Control of tethered airfoils for sustainable marine transportation

M. Canale*, L. Fagiano*, M. Milanese*, V. Razza*

***Abstract*— The application to marine transportation of an innovative technology for high-altitude wind power generation is presented in this paper. The key idea is to pull a boat and to generate electricity onboard by exploiting the traction forces generated by automatically controlled tethered power kites. The kites are able to fly fast in crosswind conditions, between 200 m and 600 m above the sea, thus exploiting the stronger and less variable high-altitude winds. Numerical analyses are carried out, using a mathematical model of the system and an efficient Nonlinear Model Predictive Control (NMPC) law. The control law aims to maximize a cost function that takes into account both the traction forces exerted on the boat and the generated electricity, while satisfying the kite operational constraints. The obtained numerical results are compared with the data collected during experimental tests carried out with a small-scale prototype in the project KiteNav, undergoing at Politecnico di Torino.**

I. INTRODUCTION

The use of tethered airfoils to extract energy from high-altitude wind flows has been firstly investigated in the late '70s, showing that significant traction forces on the tethers can be obtained by making the airfoil fly fast in crosswind direction [1]. Such traction forces can then be exploited to generate energy in different possible ways. Yet, only in relatively recent times deeper studies have been carried out (see e.g. [2], [3], [4], [5]) to assess the potential of this concept of high-altitude wind energy through theoretical, numerical and experimental research activities. The idea is to harvest wind energy using airfoils (e.g. power kites used for surfing or sailing), linked to the ground by one or two cables, whose flight is suitably driven by an automatic control unit. Wind energy is then collected at ground level by converting the mechanical power transferred by the kite lines into electrical power, using suitable rotating mechanisms and electric generators. Such a technology, indicated here as Kitenergy, is able to exploit wind flows at higher altitudes (up to 1000 m) than the actual wind technology, where quite strong and constant wind can be found basically everywhere in the world, with reduced costs and lower environmental impact. Among the different possible configurations of Kitenergy technology, the so-called KE-yoyo generator is under investigation at Politecnico di Torino, where a small-scale prototype has been also built (see [5]).

The described concept of high-altitude wind power generation is being also applied in the field of marine transportation. In particular, the forces acting on the cable(s) can be exploited for naval propulsion, an idea that is being currently developed and industrialized by some companies around the world, like SkySails GmbH [6]. By using a 160-m^2-area kite with a single cable and actuators placed onboard of the airfoil, SkySails GmbH claims that a 30% reduction of fuel consumption can be achieved on large transportation ships. Moreover, the potential of a kite boat system similar to the one of [6] has been studied in [7], considering the problem of computing kite orbits that are optimal with respect to the traction forces applied to the boat. In [7] and in the systems developed by SkySails, the cable length is fixed and wind energy is employed only to tow the boat. Indeed, the use of tethered airfoils to tow a boat brings several advantages with respect to classical sails, due to the possibility for the airfoils to reach stronger winds blowing at higher altitudes and to fly fast in crosswind direction, without being fixed with respect to the boat, thus maximizing the traction forces. Moreover, by installing a KE-yoyo generator on the ship, onboard energy generation can be added to naval propulsion. The generated energy can then be suitably stored and used to supply power to onboard electrical devices and eventually electric engines, to be used when the wind conditions and/or the boat course are not suitable for kite naval propulsion (e.g. when entering into an harbor). In this paper, the above-described idea of using a KE-yoyo generator to achieve both naval propulsion and onboard energy generation is investigated considering a small boat (i.e. a 38–feet–long yacht). Such a study is part of the KiteNav project undergoing at Politecnico di Torino, in which the existing prototype KE-yoyo has been recently installed on a boat. In the system configuration considered here, the kite is linked with two cables to the boat, instead of the single cable considered in [6], [7]. This way, the kite can be controlled by differentially pulling the lines via actuators placed on the boat and avoiding the use of wireless actuators on the airfoil. Moreover, in the case of breaking of one cable, the presence of two lines makes it possible to recover both the airfoil and the lines.

Automatic control is a key point in Kitenergy technology, since the system to be controlled is nonlinear, open-loop unstable and subject to hard operational constraints. In order to tackle such a challenging control problem, a Fast implementation of Model Predictive Control (FMPC) is used (see e.g. [8]). Differently from [3], [7], in this work no pre-computed optimal kite orbits are tracked and the control law is designed in order to directly maximize a performance index, given by a weighted sum of traction energy and electric energy generated over the considered prediction horizon. The idea is that a human operator can then change the weights employed in the cost function in

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*Politecnico di Torino, Dipartimento di Automatica e Informatica, Corso Duca degli Abruzzi 24 – 10129 Torino – Italy

e–mail addresses: massimo.canale@polito.it, lorenzo.fagiano@polito.it, mario.milanese@polito.it, valentino.razza@polito.it

order to decide whether to privilege the boat traction energy (i.e. boat speed) or electric energy generation. Moreover, simplified equations giving the generated power as a function of the kite operating conditions are employed in this paper in order to design the operating parameters of the KE-yoyo installed on the boat and to evaluate the performance of the automatic control system. Numerical simulations using the designed NMPC law are then performed to study the system behaviour and its robustness to wind turbulence. Finally, numerical results are also compared with the first experimental data, collected in the KiteNav project during tests performed near Genoa, Italy.

II. SYSTEM DESCRIPTION, MODEL EQUATIONS AND CONTROL OBJECTIVE

A. System description

In the considered application of high–altitude wind power to naval propulsion, a KE-yoyo generator is installed on a boat (see Fig. 1). In a KE-yoyo, the kite is connected to the boat by two cables, realized in composite materials, with a traction resistance 8–10 times higher than that of steel cables of the same weight. The cables are rolled around two drums, linked to two electric drives which are able to act both as generators and as motors. An electronic control system can drive the kite flight by differentially pulling the cables. The kite flight is tracked and controlled using on–board wireless instrumentation (GPS, magnetic and inertial sensors) as well as ground sensors, to measure the airfoil speed and position, the power output, the cable force and speed 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).

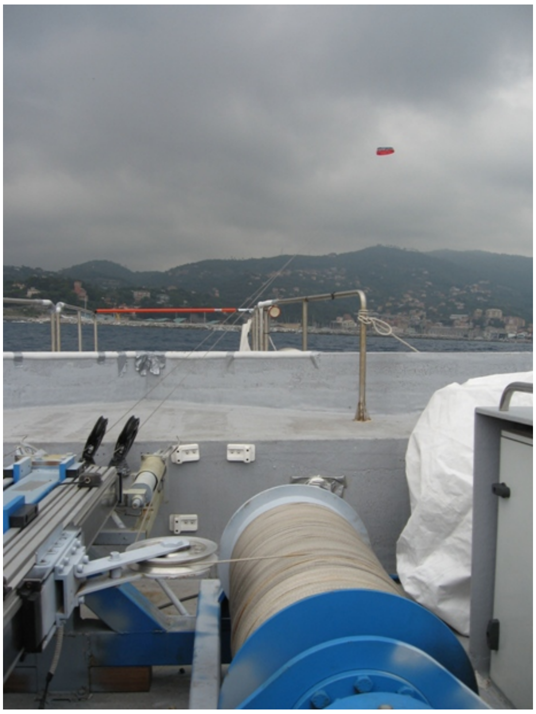

Fig. 1. KE-yoyo prototype installed on a boat and operating near Genoa, Italy.

The next Section presents the mathematical model employed to describe the dynamical behaviour of the system.

B. Model equations

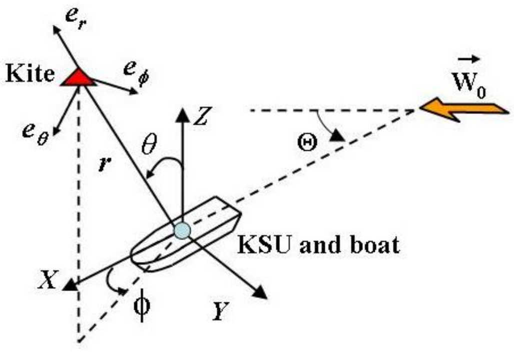

Fig. 2. Model diagram of the system.

A Cartesian coordinate system (X, Y, Z) is considered (see Fig. 2), centered at the boat location (i.e. at the KSU, which is fixed with respect to the boat), with X axis aligned with the longitudinal symmetry axis of the boat. Wind speed vector is denoted as $\vec{W}_l = \vec{W}_0 + \vec{W}_t$, where $\vec{W}_0$ is the nominal wind, supposed to be known and expressed in (X, Y, Z) as:

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

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 wind shear model (see e.g. [9]), which has been identified using the data contained in the database RAOB (RAwinsonde OBservation) of the National Oceanographic and Atmospheric Administration, see [10]. An example of winter and summer wind shear profiles related to the site of Cagliari in Italy is reported in Fig. 3. The term $\vec{W}_t$ may have components in all directions and is not supposed to be known, accounting for wind unmeasured turbulence. 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. 2, 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_θ, e_ϕ, e_r) are expressed in the Cartesian system (X, Y, Z) by:

$$\begin{pmatrix} e_\theta & e_\phi & e_r \end{pmatrix} = \begin{pmatrix} \cos(\theta)\cos(\phi) & -\sin(\phi) & \sin(\theta)\cos(\phi) \\ \cos(\theta)\sin(\phi) & \cos(\phi) & \sin(\theta)\sin(\phi) \\ -\sin(\theta) & 0 & \cos(\theta) \end{pmatrix} \tag{2}$$

The dynamical equations of motion of the boat and of the kite will be now briefly resumed.

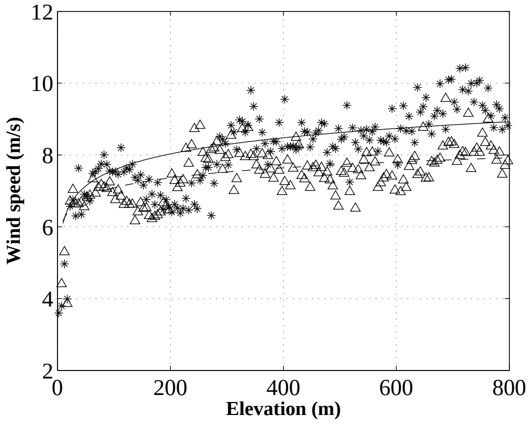

Fig. 3. Wind shear model related to the site of Cagliari, in Italy, for winter months (model: solid line, measured data: asterisks) and for summer months (model: dashed line, measured data: triangles)

1) Boat model: the following assumptions are considered:

- the boat rudder is commanded in such a way that the boat speed vector $\vec{v}$ 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.

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, which is of interest in this work. Since the speed vector $\vec{v}$ 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. On the basis of the considered assumptions, the boat model is given by the following equation:

$$\dot{v} = \frac{F^{\text{c,trc}} \sin(\theta)\cos(\phi) - F^R(v)}{M} \tag{3}$$

where M is the boat mass, $F^{\text{c,trc}}$ is the traction force exerted by the lines on the boat (see Section II-B.2) and $F^R(v)$ is the longitudinal drag force acting on the boat moving at a given speed v. Function $F^R(v)$ can be identified through experimental tests on the boat; in this paper the following form is considered:

$$F^R(v) = R_4 v^4 + R_3 v^3 + R_2 v^2 + R_1 v \tag{4}$$

where $R_4 = 56.9$, $R_3 = -130.7$, $R_2 = 256.9$ and $R_1 = 165.4$. Such values have been identified through tests on the real boat employed in the KiteNav project, built by the project partner Azimut–Benetti s.p.a., and can be considered valid for boat speed values ranging from 0 m/s to 10 m/s.

2) Airfoil's model: The airfoil's model is thoroughly presented in [5], and only a concise description is given here for the sake of completeness. By applying Newton's laws of motion to the kite in the local coordinate system $(e_\theta,\, e_\phi,\, e_r)$, the following dynamic equations are obtained:

$$\begin{aligned} \ddot{\theta} &= \frac{F_\theta}{m\,r} \\ \ddot{\phi} &= \frac{F_\phi}{m\,r\sin\theta} \\ \ddot{r} &= \frac{F_r}{m} \end{aligned} \tag{5}$$

where m is the kite mass. Forces F_θ, F_ϕ and F_r include the contributions of gravity force $\vec{F}^{\text{grav}}$ of the kite and the lines, apparent force $\vec{F}^{\text{app}}$, kite aerodynamic force $\vec{F}^{\text{aer}}$, aerodynamic drag force $\vec{F}^{\text{c,aer}}$ 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 $\vec{F}^{\text{aer}}$ can be derived via the computation of the lift and drag forces, $\vec{F}_L$ and $\vec{F}_D$ 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 respectively, which in turn depend on the kite attack angle α (see [5] for more details), finally on the command angle ψ, i.e. the control variable. The latter is defined as

$$\psi \doteq \arcsin\left(\frac{\Delta l}{d}\right) \tag{6}$$

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 $\vec{F}^{\text{c,aer}}$ and the traction force $F^{\text{c,trc}}$. $\vec{F}^{\text{c,aer}}$ 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 local 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.

3) 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)–(6) give the system dynamics in the form:

$$\dot{x}(t) = f(x(t), u(t), \Theta, \vec{W}_t(t), \dot{r}_{\text{ref}}) \tag{7}$$

where $x(t) = [\theta(t)\ \phi(t)\ r(t)\ \dot{\theta}(t)\ \dot{\phi}(t)\ \dot{r}(t)\ v(t)]^T$ 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 behaviour.

C. Control objective

As highlighted in Section I, the control objective is to maximize the weighted sum of the power used for boat propulsion and of the electrical power generated by the KE-yoyo. In a KE-yoyo, electric energy is generated by continuously repeating a two-phase cycle: in the *traction phase* the kite is controlled so to fly fast in crosswind direction and the cables are unrolled at a positive reference speed $\dot{r}^{\text{ref},1}$ with high traction forces, thus generating energy through the electric drives; when the maximal line length is reached, the *passive phase* begins and the kite is controlled so that the traction forces collapse and the cables are then rolled back at a negative reference speed $\dot{r}^{\text{ref},2}$, spending less than 10% of the energy collected in the previous phase (see [5], [11] for details on the KE-yoyo cycle). Clearly, if a KE-yoyo is installed on a boat the traction forces acting on the cables can be used both for boat propulsion and for electricity generation and a suitable tradeoff between these two effects should be set up. For example, assuming that the boat is moving with $\Theta = 0$ (i.e. downwind), electricity can be generated by unrolling the lines at the expense of lower traction forces, since the kite effective wind speed decreases due to the line unrolling. The idea of this paper is to let a human operator change the desired balance between boat propulsion and energy generation according to the navigation conditions. This can be done by modifying suitable weights, employed to compute a performance index given by the sum of the two power contributions. Then, the automatic control system is designed in order to maximize such a performance index. Moreover, the control system has also to guarantee that operational constraints are not violated (e.g. the airfoil has to fly higher than a minimal prescribed altitude and the cable must be twisted), as well as input constraints on the maximal value of angle ψ and of its speed $\dot{\psi}$, due to physical limitations of the electric drives employed to issue the line length difference Δl. Since the system model (7) is nonlinear and the described control problem involves the maximization of a performance index while satisfying input and state constraints, Nonlinear Model Predictive Control is adopted in this work, as described in the next Section.

III. CONTROL DESIGN

In Nonlinear Model Predictive Control strategy (NMPC, see e.g. [12]), 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:

$$J(U, x(t_k)) = \int_{t_k}^{t_k+T_p} L(\tilde{x}(\tau), \tilde{u}(\tau))d\tau \tag{8}$$

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 (7), 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:

$$\tilde{u}(t) = \begin{cases} \bar{u}_i,\ \forall t \in [t_i, t_{i+1}],\ i = k, \ldots, k+T_c-1 \\ \bar{u}_{k+T_c-1},\ \forall t \in [t_i, t_{i+1}],\ i = k+T_c, \ldots, k+T_p-1 \end{cases} \tag{9}$$

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 (8) has to be suitably designed on the basis of the performance to be achieved. In the considered problem, the aim is to maximize a performance index of the form:

$$E^{\text{tot}} = \mu^{\text{tow}} \int_{t_k}^{t_k+T_p} P^{\text{tow}} d\tau + \mu^{\text{elt}} \int_{t_k}^{t_k+T_p} P^{\text{elt}} d\tau. \tag{10}$$

In (10), μ^{tow} and μ^{elt} are weighting factors chosen by a human operator, P^{tow} is the mechanical power employed to tow the boat at a given speed v:

$$P^{\text{tow}} = F^{\text{c,trc}} \sin(\theta)\cos(\phi)v, \tag{11}$$

while P^{elt} is the electric power generated/spent by unrolling/rolling back the lines:

$$P^{\text{elt}} = \eta F^{\text{c,trc}} \dot{r} \tag{12}$$

where $\eta \in (0, 1)$ is the conversion efficiency of the KSU. Thus, considering equations (10)-(12), function $L(\cdot)$ is chosen as:

$$L(x, u, \Theta) = -\left(\mu^{\text{tow}} F^{\text{c,trc}} \sin(\theta)\cos(\phi)v + \mu^{\text{elt}} \eta F^{\text{c,trc}} \dot{r}\right) \tag{13}$$

i.e. the weighted sum of towing power and electrical power.

Moreover, as already pointed out in Section II-C, the KE-yoyo cycle is adopted in order to achieve a continuous system operation. The same stage cost (13) is employed during both the traction and the passive phases of the KE-yoyo cycle, while the reference speeds $\dot{r}^{\text{ref},1} > 0$ and $\dot{r}^{\text{ref},2} < 0$ employed during the cycle are chosen according to the wind conditions (see [5]). Assuming that the traction phase starts at a minimal line length $\underline{r}$, the reference speed $\dot{r}^{\text{ref},1}$ is imposed until the cable length reach a maximal value $\overline{r}$. Then, the passive phase starts and the reference speed is smoothly changed to $\underline{r}$ until the initial line length $\underline{r}$ is reached again.

Finally, in order to take into account the existing physical limitations on both the kite flight and the control input ψ, constraints of the form $\tilde{x}(t) \in \mathbb{X}$, $\tilde{u}(t) \in \mathbb{U}$ have been included too. In particular, the following state constraint is considered to keep the kite sufficiently far from the ground:

$$\theta(t) \leq \overline{\theta} \tag{14}$$

with $\overline{\theta} < \pi/2$ rad. Actuator physical limitations give rise to the constraints:

$$\begin{array}{l} |\psi(t)| \leq \overline{\psi} \\ |\dot{\psi}(t)| \leq \overline{\dot{\psi}} \end{array} \tag{15}$$

As a matter of fact, other technical constraints have been added to force the kite to go along "figure eight" trajectories rather than circular ones, in order to prevent the lines from wrapping one around the other. Such constraints force the kite ϕ angle to oscillate with double period with respect to θ angle, thus generating the proper kite trajectory.

The predictive control law is then computed using a receding horizon strategy:

1) At time instant t_k, get $x(t_k)$, Θ, $\dot{r}^{\text{ref}}(t_k)$, μ^{tow} and μ^{trc}.
2) Solve the optimization problem:

$$\min_{U} \quad J(U, t_k) \tag{16a}$$

$$\text{subject to} \tag{16b}$$

$$\tilde{x}(t_k) = x(t_k) \tag{16c}$$

$$\dot{\tilde{x}}(t) = f(\tilde{x}(t), \tilde{u}(t), \Theta) \; \forall t \in (t_k, t_{k+T_p}] \tag{16d}$$

$$\tilde{x}(t) \in \mathbb{X}, \; \tilde{u}(t) \in \mathbb{U} \; \forall t \in [t_k, t_{k+T_p}] \tag{16e}$$

3) Apply the first element of the solution sequence U to the optimization problem as the actual control action $u(t_k) = \tilde{u}(t_k)$.
4) Repeat the whole procedure at the next sampling time t_{k+1}.

The NMPC 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 weights μ^{tow} and μ^{trc} and of the reference cable speed $\dot{r}^{\text{ref}}$:

$$\psi(t_k) = \kappa(x(t_k), \Theta, \mu^{\text{tow}}, \mu^{\text{trc}}, \dot{r}^{\text{ref}}) = \kappa(w(t_k)) \tag{17}$$

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 [8].

IV. SIMULATION RESULTS

In the presented simulation tests, the nominal wind speed (1) is given by the following wind shear model:

$$W_n(Z) = \frac{\log\left(\dfrac{Z}{0.1}\right)}{\log\left(\dfrac{80}{0.1}\right)} 4.4 \tag{18}$$

Nominal wind speed is about 3.5 m/s at 20 m of altitude and grows to 4.5 m/s at 100 m of height. Moreover, uniformly distributed random wind turbulence $\vec{W}_t$ has also been introduced, with maximum absolute value along each direction equal to 1 m/s, i.e. about 25% of the nominal wind speed at 100 m of altitude. The numerical values of model and control parameters introduced in Sections II–III are reported in Table I. As it can be noted from the parameter values in Table I, a small kite with 10 m^2 area is considered, applied to a 12-t mass boat. These settings are similar to the ones of the experimental tests carried out at Politecnico di Torino (see Section V). Fig. 4 shows the obtained kite and boat trajectory during a simulation of 400 s, while the course of the boat speed is depicted in Fig. 5, together with the wind speed magnitude at the height where the kite flies. Finally, the course of the electric power generated by the KE-yoyo is shown in Fig. 6. It can be noted (see Fig. 4) that the controller is able to effectively control the kite flight during the KE-yoyo traction and passive phases while towing the boat along its path, also in the presence of the considered wind turbulence. In particular it can be noted that, with the considered weights μ^{tow}, μ^{elt}, during the traction phases the NMPC controller makes the kite fly fast in crosswind conditions, along "figure eight" trajectories, while in the passive phases the kite is maneuvers in such a way that the traction force collapses. As a consequence, during passive phases the boat speed decreases (see Fig. 5) but low electric power is spent to roll back the cables (see Fig. 6). The average boat speed is $\tilde{v} = 1$ m/s, with small oscillations due to the kite movement and wind turbulence and larger oscillations due to the KE-yoyo generation cycles (see Fig. 5). The average wind speed at the kite altitude is $\tilde{W} = 4.78$ m/s: considering that a small kite is employed, this result confirms the great potential of wind power generation using airfoils. As regards the electric power, an average power of 356 W is obtained over two full KE-yoyo cycles (see Fig. 6), indicating that both ship propulsion and positive net electricity generation can be obtained. Indeed, the scalability results of Kitenergy systems performed in [5], [11] apply also

TABLE I

YO–YO CONFIGURATION: MODEL AND CONTROL PARAMETERS

m	3	Kite mass (kg)
A	10	Characteristic area (m^2)
d_l	0.0035	Diameter of a single line (m)
ρ_l	970	Line density (kg/m^3)
$C_{D,l}$	1	Line drag coefficient
α_0	3.5	Base angle of attack (°)
ρ	1.2	Air density (kg/m^3)
M	12	Boat mass (t)
Θ	45	Boat direction (°)
Δ_t	0.2	Sample time (s)
N_c	1	Control horizon (steps)
N_p	10	Prediction horizon (steps)
μ^{tow}	0.1	Towing power weight
μ^{elt}	1	Electrical power weight
$\overline{r}$	300 m	Maximal line length
$\underline{r}$	200 m	Minimal line length
$\dot{r}^{\text{ref},1}$	0.6 m/s	Reference cable speed (traction phase)
$\dot{r}^{\text{ref},2}$	-1.2 m/s	Reference cable speed (passive phase)
$\overline{\theta}$	70°	State constraint
$\overline{\psi}$	10°	Input constraints
$\overline{\dot{\psi}}$	40 °/s	

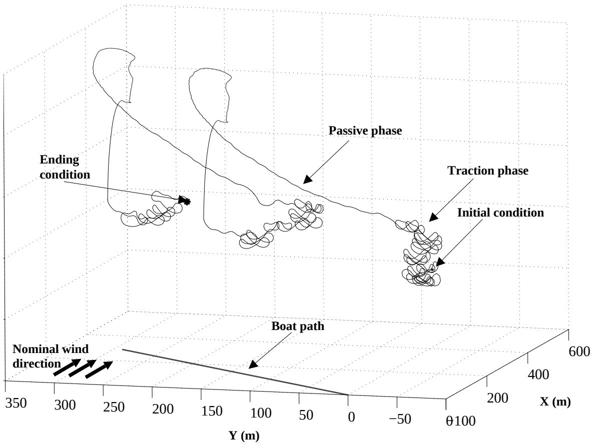

Fig. 4. Simulation results with $\Theta = 45°$: paths of the boat (thick solid line) and of the airfoil (thin solid line).

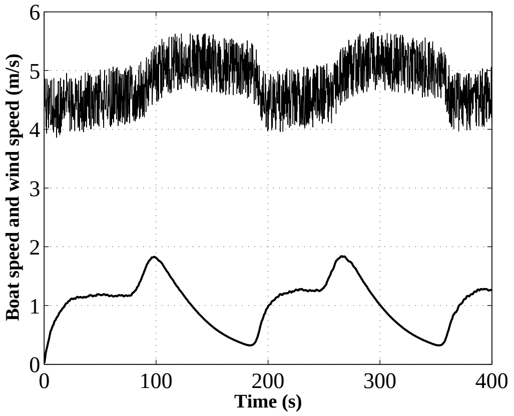

Fig. 5. Simulation results with $\Theta = 45^\circ$: courses of wind speed magnitude at the kite location (thin solid line) and of the boat speed (thick solid line).

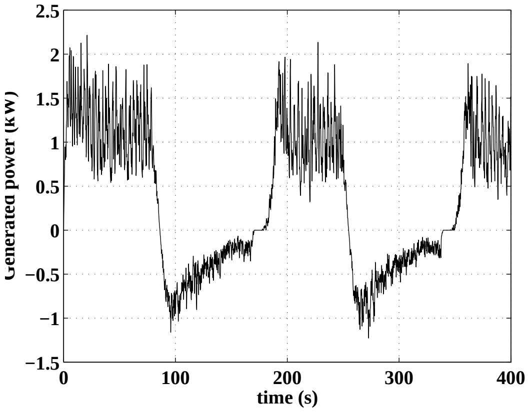

Fig. 6. Simulation results with $\Theta = 45^\circ$: course of generated electrical power during KE-yoyo operation.

in this context: thus, in the same conditions with a 160-m^2-area kite (which could be applied to the same boat) would produce traction forces 16 times higher, resulting in a net electrical power of 3.56 kW and an average boat speed of 3.5 m/s obtained by exploiting completely renewable high-altitude wind energy.

V. EXPERIMENTAL TESTS

The experimental data shown in this section is part of the measures collected during field tests performed near Varazze, Italy, in July 2009 (see Fig. 7). A movie of the experimental test is also available [13]. During the test, a wind of 2 m/s on average was present at sea level. The employed kite had an effective area of 10 m^2. A GPS was installed both on the kite and on the boat, moreover the kite was equipped with a magnetometer, three gyroscopes and three accelerometers in order to measure its position, speed and orientation. Fig. 8 shows the measured trajectories of the boat and the kite during part of the tests, while Fig. 9 and 10 show the courses of the boat speed and of the kite speed respectively. The kite flight was commanded by a human operator through two joysticks that allow to set reference values of torque and differential cable length for the electric drives of the KSU. Thus, the obtained kite trajectories were not optimal; however the experimental results are consistent with the numerical results obtained using the NMPC approach presented here, with fixed cable length (i.e. $\dot{r}^{\text{ref},1} = \dot{r}^{\text{ref},2} = 0$), giving a good confidence level in the accuracy of the employed model and in the obtained simulation results. In fact, the average measured speed value of the boat was $\tilde{v}$ =1.2 m/s, the average measured values of angles θ and ϕ were $\tilde{\theta} = 70^\circ$ and $\tilde{\phi} = -72^\circ$ respectively, the angle between the boat path and wind direction was about 90° and the estimated wind speed at the kite altitude (i.e. 120 m above sea level) was about 2.5 m/s. In these conditions, an average measured kite speed of 10.9 m/s was obtained. By performing numerical simulations with the same conditions, an average computed value of kite speed magnitude equal to 10.45 m/s and of boat speed equal to 1.09 are obtained.

Fig. 7. (KiteNav project, picture of the experimental test carried out near Varazze (Italy), in July 2009

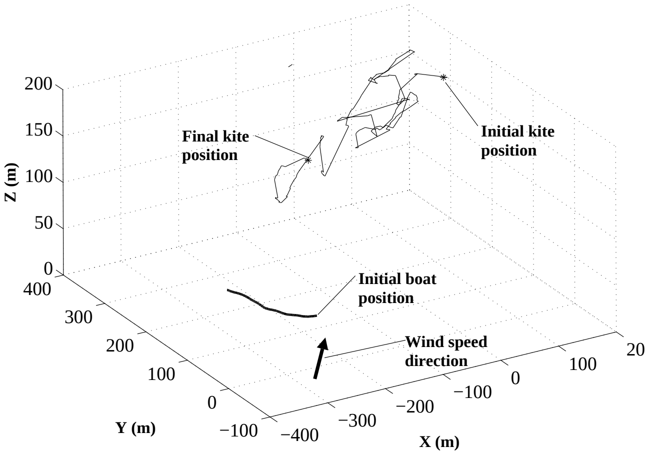

Fig. 8. KiteNav project, experimental test carried out near Varazze (Italy), in July 2009: measured paths of the boat (thick solid line) and of the airfoil (thin solid line).

VI. CONCLUSIONS AND DEVELOPMENTS

The paper presented simulation analyses and preliminary experimental results regarding an application of high–altitude

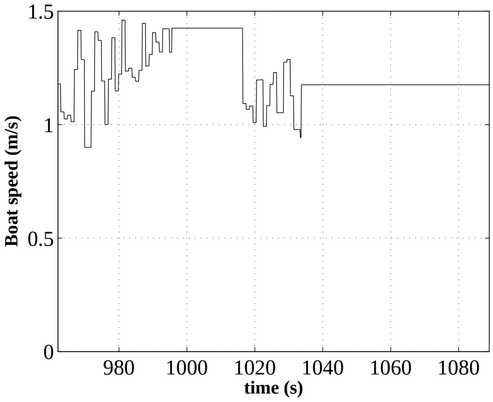

Fig. 9. KiteNav project, experimental test carried out near Varazze (Italy), in July 2009: measured course of the boat speed v.

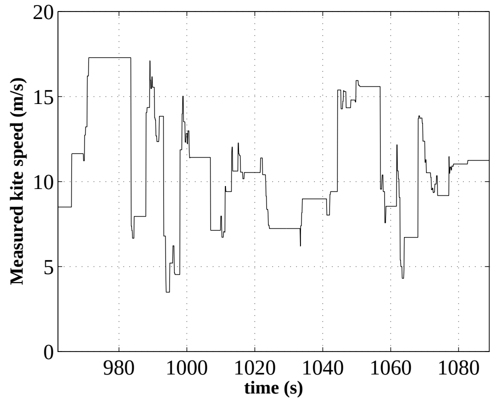

Fig. 10. KiteNav project, experimental test carried out near Varazze (Italy), in July 2009: measured course of the kite speed magnitude $|\vec{W}_a|$.

wind energy using controlled airfoils to naval propulsion and onboard energy generation. A NMPC law has been employed to maximize a suitable performance index while satisfying operational constraints. The performance index takes into account both boat propulsion end electricity generation through suitable weights. Moreover, the results of the first experimental tests carried out at Politecnico di Torino in the KiteNav project have been also presented, showing a quite good consistency with the numerical results. The next objectives of the project are the use of experimental data in order to assess and improve the accuracy of the employed mathematical model, the study of the application of kite power generators of larger size and the real-time implementation and experimental testing of a reliable and efficient automatic control law.

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