Tailsitter Kite Wind Turbine

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Contents

1 Introduction

We will describe a machine that can autonomously harvest wind energy and convert it to electricity. The autonomy goes as far as enabling it to react to any known weather condition, especially being able to launch and land autonomously. We aimed at finding the least complex design that uses the least amount of material to satisfy an electrical power demand.

You can get an overview from our flight test videos:

`https://www.youtube.com/watch?v=dGHaZ3dYGkM&t=14s` shows the whole system in action.

`https://www.youtube.com/watch?v=_y-az4ruFL0` shows the groundstation in action.

See also our online flight simulator at:

`https://www.kitesforfuture.de/simulation17/kite_simulation.html`

Its source code can easily be downloaded by pressing Ctrl-S in most web browsers.

For a general overview of airborne wind energy systems we recommend:

`https://www.youtube.com/watch?v=z94mLMAhl3s`

Our project website, which will change over time is

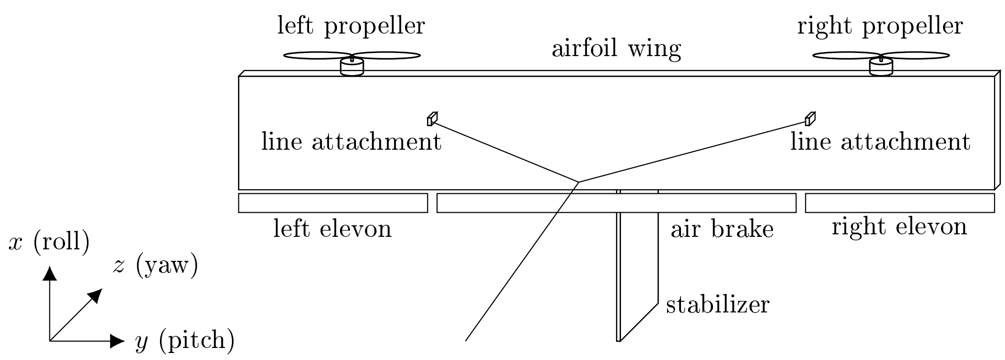
`https://www.kitesforfuture.de/`

Notable teams trying similar approaches are Kitemill, TwingTec, Enerkite, Windswept & Interesting Ltd, Ampyx, Makani among many others. There are many interesting facts to be found on their websites.

2 Mechanical Structure

2.1 Kite Structure

Figure 1: Kite Mechanical Structure



The Kite mainly consists of a dihedral-free wing. (We have chosen to use a flying wing design for practicality of transportation, but adding a fuselage and tail might also work.)

Attached to the front of the wing are two propellers, which generate an airflow that follows the airfoil from leading edge to trailing edge and flows over an elevon each. The propellers and corresponding elevons are attached near the wing tips to enable strong differential thrust control.

The propellers are folding propellers. They turn in opposite directions to avoid an undesired torque, but this might turn out to be negligible and thus unneccessary.

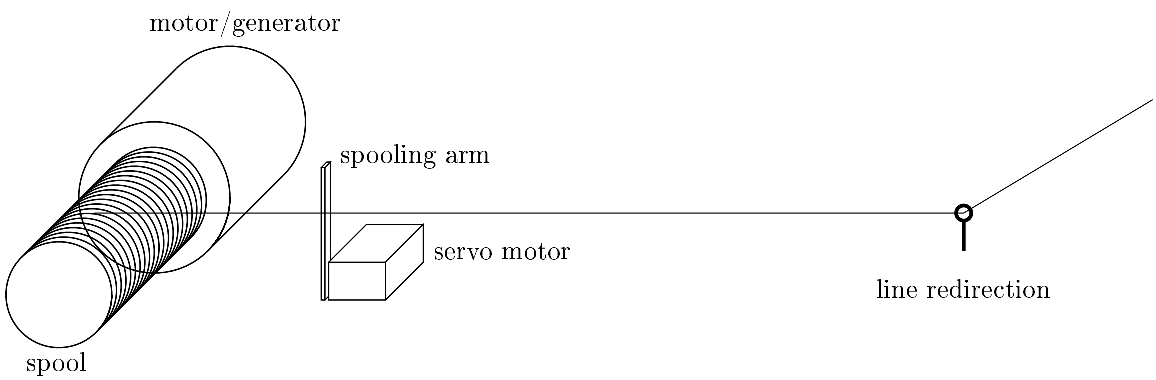
Between the elevons and thus in the middle of the wing there is an elevator attached to the trailing edge of the airfoil. While landing it is used as an airbrake in combination with the elevons: Airbrake bent down while elevons are bent up. This airbrake enables a steeper descent when landing.

The wing also has a stabilizer. It can optionally have a rudder.

Attached to the main wing spar extending in negative z-direction are the line attachment points. They are below the centre of gravity and the centre of pressure to ensure longitudinal stability. They should not be too far below to not interfere with pitch control while launching. They can be anywhere along the wing spar in any number, but there have to be at least two and those have to be far enough apart from the centre to provide roll stability. From those wing attachment points all lines meet at a common knot. The distance from this knot to the wing influences the roll stability and must be chosen accordingly. The aim of this design is to achieve a stiff roll stability but a gentle longitudinal stability that can be overpowered by the elevon forces.

2.2 Groundstation Structure

Figure 2: Groundstation Mechanical Structure



The groundstations main part is an electric motor (used as a motor and of course as a generator). We have chosen a very commonly available 3-phase BLDC brushless motor. It has a stator with 3 phases and a rotor with alternating permanent magnets.

Attached to the shaft of the motor is a spool. The line goes from the spool to a mechanism that redirects the line in any direction. This mechanism can be as simple as a screw eyelet or more sophisticated using ball bearings and pulleys.

There is an arm driven by a servo motor that pushes the line sideways to ensure it is being spooled across the whole length of the spool. The line redirection is positioned such that without the spooling arm the line reaches the spool orthogonally on one end of the spool. This way the spooling arm only needs to push the line in one direction and can move out of the way when reeling out. The other direction is passively pulled by the position of the line redirection mechanism. You can also use any other spooling mechanism.

The whole groundstation assembly is being held in the ground by a large tent peg or a ground screw or similar. The closer the line redirection mechanism is to the ground the less leverage and thus the easier it is to secure the assembly to the ground.

3 Electronics

3.1 Kite Electronics

3.1.1 Sensors

An orientation sensor including a gyroscope and an accelerometer is positioned close to the centre of gravity of the kite. We use an MPU6050, which is a common component in smartphones.

Also the kite has a barometer to measure the height. Combined with a barometer at the ground station and a radio connection the height difference can be determined even in changing air pressure due to weather.

3.1.2 Motors

The elevons and the airbrake are driven by servo motors. The propellers are driven by BLDC motors.

3.1.3 CPU

We use the arduino compatible microprocessor ESP32.

3.1.4 Radio

There is a radio connection between ground station and kite. We use the integrated Wifi functionality of the ESP32 mainly unidirectionally with the groundstation transmitting and the kite receiving.

3.1.5 Power

There is a small battery to power the kite.

3.2 Groundstation Electronics

3.2.1 Power Electronics

The 3-phase BLDC motor/generator is connected to an electronic speed controller. We use a programmable VESC (`https://vesc-project.com/`). The VESC is connected to a large battery and a microcontroller.

3.2.2 CPU

We use the same microcontroller as in the kite (ESP32). It is connected via UART to the VESC.

3.2.3 Radio

We use the integrated Wifi functionality of the ESP32 to send data from groundstation to kite.

3.2.4 Reeling Mechanism

There is a servo motor controlled by the ESP32, that pushes the line sideways while spooling.

4 Control Algorithms

4.1 Flight modes

There are three flight modes: Launching the kite, flying figure eights (synonymous: Eight mode) to generate electricity, and Descending (synonymous: landing) towards the ground station. The latter can be final, meaning that the descent will be until the ground station is being hit by the kite.

First the system is in launch mode until the kite line has reached a certain length.

If this length is not being reached fast enough, it can be deduced that the wind is not strong enough and the system goes into final landing mode.

Otherwise the system goes in to Eight mode. When a certain line length has been reached while in Eight mode, the system switches to descent mode.

Either the Descent mode is final, in which case the kite will land at the ground station. Or the Descent mode will switch to Eight mode once the line length is below a certain threshold.

The flight mode is being decided by the groundstation, which counts the line length using built-in VESC functionality.

4.1.1 Line angle

The angle of the kite line above the horizon can be calculated once its length and the height of the kite are known. The length of the kite line is being sent via Wifi from groundstation to the kite. The air pressure is being measured on the kite and at the groundstation. The latter is sent to the kite for comparison and height calculation on the kite. The line angle is being calculated on the kite.

4.1.2 Launch

While in launch mode the groundstation keeps the line tension at a minimum.

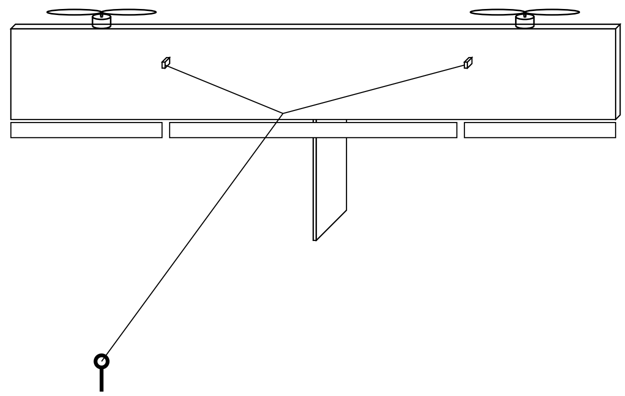
The kites propellers are spinning and the kite hovers with its pointing up, slightly to the back to ensure the line being reeled out even in low or no wind.

The algorithms for stabilizing this kind of tailsitter plane are well known and have been implemented in numerous toy airplanes.

It is however important that the kite line angle does not become too steep as in this situation the bridle would inhibit the differential thrust yaw control. The kite would lean sideways and ultimately crash.

To control the line angle, the height at which the line has its desired angle ($height = linelength/2$ for a 30 degrees angle) is being calculated and controlled by the propeller thrust.

Figure 3: Launch



This simple control is sufficient to make the kite launch in a predefined angle to the horizon in the direction of the wind. In good winds this launch takes our prototype to 50 metres of height in about 10 seconds.

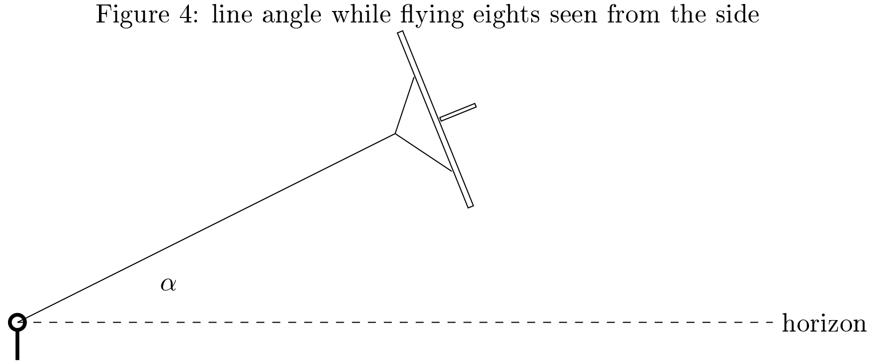
4.1.3 Transition from Launch to Figure Eights

To transition from Launch mode to Eight mode the propellers stay turned on for a small amount of time while the line tension is being increased by the ground station. This forces the kite into a stable gliding state.

4.1.4 Figure Eights

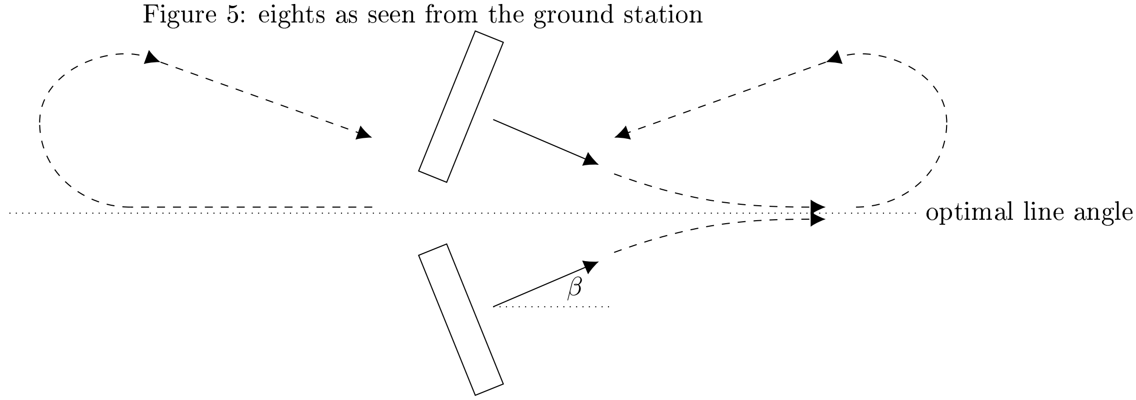
While in Eight mode the groundstation keeps the line tension high, ideally at the optimum of maximum power output but first of all large enough to enable a stable flight. It can happen that the line is being reeled in to keep the line tension up, while the kite is still flying figure eights. This can happen in low wind scenarios in the curves of the figure eight.

Figure 4: line angle while flying eights seen from the side



While flying figure eights the angle α between horizon and kite line needs to be controlled. Seen from the groundstation the eight looks as in Figure 5. We view an eight as two curves and a somewhat horizontal flight in between.

Figure 5: eights as seen from the ground station



During the horizontal part the nose of the kite can be controlled to point slightly up or down depending on whether the kite line angle is too large or too small. A P-controller sets this nose angle β depending on the deviation from the line angle α. During a turn this nose angle is changed at a predefined rate (which we call turning speed).

The angle β is held by a common PD-Controller using the aileron functionality of the elevons. Also a rudder could be used and we found this to also work very well:

See `https://youtu.be/mNy2COyMUGI?t=70` for a demonstration with rudder.

4.1.5 Descent

The kite descends in the same orientation a normal aircraft would when landing.

During the descent phase the line tension is kept just high enough to keep it straight and roll the kite slightly in case of flying too far left or right.

Steering the kite left or right is being done by the aileron functionality of the elevons. When the kite threatens to fly to far left the line tension and the bridle cause it to roll. This roll is being sensed by the orientation sensor and used as an input to a P-Controller affecting the elevons. A D-term was not neccessary during our test flights, possibly because the wing produces enough drag in roll direction.

The line angle α (Figure 4) needs to be controlled by the elevator functionality of the elevons. The desired height is calculated for example as $linelength * 0.2$ to achieve a descent with 20% steepness. Then the desired dive angle of the kite is being set by a P-Controller relative to the height error. The actual dive angle is then controlled by a PD-Controller relative to the error between the actual and the desired dive angle.

4.1.6 Transition from Descent to Figure Eights

To transition from Descent to Eight mode the desired dive angle is being set to a positive number to make the nose point up. Then Eight mode can begin from a well defined orientation and laminar air flow.

5 Open Source Code and Documentation

https://github.com/KitesForFuture/kite/tree/figure-eight-2 (Autopilot software)
https://oshwlab.com/benjamin.kutschan/kitepcb1_copy (Autopilot hardware)
https://www.youtube.com/channel/UC4pGmf6lUC09atc8GM8OyKg/videos (Flight test videos)
https://www.kitesforfuture.de/ (Project website)
The lisp code defining the VESC behaviour is included because it is short enough:

```
(define launch-line-length 180)
(define min-eight-line-length 200)
(define max-eight-line-length 250)

(define launch 0)
(define eight 1)
(define landing 2)
(define final-landing 3)
(define flightmode launch)

(define generatormode 0)
(define motormode 1)
(define mode generatormode)

(define counter 10)

(define max-reel-out-tension 10)
(define landing-request -1)

(uart-start 115200)

(define offset (get-dist))

(define arr (array-create 16))
(define array (array-create 16))

(loopwhile t
    (progn

        (define counter (- counter 1))
        (if (< counter 0) (define counter 0) 0)

        (define line-length (- 0 (- (get-dist) offset) ) )
        ; SEND line-length AND line tension(current)
        (bufset-f32 arr 0 314)
        (bufset-f32 arr 4 line-length)
        (bufset-f32 arr 8 flightmode)
        (bufset-f32 arr 12 314)
```

```
(uart-write arr)

; RECEIVE tension-request from kite
(bufclear array)
(define num-bytes-read (uart-read array 16))
(if (> num-bytes-read 15)
    (if (and (= (bufget-f32 array 0) 314) (= (bufget-f32 array 12) 314))
        ; received something, must be landing request
        (progn
         (define flightmode final-landing)
         (define mode motormode)
        )
    )
)

(if (= mode generatormode)
    (progn
        (if (= flightmode launch)
            (set-brake 0.1) ; LAUNCHING
            (set-brake 9) ; GENERATING max-reel-out-tension
        )

        ; SWITCHING TO REEL-IN
        (if (and (= flightmode eight) (> (get-current) -1) (= counter 0))
            (progn
                (define mode motormode)
                (define counter 100)
            )
        )

        (if (and (= flightmode launch) (> line-length launch-line-length))
            (define flightmode eight)
        )

        (if (and (= flightmode eight) (> line-length max-eight-line-length))
         (progn
         (define flightmode landing)
         (define mode motormode)
         )
        )
    )

    (progn
        (progn
            ; REEL-IN WITH LOW TENSION
```

```
                    (if (= flightmode eight)
                        (set-current 5)
                        ; flightmode = landing or final-landing
                        (if (> line-length 30)
                            (set-current 3)
                            (if (> line-length 0)
                                (progn
                                    (set-current (+ 1.5 (* 0.05 line-length)))
                                )
                            )
                        )
                    )

                    (if (< line-length min-eight-line-length)
                     (define flightmode eight)
                    )

                    ; SWITCHING TO REEL-OUT
                    (if (and (= flightmode eight) (< (get-duty) 0.1) (= counter 0))
                        (progn
                            ;(set-current 0)
                            (define mode generatormode)
                            (define counter 10)
                        )
                    )
                )
            )
        )

        (sleep 0.005)
    )
)
```