Path Planning for Fixed-Wing UAVs with Small Onboard Computers

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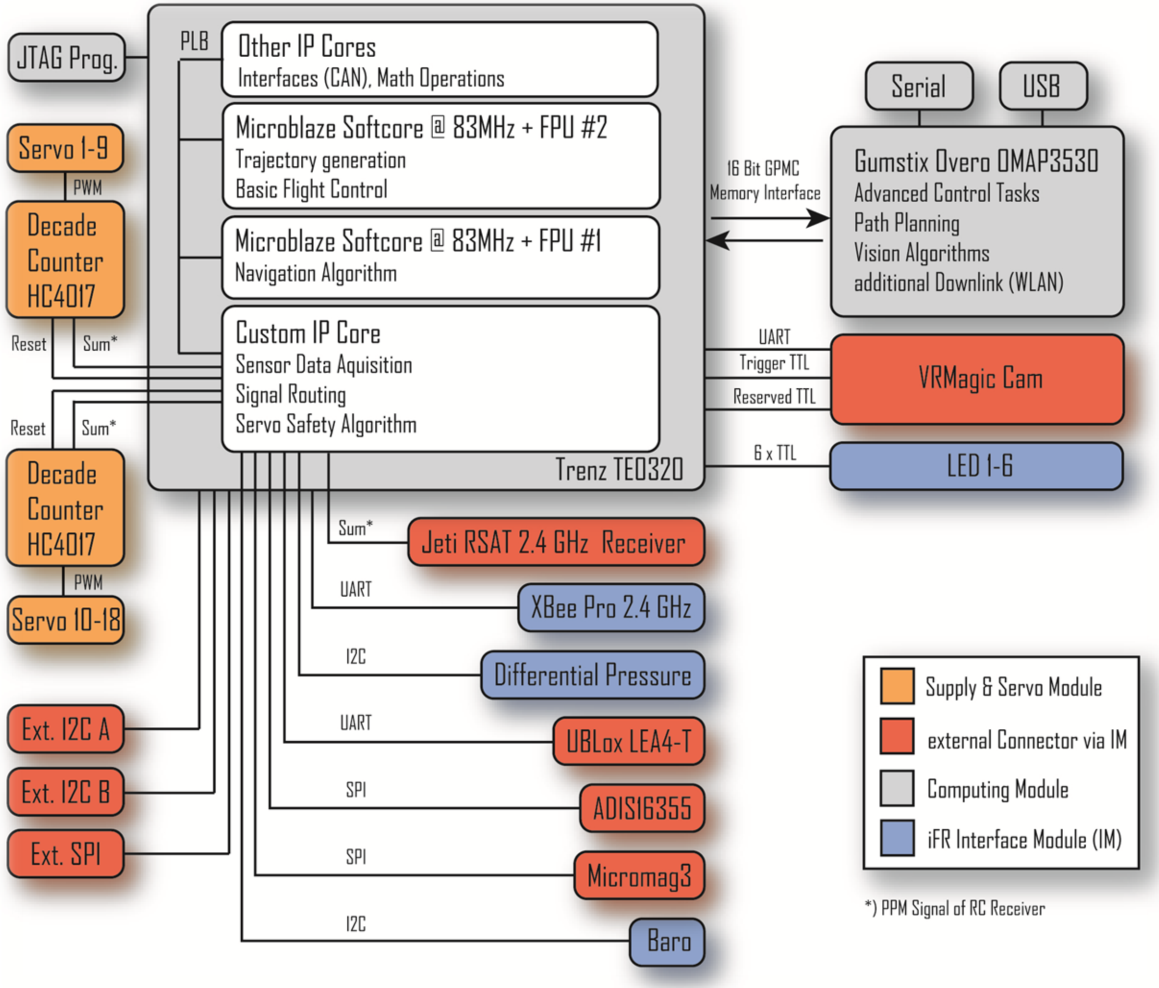
Small Fixed-Wing UAVs

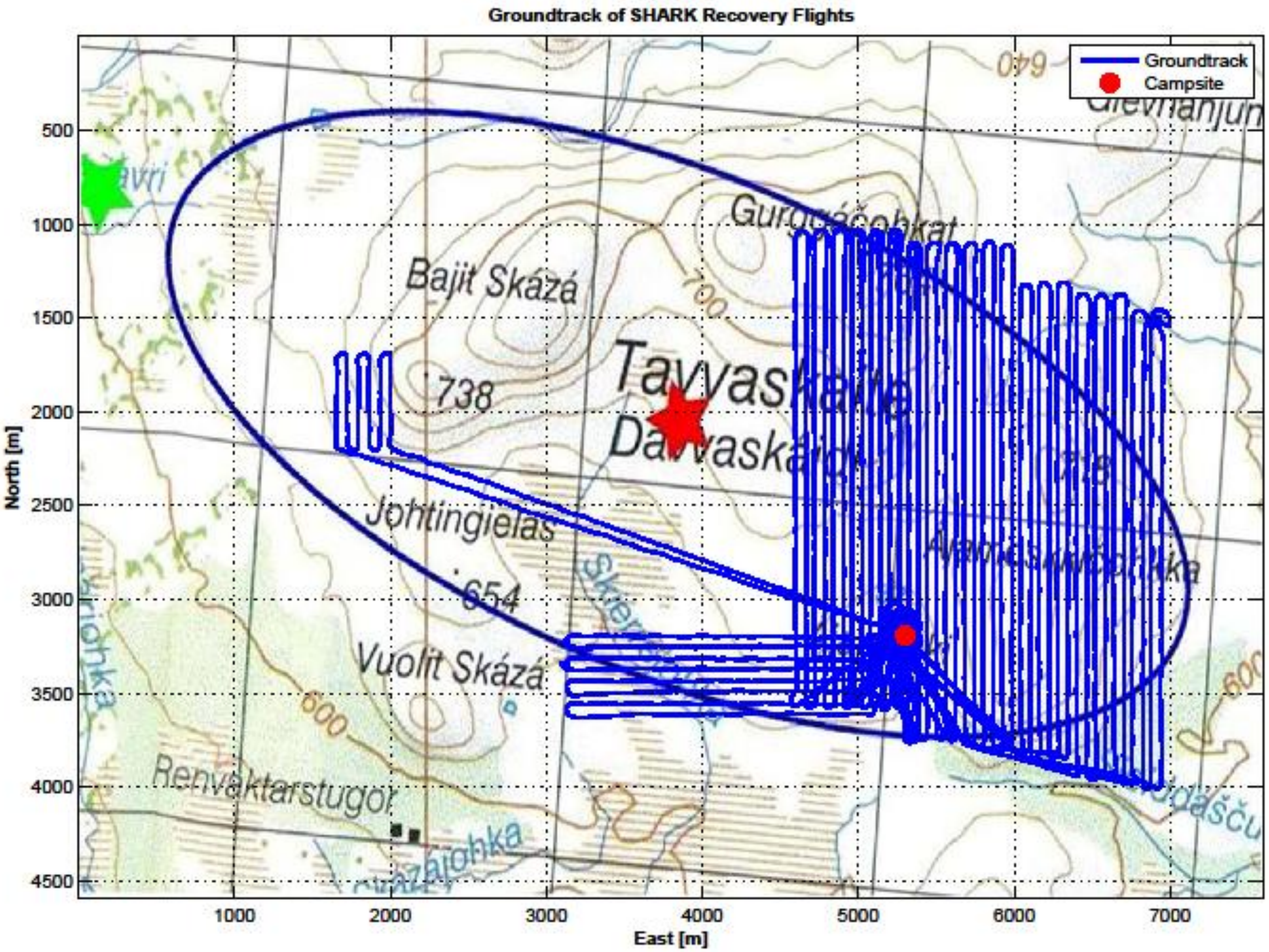
- Fixed-wing UAV
  - < 5 kg (< 25 kg)
  - wing span typically 1.5 m
- Small onboard computer
  - microcontroller, microprocessor
  - < 150 g (120 g), 10 W
  - limited computer power

Onboard System

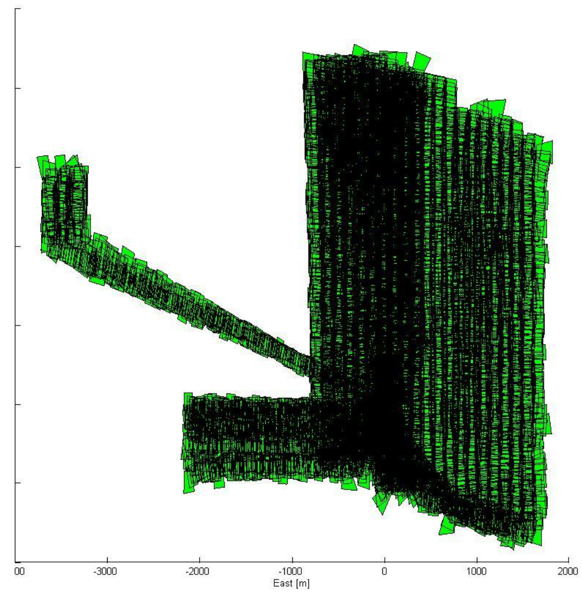


- Full functionality
  - processor(s)
  - FPGA
  - „full" instrumentation
  - camera + ground station + link
- Limited sensor performance
- Limited computation power

(Small) UAV Flight Path in Practice



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



Motion Planning – Towards Autonomy

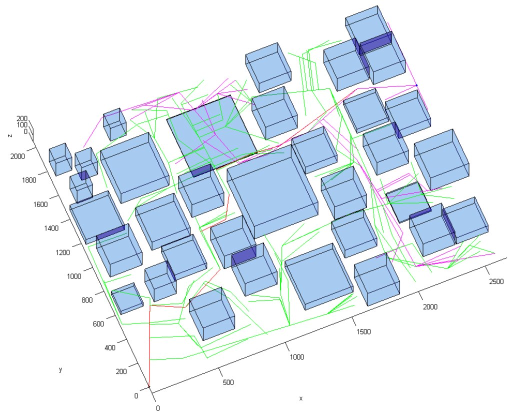
- 3 dimensional, considering 6 degrees of freedom, 12 states
- From a given initial state („in flight") to a final state („landing")
- Under constraints of
  - position (obstacles)
  - velocitiy (flight dynamics)
  - attitude (flight dynamics)
  - rates (flight dynamics)
- Real-time implementation ←!→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

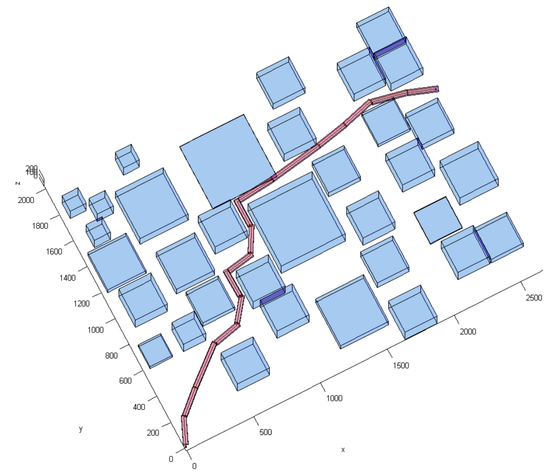
Motion Planning Research – Overview

- 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)

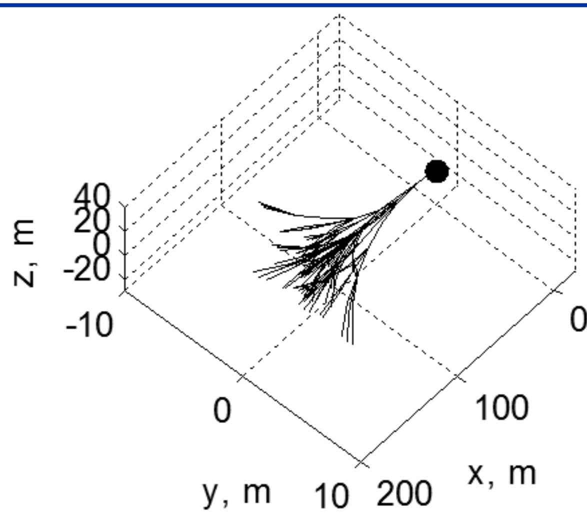
- „Embedded" into control system
- Kang&Hedrick, Linear Tracking of a Fixed-Wing UAV Using Nonlinear MPC, IEEE Trans. Contr. Syst. Technology, Sept 2009
  - 2D (horizontal) motion
  - fixed wing
  - PC104
  - real-time testbench results
- Rest of the presentation: NMPC with limited computational effort

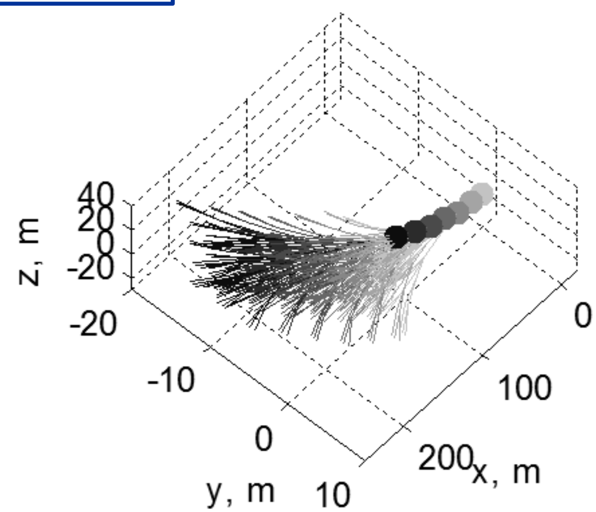
NMPC – Computational Approach

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

cost function

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



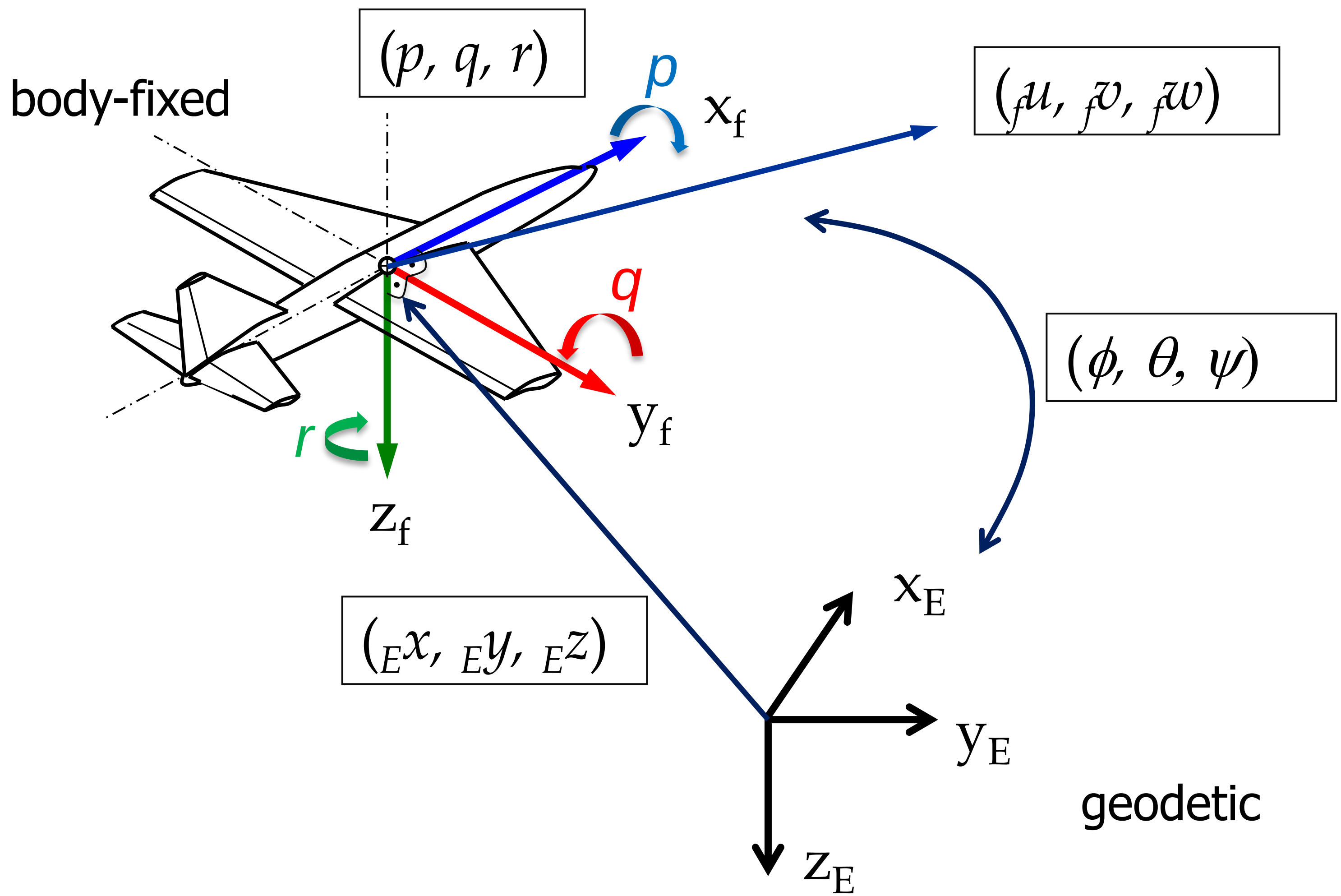


Design Parameters

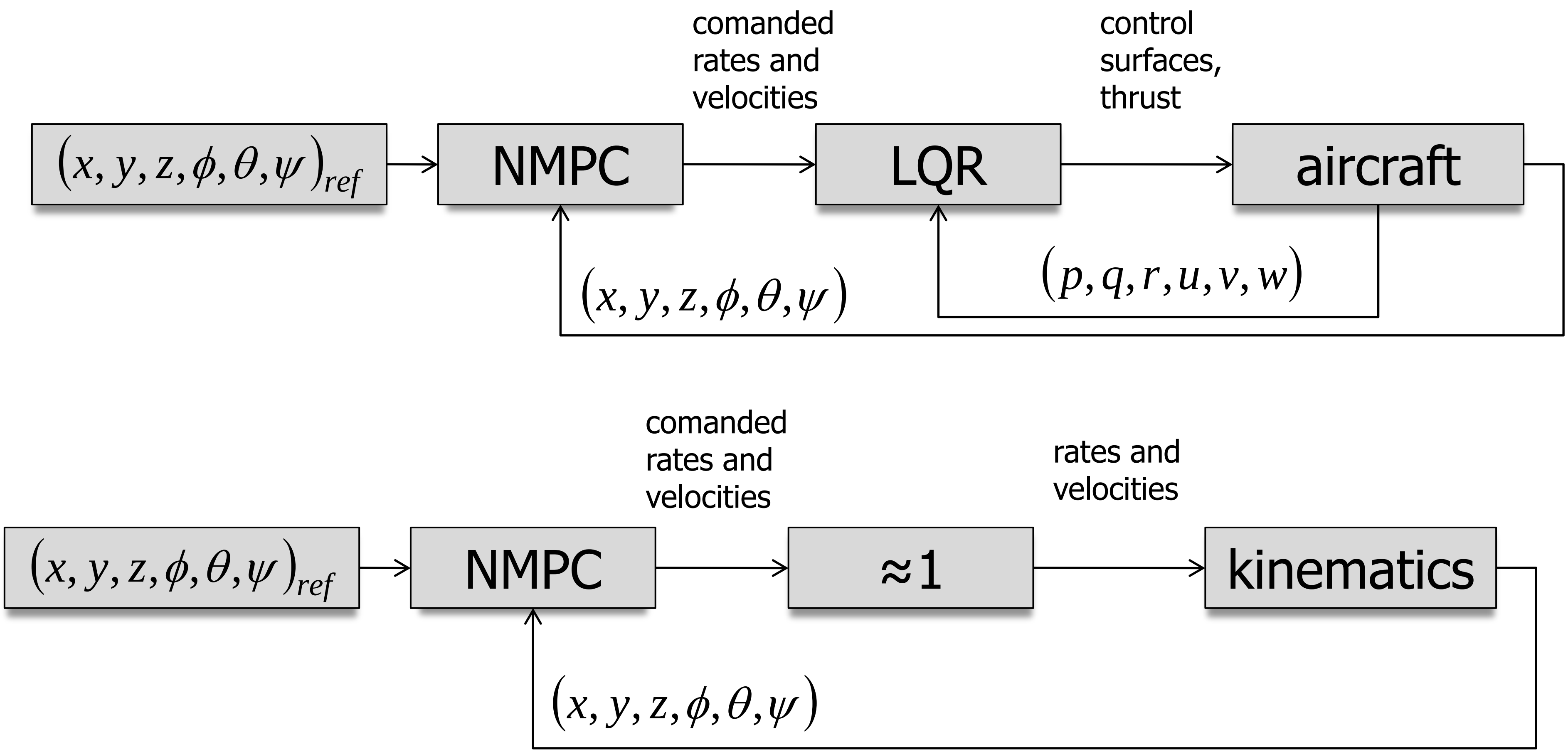
- Control system
  - plant model, required underlying control loops
  - control signals
    - number
    - quantization
    - discretization
  - cost function

- 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"

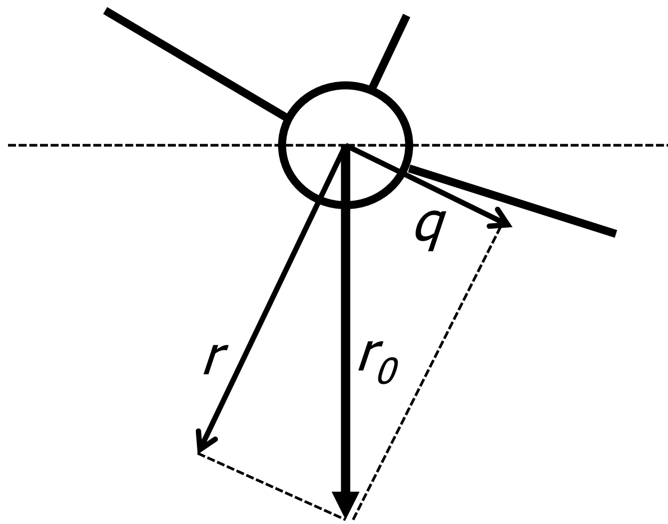
velocities
rates
body-fixed

- 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*

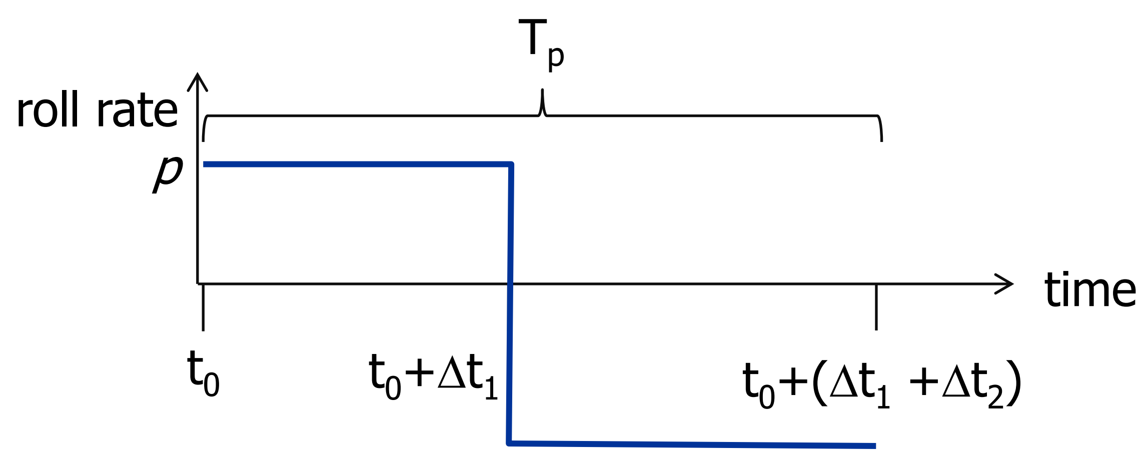
- Position subsystem
  - constant velocity vector can be oriented through angular controllability

Control Signals

- Prediction horizon T_p
- d quantization values of controls, simplest case: +1, 0, -1
- m intervals with constant controls, simplest case: Δt_1, Δt_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

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

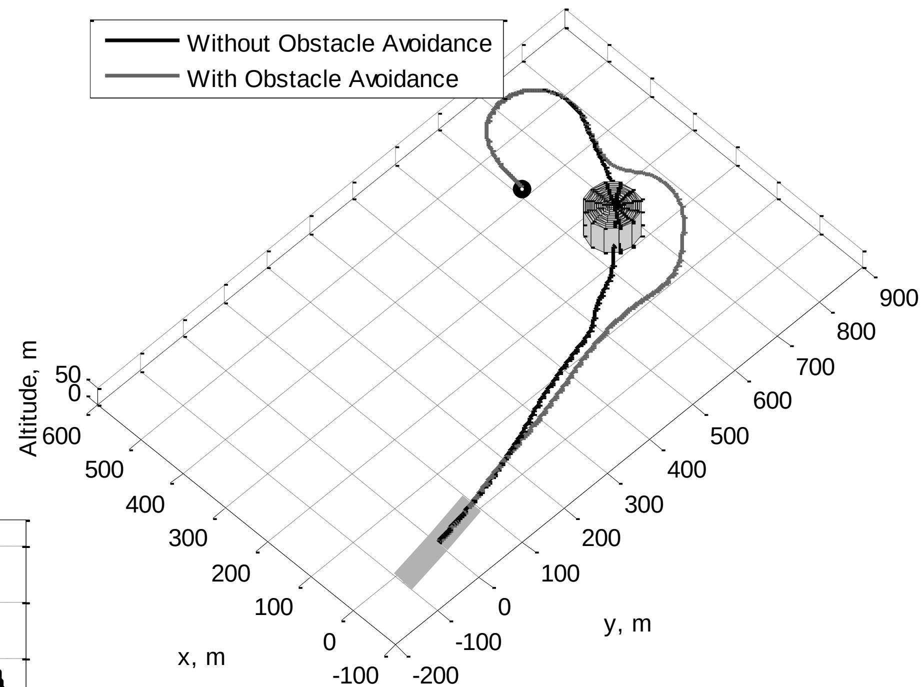
$$t_i = t_0 + \sum_{j=1}^{i} \Delta t_j, \quad i \in N \wedge 1 \le i \le m$$

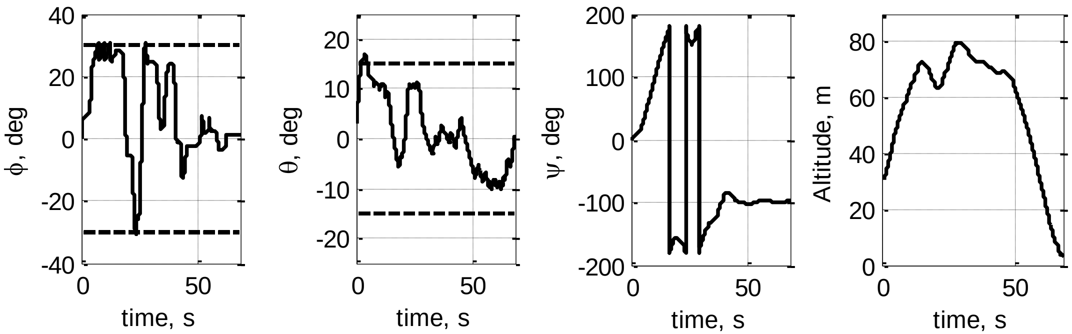
$$m = \#\text{ of time intervals with constant input}$$

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

Simulation Results (1)

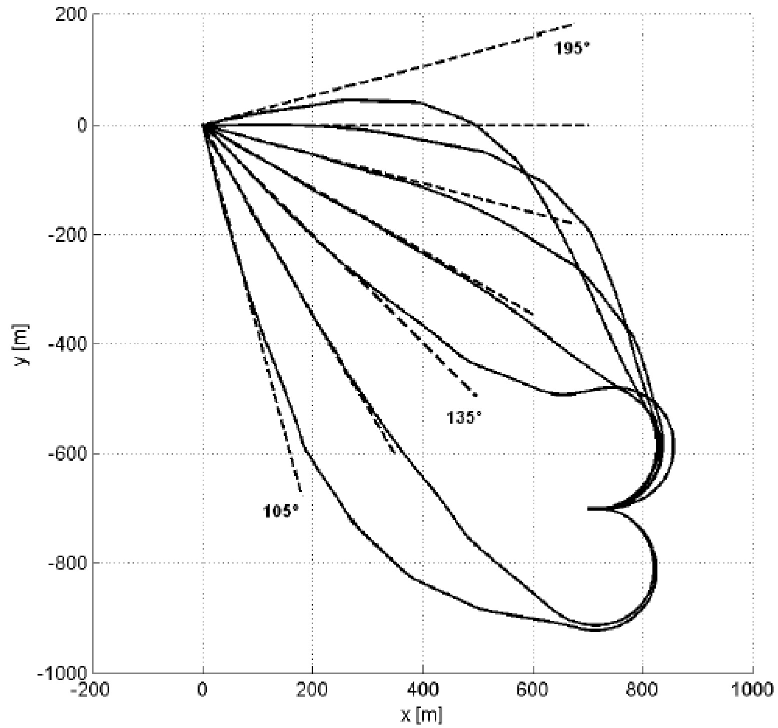
- Prediction over 8 sec
- Sample rate 10 Hz
- $d=81=3^{2\cdot 2}$ control options
  - 2 controls (p and q)
  - 3 constant values each (+1/0/-1)
  - 2 time intervals ($\Delta t_1+\Delta t_2=T_p$)

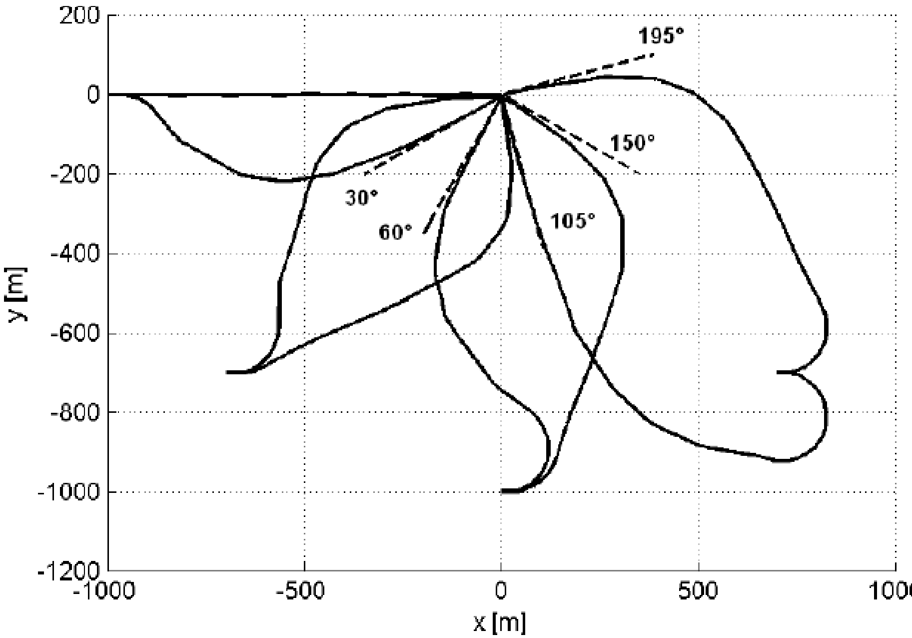


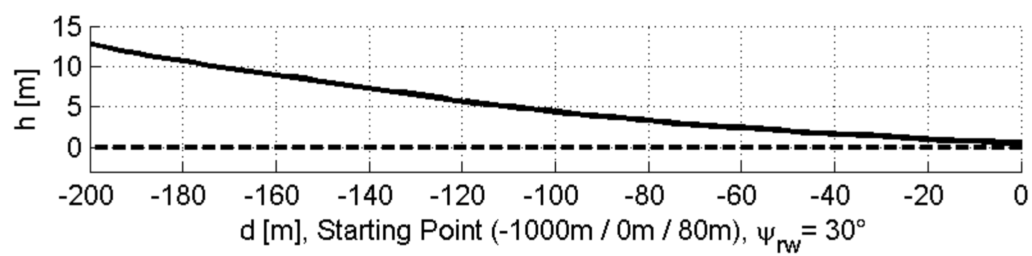


  - within constraints, obstacle avoided

Simulation Results (2)

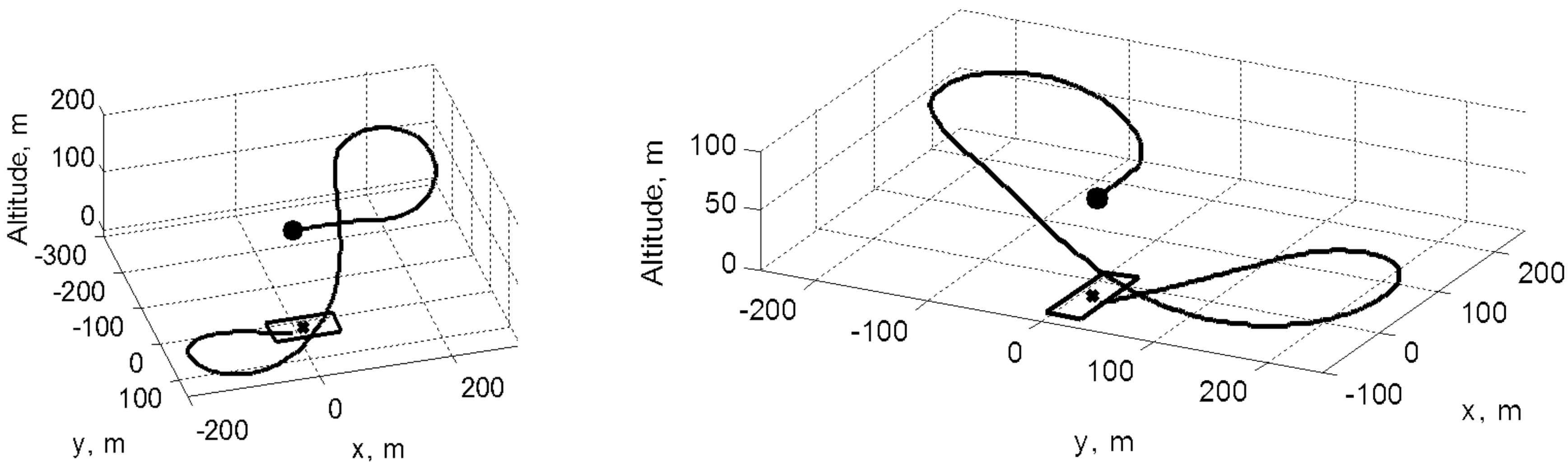






Simulation Results (3)

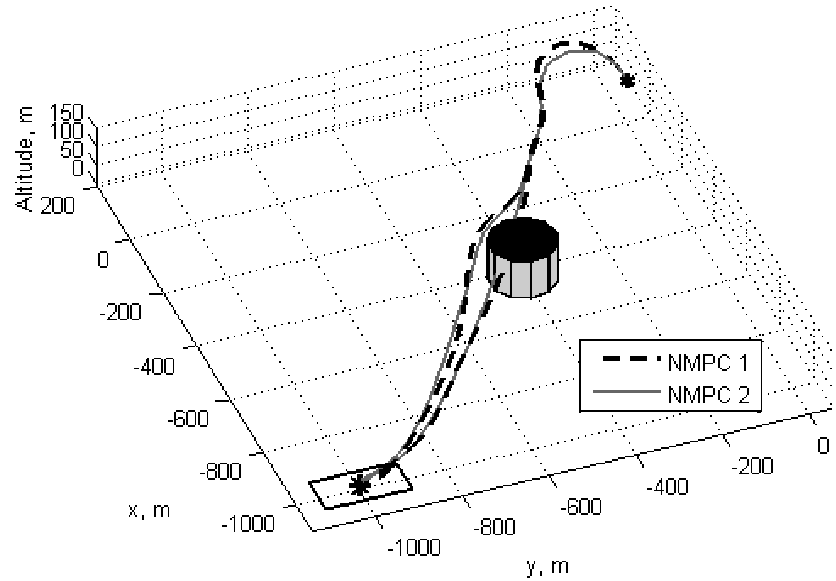
- Examples for transitions



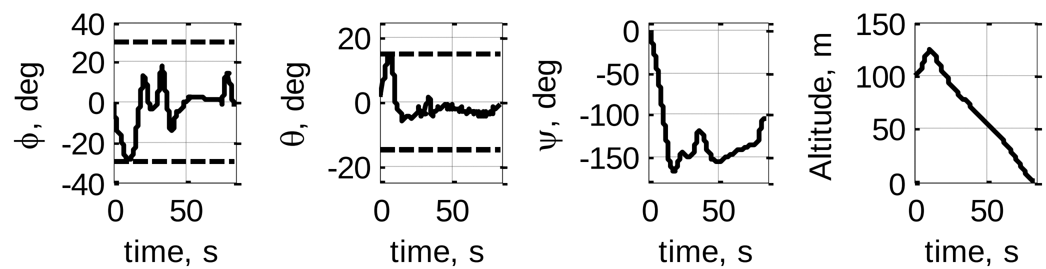
  - difficult to achieve with motion primitives (non-stationary)

Simulation Results (4)

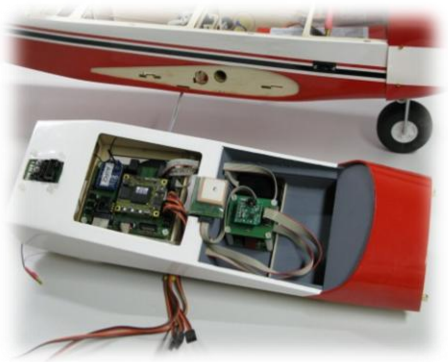
- NMPC1
  - d=3, # of quantized control values
  - n = m = 2
  - $d^{n \cdot m}$ = 81 control options

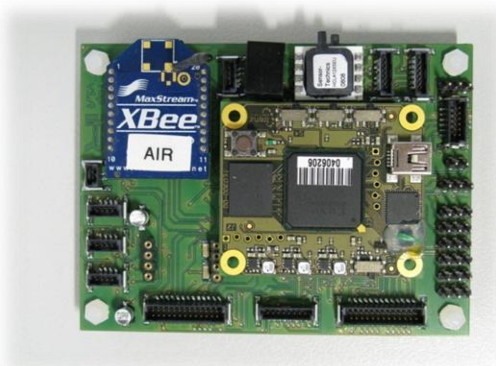


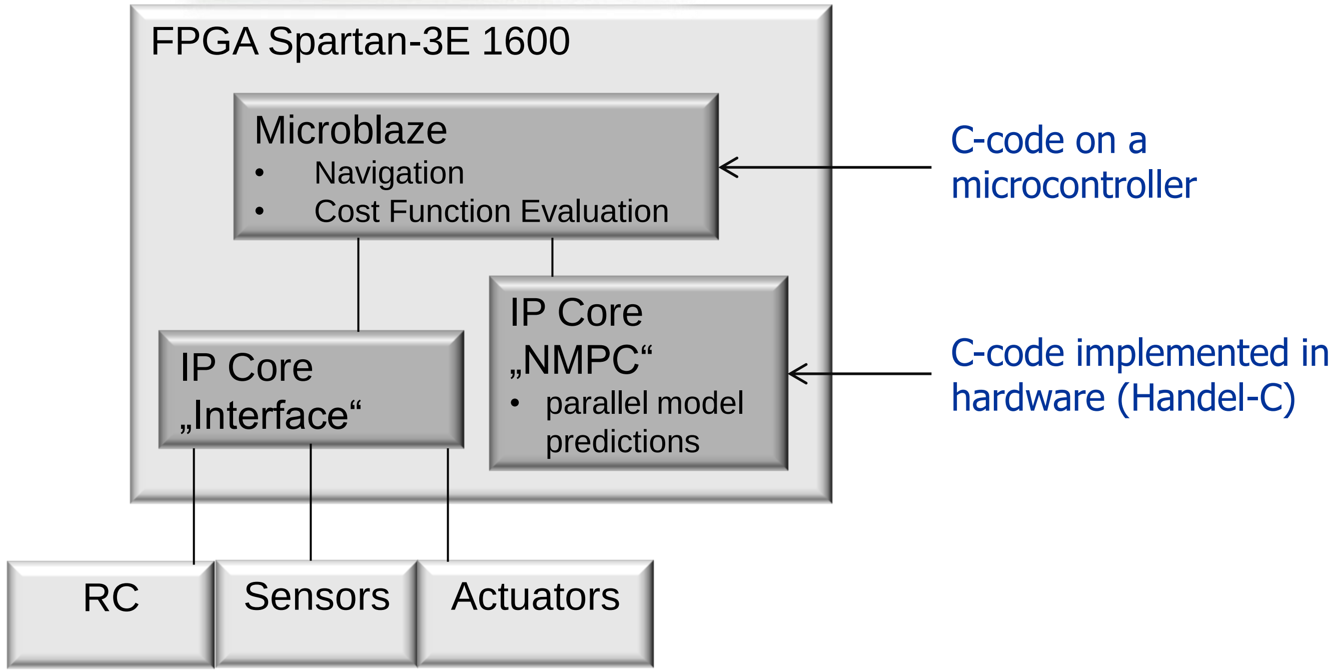
- NMPC2
  - d=9, # of quantized control value
  - n = m = 2
  - $d^{n \cdot m}$ = 6561 control options



Implementation – Use of FPGA







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

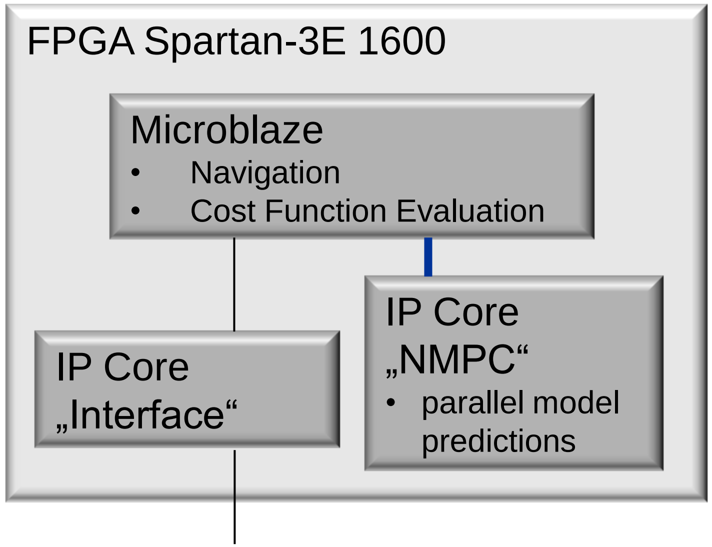
@ 83.33MHz

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 Tp
- 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 multiplicators 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 (avaible now) and 3rd generation (available 2012) boards, improve communication