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Path Planning for Fixed-Wing UAVs with Small Onboard Computers

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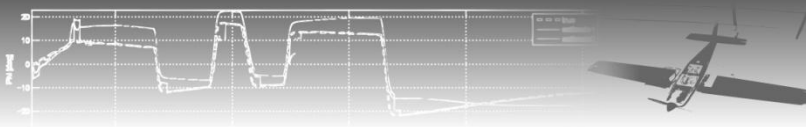
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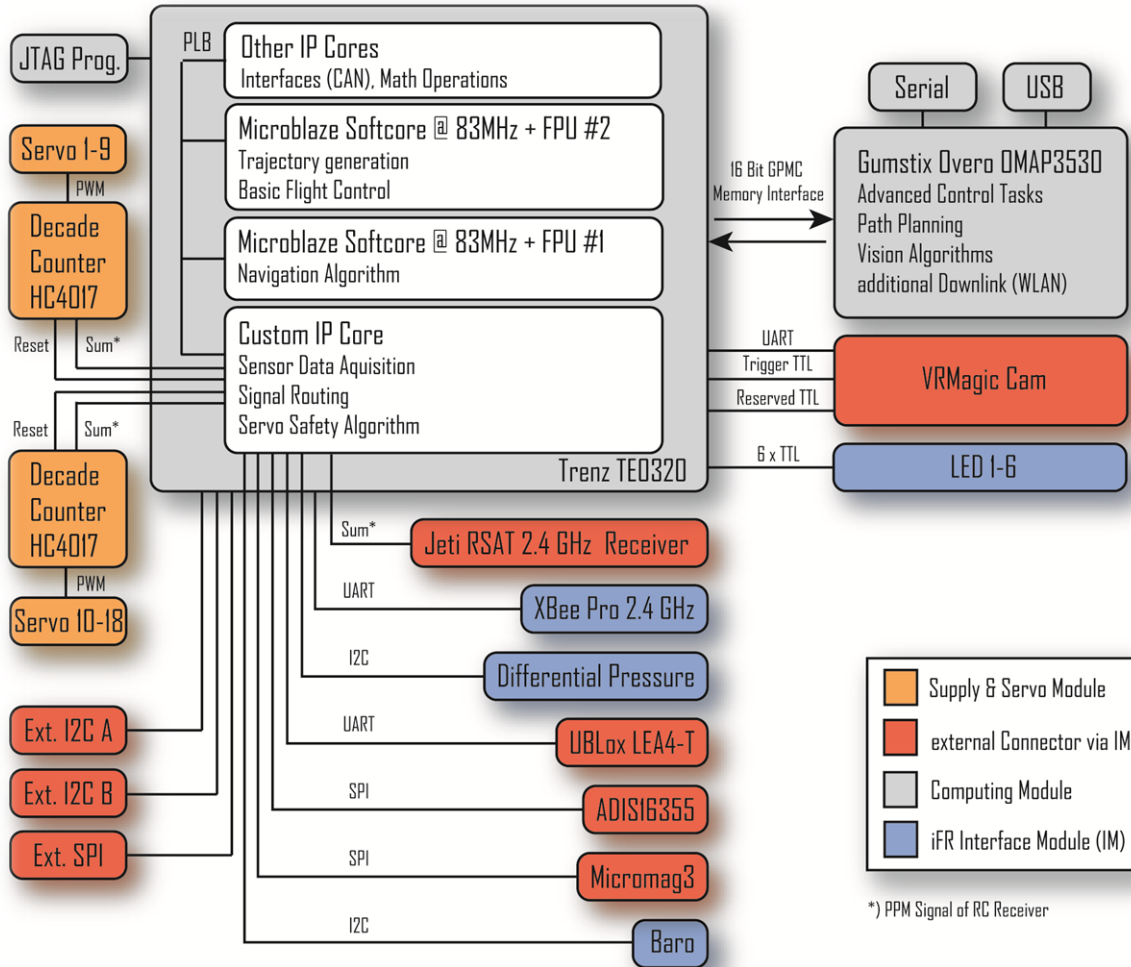
Small Fixed-Wing UAVs

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

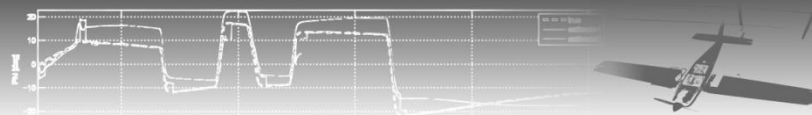




Onboard System

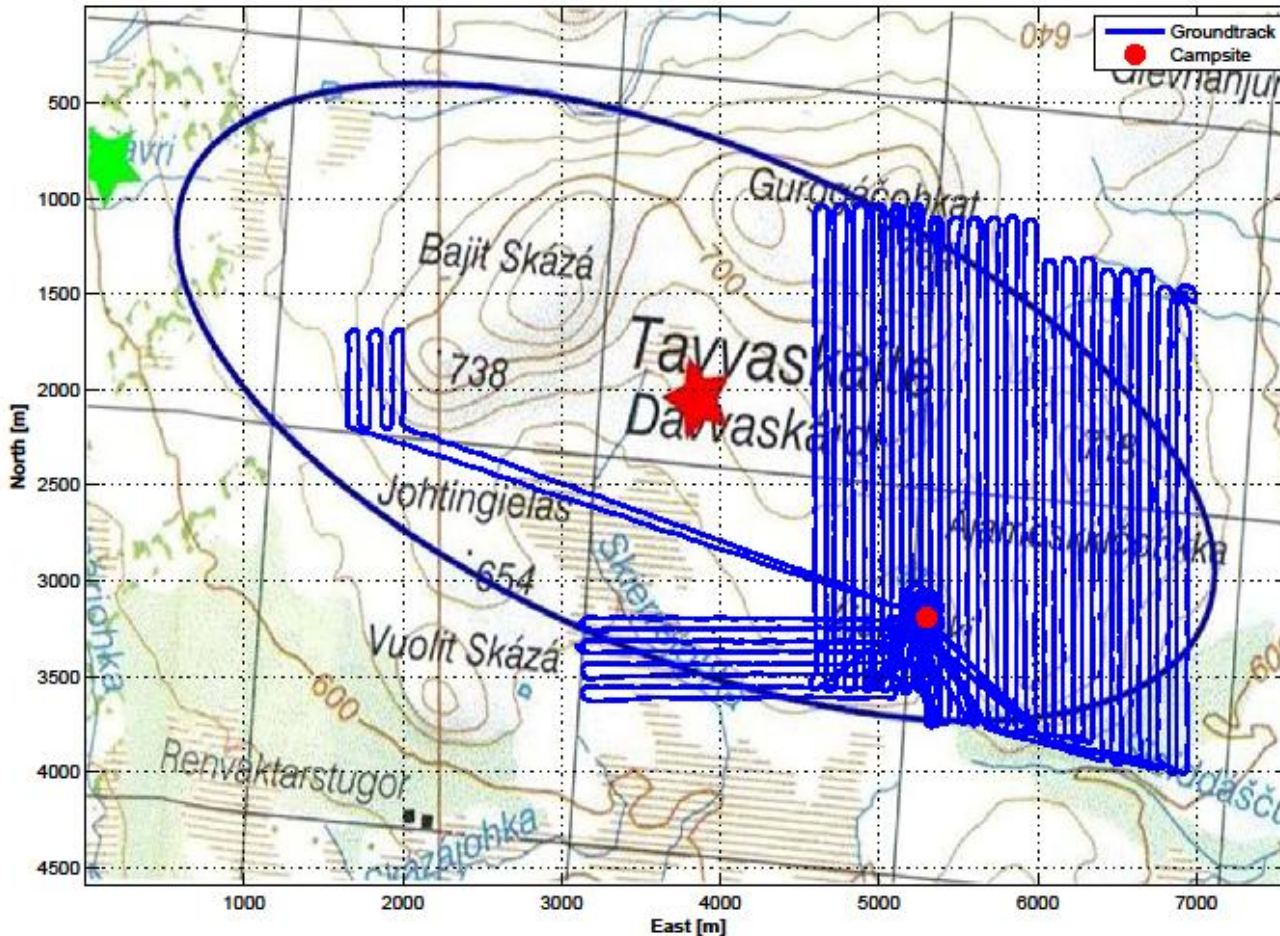


- Full functionality
 - processor(s)
 - FPGA
 - „full“ instrumentation
 - camera + ground station + link
- Limited sensor performance
- Limited computation power

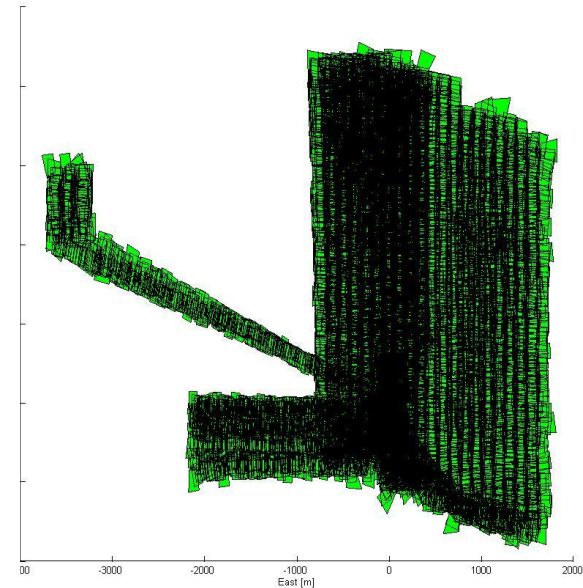


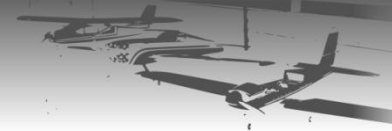
(Small) UAV Flight Path in Practice

Groundtrack of SHARK Recovery Flights




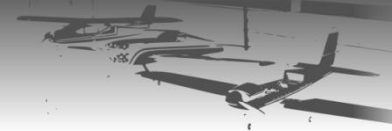
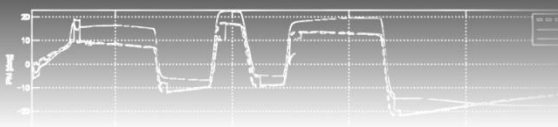
total flight time 24 h, 17 flights
 path length 260 km
 area 8 km²
 ground resolution < 2.6cm
 7600 pictures





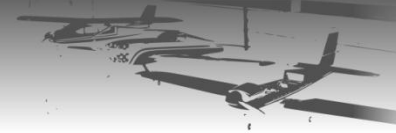
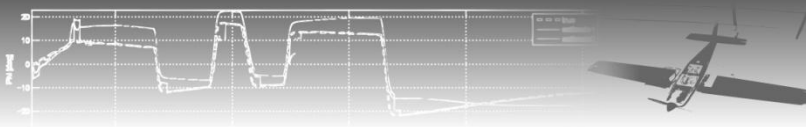
Motion Planning – Towards Autonomy

- 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



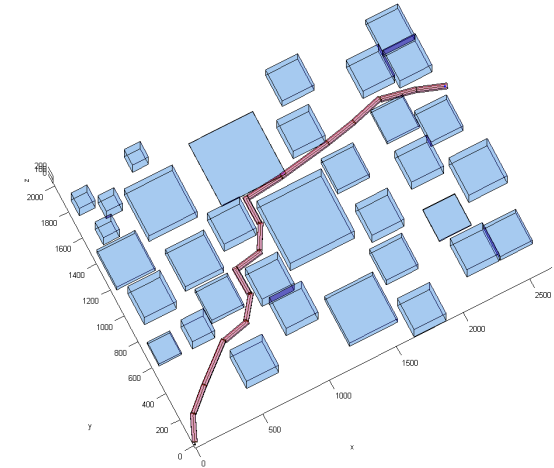
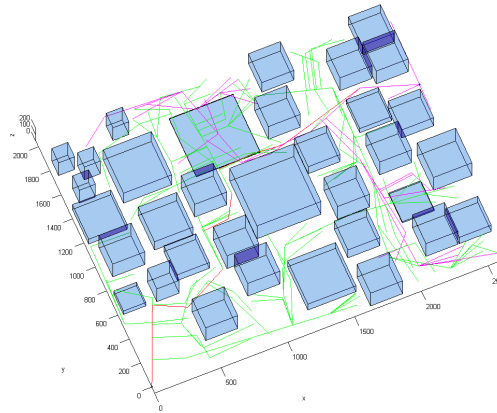
Motion Planning Research – Overview

- 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..

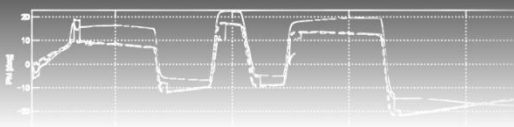


Probabilistic Methods

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

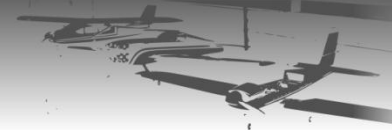


- RRTs with motion primitives
 - becomes complex with non-steady motion primitives
- RRTs with closed loop dynamics included („towards“ NMPC)



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

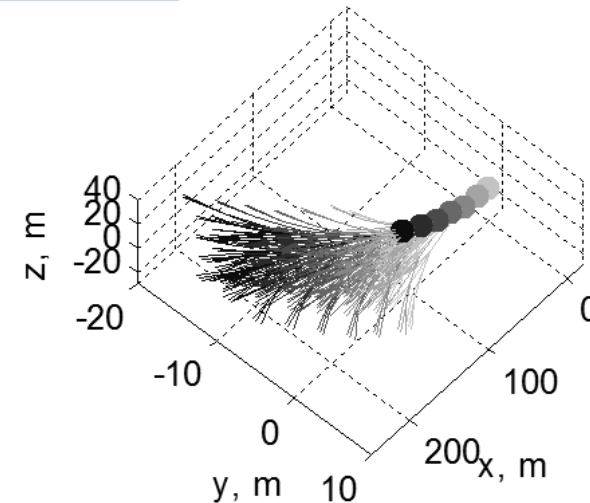
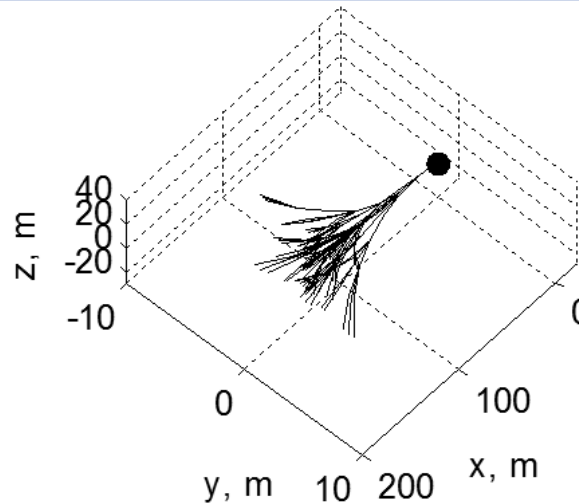


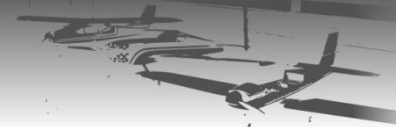
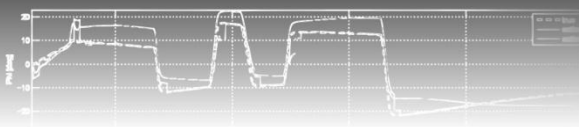
NMPC – Computational Approach

- 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

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

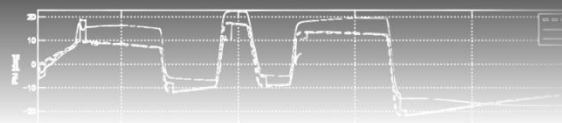




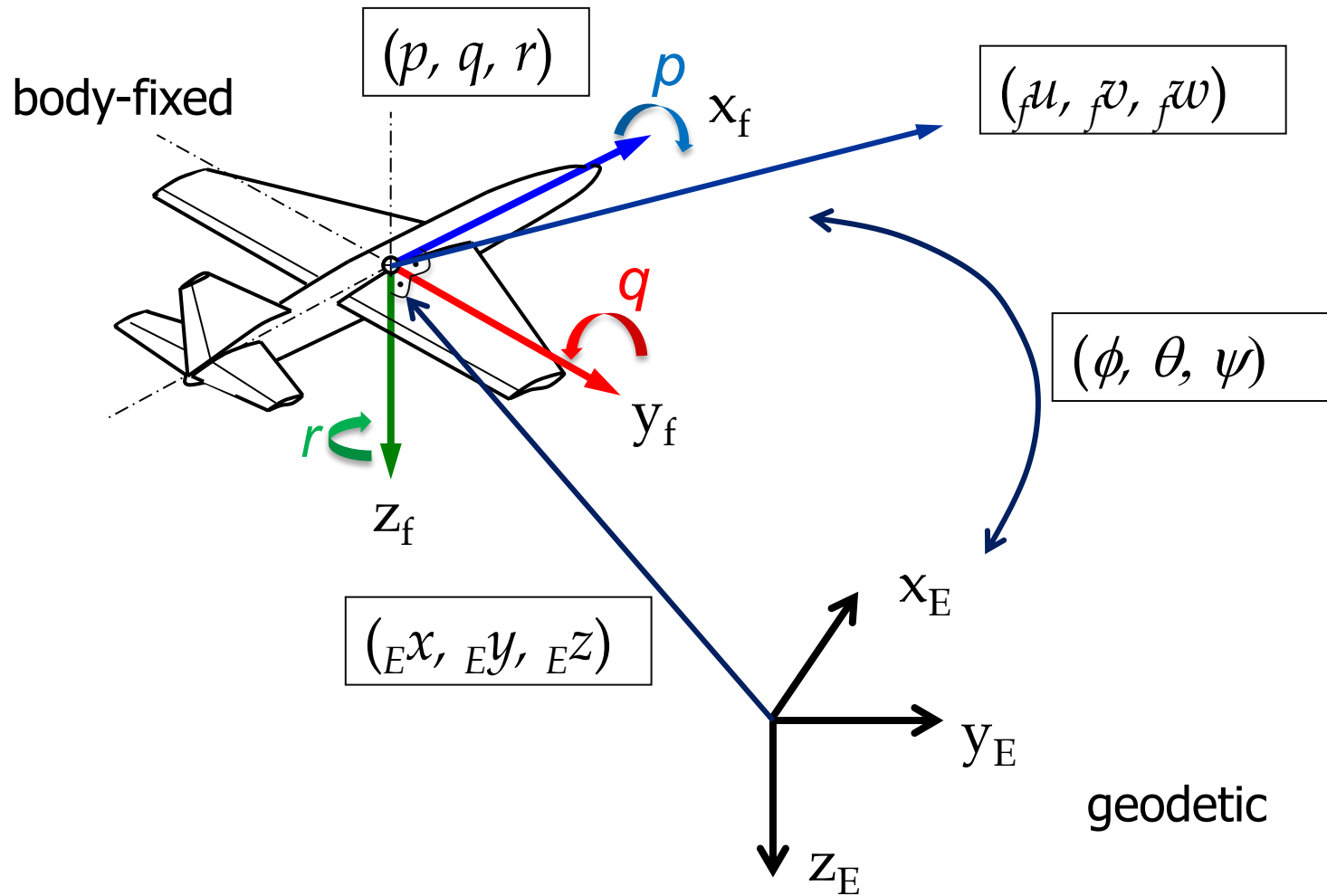
Design Parameters

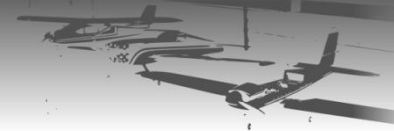
- Control system
 - plant model, required underlying control loops
 - control signals
 - number
 - quantization
 - discretization
 - cost function

- Implementation, i.e.
 - tailored hardware
 - parallel models, optimization

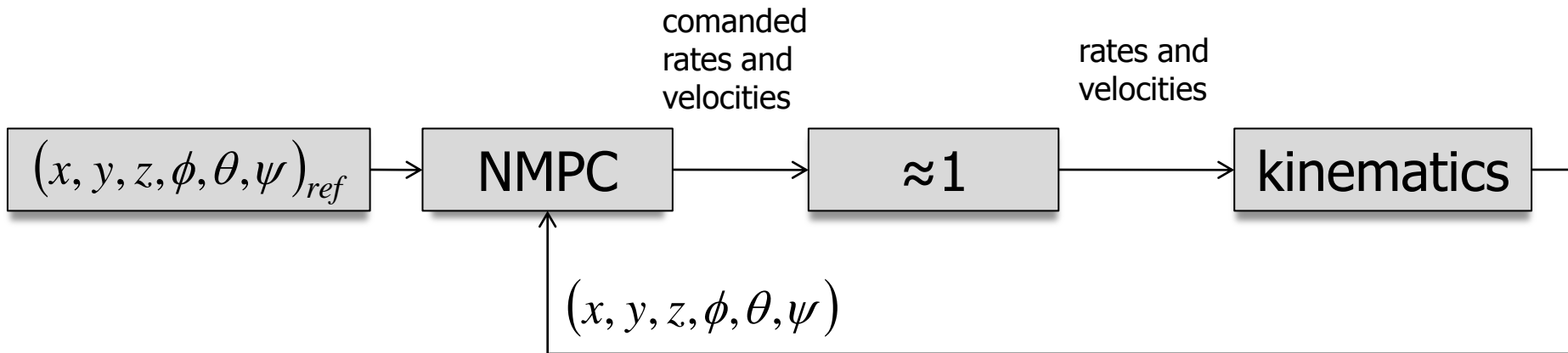
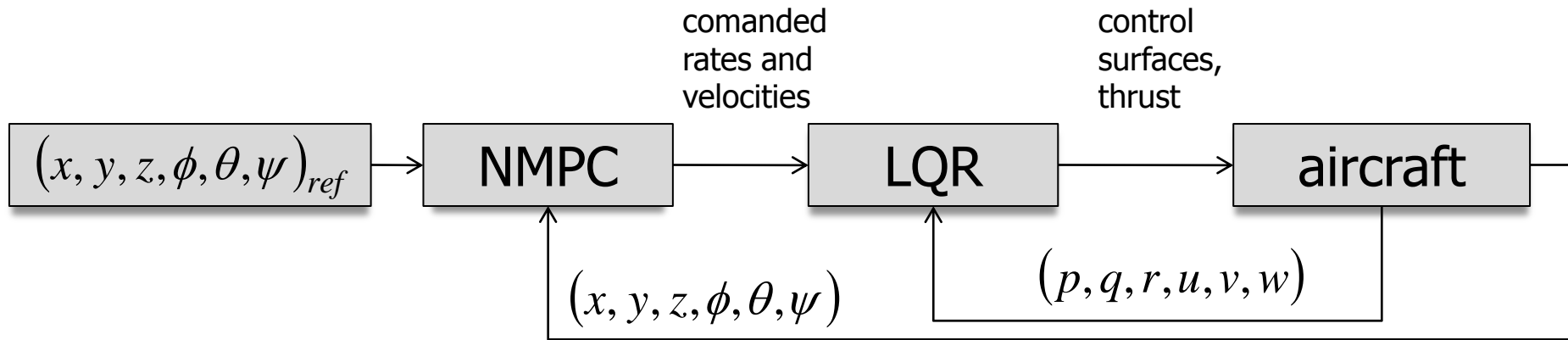


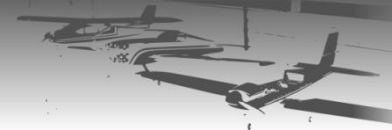
Vehicle States





Control Loops





Design Plant – Kinematics

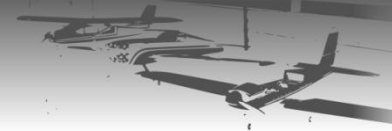
$$\begin{pmatrix} {}_E \dot{x} \\ {}_E \dot{y} \\ {}_E \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{bmatrix} c\theta c\psi & -c\phi s\psi + s\phi s\theta c\psi & s\phi s\psi + c\phi s\theta c\psi & 0 & 0 & 0 \\ c\theta s\psi & c\phi c\psi + s\phi s\theta s\psi & -s\phi c\psi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

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

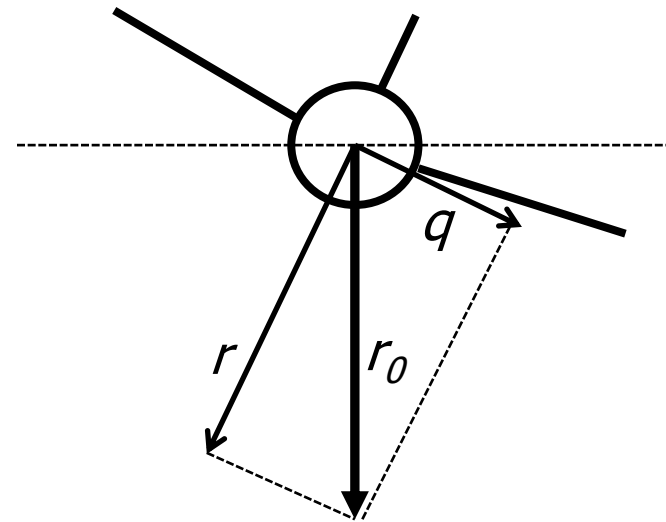


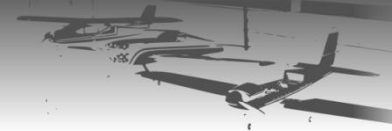
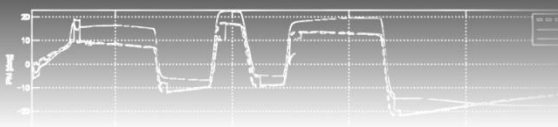


Input (Control) Signal Selection

- 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 $\mathbf{C} = (\mathbf{a}_1, \mathbf{a}_2, [\mathbf{a}_1, \mathbf{a}_2])$

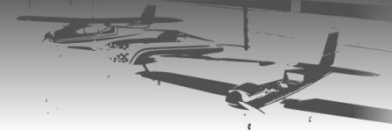
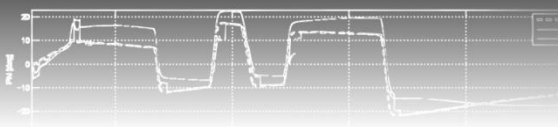
$$\mathbf{C} = \begin{bmatrix} 1 & \sin(\phi) \sin(\theta) / \cos(\theta) & \cos(\phi) \sin(\theta) / \cos(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi) / \cos(\theta) & \cos(\phi) / \cos(\theta) \end{bmatrix}$$

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

new direction =
actuation direction from yaw rate r

➤ Position subsystem

- constant velocity vector can be oriented through angular controllability

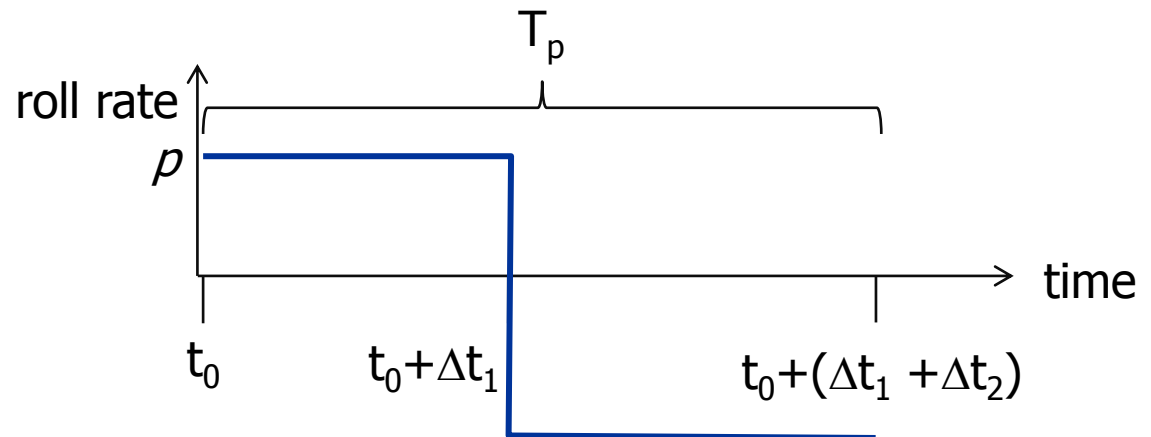


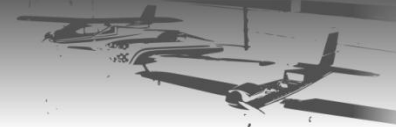
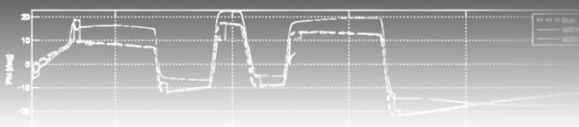
Control Signals

- 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

control error
constraints
(flight mechanics)
terminal
constraint
obstacle

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

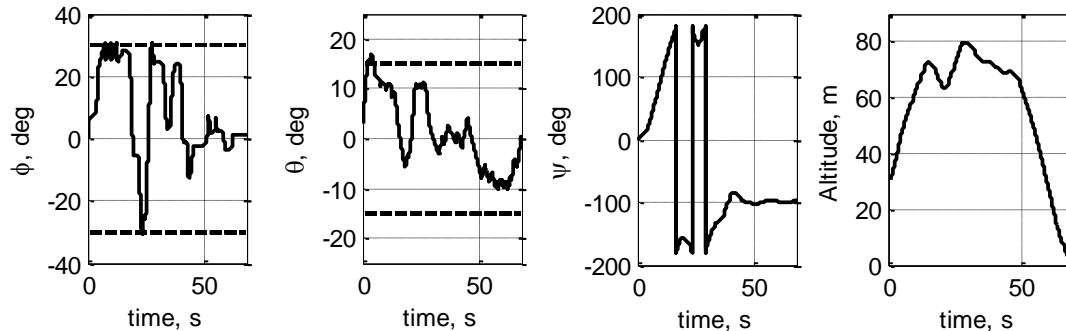
$$t_i = t_0 + \sum_{j=1}^i \Delta t_j, \quad i \in N \wedge 1 \leq i \leq m$$

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

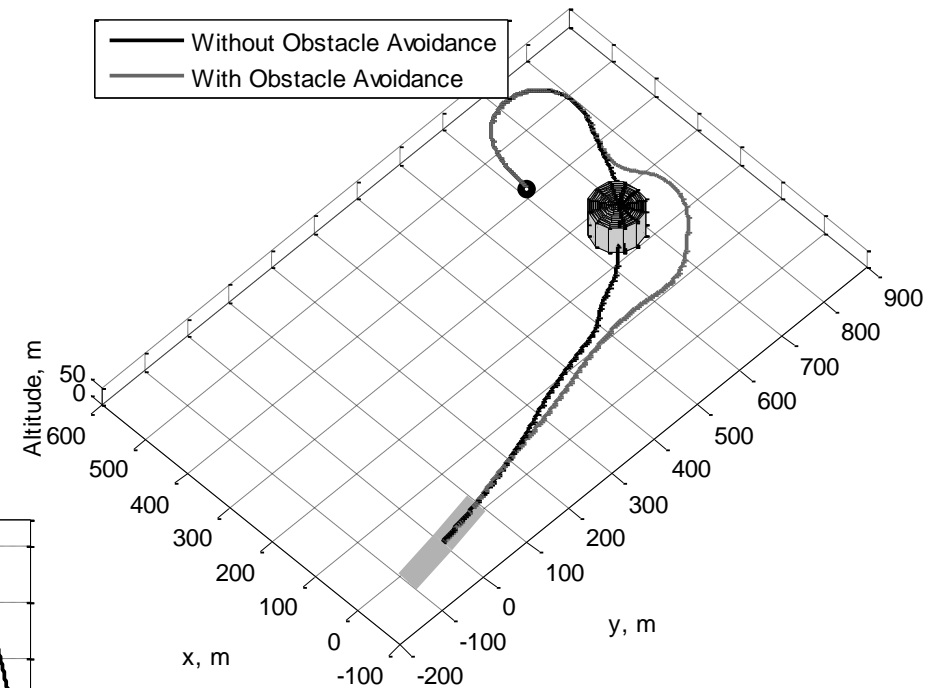
$$c_j = \begin{cases} k_j > 0 & \text{if constraint violated} \\ 0 & \text{else} \end{cases} \quad j \in \{\phi, \theta, pq, t\}$$

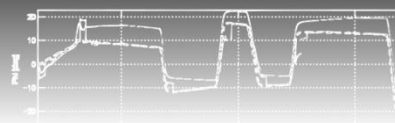
Simulation Results (1)

- 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 ($\Delta t_1 + \Delta t_2 = T_p$)

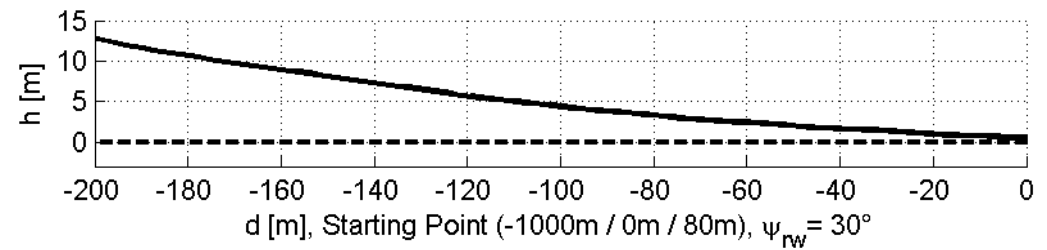
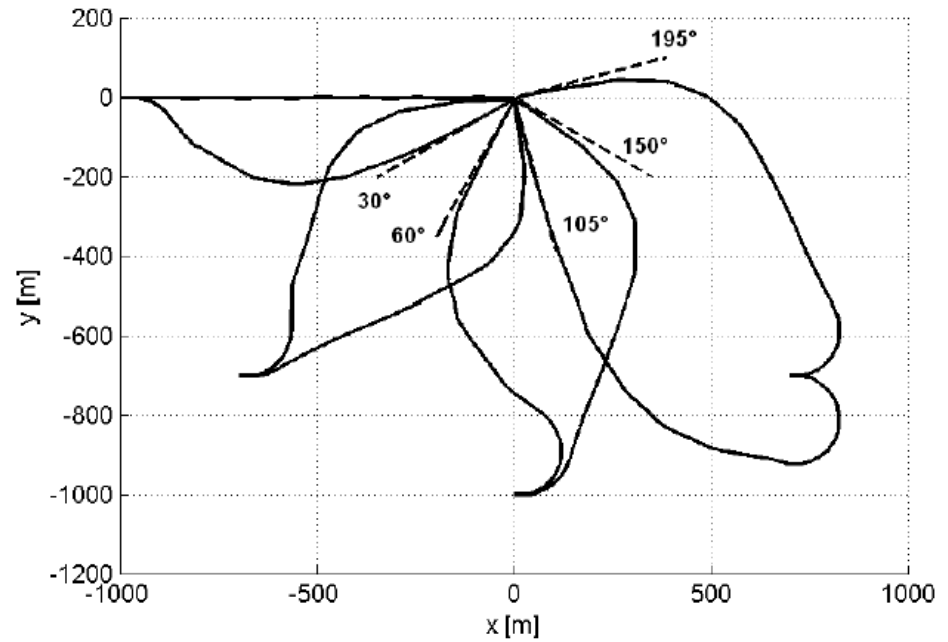
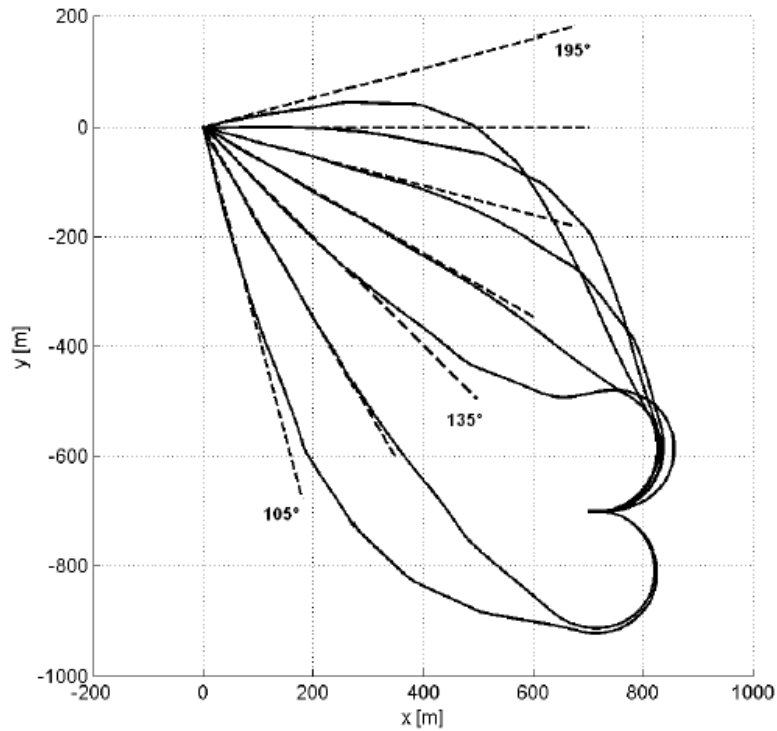


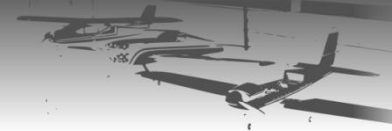
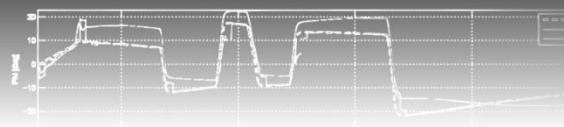
- within constraints, obstacle avoided





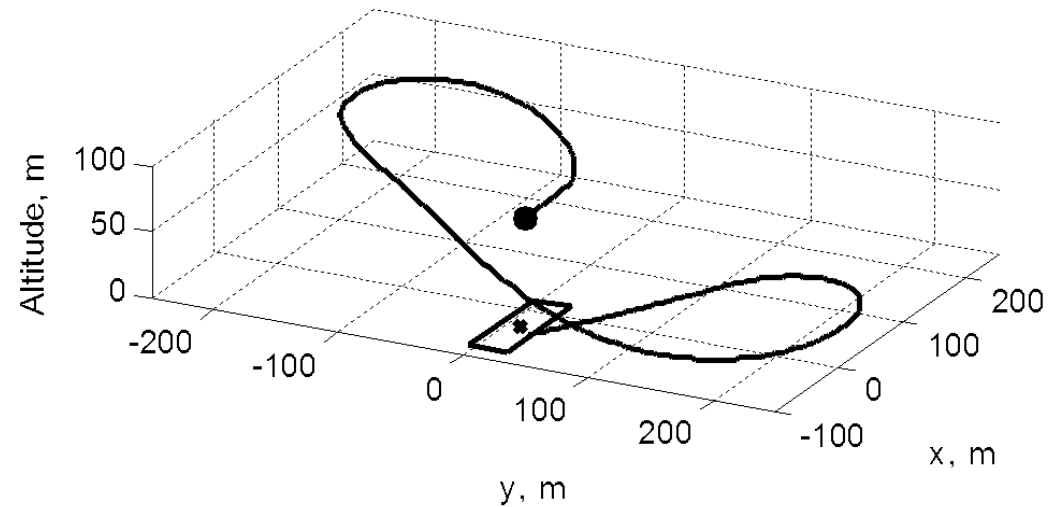
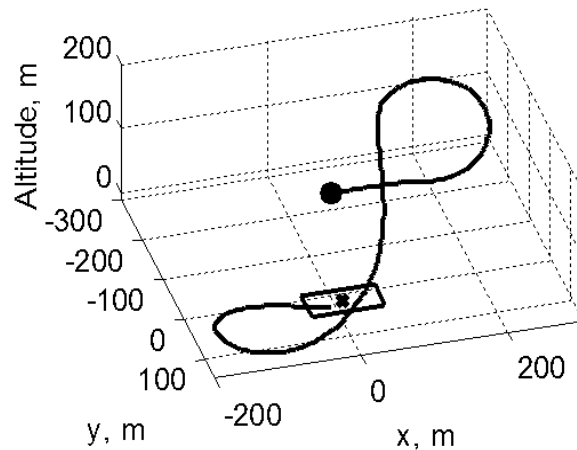
Simulation Results (2)





Simulation Results (3)

➤ Examples for transitions



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



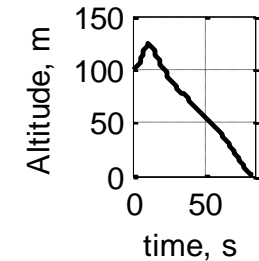
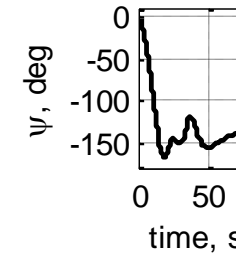
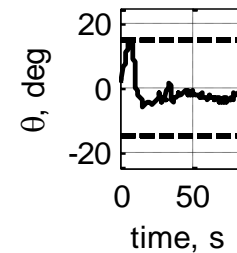
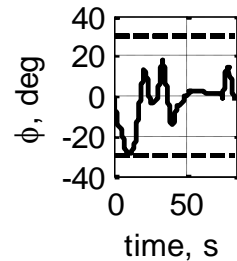
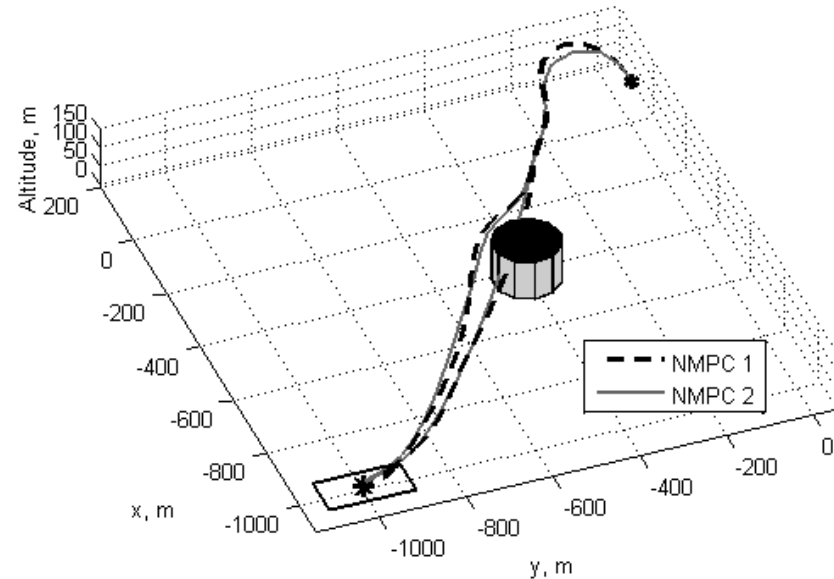
Simulation Results (4)

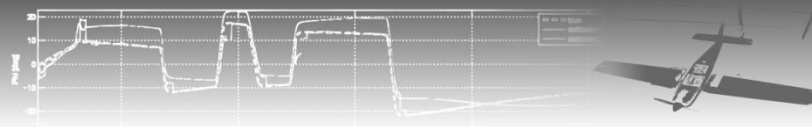
➤ NMPC1

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

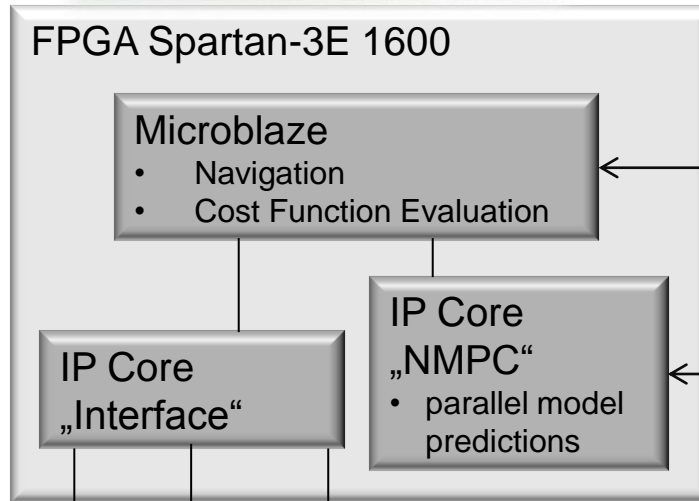
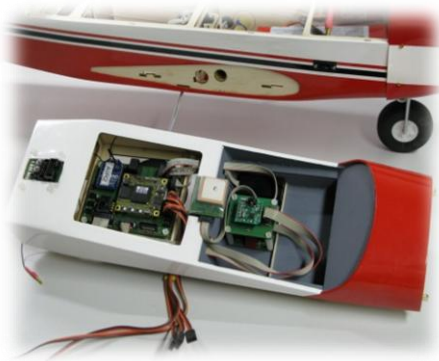
➤ NMPC2

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



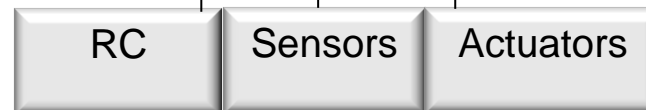


Implementation – Use of FPGA



C-code on a microcontroller

C-code implemented in hardware (Handel-C)





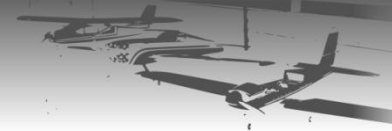
Implementation – „Synthesis“ versus „Software“

	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

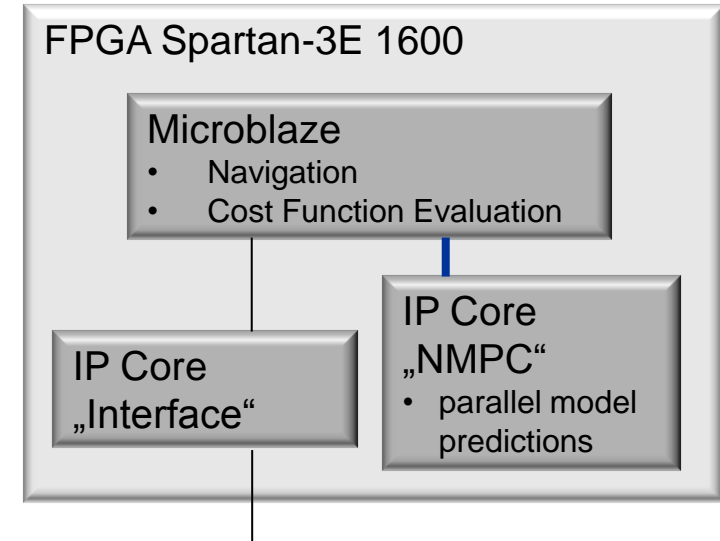
More:

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

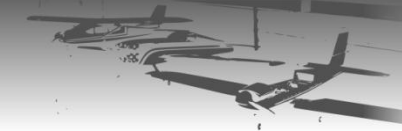
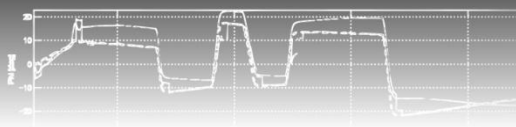


Implementation – Current Status

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

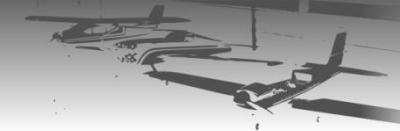
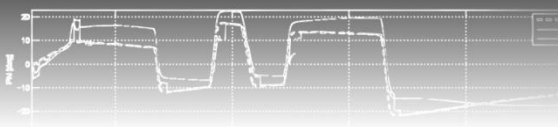


- Total computation < 1 msec
 - **includes communication** from IP Core to Microblaze



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

- 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: 2nd generation (available now) and 3rd generation (available 2012) boards, improve communication