} = \begin{bmatrix} \delta\mathbf{r} & \ldots & \text{position error} \\ \delta\mathbf{v} & \ldots & \text{velocity error} \\ \delta\varphi & \ldots & \text{attitude error} \\ \delta\boldsymbol{\omega} & \ldots & \text{error of est. gyro signal bias} \\ \delta\mathbf{a} & \ldots & \text{error of est. acc. signal bias} \\ \delta(c\,\Delta t) & \ldots & \text{error of RX clock error} \\ \delta(c\,\Delta\dot{t}) & \ldots & \text{error of RX clock drift} \end{bmatrix}$$

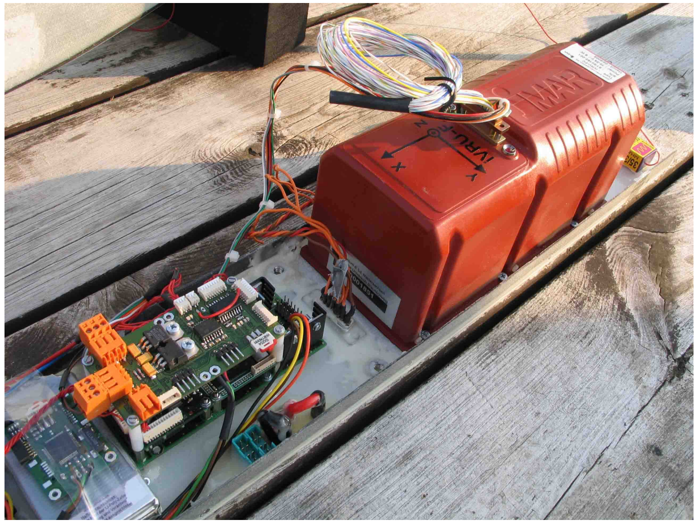
<u>meas. vector</u>

$$\mathbf{z} = \begin{pmatrix} \delta\rho_1 & \ldots & \text{RNG error to sat. 1} \\ \delta(\Delta\varphi_1) & \ldots & \text{time-diff. CP error to sat. 1} \\ \vdots & & \vdots \\ \delta\rho_i & \ldots & \text{RNG error to sat. } i \\ \delta(\Delta\varphi_i) & \ldots & \text{time-diff. CP error to sat. } i \end{pmatrix} + \mathbf{v}$$

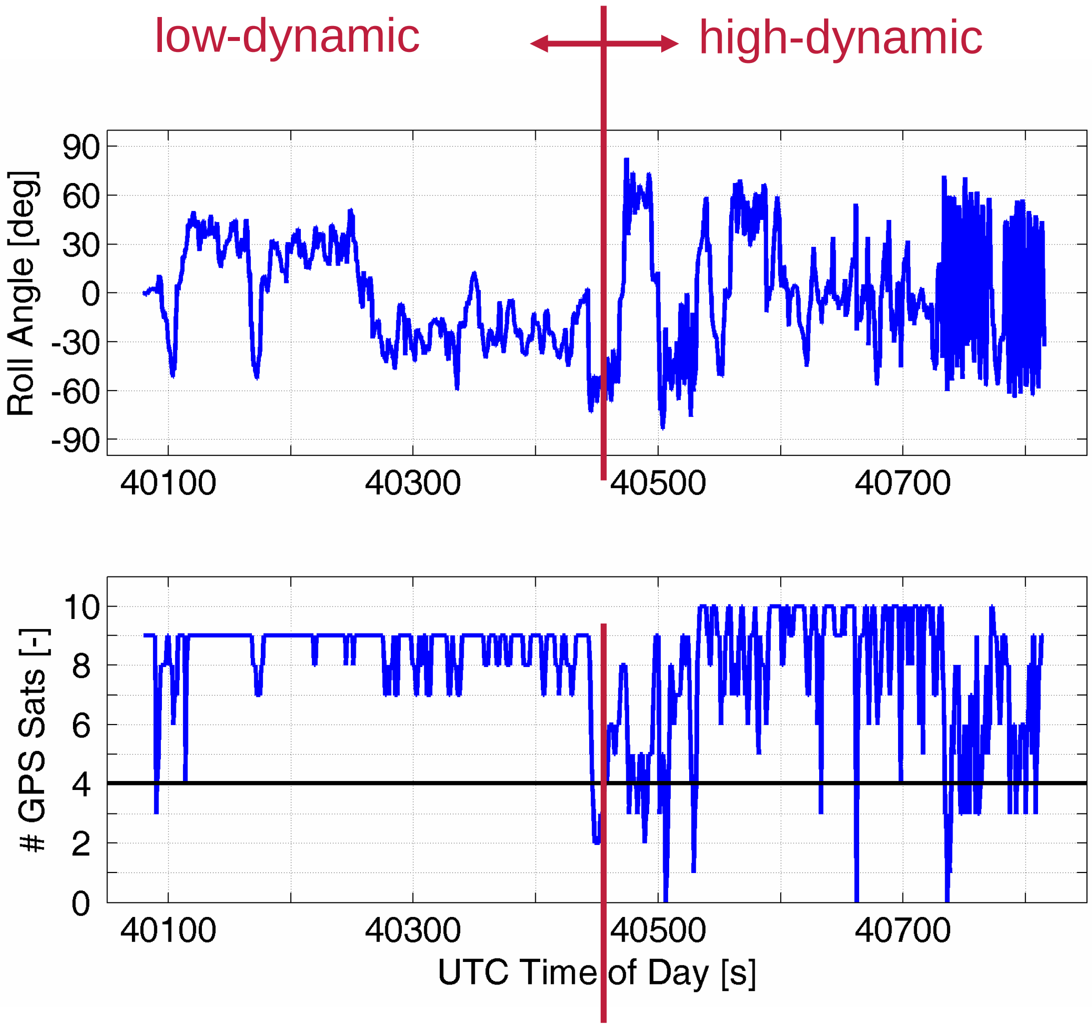
- usage of time-diff. carrier phases (CP) instead of delta-rng

4. Flight Test for Positioning and Attitude Determination

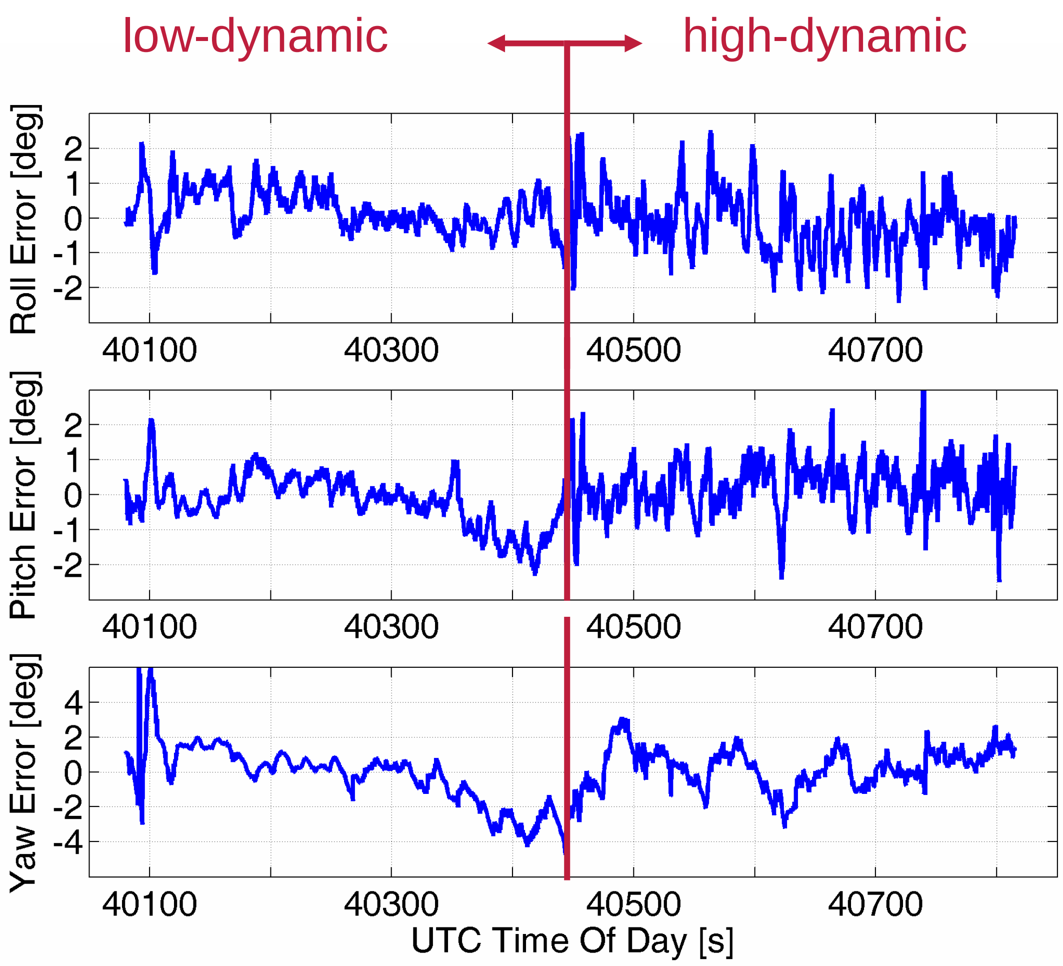
- **reference navigation system based on FOG-IMU**



4. Flight Test Results

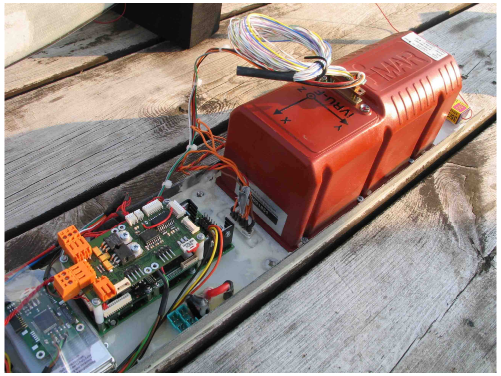


4. Flight Test Results



MINC-Autopilot Accuracy

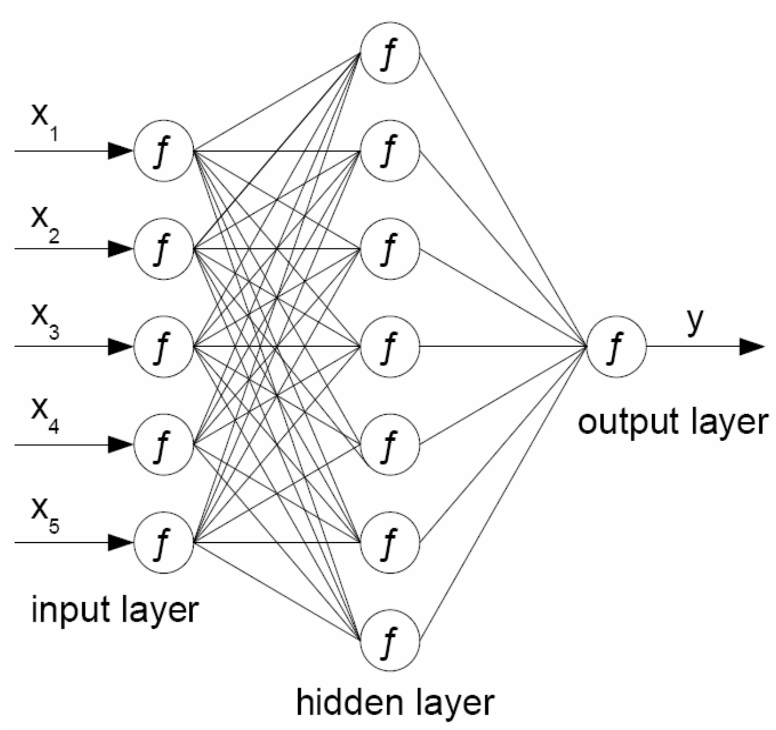
- extensive road and flight tests; reference: high-precision IMU with fibre-optic gyros (FOG-IMU)
- MINC features a 17-state Kalman navigation filter for in-flight GPS/INS data fusion:
  - tightly-coupling allows for GPS-based IMU aiding even with less than 4 satellites in view
  - tested and verified long-term-stable accuracy
  - **typical pitch & roll error: better 0.5° (1 σ)**
  - **typical yaw error: better 0.9° (1 σ)**
  - navigation filter tested on both air and surface vehicles



test flight set-up:
MINC and FOG- IMU

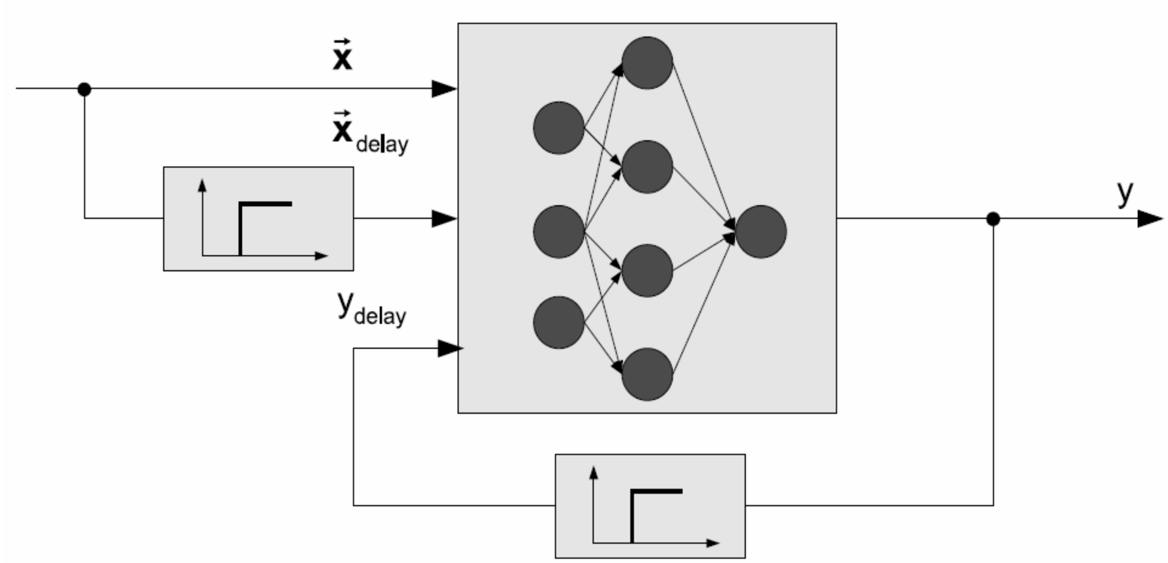
test aircraft “Carolo T200”
(bungee start)

Flight Control using Neural Network Topology



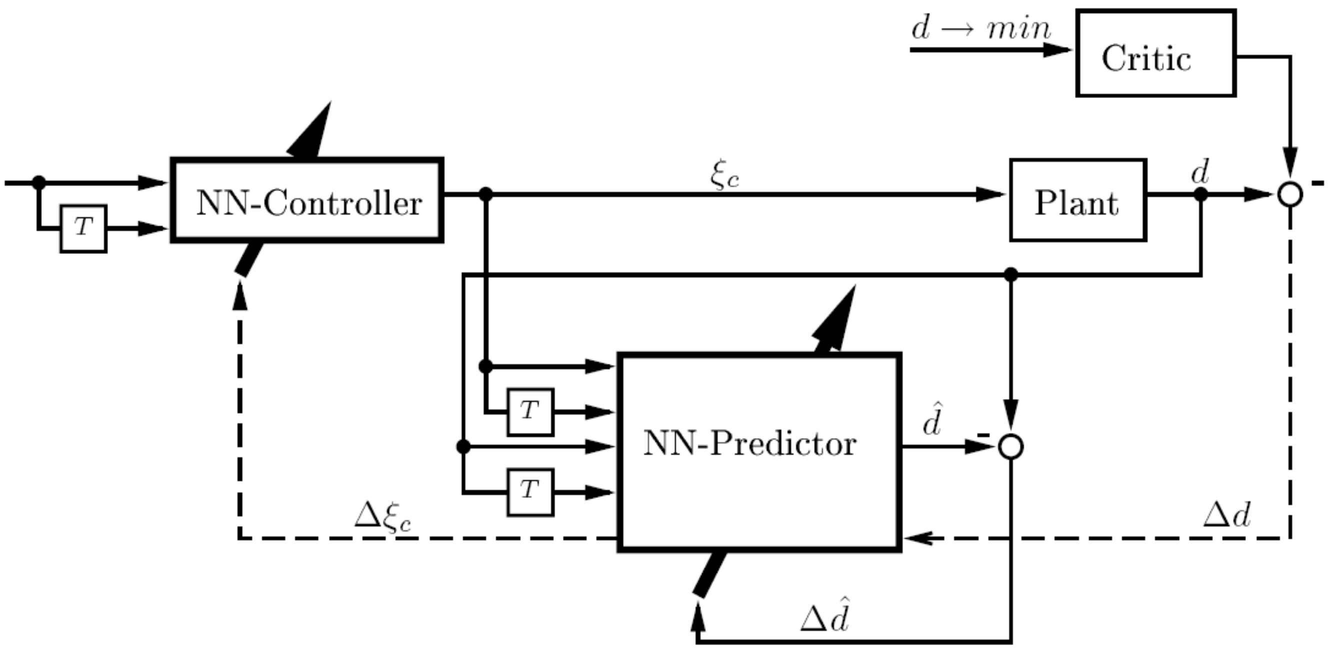
- multi-layer feedforward networks
- linear and sigmoid transfer functions
- backpropagation training-algorithm
- learning from experience

Short Term Memory



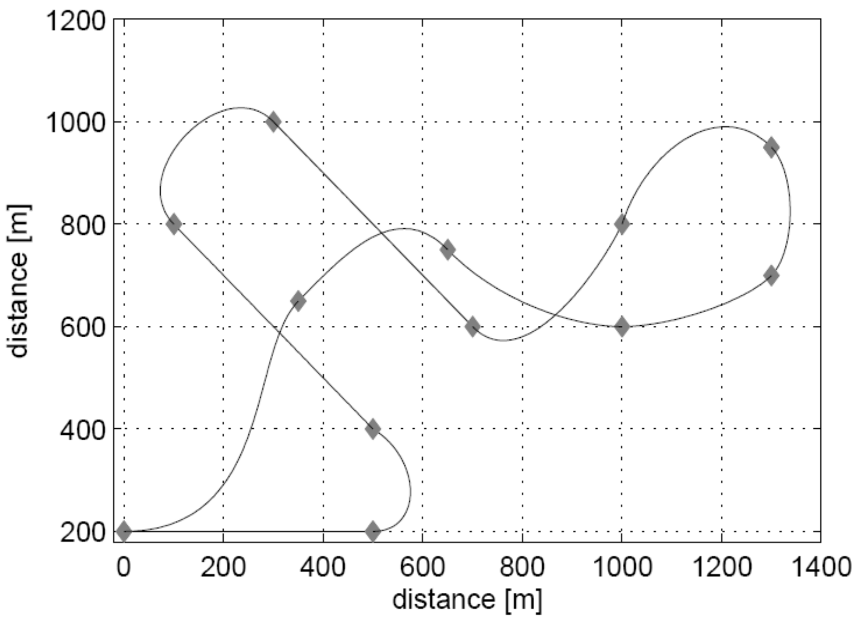
- **modular neural controller and predictor units**
- **time delayed inputs**
- **short term memory due to historical data**
- **modelling of non-linear relationships**

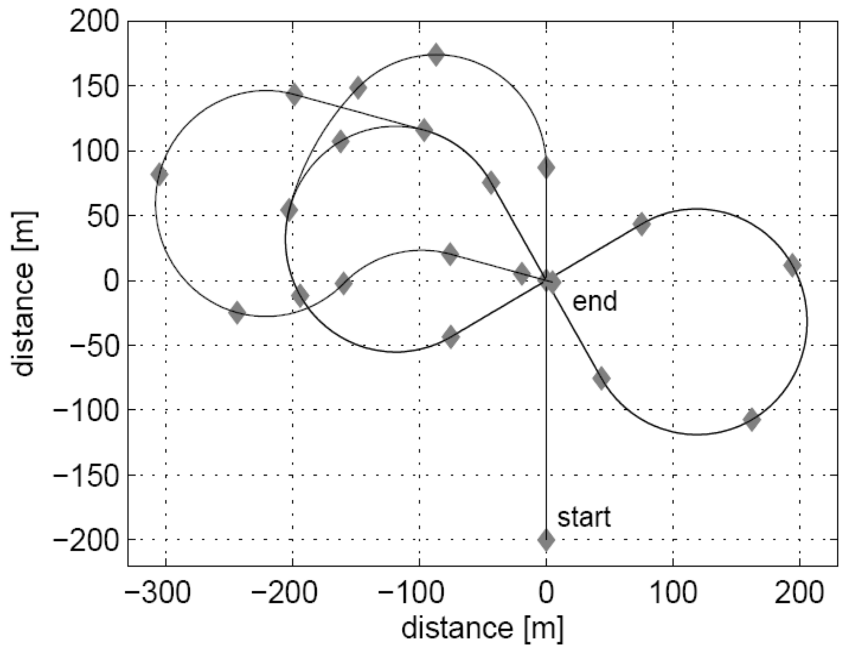
Control Loop Architecture



Creation of a controller error signal by backpropagation of the spline deviation through the inverse dynamics of the predictor.

Exemplary Trajectories





Training Approach

adequate training data is highly important for training success

systematic network design approach:

- **50-80 networks for the same learning task**
- **every network topology used 5-10 times**
- **statistical evaluation of the training success**

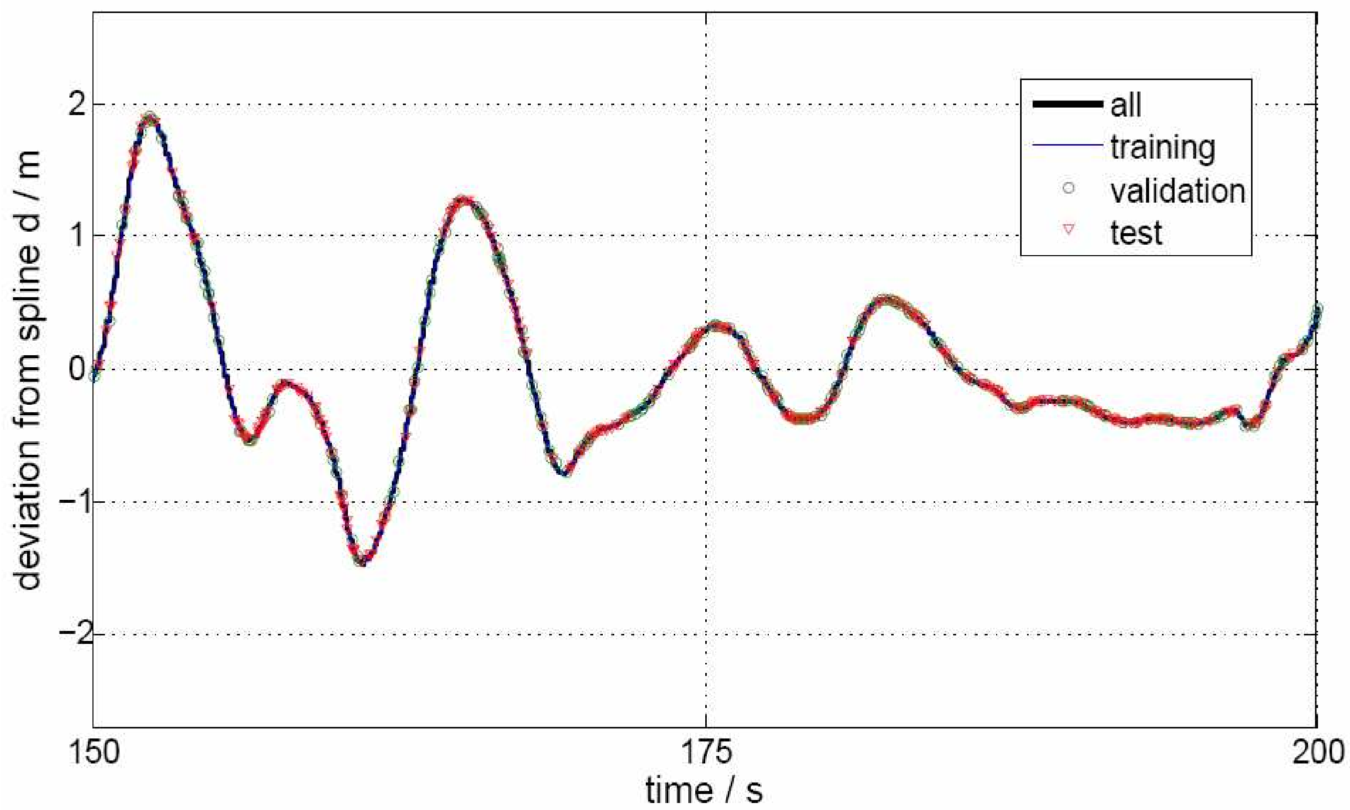
➡ no extensive network tuning and less coincidence regarding learning success

training data synthesis:

- **trajectory contains manoeuvres of an UAV-mission flight envelope**
- **modelling of atmospheric influences including Dryden turbulence spectrum**
- **10000 training patterns used**

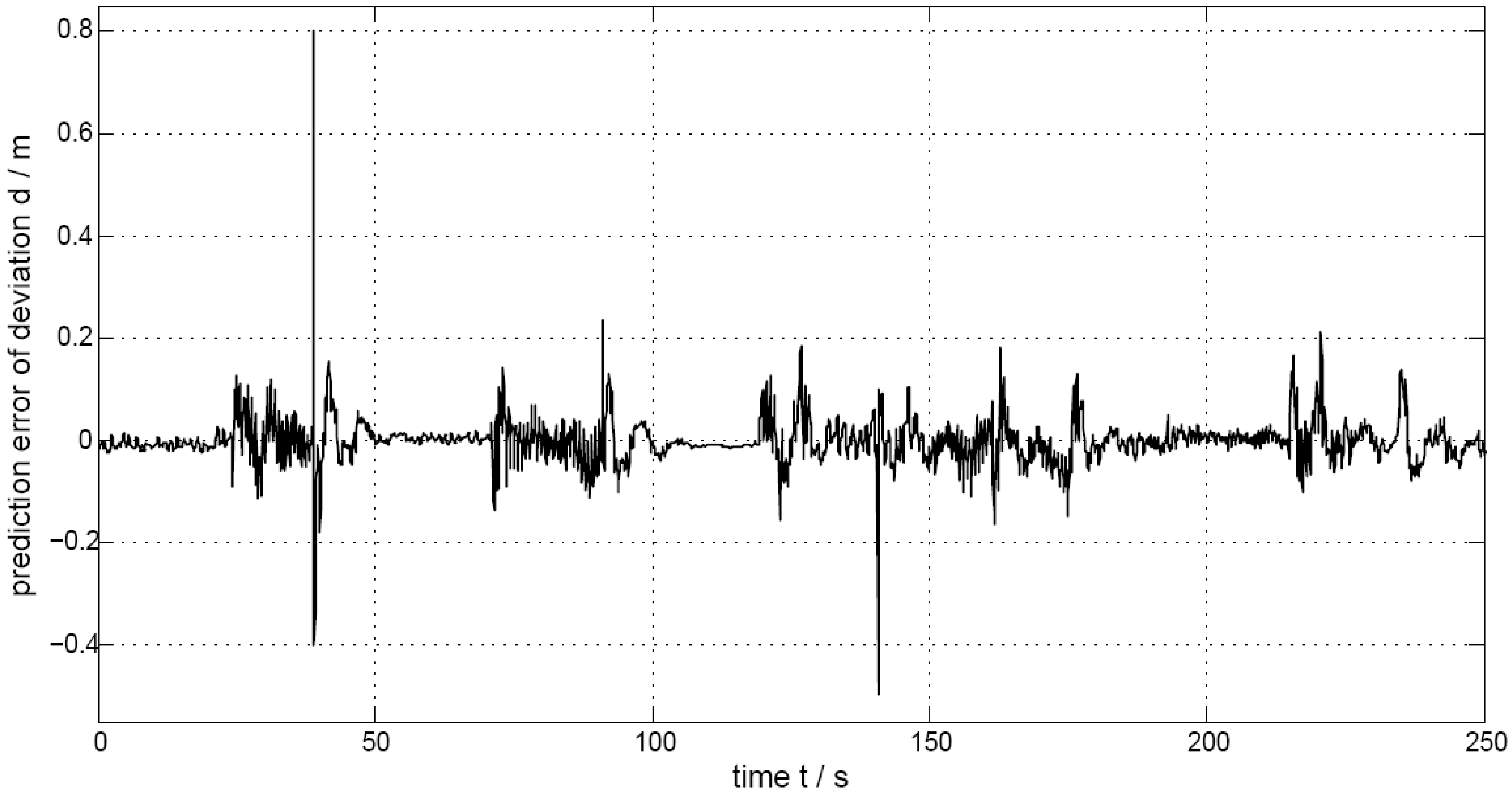
➡ training data selection is a premise for good basic knowledge

Trainings Results – Basic Knowledge

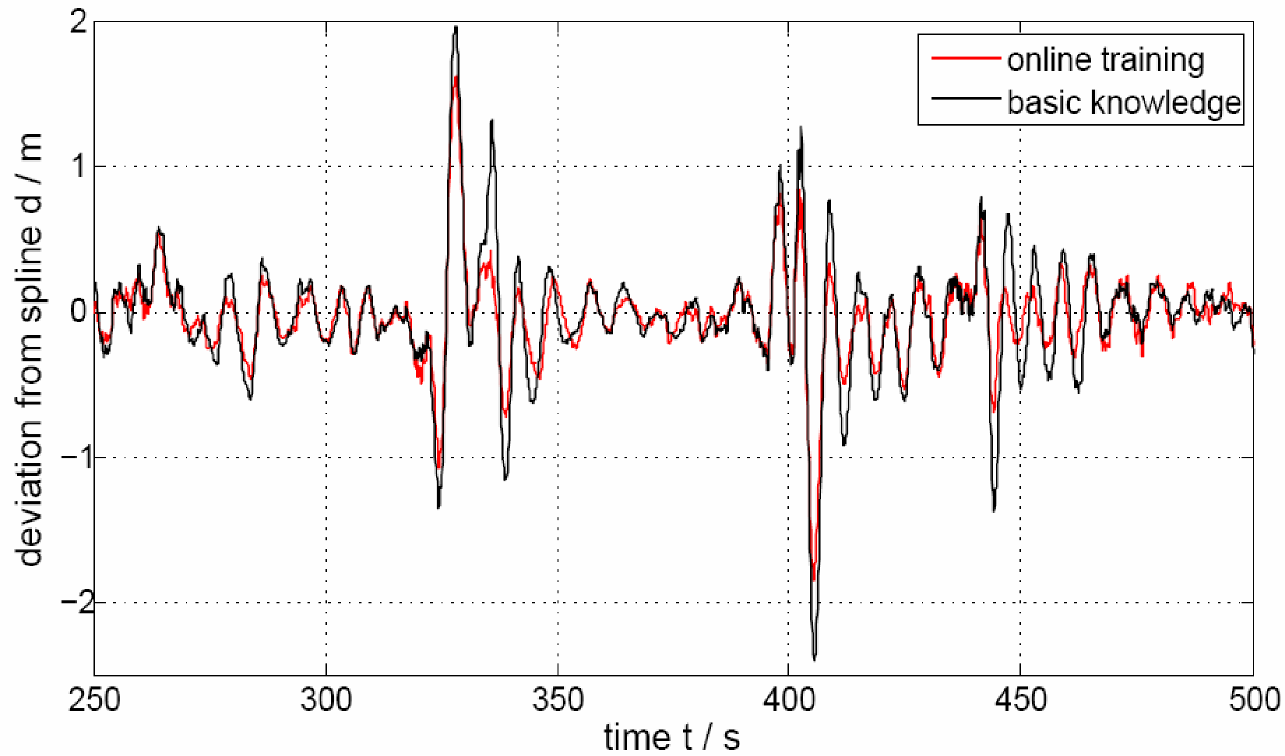


validation and test show very small errors
➡ adequate generalisation capabilities

Neural Predictor Error



Online Training Results



The offline-trained basic knowledge can be recalled on an untrained trajectory and is improved during operation.

Review and Outlook

Attitude Determination and Flight Control

- **Attitude better than 1 Degree using MEMS sensors and Kalman-Filtering**
- **Simulation of Flight Control with Neural Networks has been proven**

Outlook for Flight Control:

- **expansion of the online-learning algorithms**
- **implementation of Ljapunow-stability analysis**
- **flight test validation**
- **combination of neural and analytic control adaptivity**

Questions?

Halley Station - Antarctica