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# Path Planning for Fixed-Wing UAVs with Small Onboard Computers

Walter Fichter

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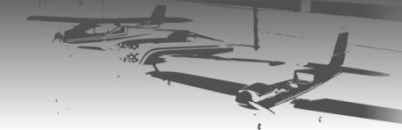
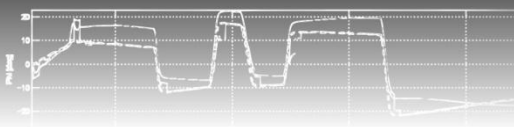
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Submitted on 13 Apr 2011

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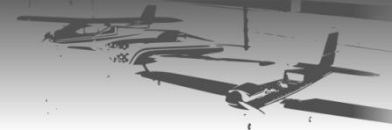
# Path Planning for Fixed-Wing UAVs with Small Onboard Computers

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Alexander Joos**

**Institute of Flight Mechanics and Control  
Universität Stuttgart**



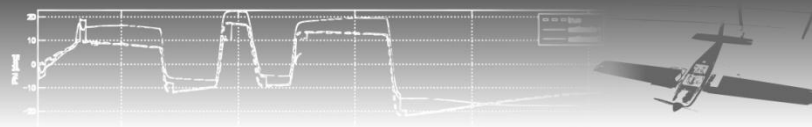
**SADCO Meeting, Paris, 2 March 2011**



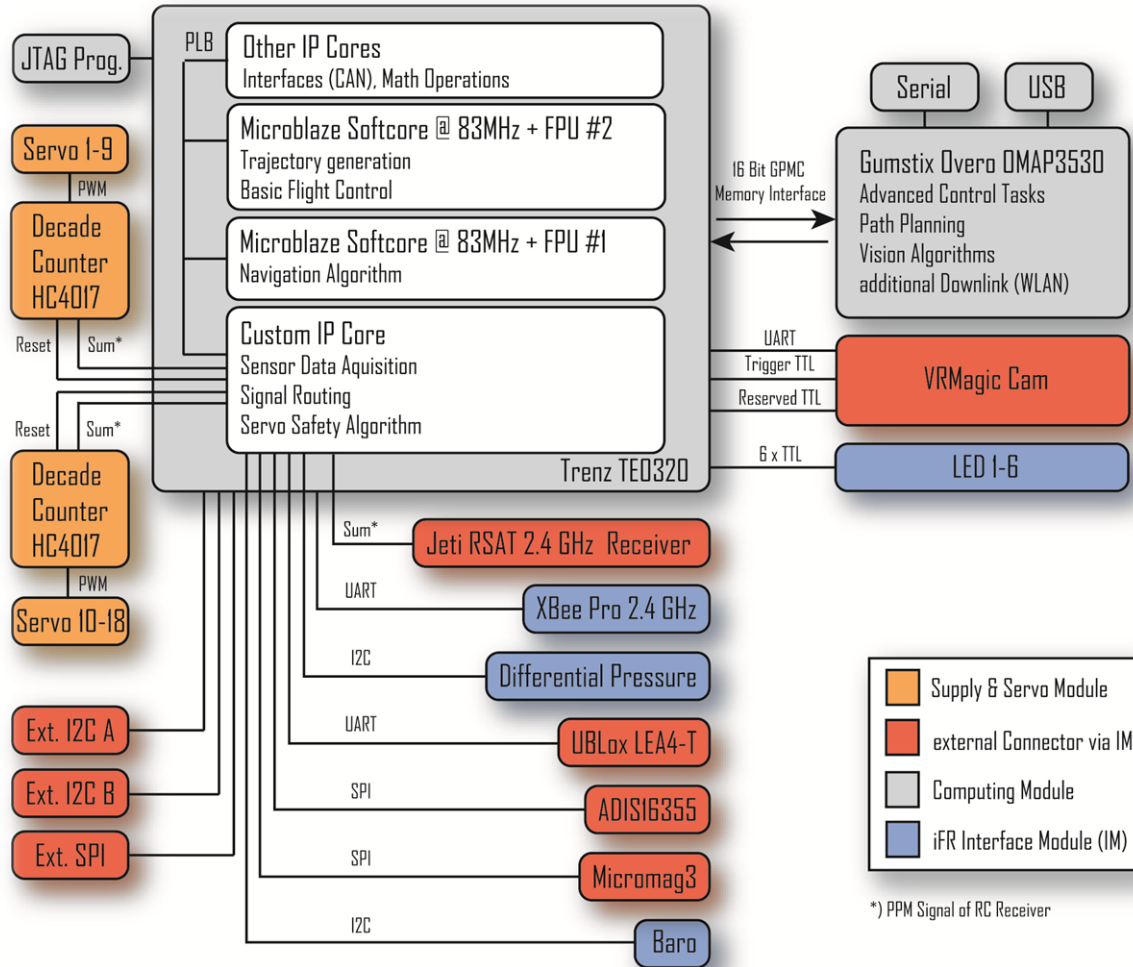
# Small Fixed-Wing UAVs

- Fixed-wing UAV
  - < 5 kg (< 25 kg)
  - wing span typically 1.5 m
- Small onboard computer
  - microcontroller, microprocessor
  - < 150 g (120 g), 10 W
  - limited computer power

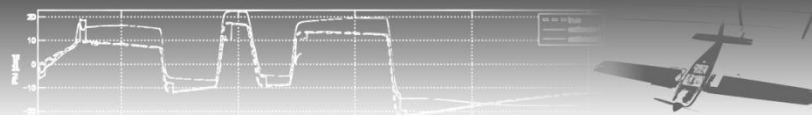




# Onboard System

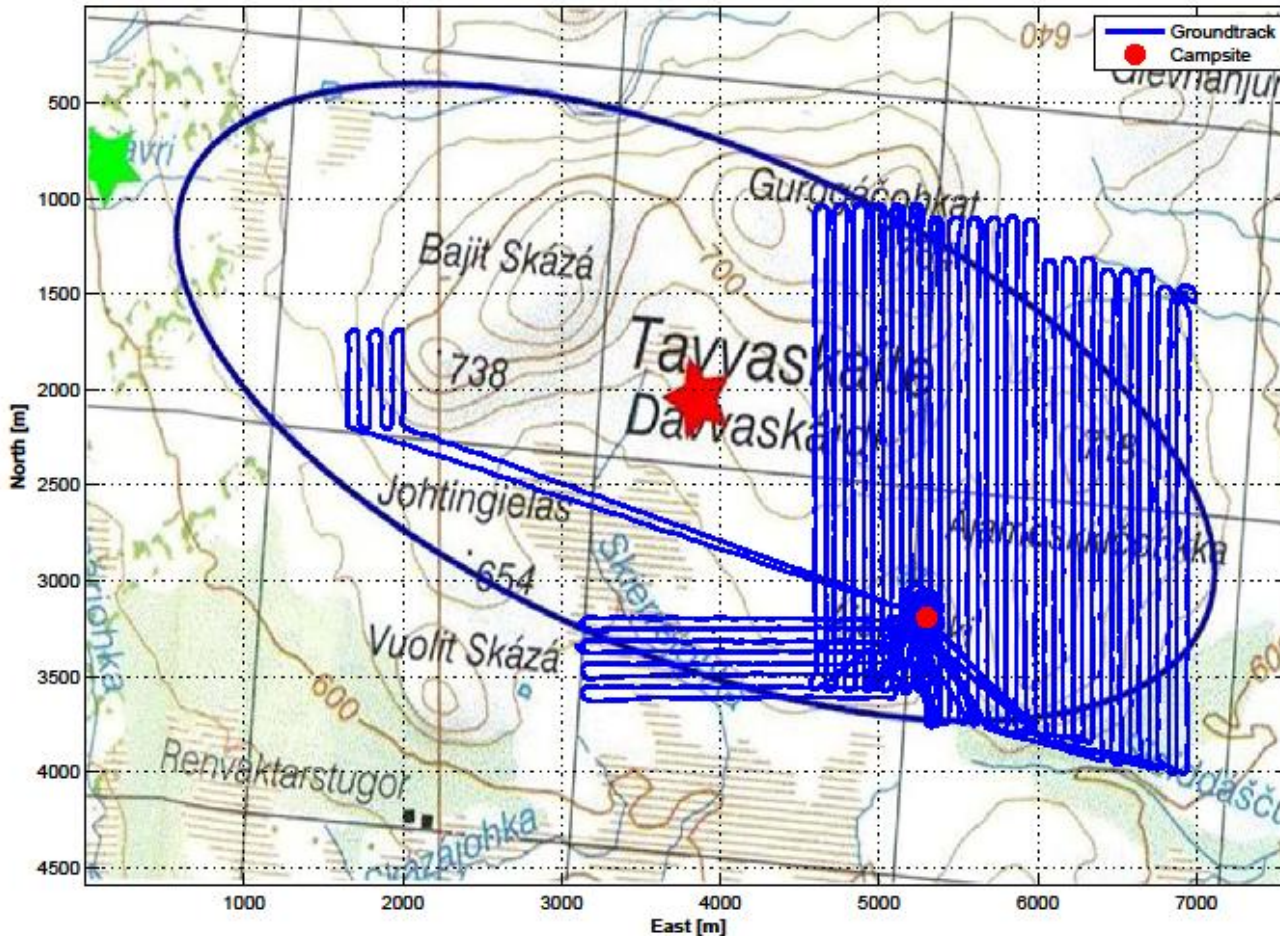


- Full functionality
  - processor(s)
  - FPGA
  - „full“ instrumentation
  - camera + ground station + link
- Limited sensor performance
- Limited computation power

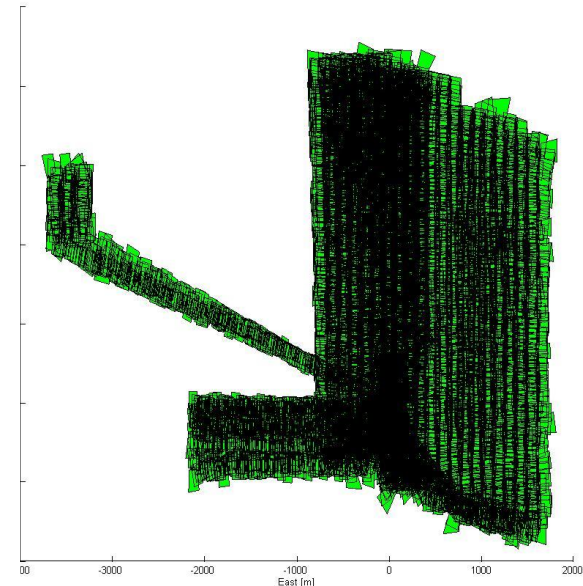


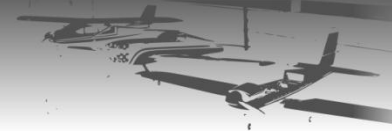
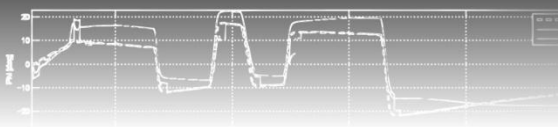
# (Small) UAV Flight Path in Practice

Groundtrack of SHARK Recovery Flights




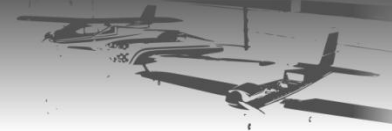
total flight time 24 h, 17 flights  
 path length 260 km  
 area 8 km<sup>2</sup>  
 ground resolution < 2.6cm  
 7600 pictures





# Motion Planning – Towards Autonomy

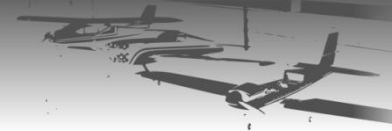
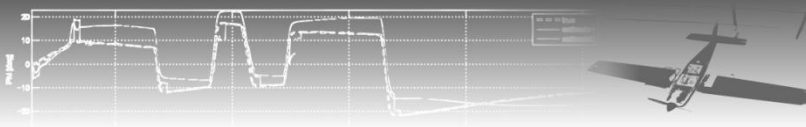
- **3 dimensional**, considering 6 degrees of freedom, 12 states
- From a given initial state („in flight“) to a final state („landing“)
- **Under constraints** of
  - position (obstacles)
  - velocity (flight dynamics)
  - attitude (flight dynamics)
  - rates (flight dynamics)
- **Real-time implementation**  **Limited computer power**



# Motion Planning Research – Overview

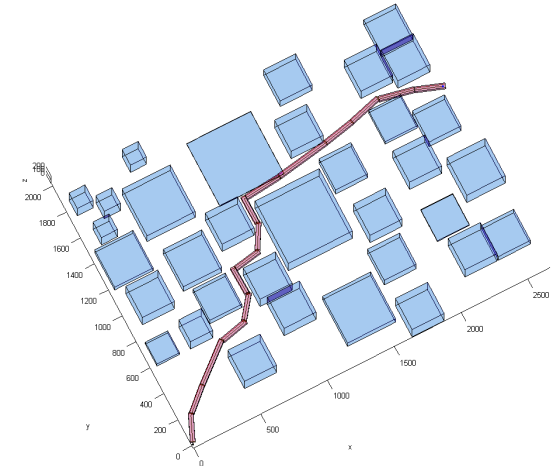
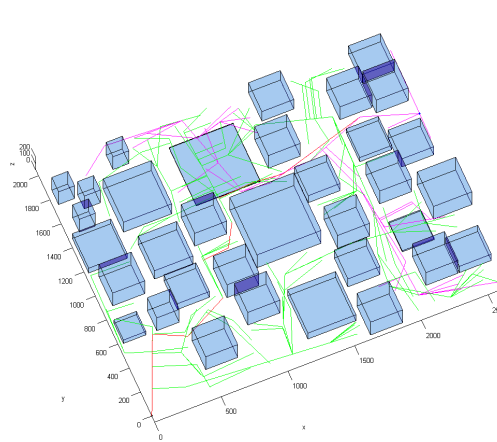
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- Goerzen/Kong/Mettler, J Intell Robot Syst (2010) 57  
A Survey of Motion Planning Algorithms from the Perspective of Autonomous UAV Guidance
  - **uncertainties and robustness** has not been studied much..
  - ..majority of methods do not include much discussion about **practical application**.
  - When they do, they often **only provide simulation** results..
  - ..most of the practical implementations of UAV guidance have been of the hierarchical **decoupled control** type..



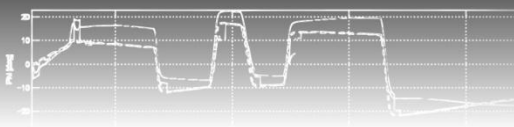
# Probabilistic Methods

- Waypoint RRT and bounding boxes
  - straight line and steady-state turns



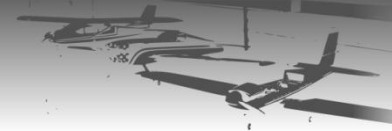
- RRTs with motion primitives
  - becomes complex with non-steady motion primitives
- RRTs with closed loop dynamics included („towards“ NMPC)





# NMPC Method(s)

- „Embedded“ into control system
- Kang&Hedrick, Linear Tracking of a Fixed-Wing UAV Using Nonlinear MPC, IEEE Trans. Contr. Syst. Technology, Sept 2009
  - 2D (horizontal) motion
  - fixed wing
  - PC104
  - real-time testbench results
- Rest of the presentation: NMPC with limited computational effort

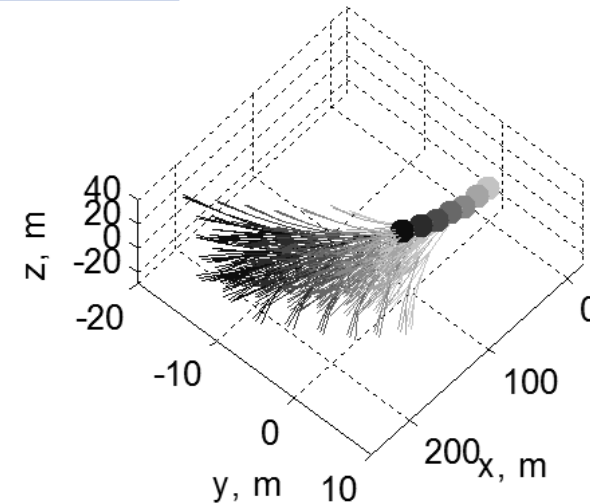
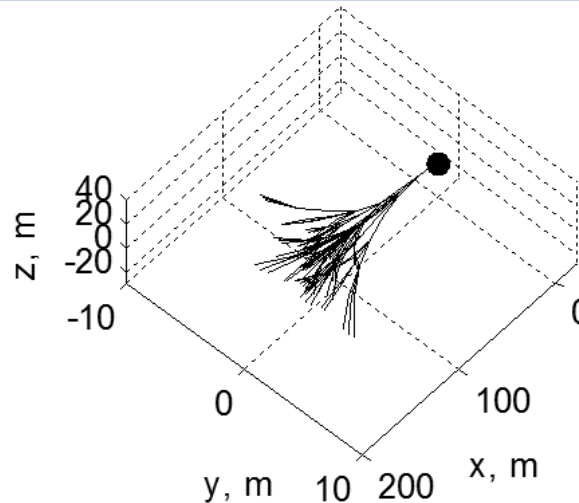


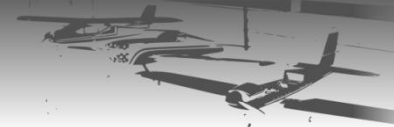
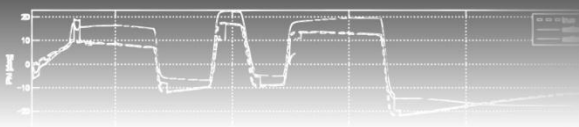
# NMPC – Computational Approach

- 1: propagate model with a **given set of inputs** from  $k \cdot T_s .. k \cdot T_s + T_p$
- 2:  $J_{min,k} \leftarrow$  minimum cost function
- 3: **if**  $J_{min,k} < J_{min,k-1}$  , **then**
- 4:       apply input with minimum cost
- 5: **else**
- 6:       apply previous input
- 7: **end**
- 8:  $k \leftarrow k+1$

cost function

$$J(\bar{u}) = \sum_{i=t_0}^{t_0+T_p} F(\bar{x}(i), \bar{u}(i))$$

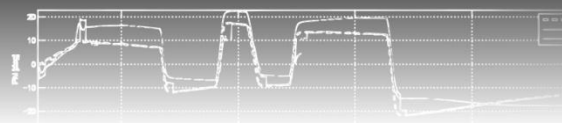




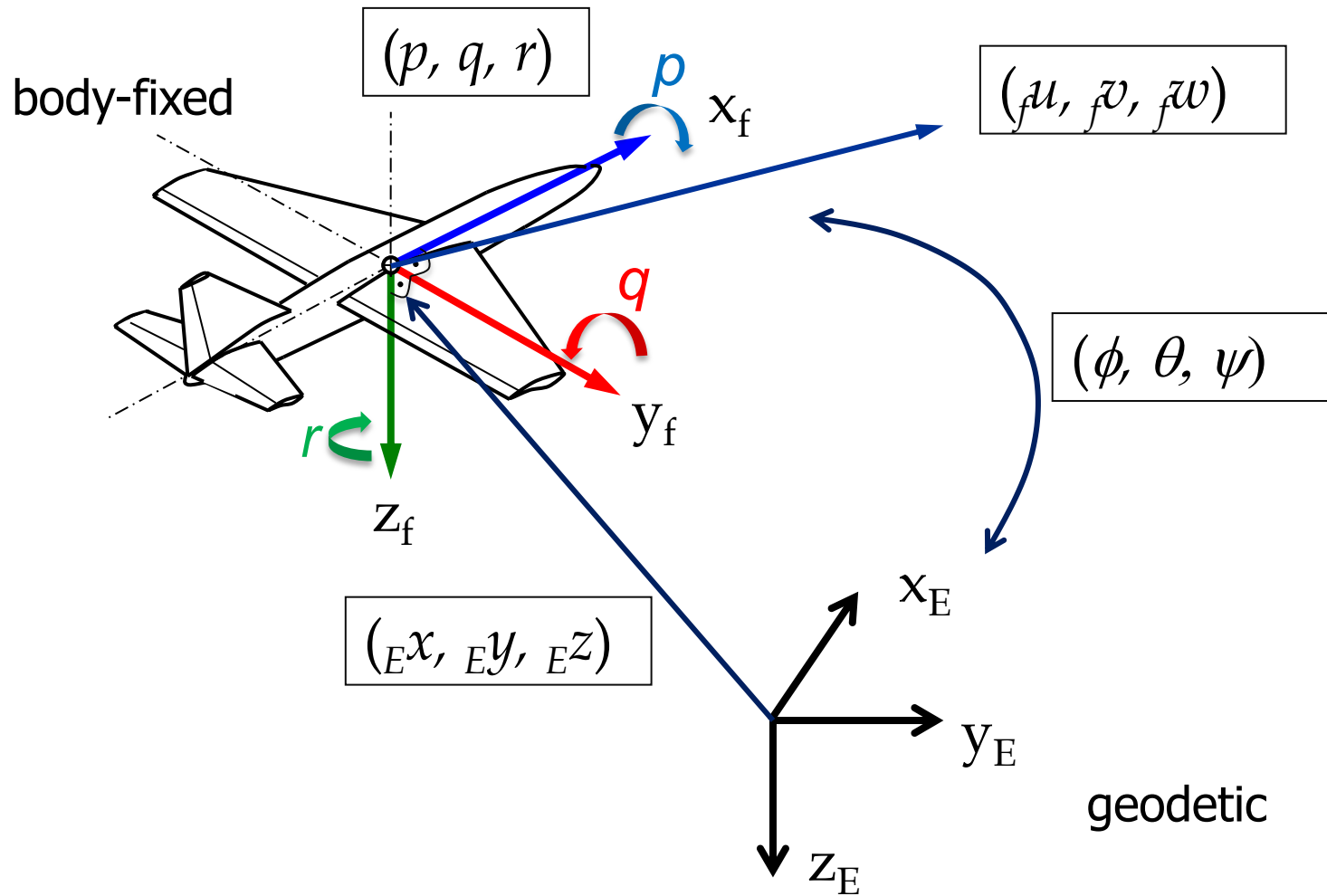
# Design Parameters

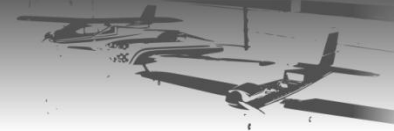
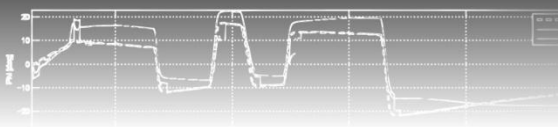
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- Control system
  - plant model, required underlying control loops
  - control signals
    - number
    - quantization
    - discretization
  - cost function
  
- Implementation, i.e.
  - tailored hardware
  - parallel models, optimization

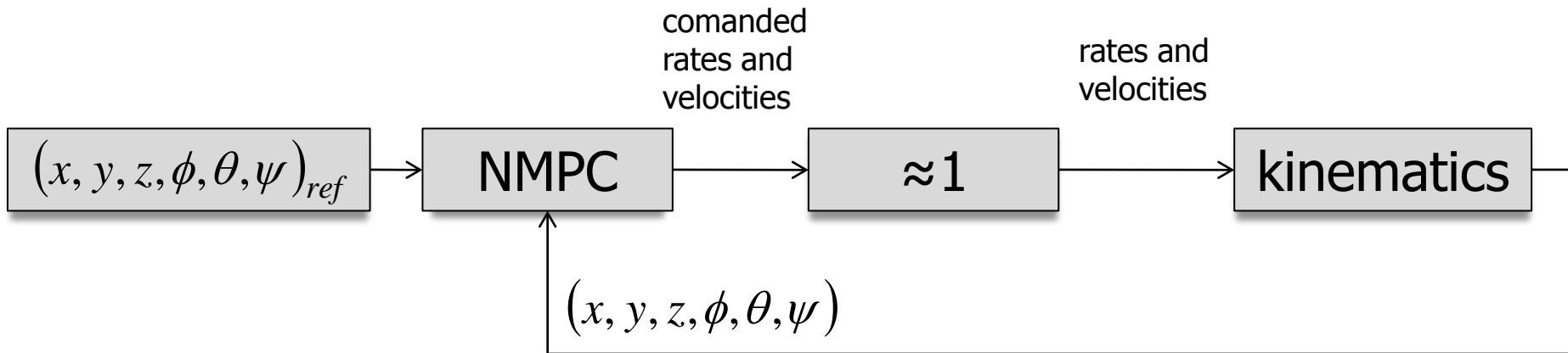
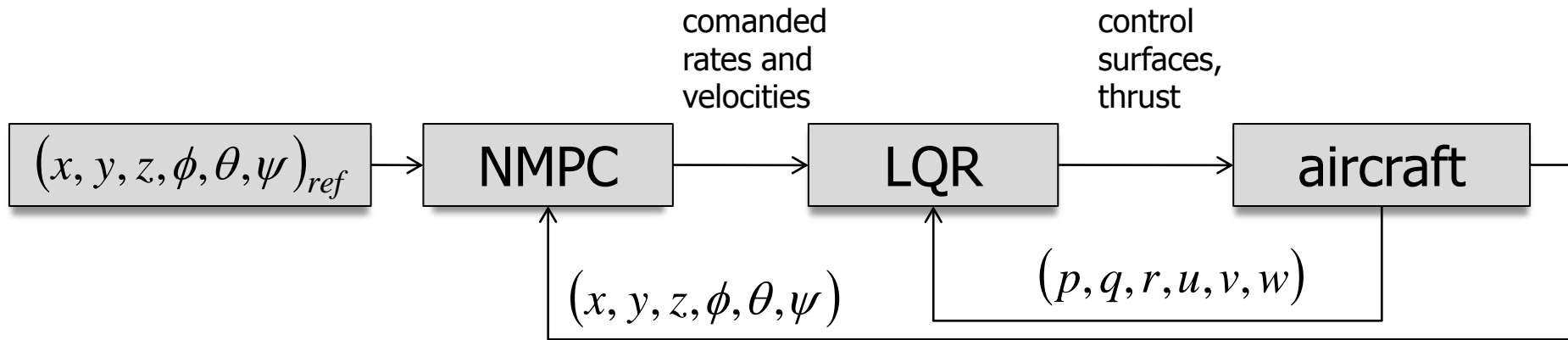


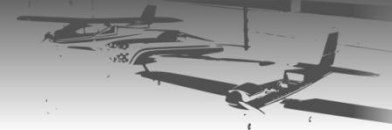
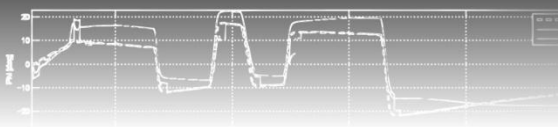
# Vehicle States





# Control Loops





# Design Plant – Kinematics

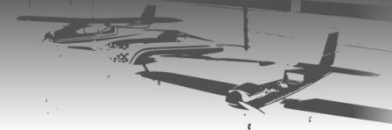
$$\begin{pmatrix} {}_E \dot{x} \\ {}_E \dot{y} \\ {}_E \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{bmatrix} c\theta c\psi & -c\phi s\psi + s\phi s\theta c\psi & s\phi s\psi + c\phi s\theta c\psi & 0 & 0 & 0 \\ c\theta s\psi & c\phi c\psi + s\phi s\theta s\psi & -s\phi c\psi + c\phi s\theta s\psi & 0 & 0 & 0 \\ -s\theta & s\phi c\theta & c\phi c\theta & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & s\phi s\theta/c\theta & c\phi s\theta/c\theta \\ 0 & 0 & 0 & 0 & c\phi & -s\phi \\ 0 & 0 & 0 & 0 & s\phi/c\theta & c\phi/c\theta \end{bmatrix} \cdot \begin{pmatrix} {}_f u \\ {}_f v \\ {}_f w \\ p \\ q \\ r \end{pmatrix}$$

d/dt {positions}  
d/dt {attitude}  
„geodetic“

velocities  
rates  
body-fixed

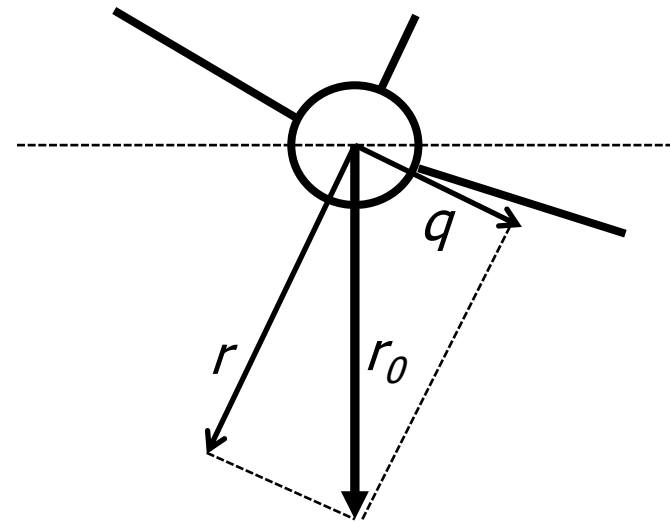
- Design plant for NMPC now reduced to 6 states
- Exact
- Still 3D, nonlinear, 6 inputs

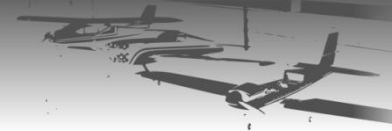




# Input (Control) Signal Selection

- Minimize # of inputs: select
  - roll rate  $p$ , pitch rate  $q$
  - yaw rate  $r = 0$
  
- But: conventional approach, i.e. „flight mechanics“, requires  $r \neq 0$ 
  - check controllability





# Controllability

➤ Attitude subsystem  $\dot{\mathbf{x}}_{\Phi} = \mathbf{a}_1 \cdot u_1 + \mathbf{a}_2 \cdot u_2$

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \cdot p + \begin{pmatrix} \sin(\phi) \sin(\theta) / \cos(\theta) \\ \cos(\phi) \\ \sin(\phi) / \cos(\theta) \end{pmatrix} \cdot q$$

– controllability matrix  $\mathbf{C} = (\mathbf{a}_1, \mathbf{a}_2, [\mathbf{a}_1, \mathbf{a}_2])$

$$\mathbf{C} = \begin{bmatrix} 1 & \sin(\phi) \sin(\theta) / \cos(\theta) & \cos(\phi) \sin(\theta) / \cos(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi) / \cos(\theta) & \cos(\phi) / \cos(\theta) \end{bmatrix}$$

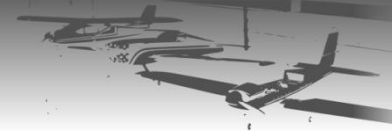
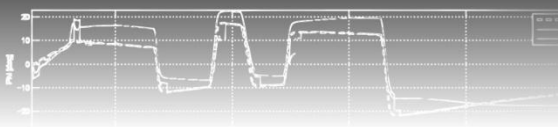
$$\det(\mathbf{C}) = \frac{1}{\cos(\theta)} \neq 0$$

new direction =  
actuation direction from yaw rate  $r$

➤ Position subsystem

- constant velocity vector can be oriented through angular controllability



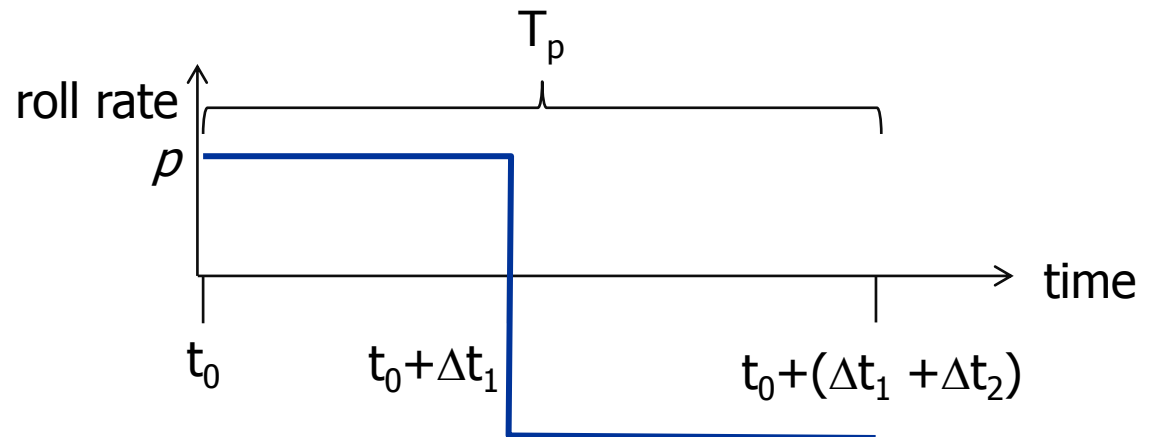


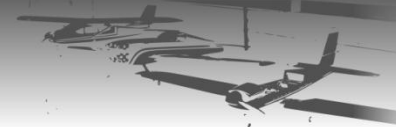
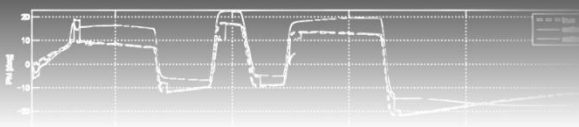
# Control Signals

- Prediction horizon  $T_p$
- $d$  quantization values of controls, simplest case:  $+1, 0, -1$
- $m$  intervals with constant controls, simplest case:  $\Delta t_1, \Delta t_2$
- $n$  control signals, simplest case:  $p$  and  $q$  (roll/pitch rate)

▪  $d^{n \cdot m}$  control options

➤ Example:





# Cost Function

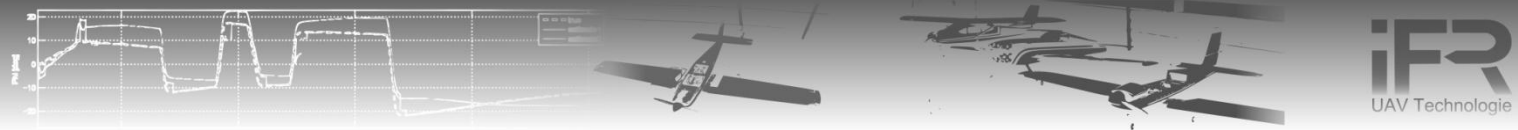
$$J(\bar{u}) = \sum_{i=1}^m (\bar{x}(t_i)^T Q(t_i) \bar{x}(t_i) + c_{\phi}(t_i) + c_{\theta}(t_i) + c_{pq}(t_i) + c_t(t_i) + \frac{k(t_i)}{\bar{o}(t_i)})$$

control error
constraints  
(flight mechanics)
terminal  
constraint
obstacle

$$t_i = t_0 + \sum_{j=1}^i \Delta t_j, \quad i \in N \wedge 1 \leq i \leq m$$

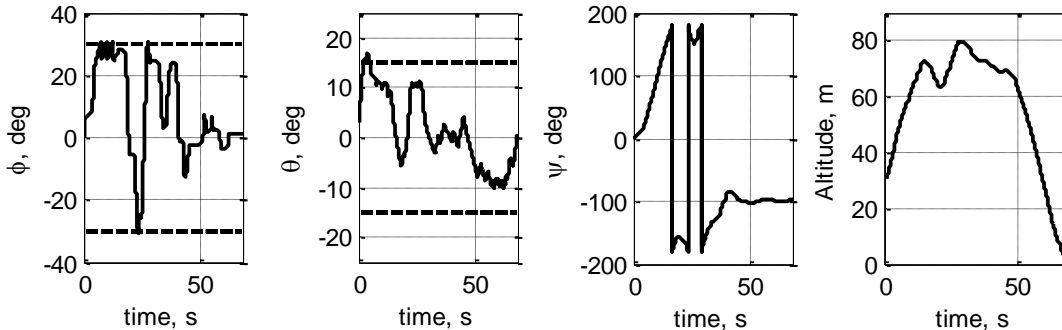
$m = \#$  of time intervals with constant input

$$c_j = \begin{cases} k_j > 0 & \text{if constraint violated} \\ 0 & \text{else} \end{cases} \quad j \in \{\phi, \theta, pq, t\}$$

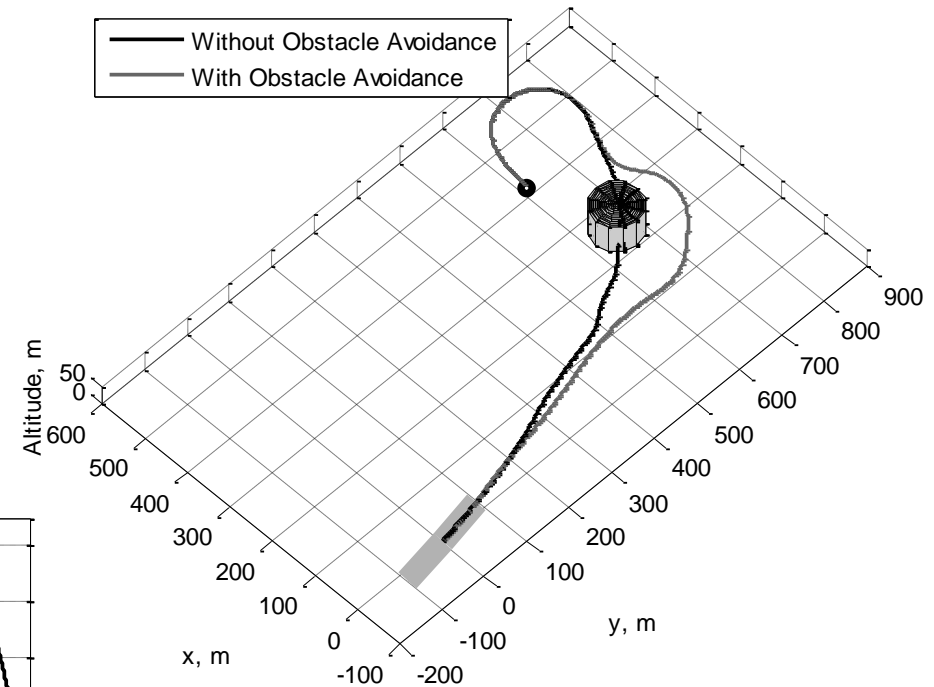


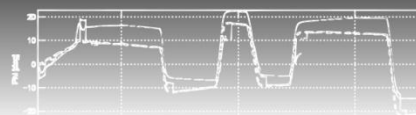
# Simulation Results (1)

- Prediction over 8 sec
- Sample rate 10 Hz
- $d=81=3^{2 \cdot 2}$  control options
  - 2 controls (p and q)
  - 3 constant values each (+1/0/-1)
  - 2 time intervals ( $\Delta t_1 + \Delta t_2 = T_p$ )

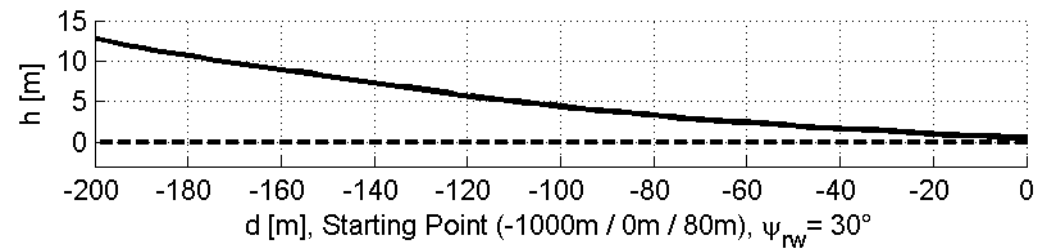
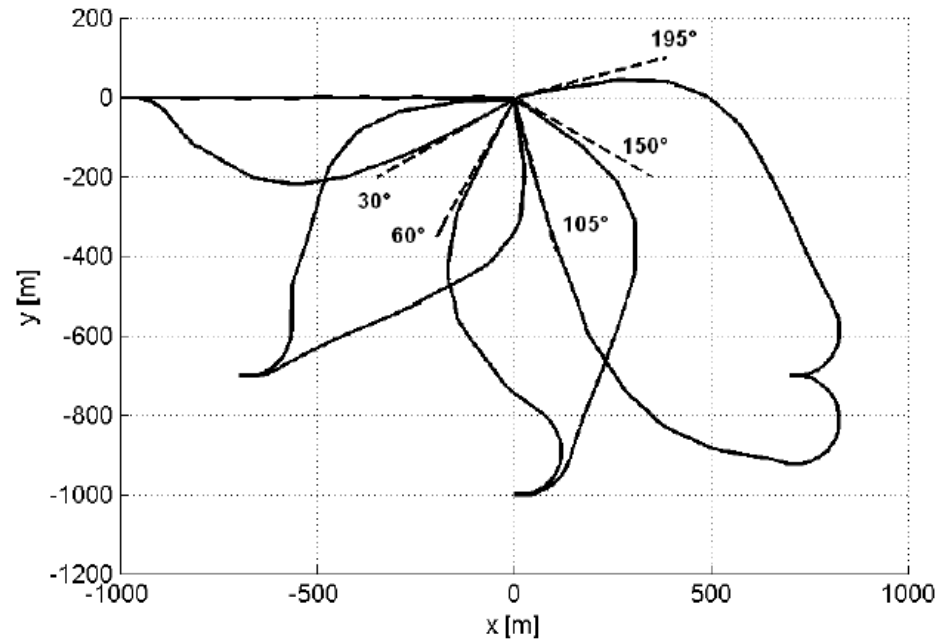
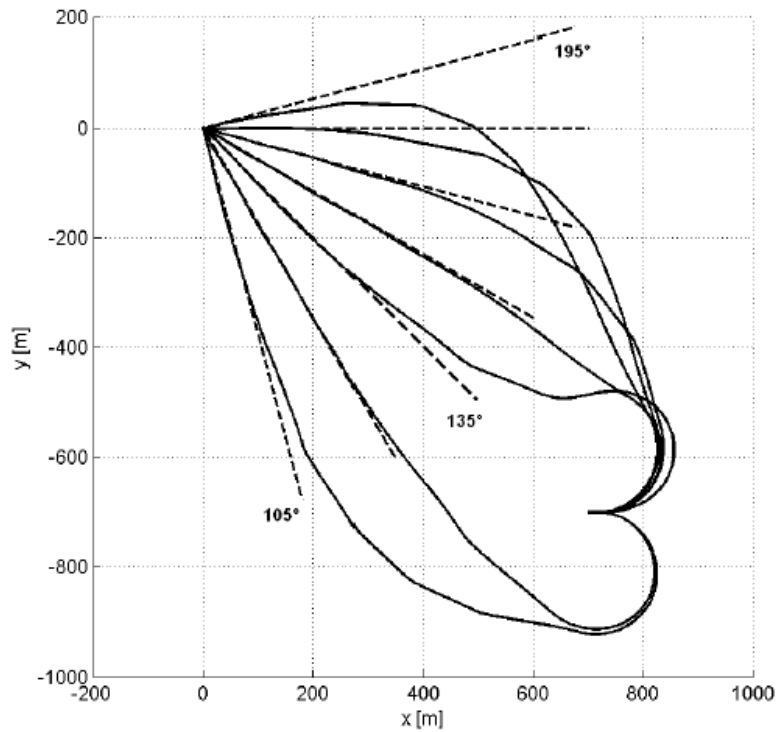


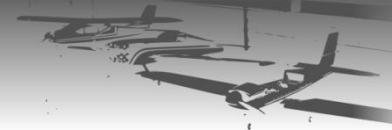
- within constraints, obstacle avoided





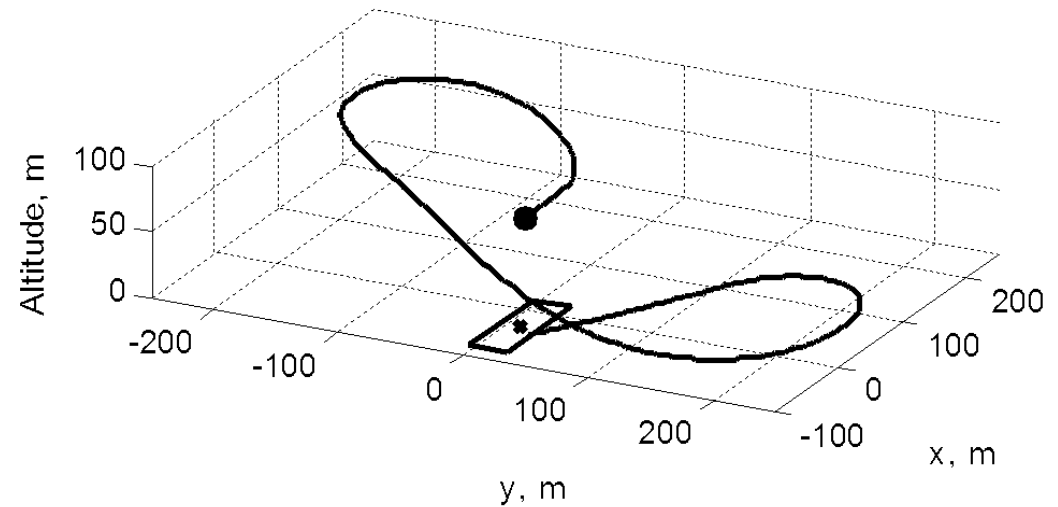
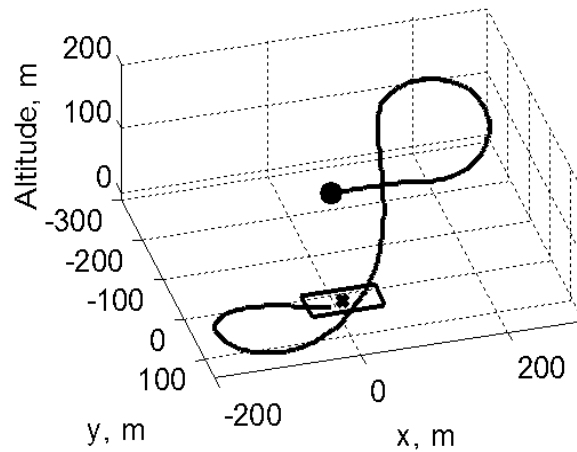
# Simulation Results (2)



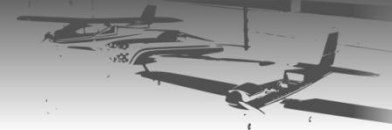


# Simulation Results (3)

## ➤ Examples for transitions



- difficult to achieve with motion primitives (non-stationary)



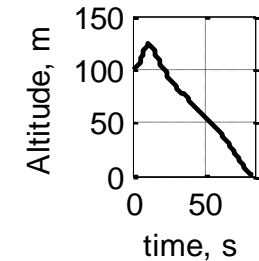
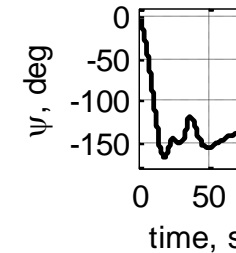
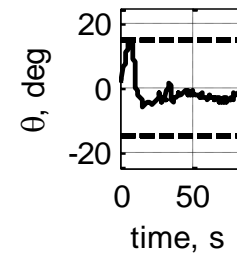
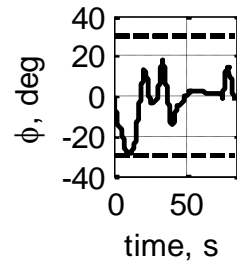
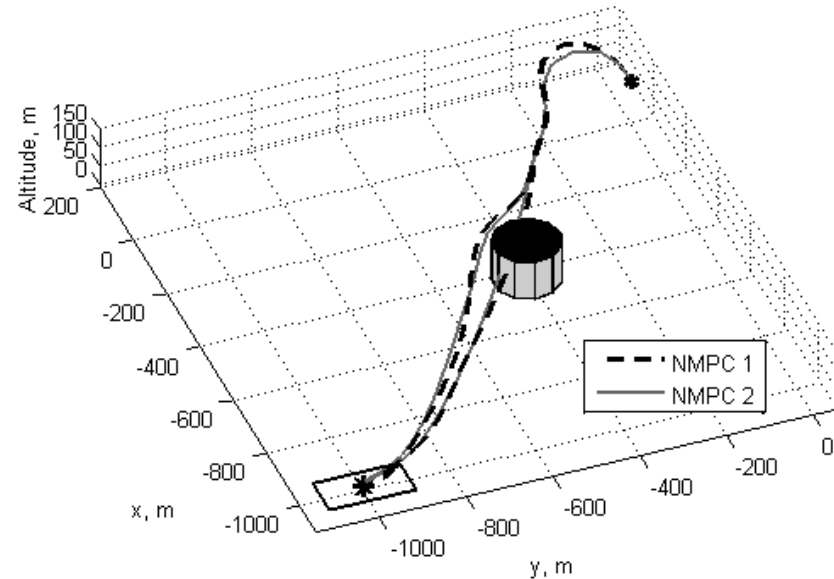
# Simulation Results (4)

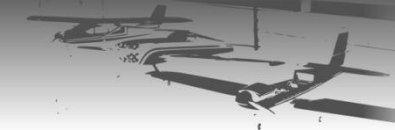
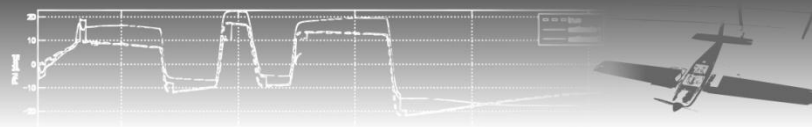
## ➤ NMPC1

- $d=3$ , # of quantized control values
- $n = m = 2$
- $d^{n \cdot m} = 81$  control options

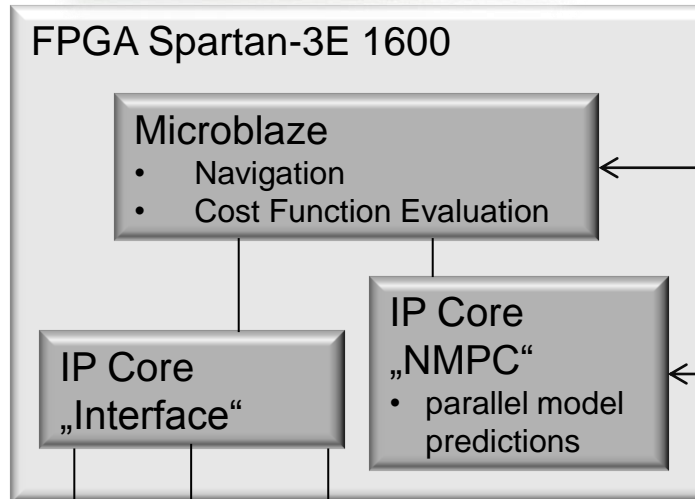
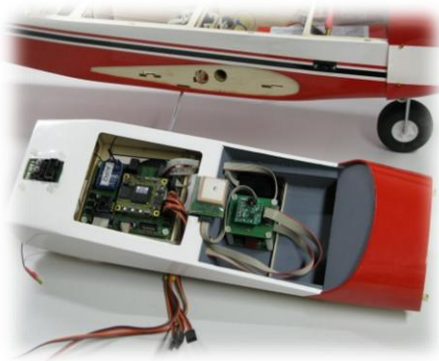
## ➤ NMPC2

- $d=9$ , # of quantized control value
- $n = m = 2$
- $d^{n \cdot m} = 6561$  control options





# Implementation – Use of FPGA



C-code on a microcontroller

C-code implemented in hardware (Handel-C)





# Implementation – „Synthesis“ versus „Software“

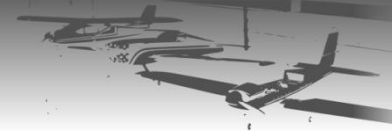
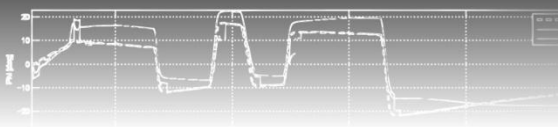
	Hardware IP Core on FPGA	Software Microblaze on FPGA
1 multiplication	$4.2 \cdot 10^{-8}$ sec	$2.9 \cdot 10^{-7}$ sec
9 multiplications	$4.2 \cdot 10^{-8}$ sec	$2.61 \cdot 10^{-6}$ sec

@ 83.33MHz

**More:**

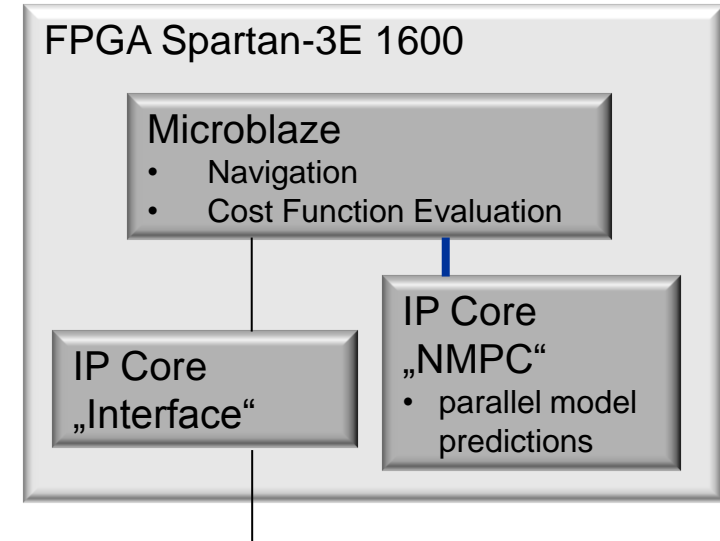
F. Weimer, M. Trittler, A. Joos, M. Gros, A. Posch, W. Fichter, FPGA-Based Onboard Computer System for Mini Aerial Vehicles, International Micro Air Vehicle Conference and Flight Competition, 2010, Braunschweig, Germany



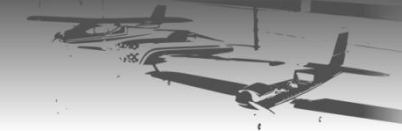
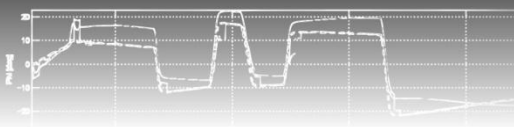


# Implementation – Current Status

- $d=81$  control options
  - 81 model predictions over  $T_p$
- 8 numerical integration steps / model
  - Euler
- 9 parallel multiplications (Spartan-3E 1600)
  - 1st generation board

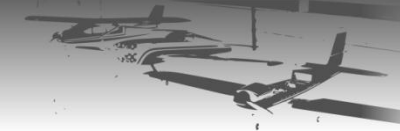
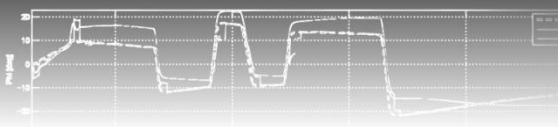


- Total computation < 1 msec
  - **includes communication** from IP Core to Microblaze



# Implementation – Potential

- Model: kinematics, 6 states, nonlinear
- # of numerical integration steps /sec =  $c \cdot p / l = 3.2 \cdot 10^7$  1/sec
  - clock rate  $c \approx 1/25.44 \cdot 10^{-9} \cdot 1/s$
  - number of multipliers  $p = 81$  (FPGA of 2nd generation computer)
  - number of lines of code  $l = 100$
- Assume 10 integration steps / prediction horizon:  $10^6$  control options
- Caution: upper bound, does not include communication!



# Current and Future Work

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- Real-time testing → flight testing
- On-board
  - variable speed, with constraints
  - additional inputs
  - response to disturbances (wind)
  - refined optimization schemes
- Offline
  - benchmarks
- Hardware
  - larger FPGAs: 2<sup>nd</sup> generation (available now) and 3<sup>rd</sup> generation (available 2012) boards, improve communication