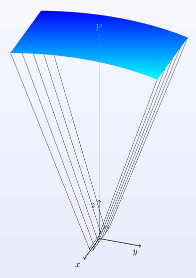

Wind Powered Marine Vehicle

Master Thesis in Marine Cybernetics - 2015

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Description

Remotely operated or autonomous vehicles can carry out many measuring and monitoring tasks more cheaply than crewed vehicles, but due to their smaller sizes, they may lack endurance. One solution is to extract energy from the environment. Wind-powered vessels can extract a lot of energy quite efficiently, but mostly suffer from slow speed. A limiting factor is that the normal arrangement of foils in the air and the water generates a turning moment, which must be countered by a righting moment that is related to size. Small and cheap vehicles of conventional design are vulnerable. This limitation is removed if force vectors from air and water foils can be aligned without a turning moment. [2] and [4] proposed that either a paraglider or an airship could serve as sail, and a paravane as the foil in the water. The high vantage point of the aerial element would further be useful for monitoring, for spotting other vessels, whether for collision avoidance or for spotting vessels fishing in marine sanctuaries, and for returning a radar echo that stays well clear of the clutter generated by a seaway. The speed of the vessel is not limited by stability, but only by how reliably the paravane remains hooked into the water, by structural integrity, and eventually by cavitation.

Scope

- Review relevant litterature on aerodynamic loads and control systems associated with kites and surface/underwater vehicles
- Evaluate feasibility of different concepts considering operational conditions and limitations, cost and functionality
- Develop mathematical model of selected concept, studying aero- and hydrodynamics
- Propose feasible control concept for propulsion considering operational requirements
- Carry out simulations using the mathematical model to identify important loads
- Verify the mathematical model by simulations and comparison to empiric data
- Field study: empiric data sampling

Sailing challenges

A conventional sailboat has a configuration of rigid connected hydrofoils and aerofoils where a hull acts as a float and the connecting link between the forces exerted by air and water. In figure 1 a sketch of a close-hauled sailboat demonstrates the resulting forces from aero- and hydrofoils, in which generates a forward momentum (thrust). The boat accelerates until drag equals thrust, and the maximum velocity is reached. The turning moment exerted by the aerofoils has to be countered by the keel, and is traditionally based on weight suspension, in combination with foil forces, in which increases hull volume and associated drag.

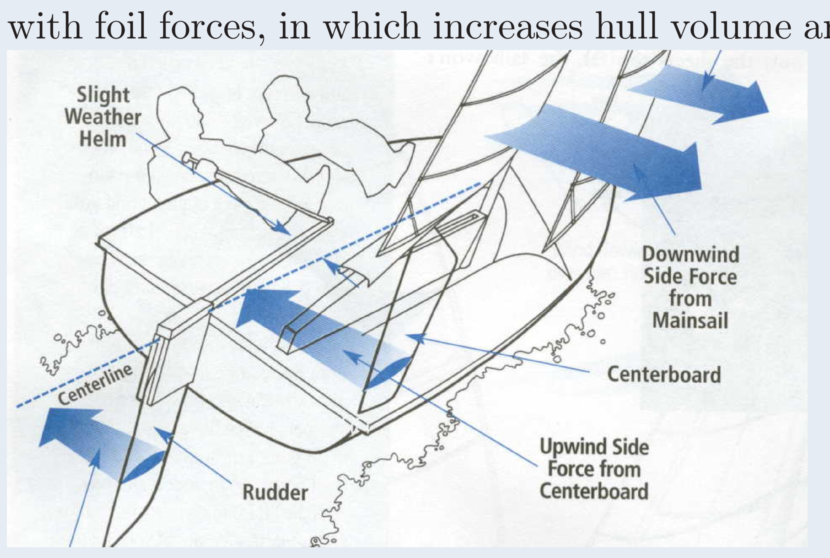

Figure 1: Conventional sailboat

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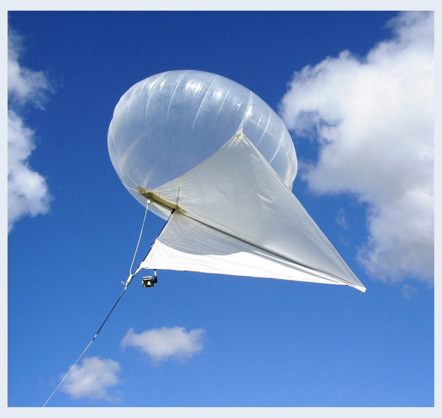
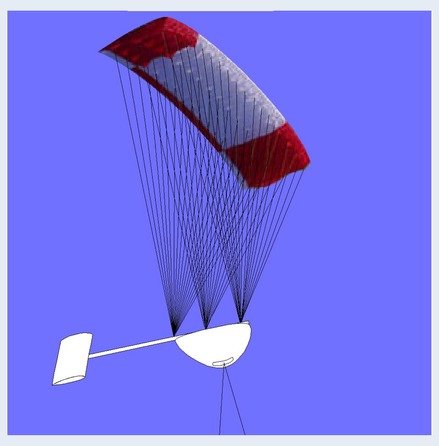
Concepts

Several people have been intrigued by the idea of improving the performance of sailboats. Smith's ideas covered in [4] is to offset the foils in water and air laterally and inclining them to line up the resulting forces, in order to decrease and ultimately remove heeling moment. The Sailrocket project is highly based on Smiths work. Didier Costes and J.G Hagedoorn worked on removing the rigid connection between foils by introducing tensile connections resulting in great weight reductions. The hydrodynamic foil structure involved in such a design, such as hapas and paravanes, can be understood as kites in the water.





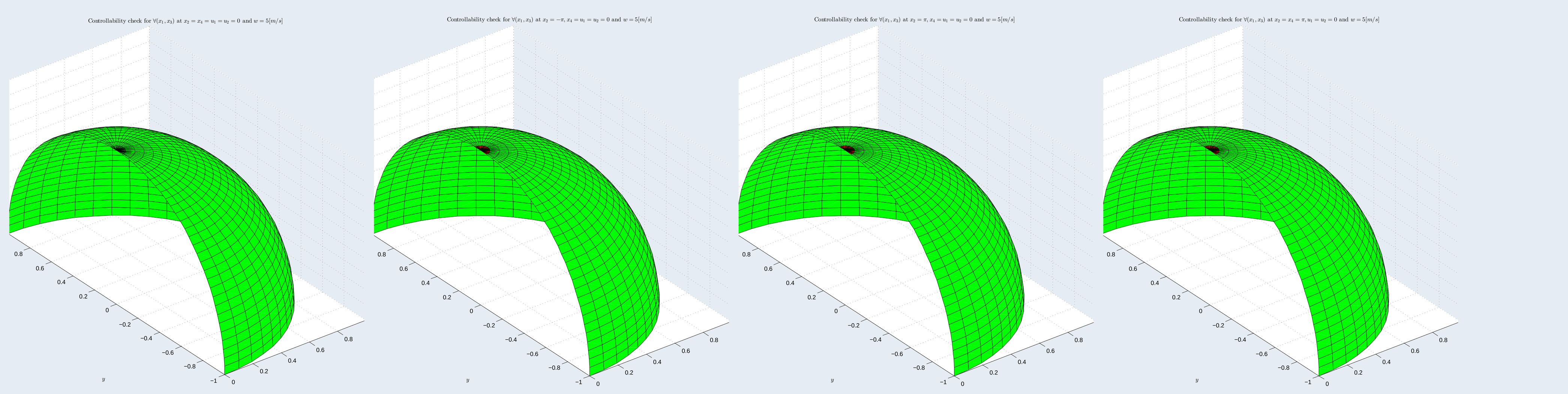
Tethered aerofoils, mainly kites, have been used in automated designs for ship propulsion and power generation, such as [5], [6], [7] and [8]. Several designs for wind power exploitation were evaluated, categorized by performance in conditions ranging from low wind (lighter-than-air (LTA) capabilities) to extreme wind conditions (high performance aerofoils). The minimum operational requirements of the wind power exploitation concept will be to carry a necessary payload consisting of sensors essential for control and navigation as well as a power supply. LTA-capabilities can extend the operation window to include zero-wind conditions, by suspending a propulsion system from the aerofoil, that can be converted into an energy harvesting system elsewhere. In this thesis the multi-panel soft fabric parawing was chosen due to its combination of LTA-capabilities (inflation by helium) and its aspect ratio (usually around $L/D = 3$). In a grid scan operation, a high speed sailing vehicle can cover a great area in short time, and the high vantage point of a kite can ensure communication bandwidth as well as marine traffic and wildlife monitoring.

Kite dynamics, Control Strategy and Controllability

The kites local coordinate system is rotated with the positive x-axis parallel to the apparent wind seen at the kite control bar center of rotation. A spherical coordinate system was used to describe its flight dynamics, based on [9], including drag on tether lines based on [7]. The total force is divided in the projected components $\mathbf{F} = F_\theta \mathbf{e}_\theta + F_\phi \mathbf{e}_\phi + F_r \mathbf{e}_r$. Due to the constant tether length $r = l_k$, the system state representation becomes $x = (\theta, \dot{\theta}, \phi, \dot{\phi})$, where θ is the elevation angle and ϕ is the azimuth angle, with control input $u = (\psi_c, \varphi_c)$, where ψ_c is control input in yaw, and φ_c is control input in pitch of the control bar. F_r is used in order to compute the tether tension, and eventually the thrust component F_{xy} and the vertical component F_z, which are subject to investigation of important system loads. The system state representation $\dot{x} = f(x, u)$ is defined as:

$$f(x,u) = \begin{pmatrix} \dot{\theta} \\ \frac{F_\theta}{l_t} + \sin(\theta)\frac{g}{l_t m} + \sin(\theta)\cos(\theta)\dot{\phi}^2 \\ \dot{\phi} \\ \frac{F_\phi}{l_t m} - 2\cot(\theta)\dot{\theta}\dot{\phi} \end{pmatrix} \quad (1)$$

where l_k is the mean length of the tether lines, m is the system mass. In order to maximize power output from the kite in the direction of travel, periodic trajectories like 8-pattern downwind or sinusoidal pattern upwind is commonly utilized by kite surfers. According to Sørensen, this is a typical moving horizon problem to be solved using Model Predictive Control (MPC) theory and Non Linear Programming (NLP) algorithms, which is beyond the scope of this thesis. A controllability analysis for the linearized system was computed in MATLAB for $(\dot{\theta} = \dot{\phi} = \psi_c = \varphi_c = 0)$, $(\dot{\theta} = -\pi, \dot{\phi} = \psi_c = \varphi_c = 0)$, $(\dot{\theta} = \pi, \dot{\phi} = \psi_c = \varphi_c = 0)$, $(\dot{\theta} = \dot{\phi} = \pi, \psi_c = \varphi_c = 0)$ at $(\theta \in [0, \pi/2], \phi \in [-\pi/2, \pi/2])$, for $N \times N, N = 100$ data points with ambient wind $w = 5[m/s]$ for a $10[m^2]$kite with lift to drag ratio $L/D = 3[-]$ and mass $1.8[kg]$, with tether line length $l_t = 7.5[m]$:



where the result was that the system was fully controllable (green) in all occasions for all data points, not including the boundary $\theta = 0$, in which resulted in an undefined (red) controllability check due to singularities in the solution. An attempt in designing a controller combining feedback linearization and PID algorithms was performed. Due to the highly non-linear dynamics of the kite model, the linearization included approximation by series expansion, as well as established methods, which may introduce significant error accumulation. It is stated in [9] that small errors accumulate very quickly for the uncontrolled system. An analysis of the applicability of the thrust allocation method was performed and argued that this method may not always have an existing solution.

It is worth mentioning that for a real world application obtaining essential state information may introduce challenges. As discussed in [7], the apparent wind vector at the kite can be measured directly using an anenometer. The position of the kite however is somewhat more difficult. Professor T.I. Fossen at the department of Engineering Cybernetics, NTNU suggested that the state information problem is a typical attitude estimation problem, where the measurements from instruments such as gyroscopes, accelerometers and magnetometers can be used in combination with integrated inertial and satellite navigation systems.

For navigation purposes, a path planning algorithm based on Dubin's path, extended to ensure continuity in the complete path, can be used as a basis for a gybing only system in order to find the shortest path from the initial to the final waypoint.

Field Study

A series of field studies was carried out, examining Robert Bieglers paravane design as well as observing kite performance of the kite described in section **Kite dynamics, Control Strategy and Controllability**. The operational requirements for the paravane was to reflect kite forces in the transverse and vertical direction of travel, while minimizing drag and still be able to steer the paravane using a conventional rudder. The test of the paravane was conducted on two design iterations. The first design proved to lack steering, while the second had greatly improved steering and gybing capabilities. The main challenge seemed to be to reduce drag while retaining structural integrity. Field study of kite dynamics was carried out in order to discuss the validity of the mathematical model.

Image references

Figure 1: image taken from www.boatdesign.net

Images under **Concepts** from left to right: ·Altaeros airborne wind turbine, image taken from www.altaerosenergies.com, ·Allsopp Helikite, image taken from www.allsopp.co.uk, ·Parawing, image courtesy from Robert Biegler, ·Ocean Rodeo Razor kite, image taken from www.sideshore.no, · Tensairity kite, image taken from Joep C.M. Bruer and Rolf H. Luchsinger *Inflatable kites using the concept of tensairity* Elseveier, Aerospace Science and Technology, 2010.