Adaptive sampling with a fleet of autonomous sailing boats using artificial potential fields

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Robotic Sailboats

- Growing activity since ~2006

- Main advantage (and drawback):
  - no need to have embedded power for propulsion
  - autonomy: can be fully autonomous during several days

- Applications
  - Ocean's monitoring
  - Surveillance
  - …

Robotic Sailboats

Large(more than 2m) sailing robots


(a)


(b)


(c)

(a) Iboat II, ISAE (b) FASt, University of Porto (c) Pinta, University of Aberystwyth (d) Beagle-B, University of Aberystwyth
(e) ASV Roboat, INNOC (f) Avalon, ETH Zurich (g) VAIMOS from ENSTA and IFREMER


(d)


(e)

(f)

(g)

Robotic Sailboats

Commercial products

(a) Saildrone (USA),
(b) Sailbuoy, Offshore sensing AS (No)
(c) MARS Mayflower Autonomous Research Ship (Project, UK)

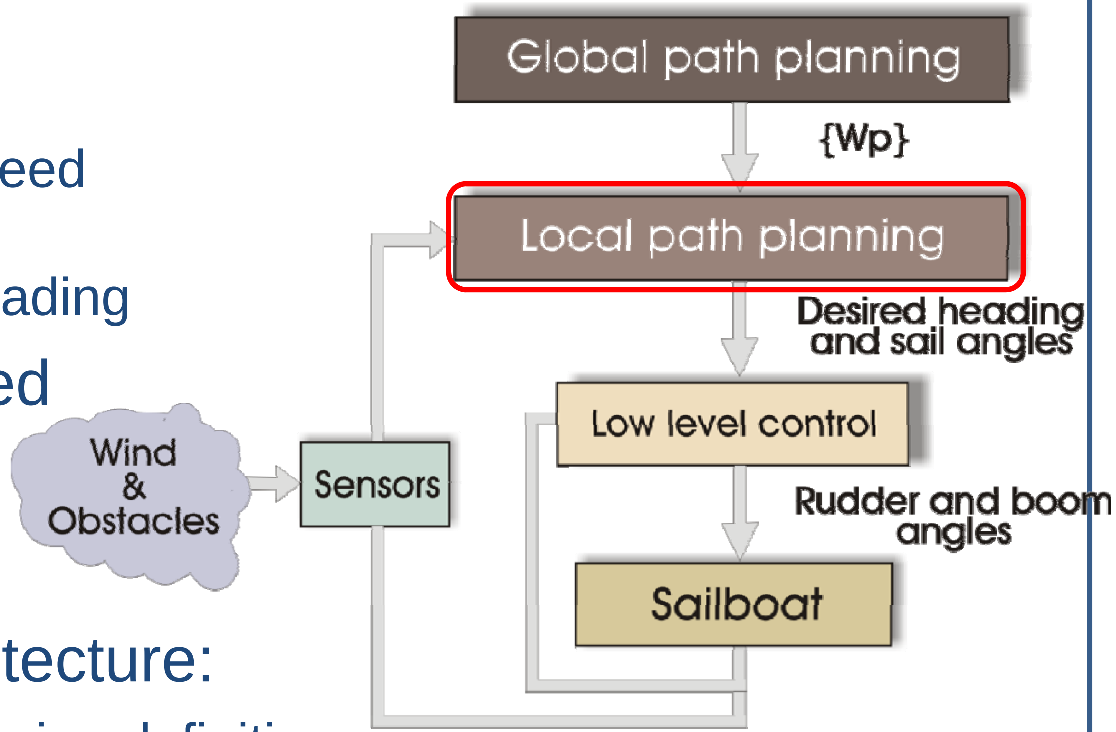
(a)

(b)

(c)

Control architecture

- Control inputs:
  - Sail angle
    - ⇨ mainly acts on speed
  - Rudder angle
    - ⇨ mainly acts on heading
- Hypothesis: uncoupled



- Layered control architecture:
  - High level control: mission definition
  - Mid level control: local (**reactive**) path planning
  - Low level control

Local path planning

Objectives

- Autonomous navigation of a formation of sailboats to perform adaptive sampling (gradient following,…),
- Dynamic adaptation to environmental conditions (wind, current,…)
- Real-time on-board implementation

Solution

- Potential field based path planning method
- Virtual obstacles for no-go zones constraints

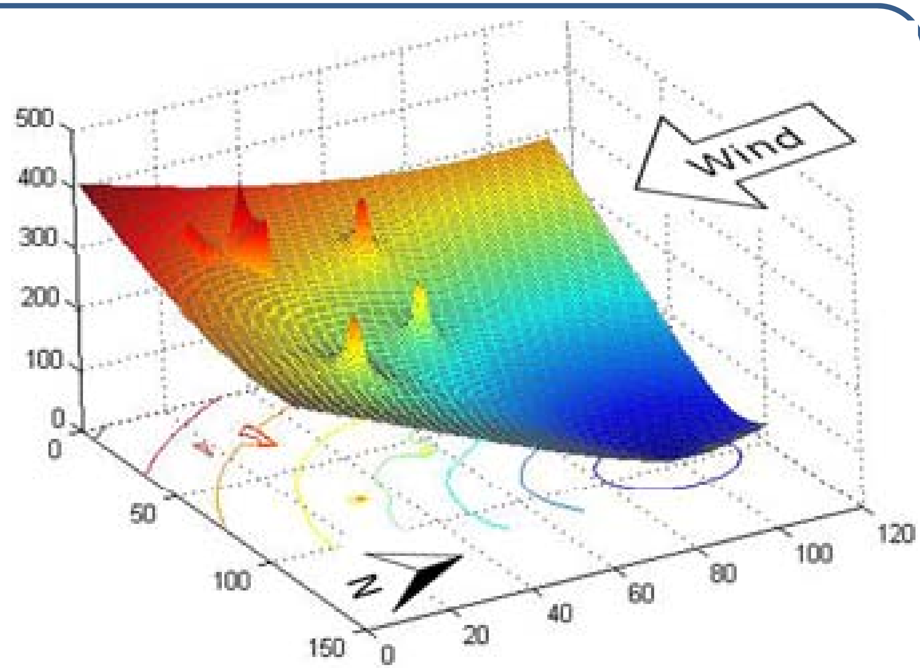
Local path planning

- Use of artificial potential fields method [Khatib87]:
- Principle : $U_t = U_g + \sum U_{ob} + U_{other}$
  - Attractive potential U_g attached to the goal (waypoint)
  - Repulsive potential U_{ob} attached to the obstacles
  - The resulting force (gradient of the potential) drives the robot towards the goal while avoiding obstacles
- Advantages/drawbacks: local
  - Not convenient for dense environment (many obstacles)
  - Can be stuck in local minima
  - **Local** method: numerical evaluation of the gradient in the vicinity of the vehicle
    ⇨ no need to re-compute the entire path in case of **moving** obstacles or goal

Exo-potential

- Attraction to the goal

$$U_g = G_g \, d_g$$



- Repulsion from the obstacles

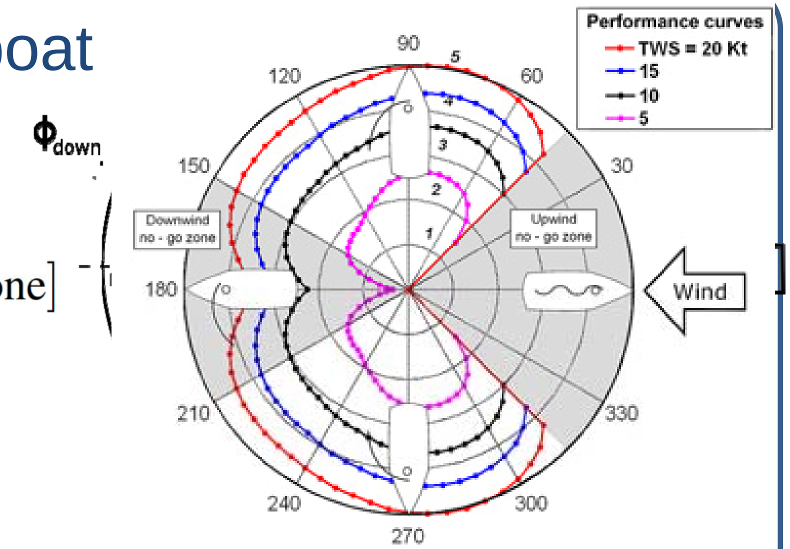
$$U_o^{(j)} = G_o \left(\frac{1}{d_o^{(j)}} - \frac{1}{d_{inf}} \right) + G_L \left(\frac{d_{inf} - d_o^{(j)}}{d_{inf}} \right)$$

$$G_L = G_{off} \left(\mathbf{V}.\mathbf{U} + ||\mathbf{V}|| \right)$$

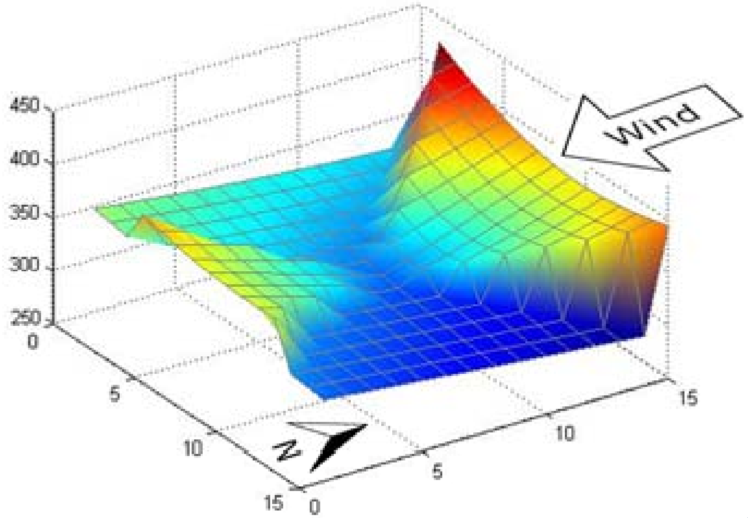
Endo-potential

- Virtual obstacle, moving with the boat
  - ⇨ Encompass the specific kinematic of the sailboat (speed polar diagram)

$$U_w = \begin{cases} P_{ngz} & \text{if } \phi \in [\text{no-go zone}] \\ P_h + G_v \dfrac{V - V_{max}}{V_{max}} & \text{otherwise} \end{cases}$$

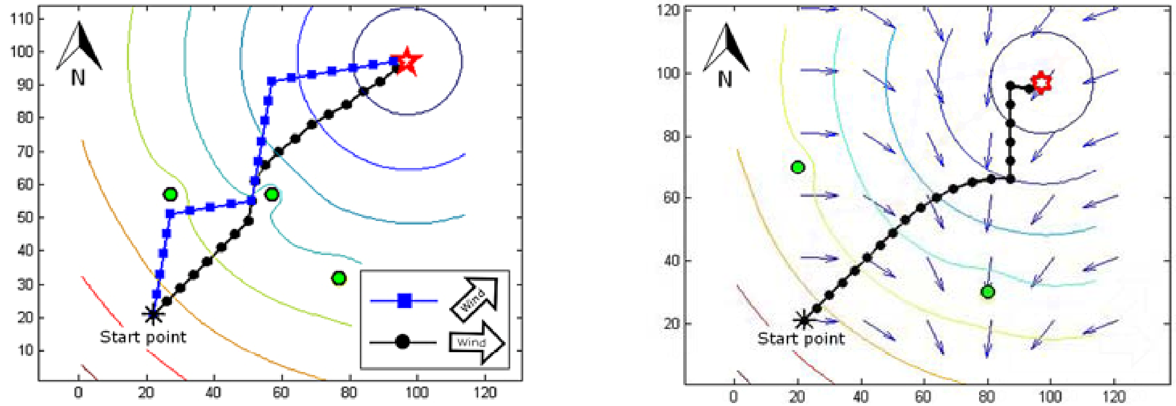


- P_h: hysteresis potential to fit the cost of tack and gybe manoeuvers

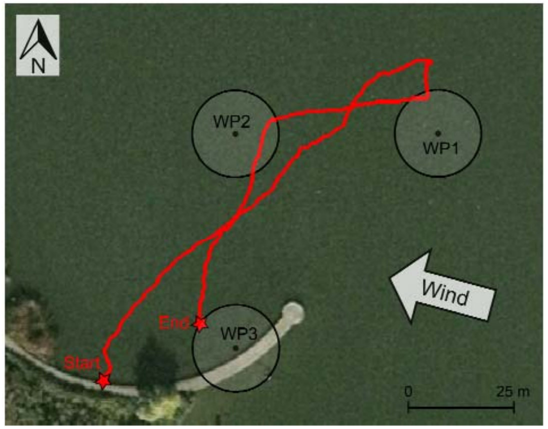


Local path planning

- Classical method: goal = waypoint



Simulation results



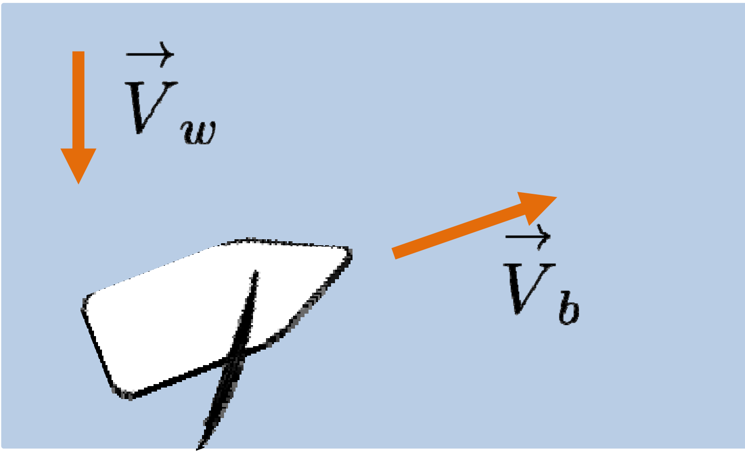
Field trials(Tiny-Sailboat)

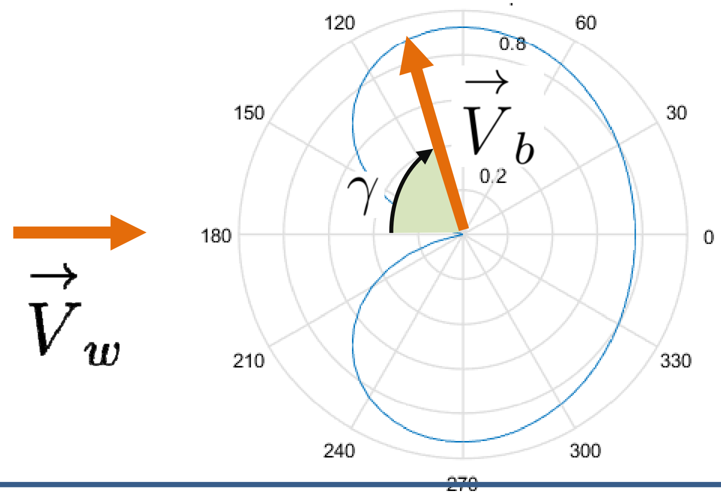
Field trials (Large-Sailboat)

Marine current

- Objective: taking into account the marine current in the local planning
  ⇨ modify the speed polar diagram
- Hyp.: known current
- Rem. speed polar diagram:

$$\vec{V}_b = P\left(\vec{V}_w, \gamma\right)$$

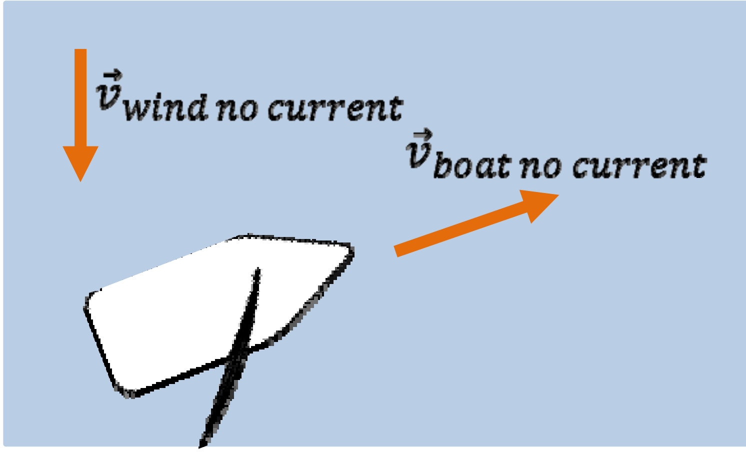




Marine current

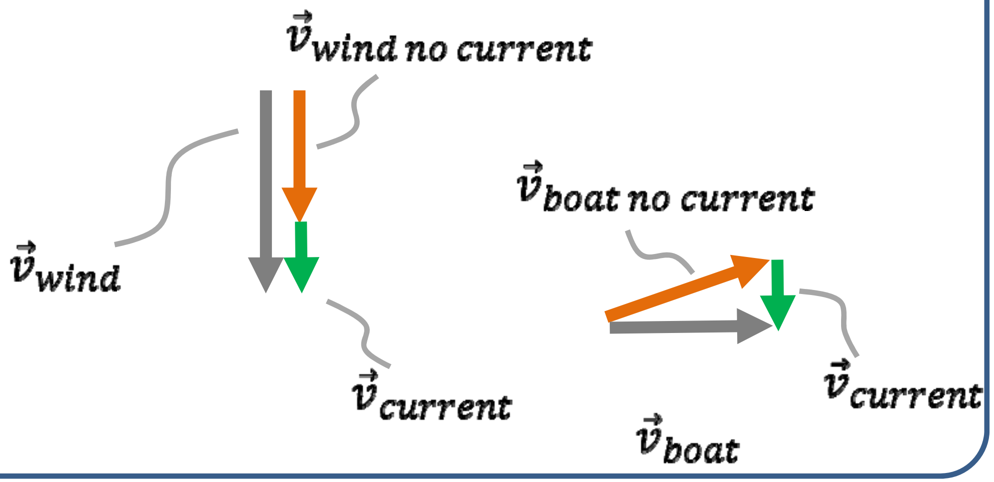
- In other words:

$$\vec{V}^{I}_{b} = \vec{V}^{C}_{b} + \vec{V}^{I}_{c} \quad \text{and} \quad \vec{V}^{I}_{w} = \vec{V}^{C}_{w} + \vec{V}^{I}_{c}$$



- Speed polar diagram remains usable if both vectors are in the same frame:

$$\begin{aligned}\vec{V}^{I}_{b} &= \vec{V}^{C}_{b} + \vec{V}^{I}_{c} \\ &= P\left(\vec{V}^{C}_{w}, \gamma\right) + \vec{V}^{I}_{c} \\ &= P\left(\vec{V}^{I}_{w} - \vec{V}^{I}_{c}, \gamma\right) + \vec{V}^{I}_{c}\end{aligned}$$

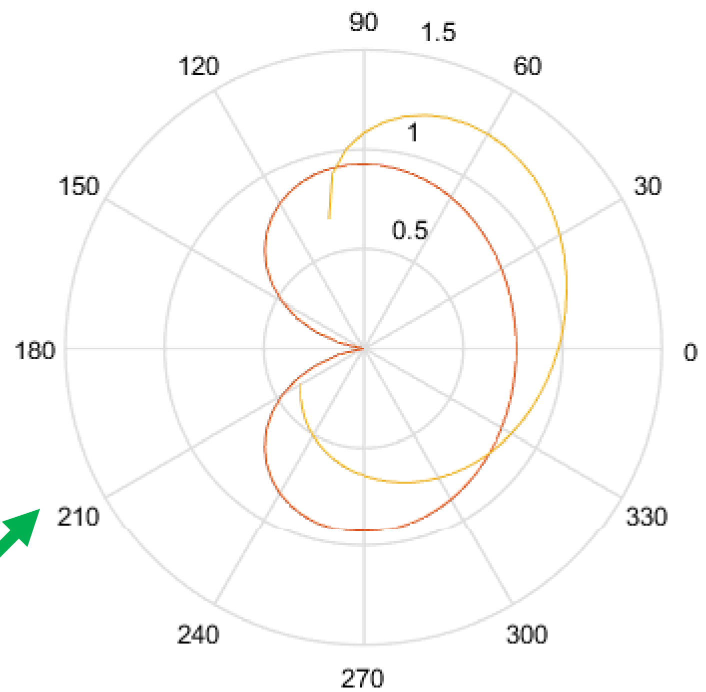


Marine current

- Effects of marine current on the speed polar diagram
  - Translation
  - Distortion

$$\vec{V}_w = \begin{bmatrix} 2 \\ 0 \end{bmatrix}$$

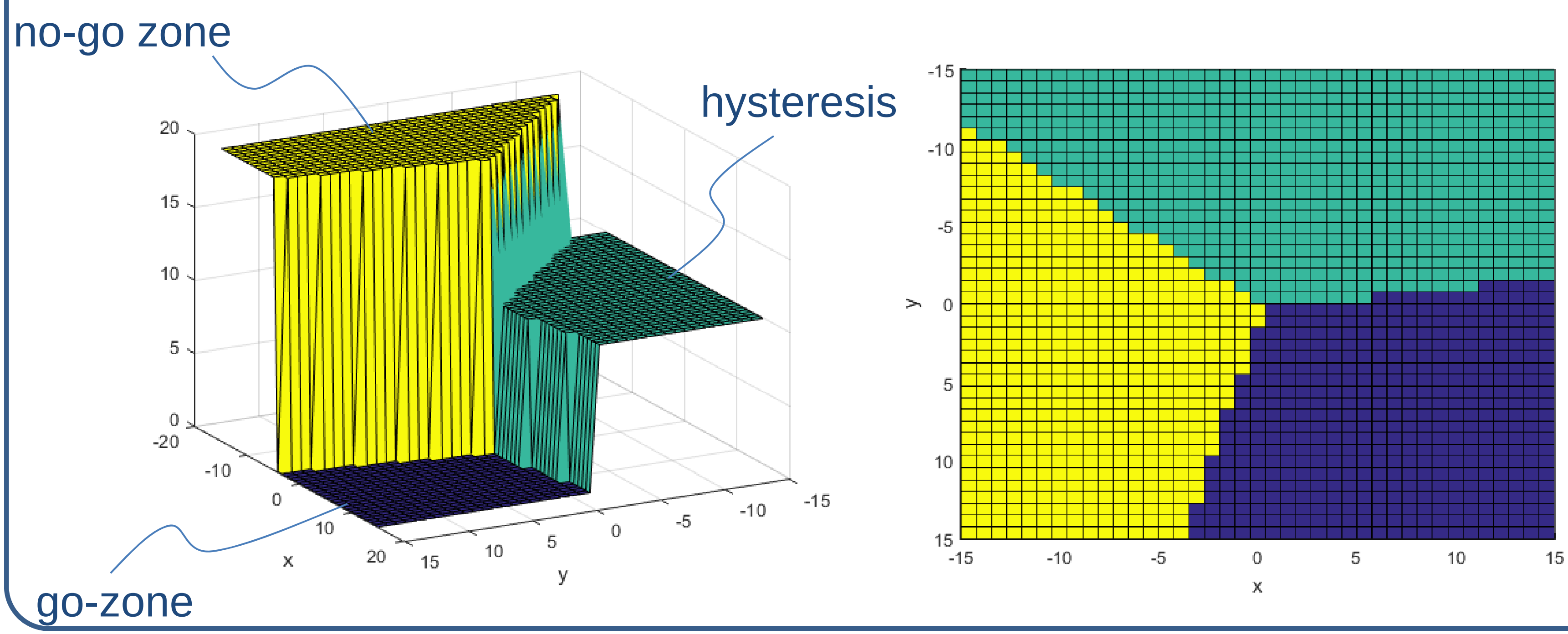
$$\vec{V}_c = \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}$$



Marine current

- Wind and current potential fields (endo-potentials)

$$\vec{V}_w = \begin{bmatrix} 2 \\ 0 \end{bmatrix} \qquad \vec{V}_c = \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}$$



Marine current

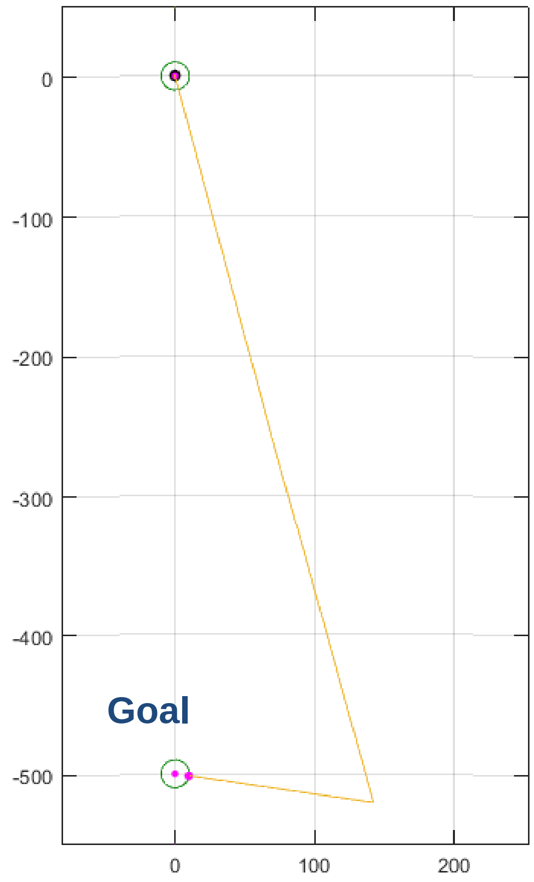
- Simulation results

$$\vec{V}_w = \begin{bmatrix} 0 \\ -4 \end{bmatrix}$$

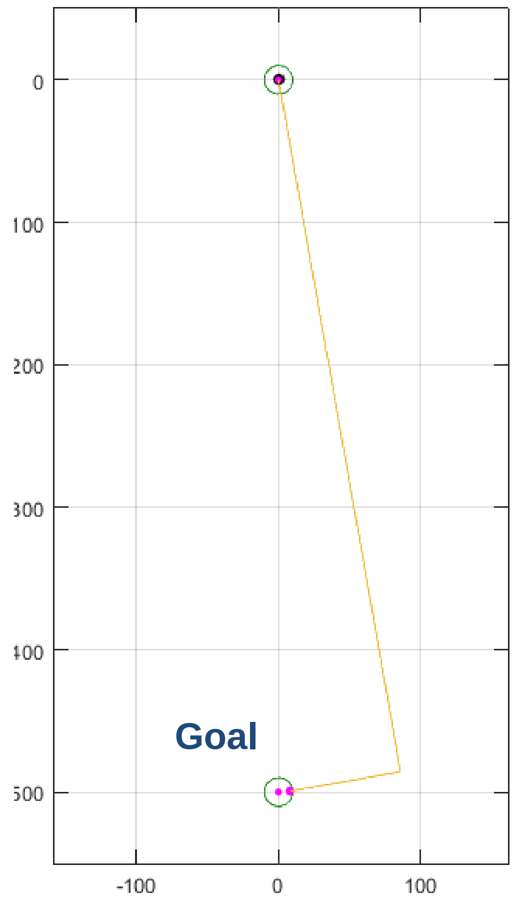
$$\vec{V}_c = \begin{bmatrix} -0.5 \\ 0 \end{bmatrix}$$

- Cruising time:
  - classic PF: 10.8 s
  - adapted PF: 9.1 s

Classic PF

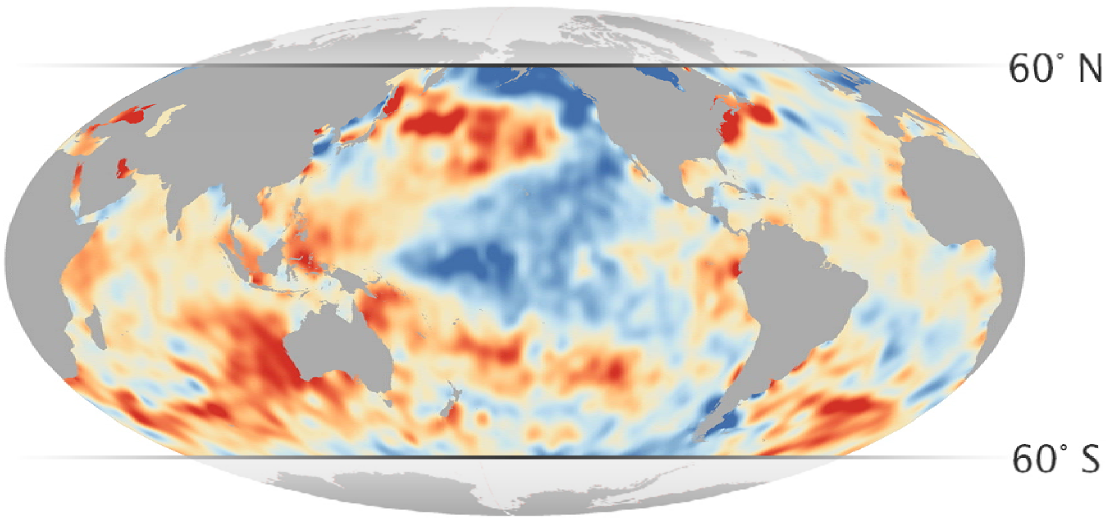


Adapted PF



Formation control

- Motivation: adaptive sampling of the oceans
  ⇨ following a front or an eddy of some natural field (temperature, salinity, …)



- Move a formation of sailboats in the direction defined by the gradient of the natural field

Formation control

- Following a natural gradient fits well within the general framework of the local path planning using (artificial) Potential Fields.

- Remember that PF planning is a **local** method:

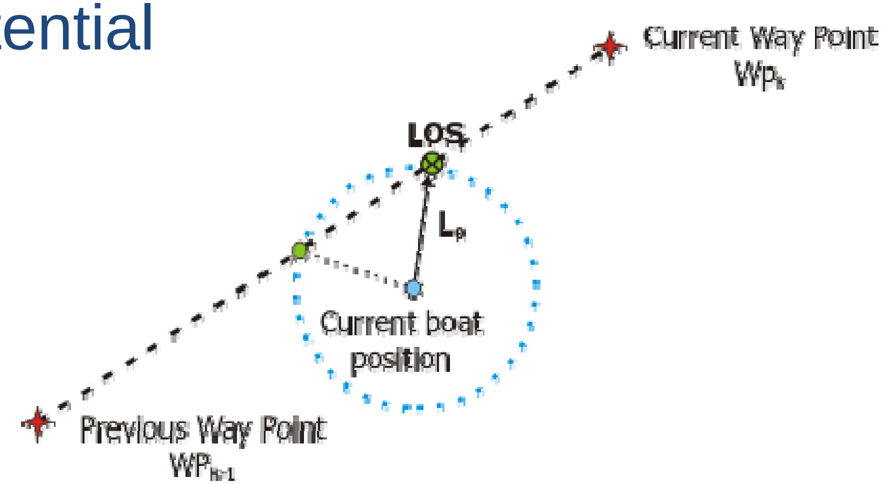
  Local method: numerical evaluation of the gradient in the vicinity of the vehicle
  ⇨ no need to re-compute the entire path in case of **moving** goal

- Previous work: use of a moving goal for line following with a sailboat

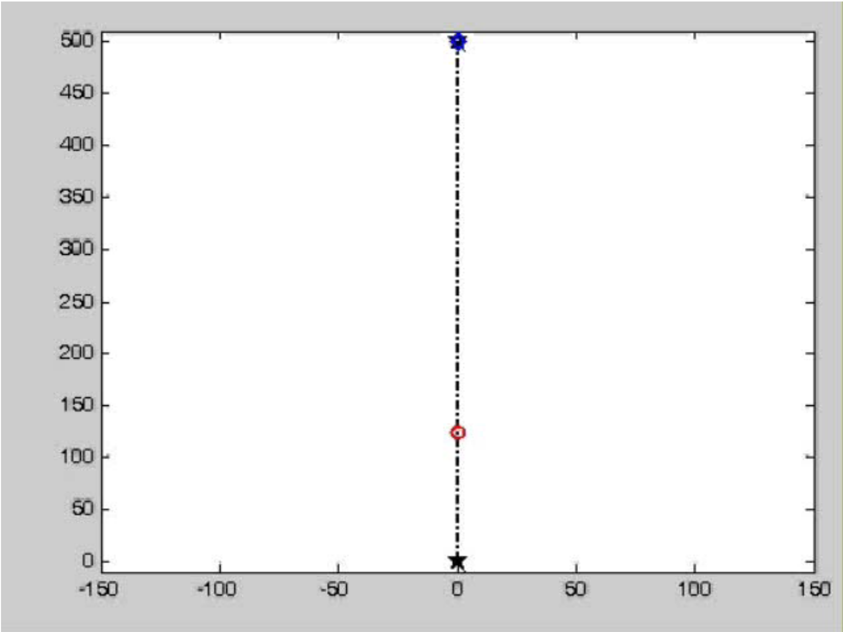
Example: line following between WP

- Basic idea:
  - the donkey follows the carrot,
  - the carrot follows the line.

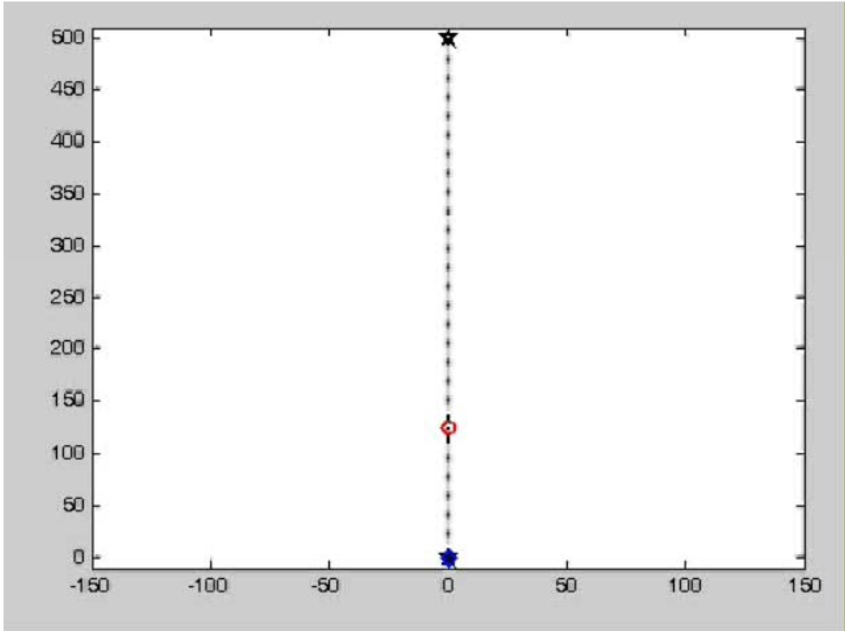
- Easily done by defining the goal as a moving Line of Sight (LOS) Point
  ⇨ moving attractive potential



Line following : Simulation results



Way point guidance



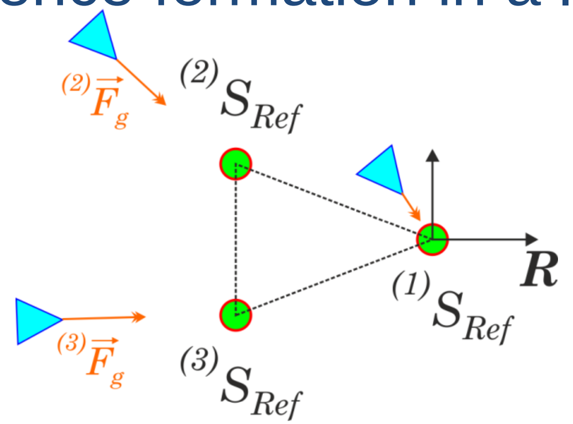
LoS line following

Guaranteed accuracy: less than the LoS length

Formation control

- Define a rigid reference formation in a local frame $\boldsymbol{R}$

Example with a triangular formation



- Each real vehicle is "linked" to its ref. vehicle in the formation
  - For each real vehicle, the resulting force is:

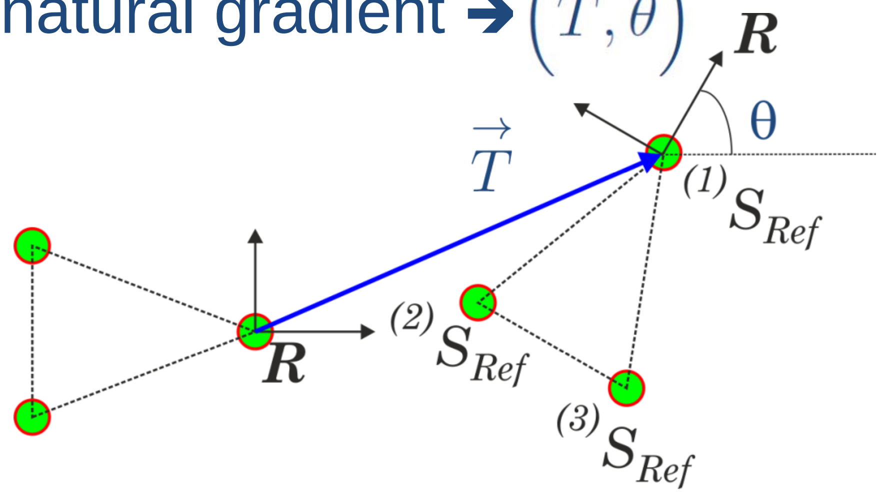
$$ {}^{(i)}\vec{F} = \overrightarrow{grad}\left({}^{(i)}U\right) = {}^{(i)}\vec{F}_g + {}^{(i)}\vec{F}_o + {}^{(i)}\vec{F}_w $$

Including marine current

with ${}^{(i)}\vec{F}_g$ = attractive force coming from the (i) ref. vehicle

Formation control

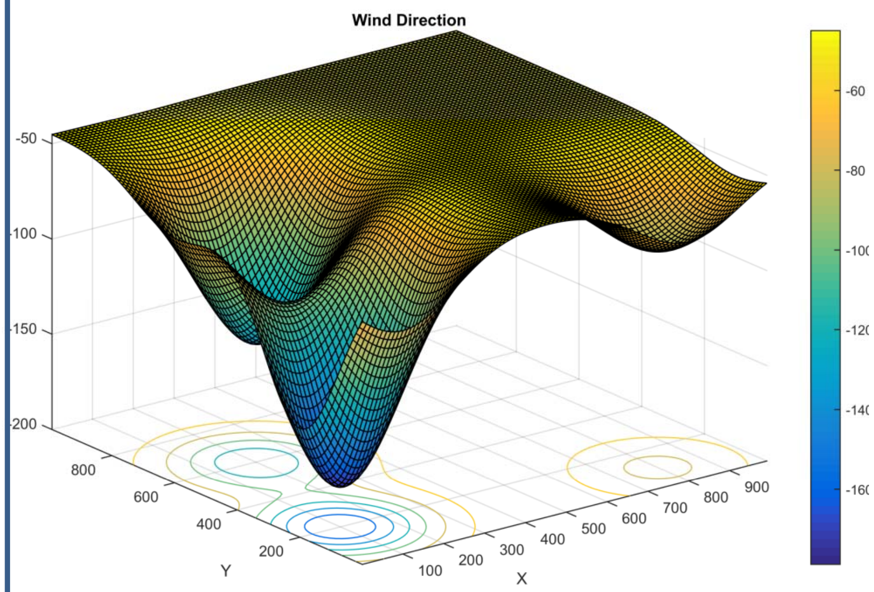
- Drives the reference formation towards the goal (WP) or to follow some natural gradient ➔ $\left(\vec{T}, \theta\right)$



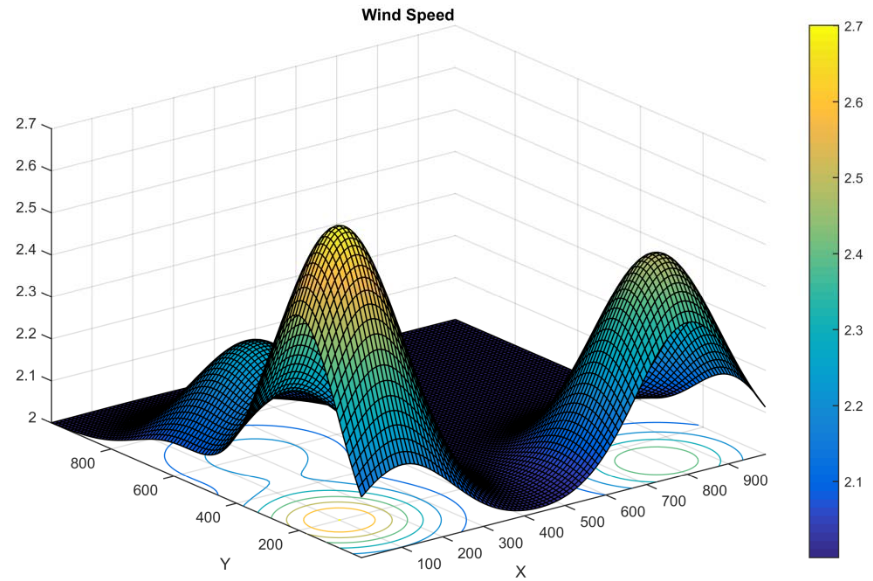
Choice of $\left(\vec{T}, \theta\right)$

- *Translation : cruise control* $\left|\vec{T}\right| = V_{max}dt - K_v\,\overline{dist}$
- *Rotation: arbitrary*
  - *$\theta = 0$: orientation remains constant in a fixed frame*
  - *θ such that* $\overrightarrow{^{(2)}S_{Ref}\,^{(3)}S_{Ref}} \perp \vec{T}$ *: formation is pointing toward the goal*

- Simulation : reaching a way point (varying wind field)



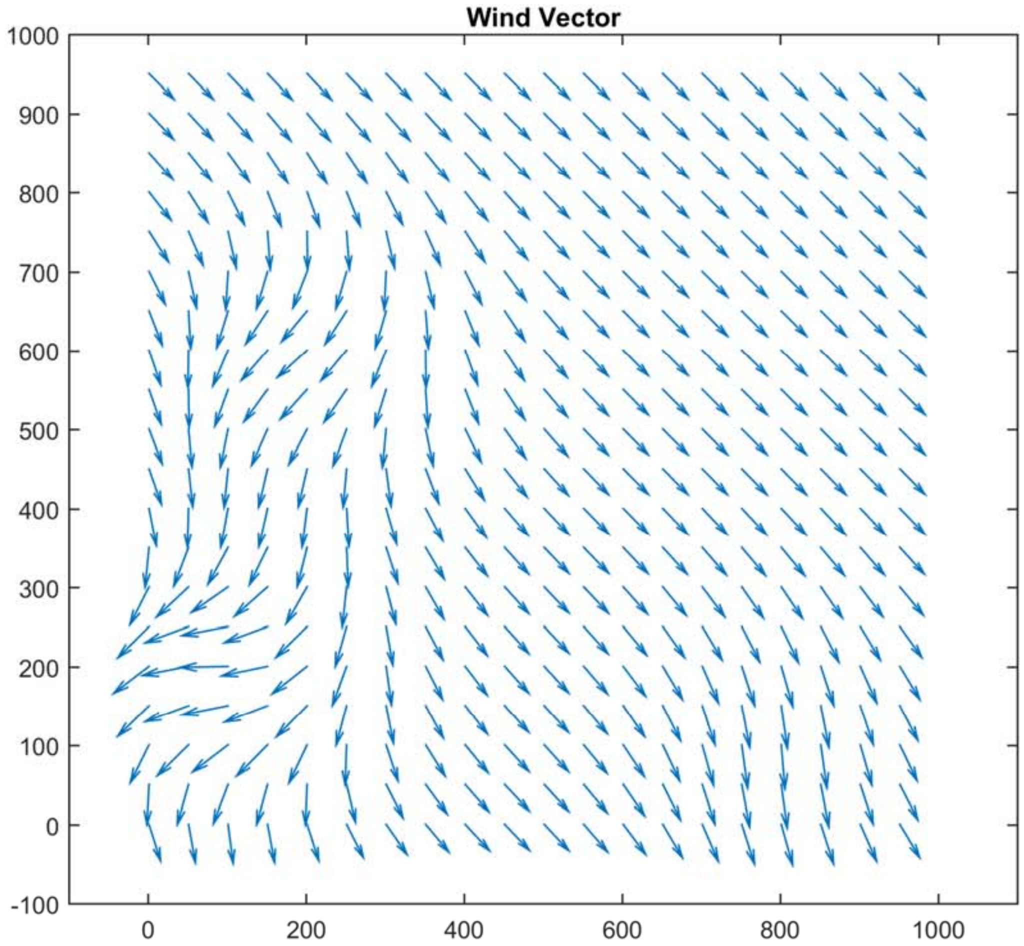
Wind angle



Wind speed

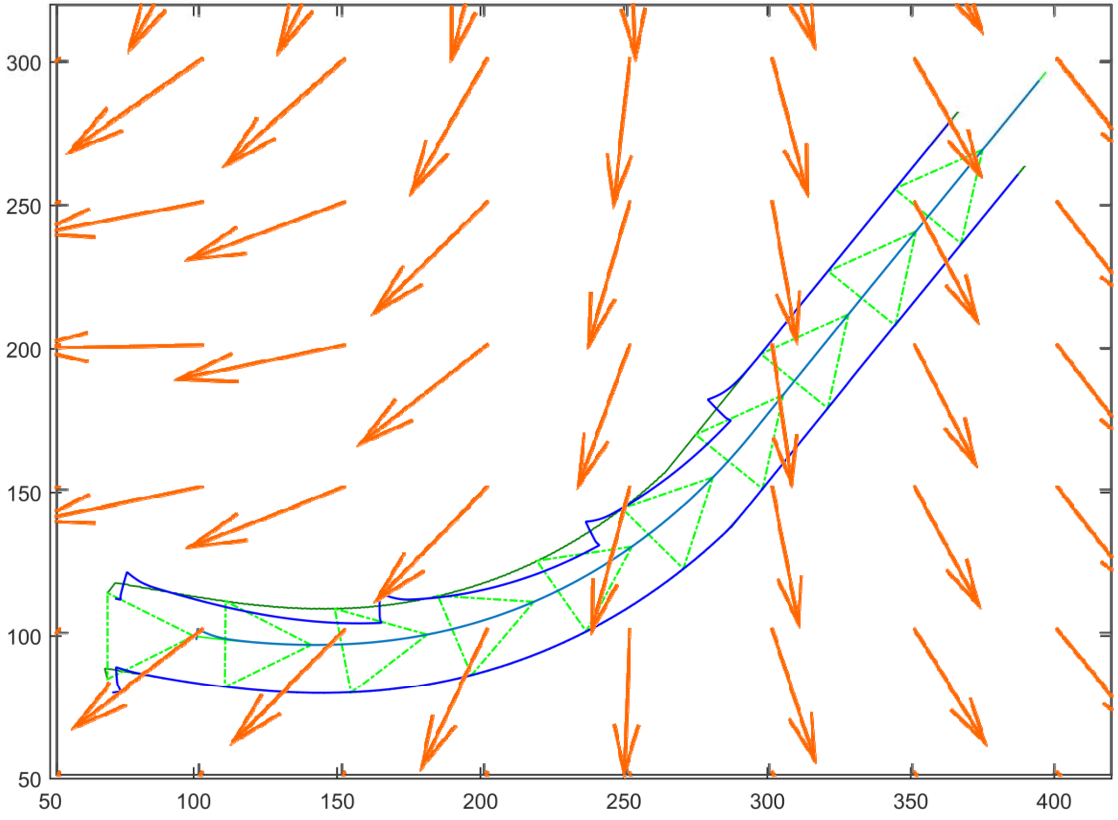
Formation control

- Simulation : reaching a way point (varying wind field)



Formation control

- Simulation : reaching a way point (varying wind field)

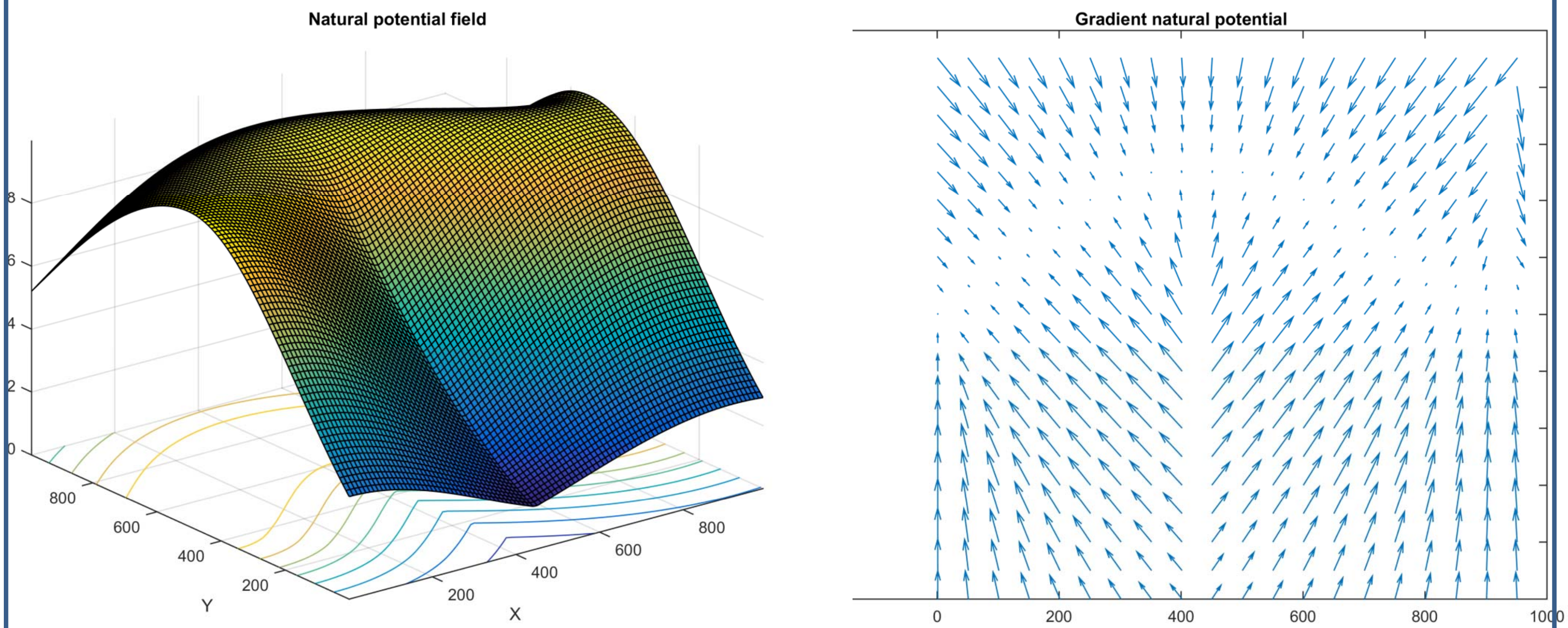


Leader-Follower formation

PF planning applied to the ref. Leader

Formation control

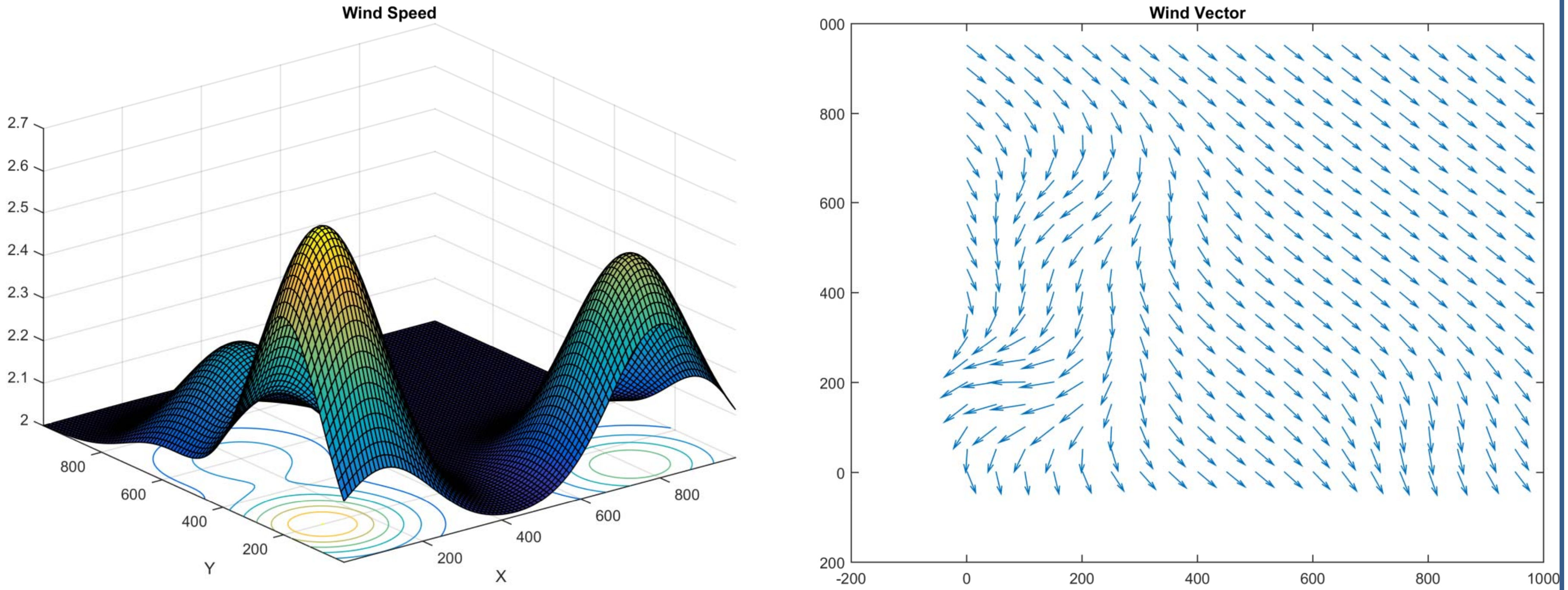
- Simulation : following a natural field gradient (varying wind field)



Natural potential field

Formation control

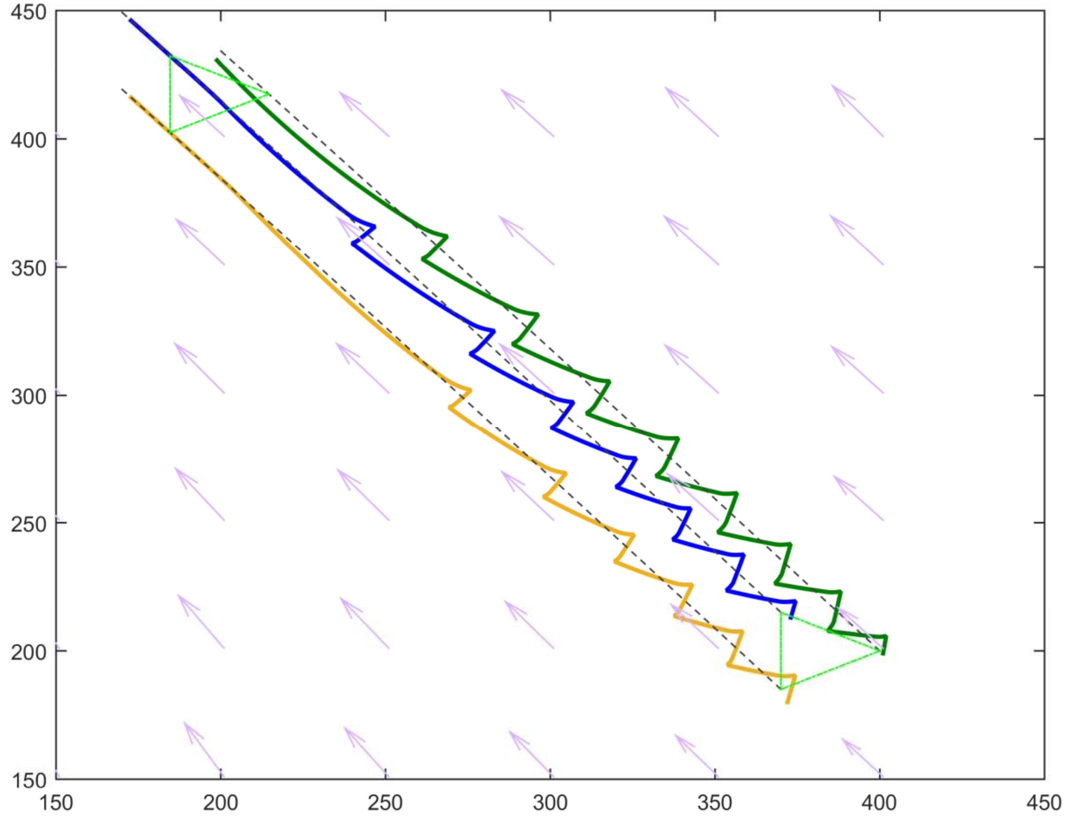
- Simulation : following a natural field gradient (varying wind field)



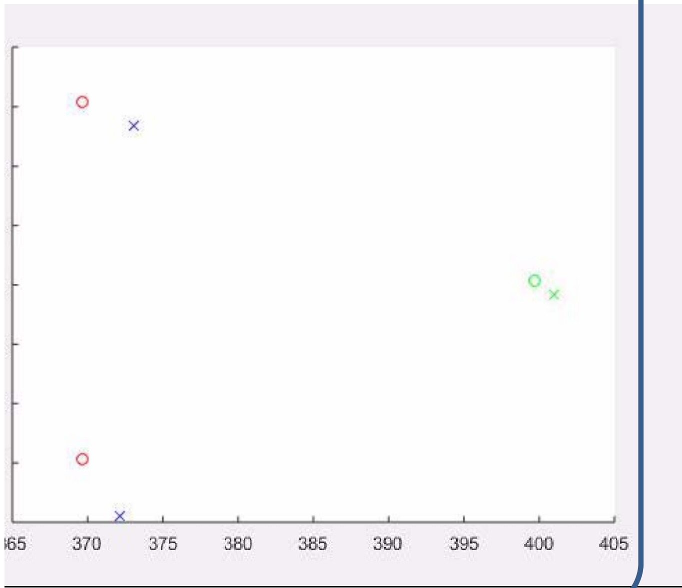
Wind field

Formation control

- Simulation : following a natural field gradient (varying wind field)

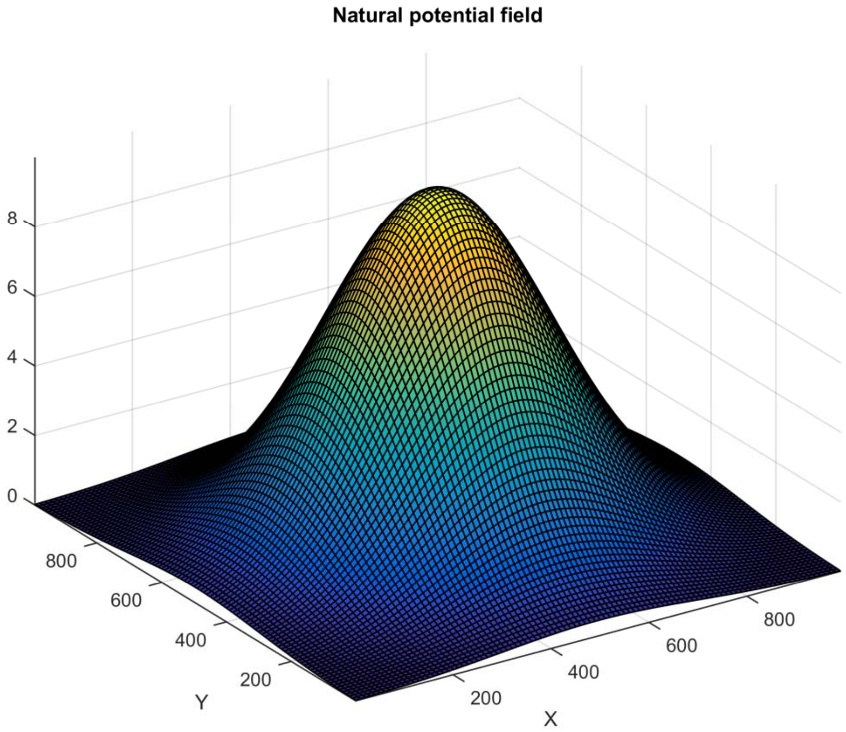


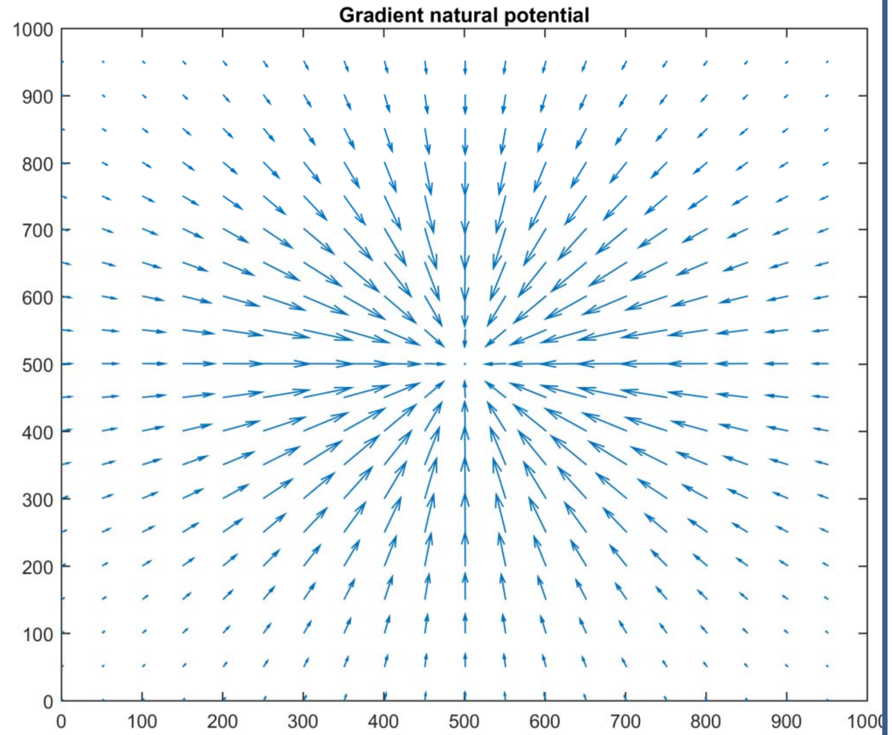
PF planning **not** applied to the ref. formation
Constant orientation in a fixed frame



Formation control

- Simulation : following a natural field gradient then follow an isoline (varying wind field)

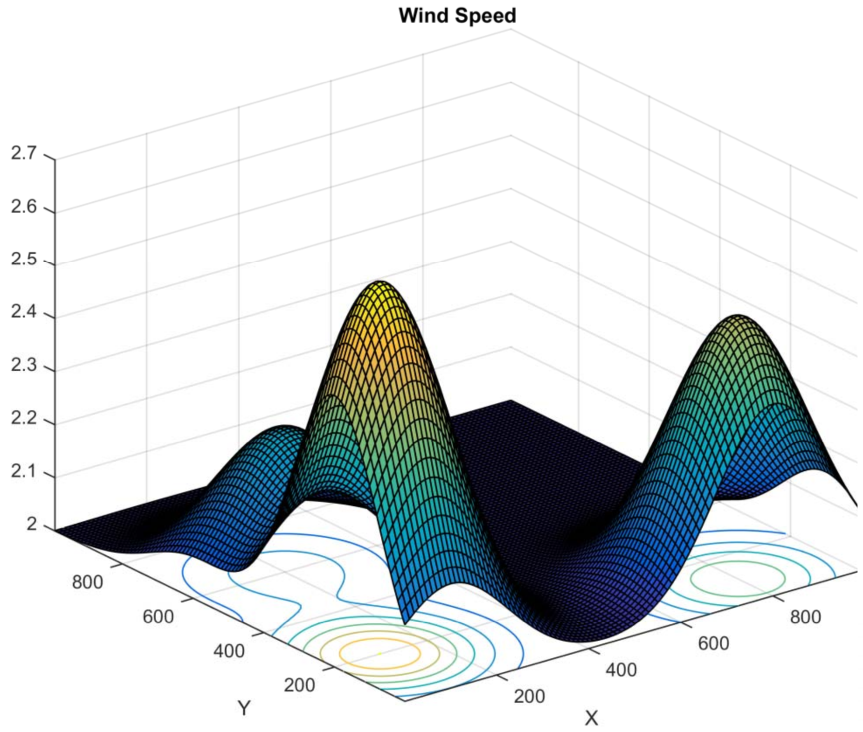


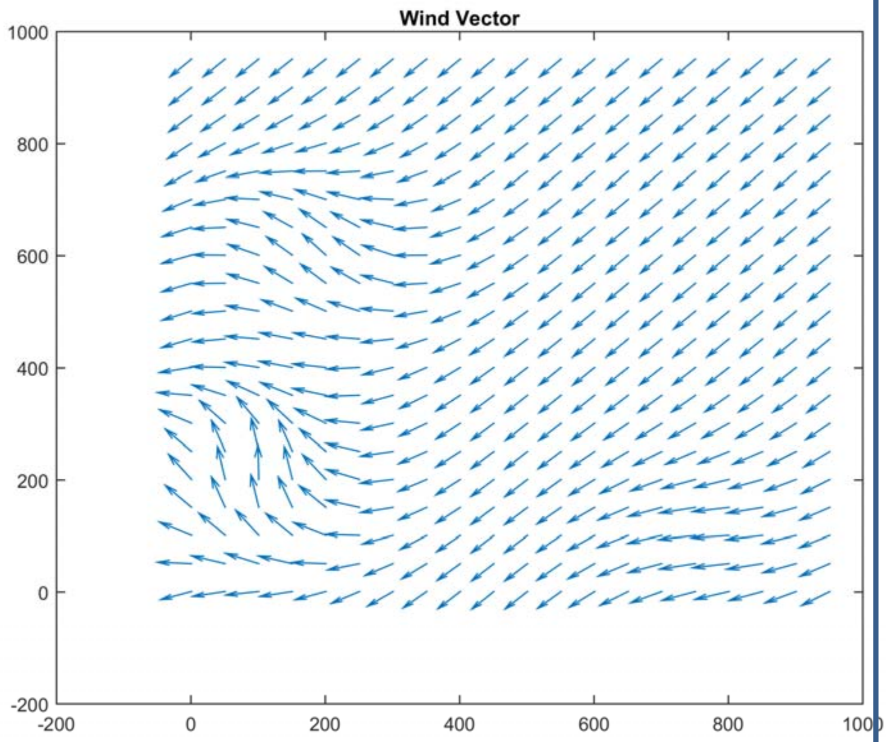


Natural potential field

Formation control

- Simulation : following a natural field gradient then follow an isoline (varying wind field)

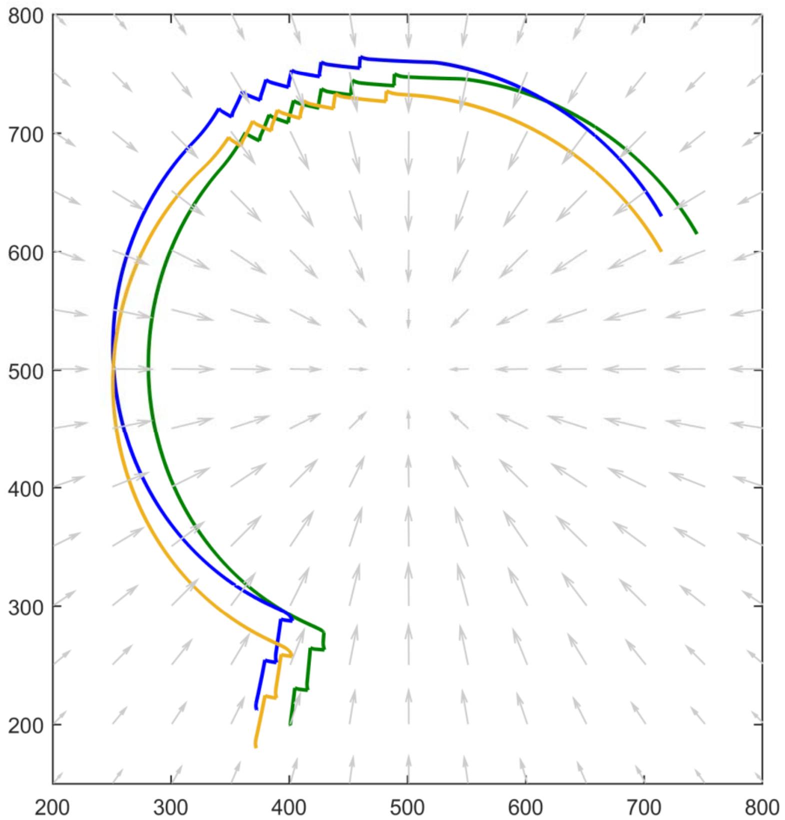




Wind field

Formation control

- Simulation : following a natural field gradient then follow an isoline (varying wind field)



PF planning **not** applied to the ref. formation
Constant orientation in a fixed frame

Conclusion

Formation control of sailboats for adaptive sampling

⇨ different features (Way point reaching, gradient or isoline following)

Includes wind and marine current

Light code

⇨ Easy on-board implementation