# $FREE_{sub}NET$ Progress Report Presentation

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# Total progress to date

## Courses attended

- Dynamical Systems and Optimization
- Nonlinear Systems and Control
- Optimization and Algorithms
- Nonlinear Optimization

## Visible results

- 8 IST internal reports
- 1 *FREE*$_{\text{sub}}$*NET* report
- 2 accepted/published conference papers
- 1 more paper almost ready for submission
- 4 *FREE*$_{\text{sub}}$*NET* newsletter contributions

# Past six months

- IST internal report # 6 on path planning
- IST internal report # 7 on state-of-the-art literature
- IST internal report # 8 on path optimization
- Report # 9 on research progress
- 5 seven-day projects on nonlinear optimization
- 1 paper published at Oceans '09
- 1 paper accepted at MCMC 2009
- Secondment of Mernout Burger
- Internship at Naval Postgraduate School (Monterey, CA, USA)

# Thesis outline

**Title: Mission Planning for Multiple Cooperative Robotic Vehicles**

- Multiple vehicle trajectory and path planning under dynamic and environmental constraints
- Adaptive trajectory and path planning in response to on-line measurements and detection of episodic events
- Bridging the gap between theory and practice: applications to cooperative mission planning and mission execution of multiple vehicles at sea

# Path Planning in General

## Describing the paths

Lines-and-arcs, Splines, Dubins Paths, Pythagorean Hodographs, Bézier Curves

## Online Path Generation & Replanning

Replanning Existing Paths, Advance Planning, Path Refinement

## Multiple Vehicle Path Planning Possibilities

Dealing with different sensor/actuator capabilities per vehicle, Paths from Voronoi cells around obstacles, Lyapunov-based optimal solutions

# Path Planning for Marine Vehicles

## Describing the paths

Polynomial-based, metrics for optimal paths

## Optimization Criteria for Multiple Vehicle Missions

High mission performance (maximum survey area covered, maximum amount of data collected), energy minimization, simultaneous arrival

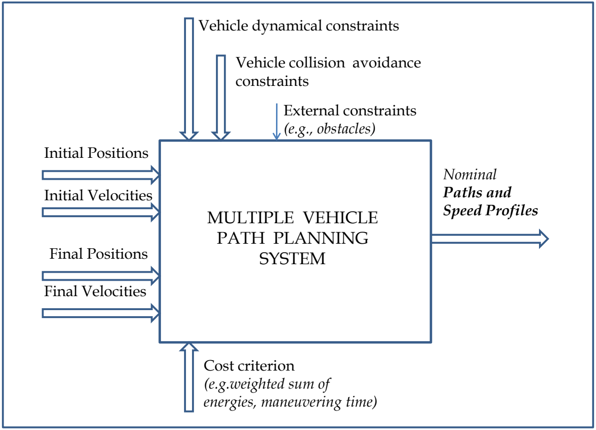
# Our Approach

## 1. Key Contributions

- Polynomial-based path formulation
- Direct search optimization for spatial and temporal deconfliction in 2D and 3D
- Flexibility in number of design variables (easy to select which boundary conditions to fix and which to include in the optimization space)
- Easy to add/remove constraints

# Our Approach

## 2. Problem Constellation



# Our Approach

## 3. Major steps in implementation

- Criterion: applicability in (almost) real time
- Criterion: minimize runtime while increasing cost function complexity
- Constraint: cost function is convex for more problems concerned with more than one path
- Solution: direct search methods
- Problem: how to get constraints into the picture in an expicable way
- Solution: normalization of gains allows for optimal outcomes

# Path polynomials

## Mathematical form

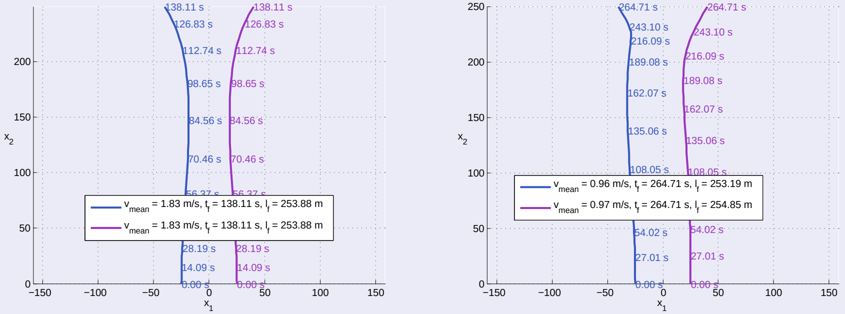
- Single vehicle path $p(\tau) = \left[\, x(\tau) \;\; y(\tau) \;\; z(\tau) \,\right]^{\mathrm{T}}$
- Coordinate polynomial $x_i(\tau) = \sum_{r=0}^{N} a_{x_i,r}\tau^r$
- Coefficients

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 1 & \tau_f & \tau_f^2 & \tau_f^3 & \tau_f^4 & \tau_f^5 \\ 0 & 1 & 2\tau_f & 3\tau_f^2 & 4\tau_f^3 & 5\tau_f^4 \\ 0 & 0 & 2 & 6\tau_f & 12\tau_f^2 & 20\tau_f^3 \end{pmatrix} \cdot \begin{pmatrix} a_{x_i,0} \\ a_{x_i,1} \\ a_{x_i,2} \\ a_{x_i,3} \\ a_{x_i,4} \\ a_{x_i,5} \end{pmatrix} = \begin{pmatrix} x_i(0) \\ x_i'(0) \\ x_i''(0) \\ x_i(\tau_f) \\ x_i'(\tau_f) \\ x_i''(\tau_f) \end{pmatrix}$$

# Path polynomials

## Effects of increasing the polynomials’ degree

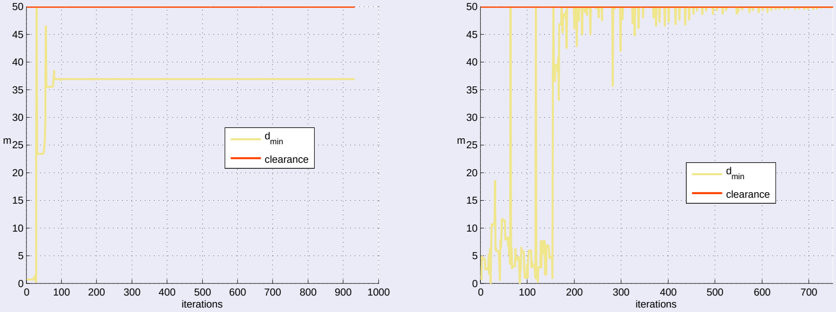
### Path Shapes



# Path polynomials

## Effects of increasing the polynomials' degree

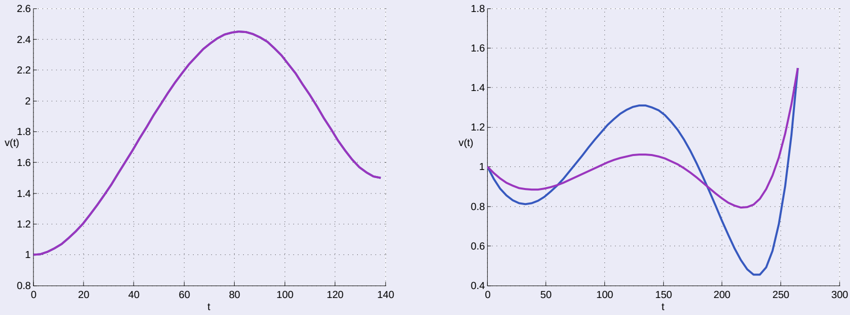
### Spatial Clearance: Development over Optimization Runs



# Path polynomials

## Effects of increasing the polynomials' degree

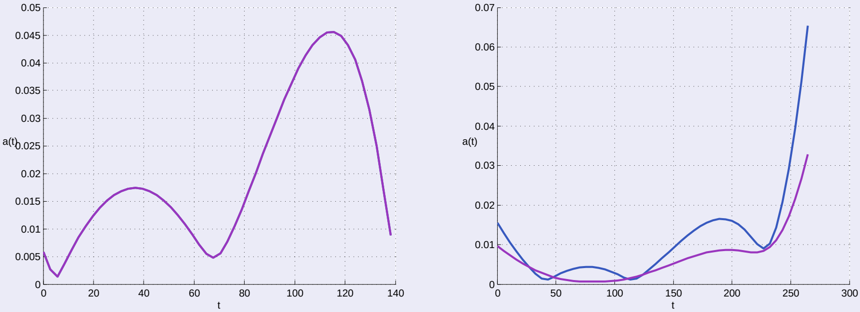
### Velocity Profiles



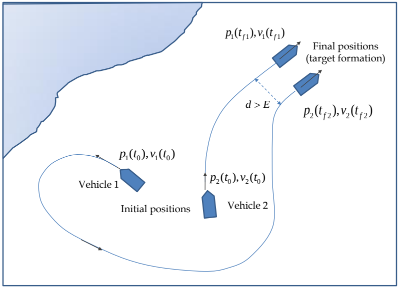
# Path polynomials

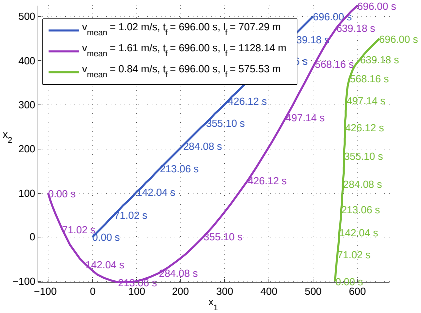
## Effects of increasing the polynomials' degree

### Acceleration Profiles

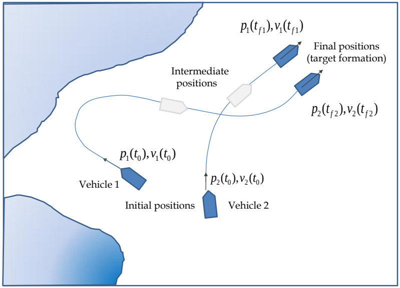


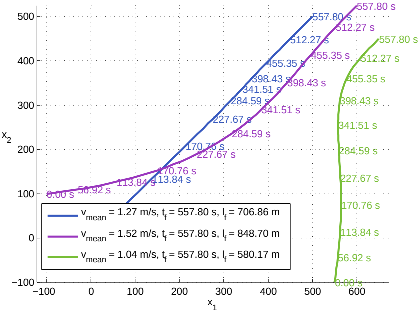
# Spatial deconfliction



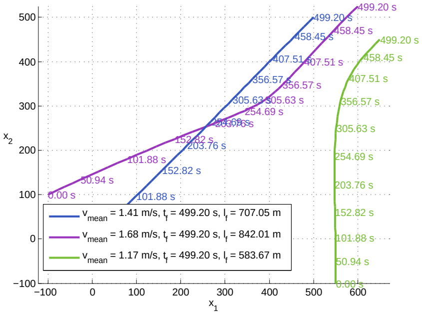



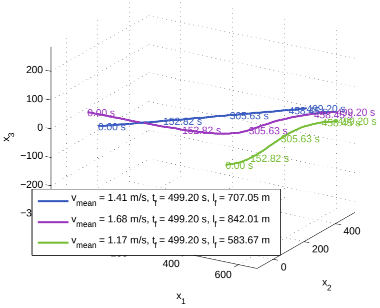
# Temporal Deconfliction



# First results in 3D



# Progress so far

## Theoretical work

- Better understanding of each other's work
- Valuable insight in integration points of both our research topics

## Practical work

- Working on optimization projects
- Collaboration plan for 2nd secondment

⇒ Lesson to be learned, as this was the first *FREE*$_{\text{sub}}$*NET* long-term secondment: during a secondment, reduce number of papers to be worked on and lectures to be attended ⇒ much more time for joint research work!

# Plans for my secondment at NTNU

## Plans for my secondment at NTNU

- Incorporate communication constraints
- Change the algorithm to return functions instead of discretized paths
- Incorporate waiting maneouvres
- Incorporate replanning actions

## General outlook

- Incorporate stationary obstacle avoidance (dynamic obstacles to be taken care off by Mernout)
- Incorporate different dynamic constraints for each vehicle
- Make the discretization steps dependent on curvature to guarantee a certain accuracy

# Publications constituting this report (15 pages total)


- A. J. Häusler, R. Ghabcheloo, I. Kaminer, A. M. Pascoal and A. P. Aguiar.
  *Path Planning for Multiple Marine Vehicles*.
  Oceans '09 IEEE Bremen, Germany. May 2009.

- A. J. Häusler, R. Ghabcheloo, A. M. Pascoal, A. P. Aguiar, I. I. Kaminer and V. N. Dobrokhodov.
  *Temporally and Spatially Deconflicted Path Planning for Multiple Autonomous Marine Vehicles*.
  MCMC 2009, São Paulo, Brazil. September 2009. *To be published.*