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Flight control of tethered kites in autonomous pumping cycles for airborne wind energy

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ABSTRACT

Energy harvesting based on tethered kites benefits from exploiting higher wind speeds at higher altitudes. The setup considered in this paper is based on a pumping cycle. It generates energy by winching out at high tether forces, driving an electrical generator while flying crosswind. Then it winches in at a stationary neutral position, thus leaving a net amount of generated energy.

The focus of this paper is put on the flight control design, which implements an accurate direction control towards target points and allows for a flight with an eight-down pattern. An extended overview on the control system approach, as well as details of each element of the flight controller, is presented. The control architecture is motivated by a simple, yet comprehensive model for the kite dynamics.

In addition, winch strategies based on an optimization scheme are presented. In order to demonstrate the real world functionality of the presented algorithms, flight data from a fully automated pumping-cycle operation of a small-scale prototype are given. The setup is based on a 30 m^2 kite linked to a ground-based 50 kW electrical motor/generator by a single line.

1. Introduction

More than thirty years ago (Loyd, 1980) energy generation using tethered wings has been proposed for the first time. Since then a great interest in this kind of renewable energy source has emerged, especially during the last decade. The application of tethered wings or kites appears very attractive, as they combine high achievable forces in crosswind flight together with the possibility of easily venturing into higher flight altitudes thereby taking advantage of the higher wind speeds.

The different concepts can be grouped together by using the term 'airborne wind energy', for an overview see e.g. Fagiano and Milanese (2012). An extended summary on geometries, theory oriented research activities, realized prototype systems and planned setups can be found in the recent textbook on airborne wind energy (Ahrens, Diehl, & Schmehl, 2013).

The economic operation of airborne wind energy plants demands for reliable and fully automatic operation of the power generation process. Thus, numerous theoretical control proposals (Baayen & Ockels, 2012; Diehl, 2001; Fagiano, Milanese, & Piga, 2012; Ilzhöfer, Houska, & Diehl, 2007; De Lellis, Saraiva, & Trofino, 2013) as well as experimental implementations have been published (Erhard & Strauch, 2013b; Fagiano, Zgraggen, Morari, & Khammash, 2013; Jehle, 2012; Jehle & Schmehl, 2014). However, the robust autonomous operation of complete energy production cycles turns out to be quite challenging, especially as optimization of energy output, i.e. performance and robustness, often appears as opposing design prerequisites. Hence, a design process for the control system, which takes into account real world circumstances to the necessary degree, is required. We are convinced that simplicity, separation of problems and modular structure, grounded in a clear understanding of the physical basis of the controlled plant, are keys to success in mastering the high perturbations and significant uncertainties, which are inevitably coming along with the natural energy resource wind.

This paper will report on the control system for complete autonomous power cycles with a small-scale 50 kW prototype system using a 30 m^2 kite. The focus is put on flight control of efficient dynamical pattern-eight trajectories, which are crucial in order to obtain an optimal power generation output. A distinguishing feature of the pattern-eight flight trajectories is the option of flying them in two ways. From the practical point of view, one would prefer the so-called eight-down trajectories as these significantly decrease force variability. This allows for a broader operational range of wind conditions and thus increases the average power output. However, the performance advantage comes along with drawbacks of temporarily flying ahead towards the surface and with the need for proper curve flights, which pose special requirements to the flight control system. As a consequence, the previously published control system (Erhard &

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Strauch, 2013b) was extended in order to combine it with target point concepts similar to Fagiano et al. (2013) and van der Vlugt, Peschel, and Schmehl (2013). For the overall power generation control, a compact description with three states and simple winch control strategies for the different phases have been added, which have already yielded remarkable results.

In this paper, the complete control design shall be presented, based on the equations of motion of a model (Erhard & Strauch, 2013b), which describes the steering behavior of the kite as well as the kinematics, and has been extended for changing tether lengths in Erhard and Strauch (2013c). The single design steps towards a robust pattern eight-down flight are discussed in detail and the applicability is illustrated by the discussion of real flight data results.

The paper is organized as follows: starting with a brief summary of the system setup and power generation principle in Section 2, the pattern eight-down flight and control prerequisites are motivated in Section 3. After summarizing the equations of motion in Section 4, an overview on the complete control setup is presented in Section 5. Sections 6–10 present details of the single controller parts and illustrate their principle of operation by discussing experimental flight data in Section 11. A summary and outlook is given in Section 12.

2. Implemented prototype and power generation

In this section, a general overview on the architecture and the operation principle for power generation will be given. An extended description of involved components and background information can be found in Fritz et al. (2013).

2.1. Setup

A picture of the small-scale prototype is shown in Fig. 1. The ram-air kite of 30 m^2 is controlled by steering lines, which are pulled by an actuator placed in a control pod. The pod is directly located under the kite. This geometry allows for a *single* main towing line, consisting of 6 mm diameter high-performance Dyneema® rope, which connects the flying system to the ground station and transfers the aerodynamic forces. The prototype features 300 m of tether length on the main winch, which is attached to a 50 kW electrical motor/generator-combination.

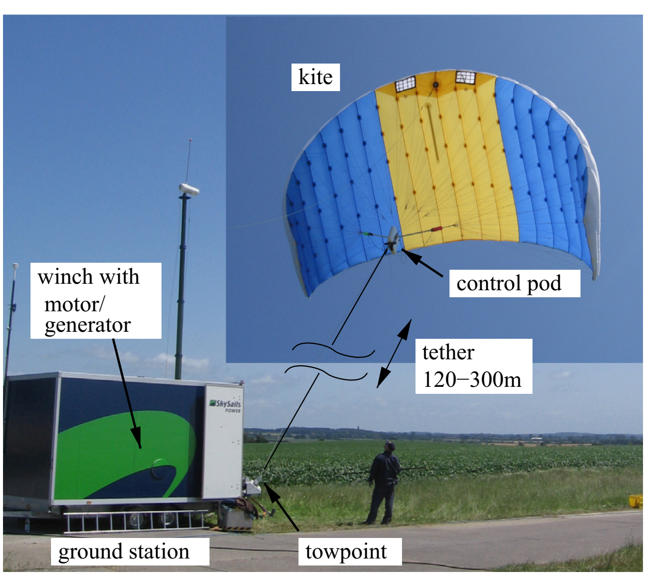

Fig. 1. Small scale prototype system for kites of sizes ranging from 20 to 40 m^2 (30 m^2 shown here). The main winch with motor/generator is located in the ground station. A tether line of length typically in the range 150–300 m transfers the forces from the flying system. A distinguishing feature of the latter is the control pod located under the kite, which allows for a single towing rope. The actuator in the control pod pulls certain lines in order to steer the kite.

In order to support research and development projects, the prototype is equipped with several sensors. Although the specific choice of sensors and signal preprocessing is important for the whole control design, a detailed discussion would go beyond the scope of this paper with its emphasis on control. However in order to allow for a proper understanding of the subsequent sections, a short summary on the most important sensors is given in Table 1. For a detailed overview on the sensors for flight control of tethered kites, the interested reader is referred to Erhard and Strauch (2013a), Fagiano, Huynh, Bamieh, and Khammash (2014), and Ranneberg (2013) for application examples of fusion algorithms. In the following, measured sensor quantities are indicated by the subscript ‘m’.

2.2. Power generation cycle

This subsection focuses on the applied principles of power generation. A typical flight trajectory during operation is sketched in Fig. 2. The power generation is done in cycles, which consist of the following three phases:

1. In the *power generation phase*, the kite is flown dynamically in pattern-eight configuration, which induces high line forces. Meanwhile the line is winched out, driving an electrical generator producing energy.
2. When a certain line length is reached, the *transfer phase* brings the kite to a neutral position. The heading is against the wind resulting in a low line force.
3. During the *return phase*, the line is winched in, operating the generator as motor while the kite is kept at a neutral wind window position. This phase consumes a certain amount of the energy produced in phase 1. As the tether force at neutral position is much lower than during dynamic flight, only a minor fraction of the generated energy of phase 1 is needed leaving a considerable net amount of generated energy. When the lower line length threshold is reached, the whole cycle repeats starting at (1).

This periodic winching process is also called pumping cycle or yo–yo operation configuration.

Finally, it should be remarked that the kite is flown with constant angle of attack during all phases and there is no de-powering feature for the return phase implemented as e.g. in van der Vlugt et al. (2013). Therefore, the return phase is accomplished by winching the kite directly against the wind. At first sight, this strategy seems to be inefficient as it suggests slow winching speed in order to keep down tether forces. However, rather contrary to intuition, the air flow at the kite and subsequently the tether forces are even reduced by increasing the winch speed as shown in Section 4.5, making this power generation scheme competitive. The extension of the scheme by variation of the angle of attack would demand for an additional control actuator, which increases complexity and weight of the airborne system. Evaluation of the performance gains versus costs is subject to current theoretical and experimental research activities.

3. Effective power pattern

Effective power generation with tethered kites makes use of the huge traction forces, which are generated by dynamical pattern-eight flight. An important distinguishing feature is that the pattern-eight can be flown in two ways as illustrated in Fig. 3. Note the triangles drawn on the trajectories in the figures indicate the flight directions. Comparing the eight-up and eight-down configurations with respect to