Sailing Adaptation:

Merging Physics and Data for an Energy-Efficient Shipping

E. Witrant, UGA – M1 EECS, Jan. 6th, 2026

Infinity *research team*

=> *New methods for modeling, estimation, and control of infinite-dimensional systems*

- **Data assimilation and inverse problems** for infinite-dimensional dynamics (IDD) : system identification / machine learning for PDEs provide optimal sensor placement and real-time models ;
- **Observation and estimation**: regardless of instrumentation, only sparse data are available to reconstruct IDD, to design virtual sensors;
- **Feedback Control Design**: the synthesis of control laws for IDD remains a largely open problem, especially when considering coupled and/or nonlinear PDE systems : allow for physics-based controller that easily addapt to various processes ;
- **Tackling new problems in physics**: our methods are motivated by and validated on practical problems with high societal impact involving IDD. E.g. thermonuclear fusion, thermal engines, minings and buildings ventilation systems, COVID, risk management, glaciology and climate change...

Initial Motivation (1)

VOILES et voiliers

Northpower : rotor sails

Yara Marine Technologies : hard sails

Michelin WISAMO : inflatable sails

Initial Motivation (2)

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Modeling and Nonlinear Heading Control of Sailing Yachts

Lin Xiao and Jerome Jouffroy

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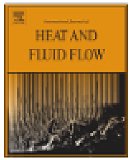


Upwind sail aerodynamics: A RANS numerical investigation validated with wind tunnel pressure measurements

I.M. Viola [a,*], P. Bot [b], M. Riotte [a]

Optimized Trajectory Planning for USVs Under Ocean Currents

Behzad Akbari, *Member, IEEE*, Ya-Jun Pan, *Senior Member, IEEE*, Shiwei Liu, and Tianye Wang

Sabbatical project (2 years)

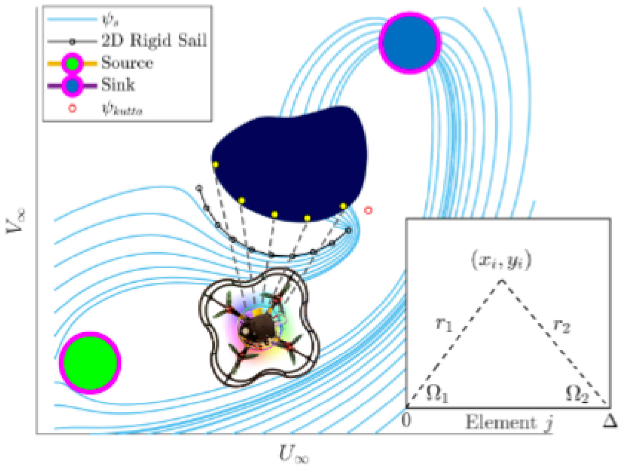
Sailing Adaptation: Towards Energy-Efficient Shipping with Adaptive and Optimal Control

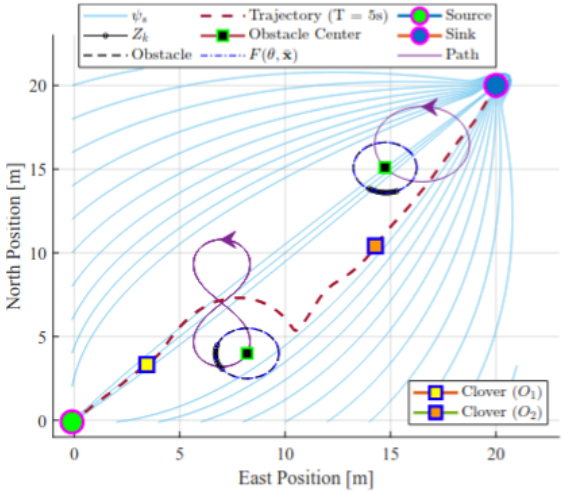
- use of wind energy and sail-assisted cargo ships can be a potential solution for sustainable and efficient shipping
- design feedback control methods for sailing adaptation according to information provided by different proxies :
  - adaptation of the sail and rudder operation according to local wind and waves conditions
  - autonomous surface vehicles (ASVs) need an intelligent guidance, navigation and control (GNC) unit to have a safe navigation with hybrid path planning, obstacle avoidance, intelligent robust and optimal control with respect to wave, current and wind in harsh marine environment.

Some first results

S. Smith, J. Wu, Y.-J. Pan, E. Witrant

- Potential function based navigation : avoid moving obstacles in 3D





Stream Function Navigation in Inviscid Flow with Higher-Order Control Barrier Function Based Model Predictive Control for Quadcopter Obstacle Avoidance, Sean Smith, E. Witrant, Y.-J. Pan.

High-Precision Heading Control of an Autonomous Sailboat: a Robust Nonlinear Approach, S. Smith, E. Witrant, Y.-J. Pan, OCEANS 24

- non-singular fast terminal conditioned super-twisting sliding mode (NFT-CSTSM) controller with adaptive gains.
- Lift and drag from thin airfoil theory
- fast and robust convergence in the presence of bounded disturbances and system uncertainty
- conditioning integrated into the super-twisting algorithm to offset limited control actuation and the windup effect
- stability proof conducted for the adaptive NFT-CSTSM controller and unknown system dynamics estimator system (Lyapunov with Lebesgue-measurable noise)

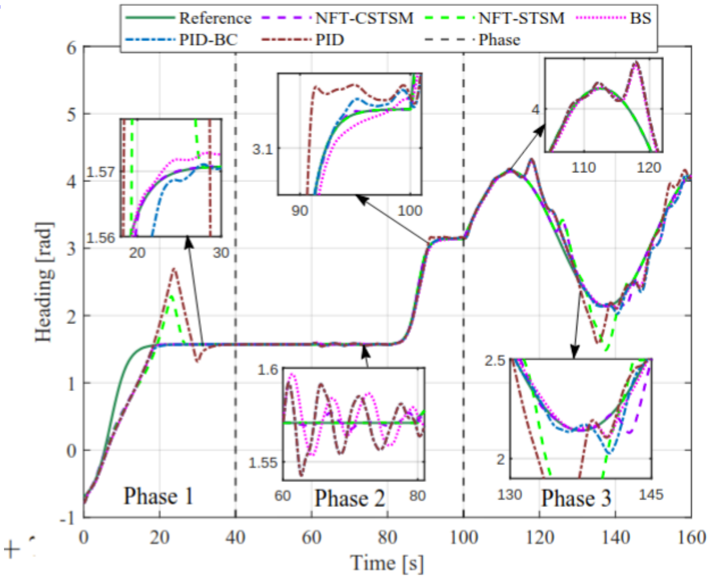


Fig. 2. Multi-Phase simulation heading response profiles under various conditions: Phase 1) Tacking maneuver in calm water conditions; Phase 2) Constant heading reference while introducing rough water conditions at $t = 60$ s; Phase 3) Jibing maneuvers in rough water conditions.

Optimization of Sail Angle

Junzhuo Wu, Y.-J. Pan, C. Shen, S. Smith, and E. Witrant, OCEANS 24

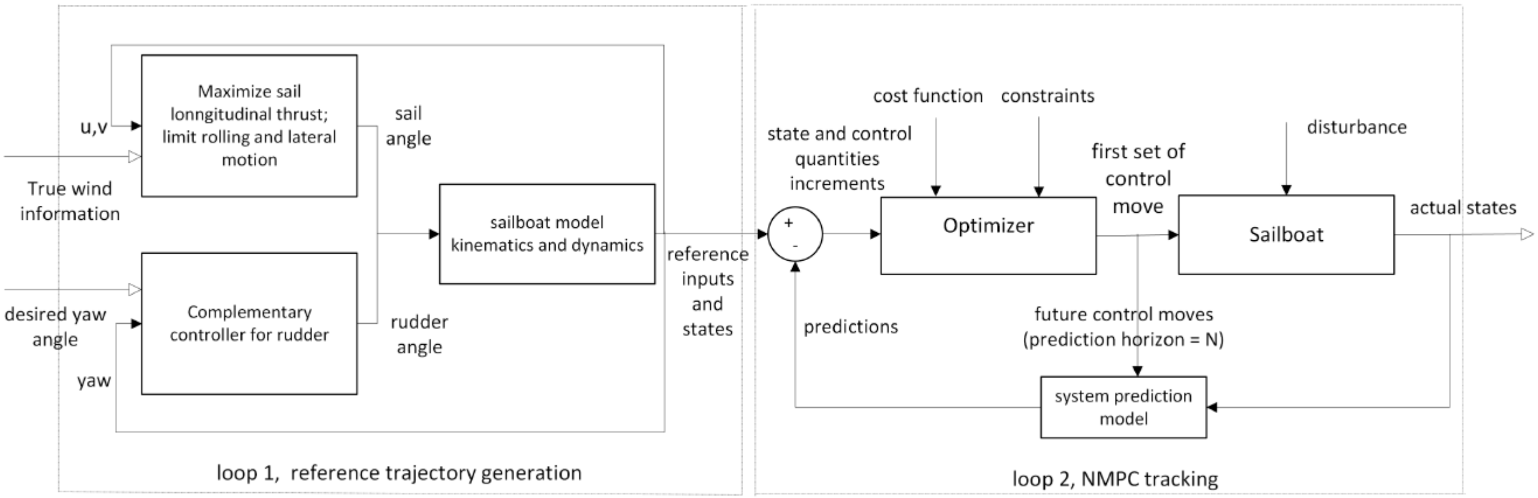
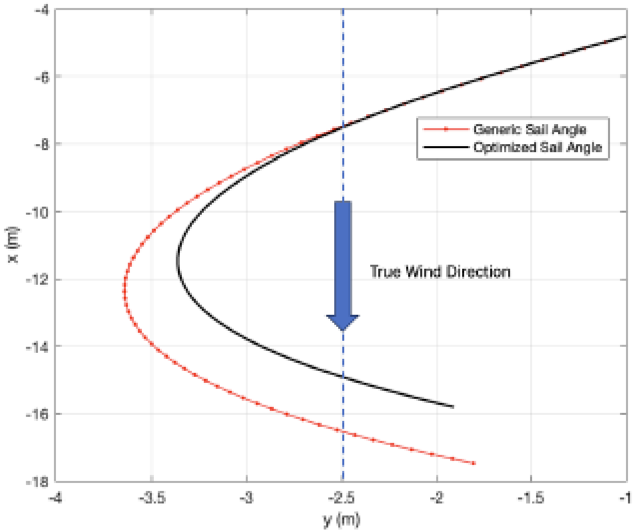
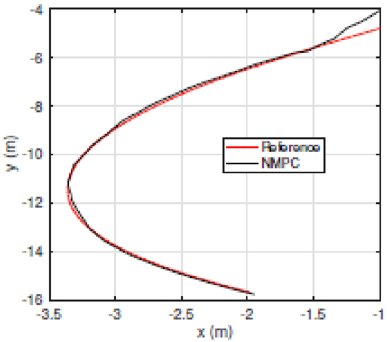


Fig. 1: Sailboat control flow block diagram

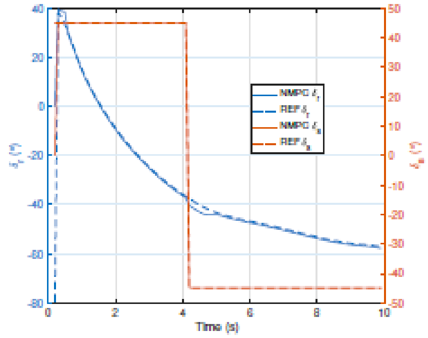


(b) Trajectory comparison when when v_{tw}= 6m/s (jibing maneuver)

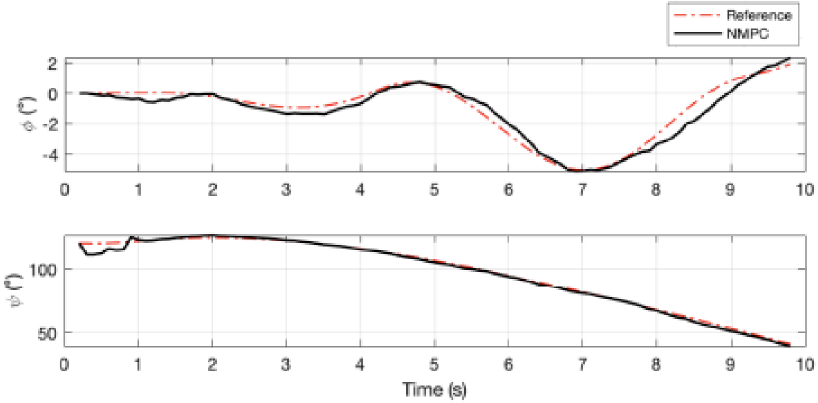
Fig. 4: Sail angle generation of the jibing maneuver



(a) Jibing Trajectory Tracking



(b) Time Evolution of Jibing Inputs



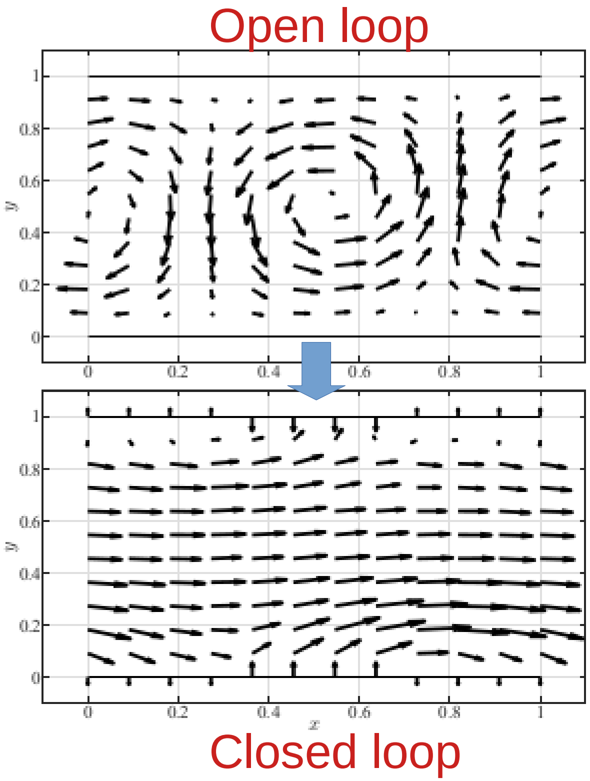
(c) Jibing Angle Tracking

Fig. 6: Trajectory tracking of the jibing maneuver

Convection-Enabled Boundary Control of a 2D Channel Flow

M. Belhadjoudja, M. Krstic, and E. Witrant, CDC 2024.

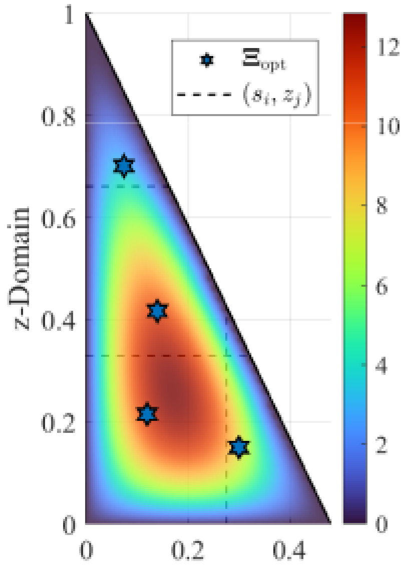
- Nonlinear convection may hold the key to stabilizing turbulence by solving a specific cubic polynomial equation.
- Incompressible 2D Navier-Stokes equations:
- Hyp: tangential and normal velocities are periodic in the streamwise direction, Delta P in/out constant, no-slip boundary conditions
- the boundary control inputs: normal velocity actuation at the top and bottom walls
- => global exponential stabilization, in the L2 sense, of a chosen Poiseuille equilibrium profile for an arbitrarily large Re



Optimal Observer-Based Pressure Sensor Placement

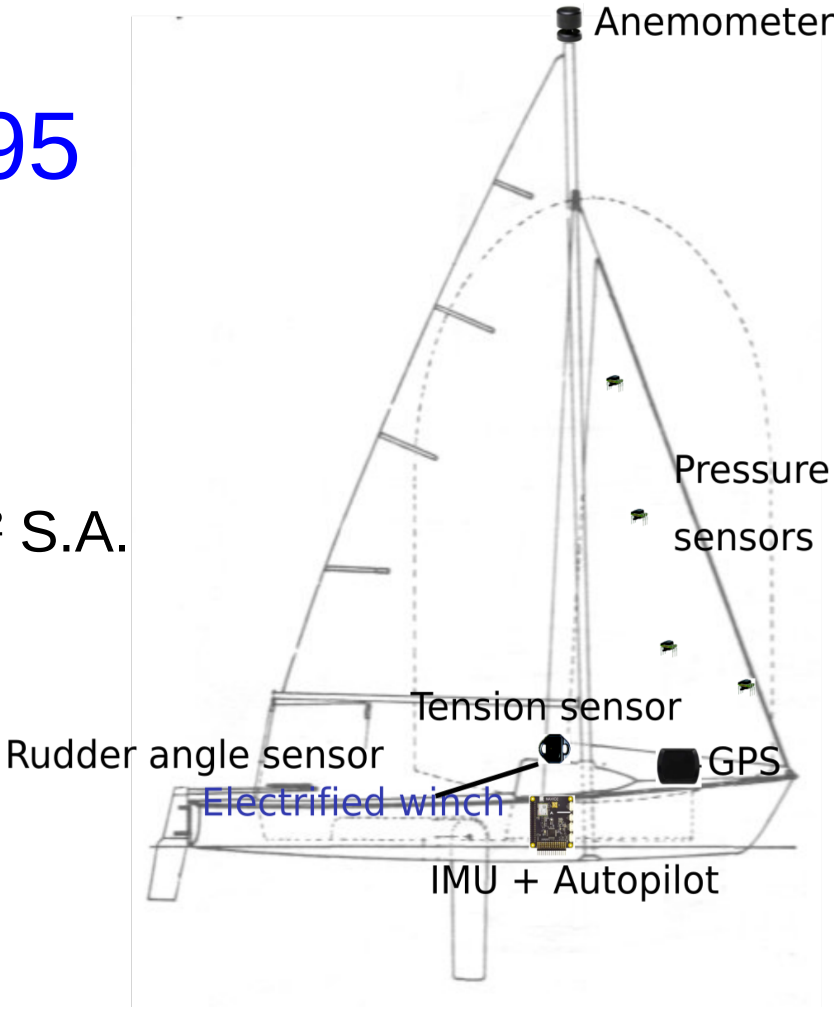
S. Smith, E. Witrant, Y.-J. Pan, IFAC 2026.

- Model: The sail pressure dynamics are described by a linearized General Pressure Equation (quasi-steady aerodynamic model) posed on the sail surface.
- Observer design: A pointwise Luenberger observer is proposed; exponential convergence in L2 is guaranteed using LMI-based conditions.
- Sensor placement: Pressure sensor locations are computed by a closed-loop adjoint-based optimization, formulated directly in the infinite-dimensional PDE setting (no reduced-order model).
- Key finding: Optimal sensors concentrate in regions of high pressure gradients and observability, leading to faster estimation error decay.
- Validation: Numerical simulations and experimental results on a 6 m sailing yacht jib confirm significant performance improvement over heuristic placements.



Birdie and Dragon Flite 95

- Mouette 19
- Paceship 1974
- 6 m, 290 kg, 14.3 m² S.A.



Moving on to a larger project

- Bring new solutions to improve WAP :
  - With data acquisition and management (network of sensors / actuators)
  - Using all the knowledge from physics in the control design
  - Virtual sensors for state reconstruction
  - Assess and optimize sailing efficiency
- Analyse and control the fluid-structure interaction in the infinite-dimensional analytical framework
- Implement in practice and assess the benefits

ANR-NSERC Project Autosail

- 3 partners : UGA / GIPSA-lab, Dalhousie University, Université du Littoral Cote d'Opale,
- 4 PhDs, 2 M.Sc., 1 boat + instrumentation, ~640 k€ over 3 years.
- 7 Researchers, 1 Engineer
- https://autosail-194045.gricad-pages.univ-grenoble-alpes.fr/

Our needs (WP structure)

- Physical and data-based models :
  - Physical analytical models (e.g. Navier-Stokes) to design stabilizing feedback controllers
  - Reference numerical models to generate (offline) data sets
  - Reduced numerical models that can be used online for prediction and model-based control design
  - Grey-box approach : intelligent « self-tunning » models that learn from sensors

- Feedback control design :
  - Boundary control of nonlinear partial differential equations (PDE)
  - Need to adress the fluid-structure interaction explicitely : network of PDE
  - Hybrid modes depending on the wind direction and flow attachement
  - Handle sparse measurements in a MIMO framework
  - Integrate with the nonlinear boat dynamics (0DE)

- Path planning and navigation
  - Both for automated and commercial sailboats
  - adaptation of the route to multiple dynamics: of the ship, of the wind, and of the ocean currents
  - e.g. search-based path planner (SBPL) and hybrid path planner first, to produce dynamically feasible and obstacle free path, then approximately optimal continuous-time motion planning approach (e.g. Gaussian Process Motion Plan)

- Control architecture and supervision:
  - Sensor integration : sails pressure and shape, tension in the sheets, anemometer, IMU and GPS
  - Sensor location : find the optimal deployement
  - Sails and rudder actuation
  - Combine with navigation system

Your contribution in this project

- Common ground (groups of 2):
  - Bibliographical research
  - Raspberry Pico, Micropython and Data Analysis
  - Computational Fluid Dynamics and numerical analysis : Dr. I. NIYONZIMA
  - Communication and connected objects : Dr. J.-M. DUCHAMP
  - 1st report and presentation by Feb. 10
- Specific research projects :
  - Tailored topics and groups
  - After the holidays
  - 2nd report and presentation by March 10