Optimization and control of a hybrid kite boat [1]

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Abstract: This paper investigates the use of a controlled tethered wing, or kite, for naval transportation. Linked to a boat by light composite-fibre cables, the kite is able to fly between 200 m and 600 m above the sea and to generate high traction forces. A mechatronic system installed on the boat, named Kite Steering Unit (KSU), controls the kite and converts the cable speed and force into electricity. Differently from previous works, the boat is also equipped with two electric propellers, so that naval propulsion can be achieved both directly, through the towing forces exerted by the cables, and indirectly, through the electricity generated by the KSU and fed to the electric propellers via a battery pack. The optimal system operating conditions, that maximize the boat speed for given wind characteristics, are computed. Then, a model predictive controller is designed and numerical simulations with a realistic model are carried out, in order to assess the performance of the control system against the optimal operating conditions. The results indicate that, by properly choosing the operating conditions of the system, a completely green naval transportation system can be obtained regardless of the wind direction.

1. INTRODUCTION

In the last decade, several research and development activities have been carried out, regarding novel wind power technologies that aim to convert the energy of high-altitude wind into electricity, by exploiting the flight of controlled tethered wings or kites (see e.g. the papers of Ilzhöfer et al. (2007); Canale et al. (2010a); Williams et al. (2008); Argatov et al. (2009)). These kites can fly at high speed in "crosswind" conditions, i.e. in a direction that is roughly perpendicular to the wind, thus generating high traction forces on the cables, as introduced in the seminal work of Loyd (1980). Such forces are then converted into mechanical and electrical energy by a suitable mechatronic system placed on the ground, according to different possible configurations (see e.g. Canale et al. (2010a); Fagiano (2009)). The studies that have been carried out so far, including theoretical and numerical analyses as well as experiments with small-scale prototypes, indicate that this kind of technology, named Kitenergy in this paper, could produce electricity at lower cost than fossil sources, Fagiano et al. (2010a). This result can be achieved mainly thanks to much lower costs for the generator construction, higher capacity factor, and lower land occupation with respect to the actual wind power technology, based on wind turbines.

Another interesting application of controlled kites is naval transportation. Also in this field, research activities have been recently carried out, mainly to study the control design for power kites used to tow a boat (see Houska and Diehl (2006); Fagiano et al. (2010b)). Moreover, a system for naval propulsion using power kites has been also industrialized (see SkySails GmbH & Co. (2010)). In all these cases, the kite is used to directly tow a boat, like a classical sail does, so that the useful effect of propelling the boat can be obtained only with limited wind conditions: roughly speaking, the kite is able to pull the boat if the angle between the wind and the boat speed ranges from 0° (i.e. the boat moves downwind) to approximately 135°. Such a limit can be removed by using a Kitenergy system, able to convert wind energy into electricity onboard, together with electric propellers placed on the boat, so that the boat propulsion can be obtained not only directly, through the towing forces exerted by the kite's cables, but also indirectly, thanks to the action of the propellers. Electricity can be supplied to the propellers by a battery pack, and the batteries can be recharged with the electric energy generated by the Kitenergy generator itself. The aim of this paper is to investigate the potentials and the control aspects of this new kind of "hybrid kite boat", which represents a novelty with respect to the existing studies and applications. Indeed, the combined use of kite traction and electric propellers opens up new possibilities, like the already mentioned capability of navigating upwind using the electric propellers, and also new conceptual issues, regarding the computation of an optimal tradeoff between the use of kite towing and of electric propulsion, for given wind direction relative to the boat, that achieves the maximal boat speed. Moreover, the system operating conditions have to be chosen in order to ensure their sustainability, in the sense that the state of charge of the batteries on the boat must be kept sufficiently high, so to avoid tension losses, while providing the required power for the electric propellers and for the onboard auxiliaries like lights, pumps, etc.. Finally, for safety reasons the kite must fly sufficiently far from the sea and the cable forces have to be contained, so to avoid cable breaking and excessive roll moments on the boat. In this work it will be shown how the described problem can be formulated, by using a simplified system model, as a constrained optimization problem, in which the boat speed is maximized subject to constraints on the average generated electric energy, on the kite position and on the cable

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forces. The devised operating conditions provide guidelines on how to design some of the system parameters, as well as a feedback controller, based on a Nonlinear Model Predictive Control (NMPC, see e.g. Mayne et al. (2000)) strategy. The latter is employed to carry out numerical simulations with a detailed dynamical model of the system, in order to assess the feasibility of the computed optimal operating conditions, as well as the system performance also in the presence of external disturbances, like wind turbulence.

2. SYSTEM LAYOUT

In the considered application of high-altitude wind power to naval propulsion, a so-called KE-yoyo generator (see e.g. Canale et al. (2010a)) is installed on a boat. In a KE-yoyo, the kite is connected to the boat by two cables, realized in com-

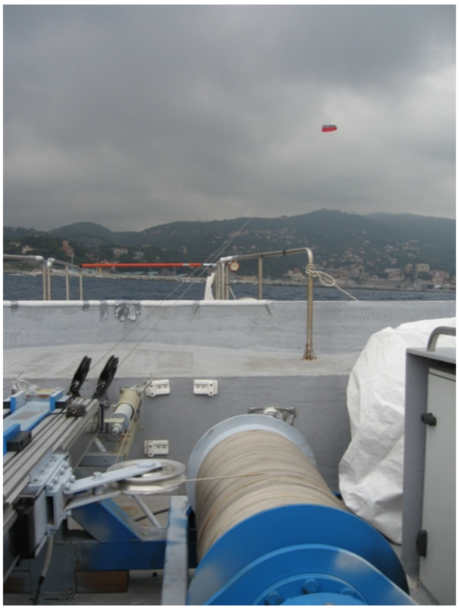


Fig. 1. KE-yoyo prototype installed on a boat and operating near Genoa, Italy.

posite materials, with a traction resistance 8-10 times higher than that of steel cables of the same weight. On the boat deck, the cables are rolled around two drums, linked to two electric drives which are able to act both as generators and as motors. The kite can be controlled by differentially pulling the cables with the electric drives and it is tracked using onboard wireless instrumentation (GPS, magnetic and inertial sensors) that allow to measure the wing speed and position. Other sensors, installed on the boat, measure the generated current i_{KSU}, the cable force, $F^{\text{t,trc}}$, length, r, and speed, $\dot{r}$, and the wind speed and direction. The system composed by the electric drives, the drums, and all the hardware needed to control a single kite is denoted as Kite Steering Unit (KSU). A prototype of the described system has been built at Politecnico di Torino, in cooperation with the yacht manufacturer Azimut-Benetti and the small company Modelway (see Fig. 1 and the movie on the KiteNav project website (2010)). In a KE-yoyo, electric energy is generated by continuously repeating a two-phase cycle, depicted in Fig. 2: in the *traction phase* the kite is controlled so to fly fast in crosswind direction and the cables are unrolled at a reference speed $\dot{r}_{\text{ref}}^{\text{trac}} > 0$, under the pull of high traction forces, thus generating energy through the electric drives. When the maximal line length is reached, the *passive phase* begins and

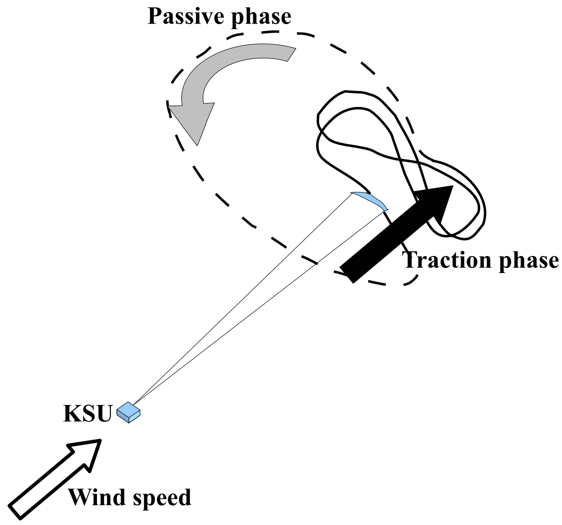


Fig. 2. Sketch of a KE-yoyo cycle: traction (solid) and passive (dashed) phases.

the kite is controlled, by modifying its angle of attack, so that the traction forces collapse: this way, the cables can be rolled back at a reference speed $\dot{r}_{\text{ref}}^{\text{pass}} < 0$, spending less than 10% of the energy collected in the previous phase (see Canale et al. (2010a); Fagiano (2009) for details on the KE-yoyo cycle). The energy produced is stored in a battery pack on the boat. The batteries supply a current i^{aux} to the boat auxiliary equipments (e.g. lights, pumps, etc.) and a current i^{motor} to a couple of electric propellers, which can be used to generate a force F^{motor} to propel the boat. A conceptual scheme of the described system is shown in Fig. 3.

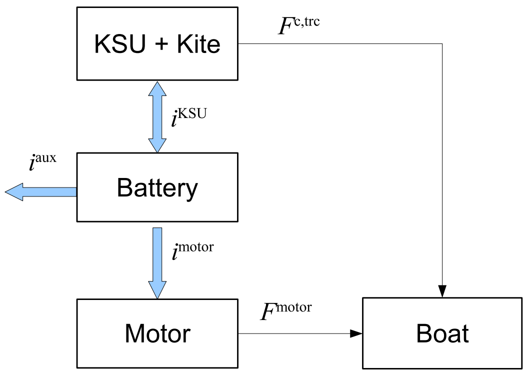


Fig. 3. Conceptual scheme of the hybrid kite boat.

3. SYSTEM MODEL

As anticipated in the Introduction, a detailed, dynamical model of the system is employed for control design and numerical simulations, while a simplified model is used to optimize the system operating conditions. These models are briefly outlined here, and more details can be found in the works of Canale et al. (2010a); Fagiano (2009).

3.1 Detailed model

Wind and boat models. A Cartesian coordinate system (X, Y, Z) is considered (see Fig. 4), centered at the boat location (i.e. at the KSU, which is fixed with respect to the boat),

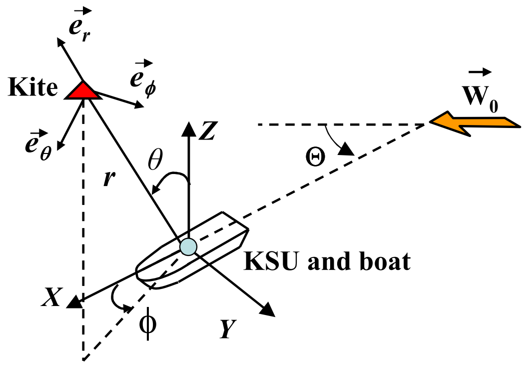


Fig. 4. Model diagram of the system.

with X axis aligned with the longitudinal symmetry axis of the boat. Wind speed vector is denoted as $\boldsymbol{W}_l = \boldsymbol{W}_0 + \boldsymbol{W}_t$, where $\boldsymbol{W}_0$ is the nominal wind, supposed to be known and expressed in (X, Y, Z) as:

$$\boldsymbol{W}_0 = \begin{pmatrix} W_n(Z)\cos(\Theta) \\ -W_n(Z)\sin(\Theta) \\ 0 \end{pmatrix} \quad (1)$$

Θ is the angle between the nominal wind speed direction and X axis, while $W_n(Z)$ is a known function which gives the nominal wind magnitude at the altitude Z. In this paper, function $W_n(Z)$ corresponds to a power-law wind shear model (see e.g. Archer and Jacobson (2005)):

$$W_n(Z) = \overline{W}\left(\frac{Z}{\overline{Z}}\right)^{\beta}, \quad (2)$$

where the values of $\overline{W}$, $\overline{Z}$ and β have been identified using the data contained in the database RAOB (RAwinsonde OBservation) of the National Oceanographic and Atmospheric Administration, see National Oceanic & Atmospheric Administration – Earth System Research Laboratory (2009). The term $\boldsymbol{W}_t$ may have components in all directions and is not supposed to be known, accounting for wind unmeasured turbulence.
As regards the boat model, the following assumptions are considered:

- the boat rudder is commanded in such a way that the boat speed vector $\boldsymbol{v}$ is aligned with axis X;
- the boat moves along a straight path;
- the boat longitudinal acceleration $\dot{v}$ is low as compared to the kite accelerations during the flight;
- the effects of the lateral forces exerted by the cables on the boat are negligible and/or balanced by a suitable action on the rudder and by a differential action of the electric propellers;
- the direction of the nominal wind speed vector $\boldsymbol{W}_0$ changes slowly in time.

According to such assumptions, the angular speed $\dot{\Theta}$ is zero or negligible. The considered assumptions are reasonable in the context of this paper and allow to describe with satisfactory accuracy the longitudinal motion of the boat pulled by the kite lines and/or under the action of the propellers. Since the speed vector $\boldsymbol{v}$ is supposed to be aligned with axis X, its direction with respect to the nominal wind speed direction is univocally defined by angle Θ. Thus, in the following the boat speed will be described simply by its magnitude v. Note that the speed vector is measured by using a GPS on the boat. On the basis of the considered assumptions, the model that describes the boat motion is given by the following equation:

$$\dot{v} = \frac{F^{\text{tow}} + F^{\text{motor}} - F^{\text{R}}(v)}{M} \quad (3)$$

where M is the boat mass, F^{tow} is the towing force exerted by the kite lines and $F^{\text{R}}(v)$ is the longitudinal drag force acting on the boat at a given speed v. Function $F^{\text{R}}(v)$, shown in Fig. 5, has been identified through experimental tests with the boat employed in the KiteNav project: it can be clearly noted that, at approximately 5 m/s speed, the boat motion regime changes from displacement to planning. The propellers' force F^{motor} can

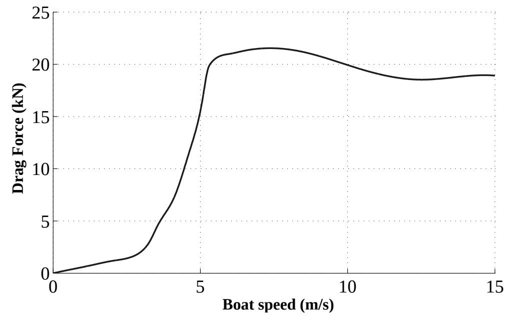


Fig. 5. Boat drag force $F^{\text{R}}(v)$

be computed according to the following formula:

$$F_{\text{motor}} = \frac{\eta_{\text{motor}} V^{\text{battery}} i^{\text{motor}}}{v} \quad (4)$$

where V^{battery} is the battery voltage and η_{motor} is the overall efficiency of the electrical propellers. A reasonable value for η_{motor} is 0.55. For the purpose of this paper, the propellers' current i^{motor} is assumed to be always positive (i.e. the propellers can draw current to push the boat forward) and it is regulated by a low-level controller in order to achieve an imposed value of the boat speed, indicated as v_{ref}.
Kite model. The kite model is thoroughly presented in Canale et al. (2010a), and only a concise description is given here for the sake of completeness. In system (X, Y, Z), the kite position can be expressed as a function of its distance r from the origin and of the two angles θ and ϕ as depicted in Fig. 4, which also shows the three unit vectors e_θ, e_ϕ and e_r of a local coordinate system, centered at the kite center of gravity. Unit vectors $(e_\theta,\, e_\phi,\, e_r)$ are expressed in the Cartesian system (X, Y, Z) by:

$$\begin{aligned} &(\, e_\theta \;\, e_\phi \;\, e_r \,) = \\ &\begin{pmatrix} \cos(\theta)\cos(\phi) & -\sin(\phi) & \sin(\theta)\cos(\phi) \\ \cos(\theta)\sin(\phi) & \cos(\phi) & \sin(\theta)\sin(\phi) \\ -\sin(\theta) & 0 & \cos(\theta) \end{pmatrix} \end{aligned} \quad (5)$$

By applying Newton's laws of motion in the system $(e_\theta,\, e_\phi,\, e_r)$, the following dynamic equations are obtained:

$$\begin{aligned} \ddot{\theta} &= \frac{F_\theta}{m\, r} \\ \ddot{\phi} &= \frac{F_\phi}{m\, r \sin\theta} \\ \ddot{r} &= \frac{F_r}{m} \end{aligned} \quad (6)$$

where m is the kite mass. Forces F_θ, F_ϕ and F_r include the contributions of gravity force $\boldsymbol{F}^{\text{grav}}$ of the kite and the lines, apparent force $\boldsymbol{F}^{\text{app}}$, kite aerodynamic force $\boldsymbol{F}^{\text{aer}}$, aerodynamic drag force $\boldsymbol{F}^{\text{c,aer}}$ of the lines and traction force $F^{\text{c,trc}}$ exerted by the lines on the kite. Gravity forces take into account the kite weight and the contribution given by the weight of the lines. Apparent forces include centrifugal and inertial forces due to the kite movement only, since little acceleration $\dot{v}$ of the boat is assumed. The kite aerodynamic force $\boldsymbol{F}^{\text{aer}}$ can be derived via the computation of the lift and drag forces, $\boldsymbol{F}_L$ and $\boldsymbol{F}_D$ respectively, that depend on the wind speed at the kite altitude, on the air density ρ, on the kite speed with respect to the sea, on the kite area A, on the kite aerodynamic lift and drag coefficients, C_L and C_D, which in turn depend on the kite attack angle α (see Canale et al. (2010a) for more details), finally on the command angle ψ, i.e. the control variable. The latter is defined as

$$\psi \doteq \arcsin\left(\frac{\Delta l}{d}\right) \tag{7}$$

with d being the distance between the two lines fixing points at the kite and Δl the length difference of the two lines, which can be issued by a suitable control of the electric drives. Finally, the influence of the lines is taken into account in the model through their drag force $\boldsymbol{F}^{\text{c,aer}}$ and the traction force $F^{\text{c,trc}}$. $\boldsymbol{F}^{\text{c,aer}}$ depends on the line drag coefficient $C_{D,l}$, on the line length r and diameter d_l. The traction force $F^{\text{c,trc}}$ is always directed along the local unit vector e_r and cannot be negative, since the kite can only pull the lines. Moreover, $F^{\text{c,trc}}$ is measured by a force transducer on the KSU and, using a low-level controller of the electric drives, it is regulated in such a way that $\dot{r}(t) = \dot{r}_{\text{ref}}$ where $\dot{r}_{\text{ref}}$ is a reference line rolling speed. The force F^{tow} is given by the projection of $F^{\text{c,trc}}$ on the X axis:

$$F^{\text{tow}} = F^{\text{c,trc}} \sin(\theta)\cos(\phi) \tag{8}$$

The electric current i^{KSU} produced or consumed by the KSU is computed as:

$$i^{\text{KSU}} = \frac{\eta_{\text{KSU}} F^{\text{c,trc}} \dot{r}}{V^{\text{battery}}}, \tag{9}$$

where η_{KSU} accounts for the mechanical and electrical efficiency of the KSU.

Battery model. A simple current integrator is sufficient as battery model for the purpose of this work:

$$\dot{Q} = i^{\text{KSU}} - i^{\text{aux}} - i^{\text{motor}}, \tag{10}$$

where Q is the state of charge of the batteries. i^{aux} and i^{motor} are always positive, since the auxiliaries and the propellers can only draw current from the batteries, while i^{KSU}, according to (9), may be either positive, when the KSU produces electricity, or negative. Effects related to voltage variations due to low Q values, temperature and current rate are not taken in account, since they are not critical for the considered problem. The supply voltage V^{battery} is assumed to be constant.

Overall model equations. Considering that the nominal wind speed magnitude $W_n(Z)$ can be obtained by computing the kite altitude Z as $Z = r\cos(\theta)$, equations (1)–(10) give the system dynamics in the form:

$$\dot{x}(t) = f(x(t), u(t), \Theta, \boldsymbol{W}_t(t), i_{\text{aux}}(t), \dot{r}_{\text{ref}}, v_{\text{ref}}) \tag{11}$$

where $x(t) = [\theta(t)\ \phi(t)\ r(t)\ \dot{\theta}(t)\ \dot{\phi}(t)\ \dot{r}(t)\ v(t)\ Q]^T$ are the model states and $u(t) = \psi(t)$ is the control input. All the model states are measured using the available sensors placed on the kite and on the KSU. The model $f(\cdot)$ can be employed to design the control law and to simulate the system behavior.

3.2 Simplified model

The model presented in this Section stems from the simplified equations of a kite flying in crosswind conditions (see e.g. Fagiano (2009) and the references therein), which have been extended in this work in order to take into account the boat

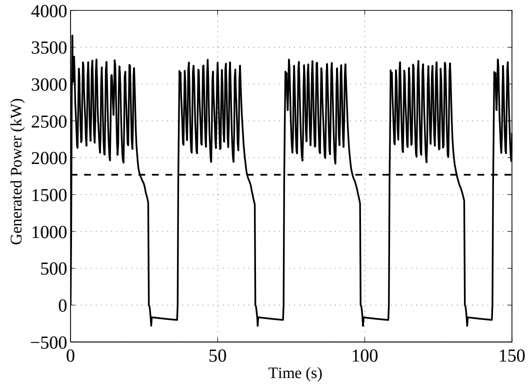


Fig. 6. Simulation of KE-yoyo cycles: course of the generated power.

motion and the KE-yoyo generating cycle. The aim of this model is to provide, with simple equations, a reliable estimate of the traction force acting on the cables and of the current generated by the KE-yoyo, for given system characteristics and operating conditions. The latter include the average values $\overline{\theta}$, $\overline{\phi}$ and $\overline{r}$ of θ, ϕ and r respectively, assumed by the kite during the KE-yoyo traction phase, the value $\dot{r}_{\text{ref}}^{\text{trac}}$ of the reference unrolling speed of the lines during the traction phase, and the reference boat speed v_{ref}. By assuming that:

- the kite flies fast in crosswind conditions;
- the inertial and apparent forces are negligible with respect to the aerodynamic forces;
- the kite speed relative to the ground is constant;
- the kite control angle ψ is small (i.e. $|\psi| \leq 10°$);

it can be shown (see Fagiano (2009) for details) that, for given system characteristics and for a given angle Θ, a simplified formulation of the traction force acting on the cables during the traction phase of the KE-yoyo (see Section 2) is:

$$\overline{F}^{\text{c,trc}}(\overline{\theta}, \overline{\phi}, \overline{r}, \dot{r}_{\text{ref}}^{\text{trac}}, v_{\text{ref}}) = \frac{1}{2}\rho A C_L E_{\text{eq}}^2 \left(1 + \frac{1}{E_{\text{eq}}^2}\right)^{\frac{3}{2}} \boldsymbol{W}_{e,r}^2 \tag{12}$$

where

$$E_{\text{eq}} = \frac{C_L}{C_D\left(1 + \frac{(2\overline{r}d_l)C_{D,l}}{4AC_D}\right)}, \tag{13}$$

$$\boldsymbol{W}_{e,r} = \left[W_n(\overline{r}\cos\overline{\theta})\cos(\Theta + \overline{\phi}) - v_{\text{ref}}\cos\overline{\phi}\right]\sin\overline{\theta} - \dot{r}_{\text{ref}}^{\text{trac}}, \tag{14}$$

In order to take into account the energy spent during the passive phase of the KE-yoyo cycle and the related duty cycle, in the simplified model an average generated power value, indicated by $\overline{P}^{\text{KE-yoyo}}$, is considered, computed as:

$$\overline{P}^{\text{KE-yoyo}} = \eta_{\text{KE-yoyo}} \eta_{\text{KSU}} \overline{F}^{\text{c,trc}} \dot{r} \tag{15}$$

where $\eta_{\text{KE-yoyo}} < 1$ is a coefficient that takes into account the efficiency of the KE-yoyo generator cycle, i.e. the ratio between the average generated power and the power generated in the traction phase only. Numerical analyses and the tests performed with a KE-yoyo prototype at the Politecnico di Torino (see, as an example, Fig. 6) show that $\eta_{\text{KE-yoyo}} \simeq 0.7$. Then, the average generated electrical current value $\overline{i}^{\text{KE-yoyo}}$ can be computed as:

$$\overline{i}^{\text{KE-yoyo}} = \frac{\overline{P}^{\text{KE-yoyo}}}{V^{\text{battery}}} \tag{16}$$

4. OPTIMIZATION OF A HYBRID KITE BOAT

The optimization problem and related objectives are now described. The variables to be optimized are $\overline{\theta}$ and $\overline{\phi}$, that roughly give the wing position with respect to the boat, the reference cable speed during the KE-yoyo traction phase, $\dot{r}_{\text{ref}}^{\text{trac}}$, and during the passive phase, $\dot{r}_{\text{ref}}^{\text{pass}}$, and the reference boat speed, v_{ref}. As highlighted in Section 1, the aim is to compute, for given wind speed and angle Θ, the operating conditions that maximize the boat speed, while feeding the boat auxiliaries with the required power and satisfying other operational constraints. The average cable length $\overline{r}$ is fixed a priori, as well as the total cable length variation during a cycle, Δr, to reasonable values that have been used also in experiments on the boat prototype (see the KiteNav project website (2010)). In particular, these values are $\overline{r} = 200\,\text{m}$ and $\Delta r = 50\,\text{m}$. The constraints to be taken into account are the following:

a) an upper limit $\theta^{\max}$ is imposed to the angle $\overline{\theta}$, to prevent the kite from getting too close to the sea;
b) in order to find an operating condition which is meaningful from a physical point of view, the projection of the effective wind speed vector along the cable direction, $\boldsymbol{W}_{e,r}$ (14), has to be positive;
c) the magnitude of the reference cable speeds, $\dot{r}_{\text{ref}}^{\text{trac}}$ and $\dot{r}_{\text{ref}}^{\text{pass}}$, is limited by a value $\overline{\dot{r}}$, to avoid excessive cable wear;
d) an upper limit to the average roll torque, $\overline{T}_{\text{roll}}$, exerted by the cables on the boat, is imposed to avoid excessive roll angles;
e) the average electrical power generated by the KE-yoyo, $\overline{P}^{\text{KE-yoyo}}$, must be higher than the power required by the onboard auxiliaries, $P_{\text{aux}}^{\text{elt}} = i^{\text{aux}} V^{\text{battery}}$. To this end, a constant value of i^{aux} is considered;
f) the amount of energy generated by the KE-yoyo during the traction phase has to be sufficiently high to supply the electric propellers during the passive phases, when the traction forces on the cable collapse and the propellers are employed to keep the boat speed constant;
g) finally, the boat reference speed must correspond to an equilibrium of the longitudinal forces applied to the boat, i.e. $\dot{v}$ (3) has to be zero.

The constraint d) can be taken into account as a constraint on the cable force, since the average roll torque can be computed as:

$$\overline{T}_{\text{roll}} = \overline{F}^{\text{c,trc}} \sin(\overline{\theta}) \sin(\overline{\phi}) d_{\text{roll}}, \tag{17}$$

where d_{roll} is the distance, along axis Z, between the KSU and the boat roll center. Constraint f) can be expressed as a minimal average power, $P_{\text{req}}^{\text{elt}}$, that has to be generated by the KE-yoyo during each traction phase. Through straightforward manipulations, $P_{\text{req}}^{\text{elt}}$ can be computed as:

$$P_{\text{req}}^{\text{elt}}(v_{\text{ref}}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}) = v_{\text{ref}} F^{\text{R}}(v_{\text{ref}}) \frac{\dot{r}_{\text{ref}}^{\text{trac}}}{\dot{r}_{\text{ref}}^{\text{pass}}} \tag{18}$$

Then, constraints e) and f) can be considered together, by asking that the average generated power is higher than an overall required power, $\overline{P}_{\text{req}}^{\text{elt}}$:

$$\overline{P}_{\text{req}}^{\text{elt}}(v_{\text{ref}}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}) = P_{\text{req}}^{\text{elt}}(v_{\text{ref}}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}) + P_{\text{aux}}^{\text{elt}} \tag{19}$$

All the generated electrical power that exceeds the value of $\overline{P}_{\text{req}}^{\text{elt}}$ is assumed to be used by the electric propellers, so that the resulting average propelling force, $\overline{F}^{\text{motor}}$, can be computed as:

$$\overline{F}^{\text{motor}} = \eta_{\text{motor}} \frac{\overline{P}^{\text{KE-yoyo}} - \overline{P}_{\text{req}}^{\text{elt}}}{v_{\text{ref}}} \tag{20}$$

Finally, the constraint g) can be enforced by imposing, according to (3), that:

$$\overline{F}^{\text{tow}} + \overline{F}^{\text{motor}} - F^{\text{R}}(v_{\text{ref}}) = 0,$$

where

$$\overline{F}^{\text{tow}} = \overline{F}^{\text{c,trc}} \cos(\overline{\phi}) \sin(\overline{\theta}).$$

The resulting optimization problem is formulated as follows:

$$\begin{array}{c} \left(\overline{\theta}^*, \overline{\phi}^*, \dot{r}_{\text{ref}}^{\text{trac}*}, \dot{r}_{\text{ref}}^{\text{pass}*}, v_{\text{ref}}^*\right) = \arg \max\limits_{\overline{\theta}, \overline{\phi}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}, v_{\text{ref}}} v_{\text{ref}} \\ \text{s. t.} \\ \overline{\theta} \leq \theta^{\max} \\ \boldsymbol{W}_{e,r} > 0 \\ \dot{r}_{\text{ref}}^{\text{trac}} \leq \overline{\dot{r}} \\ \dot{r}_{\text{ref}}^{\text{pass}} \geq -\overline{\dot{r}} \\ \overline{F}^{\text{c,trc}} \sin(\theta) \sin(\phi) d_{\text{roll}} \leq \overline{T}_{\text{roll}} \\ \overline{P}^{\text{KE-yoyo}} \geq \overline{P}_{\text{req}}^{\text{elt}}(v, \dot{r}) \\ \overline{F}^{\text{tow}} + \overline{F}^{\text{motor}} - F^{\text{R}}(v_{\text{ref}}) = 0 \end{array} \tag{21}$$

The numerical values of the parameters employed in this paper are reported in Table 1 and are related to the boat prototype of the KiteNav project, equipped with a large 160-m^2 area kite. The optimization problem (21) has been solved, by using the

Table 1. Numerical values used in the optimization problem

Kite and boat parameters		
A	160	Kite characteristic area (m^2)
d_l	0.02	Diameter of a single line (m)
E	8	Kite aerodynamic efficiency
C_L	1.1	Kite lift coefficient
$C_{D,l}$	1	Line drag coefficient
M	12	Boat mass (t)
ρ	1.2	Air density (kg/m^3)
$\overline{r}$	200	Ave. cable length (m)
Δr	50	Cable length variation (m)
d_{roll}	1.5	Vertical distance between the KSU and the boat roll center (m)
$\eta_{\text{KE-yoyo}}$	0.7	KE-yoyo cycle efficiency
η_{motor}	0.55	Electric propellers performance
Wind shear model parameters		
$\overline{Z}$	7.5	Ref. wind speed (m/s)
$\overline{W}$	70	Ref. height (m)
β	0.15	Power-law coefficient
Constraints		
$\overline{T}_{\text{roll}}$	$1\,10^5$	Maximal roll torque (Nm)
$\theta^{\max}$	80	Maximal value of $\overline{\theta}$ (°)
$\overline{\dot{r}}$	10	Maximal cable speed (m/s)

MatLab® function `fmincon`, for $\Theta \in [0, 180°]$, so that any boat direction w.r.t. the wind direction is considered, and with three different values of current i^{aux} used by the boat auxiliaries: $i^{\text{aux}} = 0$ (no auxiliaries), $i^{\text{aux}} = 1\text{kW}$ and $i^{\text{aux}} = 2\text{kW}$. The obtained results are shown in Fig. 7-8. In particular, Fig. 7 shows the speed v_{ref}^* achievable by the boat as a function of Θ: as suggested by physical intuition, the maximal speed is achieved when the boat direction is roughly perpendicular to the wind direction. The kite optimal position, in terms of average angles $\overline{\theta}^*$ and $\overline{\phi}^*$, and the optimal cable speed in the traction phase, $\dot{r}_{\text{ref}}^{\text{trac}*}$, are shown as a function of Θ in Fig. 8(a)-(c). It can be noted that for $\Theta = 0$ and up to $\Theta \simeq 120°$ the cable speed is zero or very low (the minimal needed to supply the

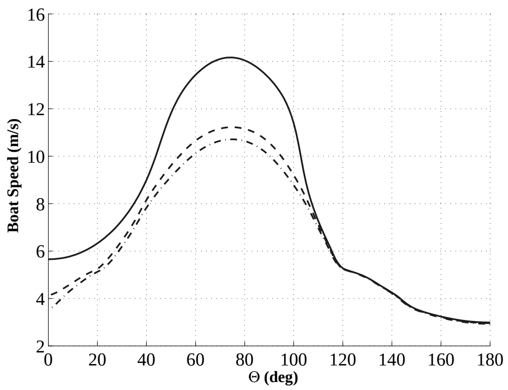


Fig. 7. Maximum achievable speed as a function of boat trajectory Θ. Solid, dashed and dash dotted lines show results for value of $P_{\text{aux}}^{\text{elt}}$ of, respectively, 0, 1 and 2 kW

auxiliaries), meaning that boat propulsion is made mainly by the traction forces exerted by the cables on the boat. Then, for higher values of Θ, up to $180°$ (i.e. when the boat travels straight in upwind direction), the cable speed is higher, since the KE-yoyo is used to generate electricity that supplies the electric propellers. As a result, a completely green naval propulsion is obtained regardless of the wind direction, with boat speed values ranging approximately from 4-6 m/s (with $\Theta = 0°$) to 10-14 m/s (with $\Theta = 80°$) to 3 m/s (with $\Theta = 180°$). The wind speed at the kite optimal operating conditions, according to the employed wind shear model, is equal to 7 m/s. Finally, the optimal value of the cable speed $r_{\text{ref}}^{\text{pass}*}$ during the recovery phase results to be equal to -10 m/s (i.e. the minimal value), independently on Θ and i^{aux}.

5. CONTROL DESIGN

In order to assess the feasibility of the results obtained in Section 4, numerical simulations are performed, using the dynamical model of the hybrid kite boat described in Section 3.1. A feedback control strategy is needed, in order to carry out such simulations. Local PID controllers are employed for the electric propellers and the cable speed of the KE-yoyo, while a NMPC technique is designed to control the kite flight.

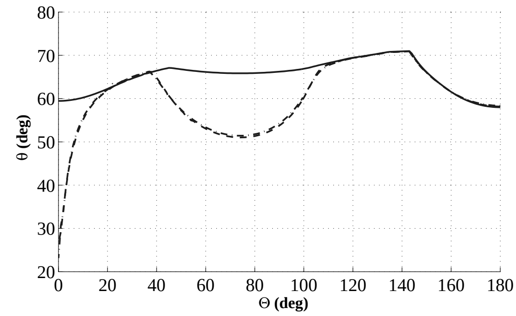
In NMPC, the control move computation is performed at discrete time instants, defined on the basis of a suitably chosen sampling period Δ_t. At each sampling time $t_k = k\Delta_t$, $k \in \mathbb{N}$, the control move is computed through the optimization of a performance index of the form:

$$J(U, x(t_k)) = \int_{t_k}^{t_k+T_p} L(\tilde{x}(\tau), \tilde{u}(\tau))d\tau \qquad (22)$$

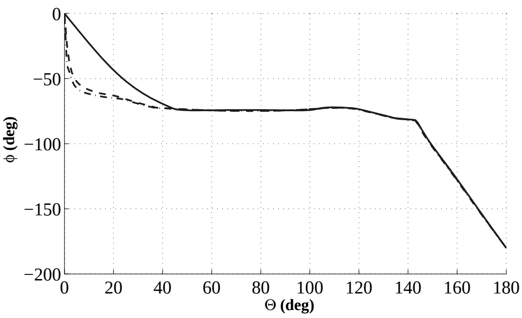
where $T_p = N_p\Delta_t,\ N_p \in \mathbb{N}$ is the prediction horizon, $\tilde{x}(\tau)$ is the state predicted inside the prediction horizon according to the state equation (11), using $\tilde{x}(t_k) = x(t_k)$ and the piecewise constant control input $\tilde{u}(t)$ belonging to the sequence $U = \{\tilde{u}(t)\}$, $t \in [t_k, t_{k+T_p}]$ defined as:

$$\tilde{u}(t) = \begin{cases} \bar{u}_i,\ \forall t \in [t_i, t_{i+1}],\ i = k, \ldots, k + T_c - 1 \\ \bar{u}_{k+T_c-1},\ \forall t \in [t_i, t_{i+1}],\ i = k + T_c, \ldots, k + T_p - 1 \end{cases} \qquad (23)$$

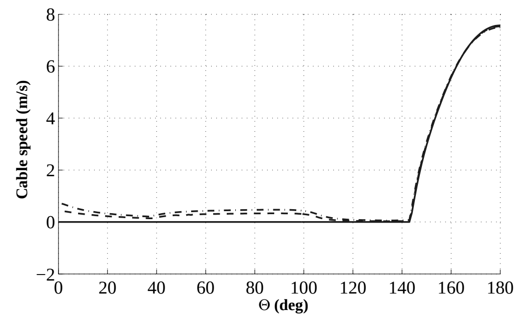
where $T_c = N_c\Delta_t,\ N_c \in \mathbb{N},\ N_c \leq N_p$ is the control horizon. The stage cost $L(\cdot)$ in (22) has to be suitably designed on the basis of the performance to be obtained. In this case, the aim is to achieve the optimal operating conditions computed in Section 4, so function $L(\cdot)$ is chosen as:



(a) Optimal angle $\overline{\theta}^*$ as a function of angle Θ between the boat direction and the wind direction.



(b) Optimal angle $\overline{\phi}^*$ as a function of angle Θ between the boat direction and the wind direction.



(c) Optimal cable unrolling speed $r_{\text{ref}}^{\text{trac}*}$ as a function of angle Θ between the boat direction and the wind direction.

Fig. 8. Hybrid kite boat optimization results for three different values of current drawn by the boat auxiliaries, $P_{\text{aux}}^{\text{elt}}$: 0 kW (solid), 1 kW (dashed) and 2 kW (dash-dotted).

$$\begin{aligned} &L(\tilde{x}(\tau), \tilde{u}(\tau)) = \\ &-\left[(\tilde{\theta}(\tau) - \overline{\theta}^*(\Theta, P_{\text{aux}}^{\text{elt}}))^2 + (\tilde{\phi}(\tau) - \overline{\phi}^*(\Theta, P_{\text{aux}}^{\text{elt}}))^2\right] \end{aligned} \qquad (24)$$

i.e. the distance between the predicted values of θ and ϕ and their optimal values for the actual values of Θ and $P_{\text{aux}}^{\text{elt}}$. Finally, the following operational constraints, described in Section 4, have been included:

$$\begin{aligned} \theta &\leq \theta^{\max} \\ F^{\text{c,trc}} \sin(\theta)\sin(\phi)d_{\text{roll}} &\leq \overline{T}_{\text{roll}}, \end{aligned} \qquad (25)$$

as well as technical constraints that force the kite to go along "figure eight" trajectories, by making the ϕ angle oscillate with double period with respect to the θ angle, in order to prevent the lines from wrapping one around the other.

The NMPC law is then computed by using a receding horizon strategy, as described e.g. by Mayne et al. (2000). The control law results to be a nonlinear static function of the system state x, of the boat direction Θ w.r.t. the nominal wind direction, of the power required by the boat auxiliaries, $P_{\text{aux}}^{\text{elt}}$, and of the wind conditions, in terms of the wind shear model parameters $\overline{Z}$, $\overline{W}$ and β:

Table 2. Model and control parameters employed for the numerical simulations

$\dot{r}_{\text{ref}}^{\text{trac}*}$	0.3	Cable speed - traction phase (m/s)
$\dot{r}_{\text{ref}}^{\text{pass}*}$	-10	Cable speed - passive phase (m/s)
v_{ref}^{*}	10.6	Boat reference speed (m/s)
Θ	80	Boat direction w.r.t. wind direction (°)
$P_{\text{aux}}^{\text{elt}}$	2	Electrical power for board equipments (kW)
V_{battery}	300	Battery voltage (V)
$\overline{\theta}^{*}$	51	Target θ value (°)
$\overline{\phi}^{*}$	-75	Target ϕ value (°)
Δ_t	0.2	Sample time (s)
N_c	1	Control horizon (steps)
N_p	10	Prediction horizon (steps)

$$\psi(t_k) = \kappa(x(t_k), \Theta, \overline{Z}, \overline{W}, \beta) \quad (26)$$

In practice, an efficient NMPC implementation is required to ensure that the control move is computed within the employed sampling time, of the order of 0.2 s. This can be obtained using e.g. the Fast Model Predictive Control (FMPC) techniques introduced and described in Canale et al. (2010b).

6. SIMULATION RESULTS

In the presented simulation tests, wind turbulence is taken into account by adding a uniformly distributed random signal to the nominal wind in all three directions X, Y, Z, with a maximal amplitude of 2.5 m/s (i.e. approx 35% of the wind speed at the kite target operating altitude). The employed numerical values of the system and control parameters are reported in Tables 1-2. The kite aerodynamic coefficients are computed, in the numerical simulations, as a function of the angle of attack, as described by Canale et al. (2010a) and Fagiano (2009). The reference values of the boat speed, v_{ref}^{*}, and of the cable speed, $r_{\text{ref}}^{\text{trac}*}$, $r_{\text{ref}}^{\text{pass}*}$, and the target values $\overline{\theta}^{*}$ and $\overline{\phi}^{*}$ for the NMPC controller (see (24)) correspond to the optimal values computed as described in Section 4 for the considered values of Θ and $P_{\text{aux}}^{\text{elt}}$, i.e. 80° and 2 kW respectively. Fig. 9 shows the obtained kite and boat trajectories during a simulation of 600 s. The value assumed by θ and ϕ angles are shown in Fig. 10 and 11: it can be noted that the average values during the traction phase are $\overline{\theta} = 49°$ and $\overline{\phi} = -73°$, quite close to the optimal ones even in the presence of wind turbulence. As regards the electric power, the energy production is sufficient to supply the onboard auxiliaries and the electric propellers, thus confirming the results of the optimization study carried out in this paper: in fact, the battery state of charge Q (reported in Fig. 12) oscillates between 76% and 85%, with an overall rising trend.

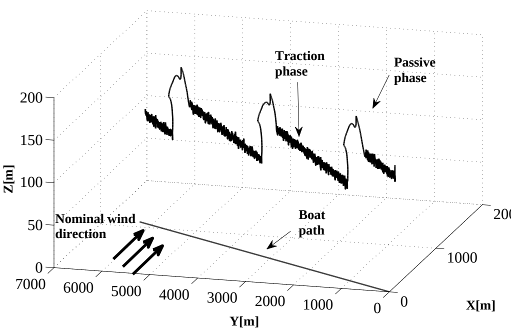


Fig. 9. Simulation results: boat and kite trajectories obtained with $\Theta = 80°$.

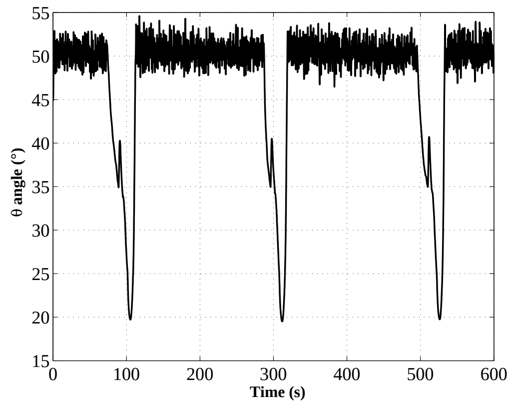


Fig. 10. Simulation results: course of θ angle obtained with $\Theta = 80°$.

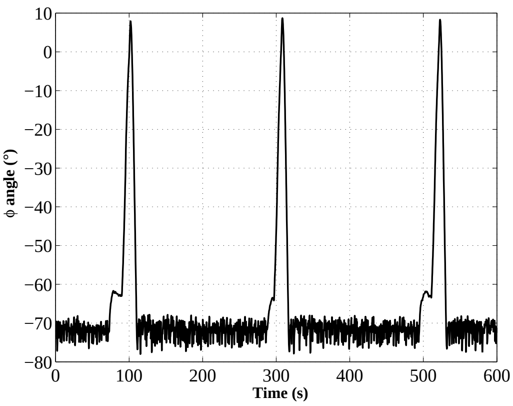


Fig. 11. Simulation results: course of ϕ angle obtained with $\Theta = 80°$.

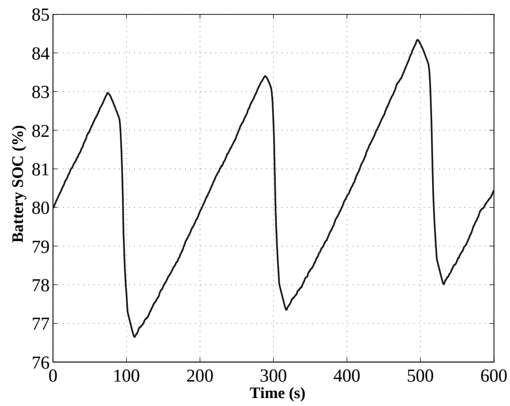


Fig. 12. Simulation results: battery state of charge obtained with $\Theta = 80°$.

7. CONCLUSIONS

The paper presented a study on the application of Kitenergy technology for marine transportation. A hybrid kite boat has been considered, i.e. a boat equipped with electric propellers and a Kitenergy generator. A constrained optimization problem has been formulated and solved numerically in order to compute the system operating conditions that maximize the boat speed. Then, numerical simulations have been carried out, by using a detailed dynamical model of the system, to assess the feasibility of the computed optimal solutions, also in the presence of wind turbulence. The obtained results indicate that a hybrid kite boat can achieve completely green naval transportation even when sailing straight upwind.

REFERENCES

C. L. Archer and M. Z. Jacobson. Evaluation of global wind power. *J. Geophys. Res.*, 110, D12110, 2005.

I. Argatov, P. Rautakorpi, and R. Silvennoinen. Estimation of the mechanical energy output of the kite wind generator. *Renewable Energy*, 34:1525, 2009.

M. Canale, L. Fagiano, and M. Milanese. High altitude wind energy generation using controlled power kites. *Control Systems Technology, IEEE Transactions on*, 18 (2):279 –293, mar. 2010a. ISSN 1063-6536. doi: 10.1109/TCST.2009.2017933.

M. Canale, L. Fagiano, and M. Milanese. Efficient model predictive control for nonlinear systems via function approximation techniques. *IEEE Transactions on Automatic Control*, 55(8):1911 –1916, august 2010b. doi: 10.1109/TAC.2010.2049776.

L. Fagiano, M. Milanese, and D. Piga. High-altitude wind power generation. *IEEE Transactions on Energy Conversion*, 25(1):168 –180, mar. 2010a. ISSN 0885-8969. doi: 10.1109/TEC.2009.2032582.

L. Fagiano, M. Milanese, V. Razza, and I. Gerlero. Control of power kites for naval propulsion. In *American Control Conference*, Balitmore, MA, 2010b.

Lorenzo Fagiano. *Control of Tethered Airfoils for High–Altitude Wind Energy Generation*. PhD thesis, Politecnico di Torino, Italy, February 2009. Available on–line: http://lorenzofagiano.altervista.org/docs/PhD_thesis_Fagiano_Final.pdf.

B. Houska and M. Diehl. Optimal control of towing kites. In *45th IEEE Conference on Decision and Control*, pages 2693–2697, San Diego, CA, 2006.

A. Ilzhöfer, B. Houska, and M. Diehl. Nonlinear MPC of kites under varying wind conditions for a new class of large-scale wind power generators. *International Journal of Robust and Nonlinear Control*, 17:1590–1599, 2007.

KiteNav project website, 2010. http://www.kitenav.com.

M. L. Loyd. Crosswind kite power. *Journal of Energy*, 4(3): 106–111, 1980.

D. Q. Mayne, J. B. Rawlings, C. V. Rao, and P.O.M. Scokaert. Constrained model predictive control: Stability and optimality. *Automatica*, 36:789–814, 2000.

National Oceanic & Atmospheric Administration – Earth System Research Laboratory, 2009. NOAA/ESRL Radiosonde Database Access: http://www.esrl.noaa.gov/raobs/.

SkySails GmbH & Co., 2010. http://www.skysails.info.

P. Williams, B. Lansdorp, and W. Ockels. Optimal crosswind towing and power generation with tethered kites. *Journal of guidance, control, and dynamics*, 31:81–93, 2008.