Development and Testing of a Control System for the Automatic Flight of Tethered Parafoils

Joseph Coleman, Hammad Ahmad, and Daniel Toal
Department of Electronic & Computer Engineering, University of Limerick, Limerick, Ireland

Received 30 July 2014; accepted 16 February 2016

This paper presents the design and testing of a control system for the robotic flight of tethered kites. The use of tethered kites as a prime mover in airborne wind energy is undergoing active research in several quarters. There also exist several additional applications for the remote or autonomous control of tethered kites, such as aerial sensor and communications platforms. The system presented is a distributed control system consisting of three primary components: an instrumented tethered kite, a kite control pod, and a ground control and power takeoff station. A detailed description of these constituent parts is provided, with design considerations and constraints outlined. Flight tests of the system have been carried out, and a range of results and system performance data from these are presented and discussed. © 2016 The Authors Journal of Field Robotics Published by Wiley Periodicals, Inc.

1. INTRODUCTION

Tethered kites including ram-air inflated parafoils, pneumatically inflated kites (Jehle & Schmehl, 2014), and rigid wings (Ruiterkamp & Sieberling, 2013) promise low-cost access to high altitudes above ground with minimal material, civil, and logistics costs. This technology effectively aims to displace the use of towers to elevate wind energy systems above ground level. The increased wind speeds at elevations up to approximately 1,000 m above ground have spurred the active area of airborne wind energy (AWE) research (Archer, 2013; Archer & Caldeira, 2009). Other applications of such technology also exist, such as low-cost aerial platforms for sensors and communications equipment. The replacement of civil structures with smart, airborne systems introduces a challenging embedded systems and control problem, namely maintaining the safe, persistent flight of the airborne system in a range of flight modes and weather conditions. Solving this challenge is a key step in the development of tethered airborne systems. A diverse range of hardware system architectures have been presented to date by many researchers and developers. Skysails in Erhard & Strauch, 2013 and Maß & Erhard, 2013 use an airborne control pod with a single actuator to fly large parafoil kites automatically ahead of cargo ships in a towing application, providing a reduction in ship fuel consumption. Skysails in Fritz (2013) outline a 55 kW land-based electrical power production prototype, which leverages the ship towing technology in a power-production application.

An alternative power production approach utilizes a parafoil kite connected to ground-based actuators in which both the power takeoff and kite-steering functions are performed from the ground. Examples of such systems are Kitenergy (Milanese, Taddei, & Milanese, 2013) and EnerKite (Bormann, Maximilian, Kövesdi, Gebhardt, & Skutnik, 2013). These systems have the advantage of increased system simplicity as the requirement for a kite control pod is eliminated, however at least two tethers are required, which increases the airborne system weight and drag with tether length more rapidly than single tether systems.

KitePower has investigated several kite types and control methods for these. The main demonstrator is a control pod actuated tube kite, where the kite geometry is defined by an inflated tube structure with a stretched membrane skin. The KitePower control pod features two servo actuators that independently control the steering and depower functions of the kite (Fechner & Schmehl, 2012). A kite-plane hybrid has also been demonstrated by van der Vlugt, Peschel, and Schmehl (2013).

Controller development and testing for AWE systems can be performed in incremental steps of increasing complexity and precision. As an initial step, pilot in-the-loop control is achieved whereby a remote fly-by-radio system is implemented. In such systems, a human pilot visually flies the wing through the movement of a joystick or similar input device providing remote control to actuators on the kite or on the kite control pod. A pilot familiar with the manual control of kites can quickly adapt to such a control system, tuning their response to the kite motion, and achieving stable flight. With the introduction of automatic controllers, increasing system autonomy can be achieved. As the complexity of the control system increases, additional sensors and processing effort are required compared to human in-the-loop operation. Such controllers require high-frequency
estimations of kite position and orientation for the provision of closed-loop feedback. The ultimate aim of such systems is the demonstration of reliable, persistent, fully autonomous control of tethered wings, and much progress has been made recently on a variety of hardware platforms. Leading examples of such systems include Fagiano, Zgraggen, Khammash, and Morari (2013a) and Fagiano, Zgraggen, Morari, and Khammash (2013b), where, using a ground-actuated control system, a number of automatic flight tests are conducted where the wing is maintained in stable figure-of-8 orbits. Good accuracy between a dynamic model of the system and the field test data is shown. Jehle and Schmehl (2014) present a tracking controller as applied in field-testing to a prototype 25 m² leading-edge inflatable (LEI) kite system for pumping-mode AWE power generation. A cascaded control system is outlined with a bearing controller as an outer loop and an attitude controller as an inner loop providing the steering actuator set point. Projecting a figure of 8 onto the tether unit sphere, they present experimental results of the controllers tracking this trajectory.

Much of the kite control systems research is focused on power takeoff (electrical or mechanical) applications within the AWE sector. In Argatov and Silvennoinen (2010), the authors present the formulation of a generic pumping mode kite system in which practical considerations such as factors of safety for the tether and minimum bend radii are included. Legislative restrictions, in this case U.S. Federal Aviation Administration (FAA) regulations, are included. The analytical modeling of apparent wind load effects on the tether of a pumping-mode AWE system is detailed in Argatov, Rautakorpi, and Silvennoinen (2011), which analyzes the degradation of system power output at extended tether lengths where the influence of tether drag becomes pronounced.

Having attained long-term stable flight systems and algorithms, an alternative application also exists: low-cost aerial sensor platforms. Using kites as aerial imaging platforms offers low-cost access to altitude, providing aerial imagery for a variety of survey and agricultural applications (Murray, Neal, & Labrosse, 2013) or geomorphology mapping (Boike & Yoshikawa, 2003). Systems under development within AWE have significantly larger payload capacity than the small-scale imaging systems, as such sensing and imaging payloads may form an auxiliary application power-generation kite system.

A kite control system design is developed that has some similarities to other approaches, focuses on the best subsystem approaches from the literature, and also focuses on areas that are not directly addressed by other researchers in the literature. The research focus and developed system have the following key features:

1. Use of tethered flexible ram-air kites due to cost efficiency, physical robustness, and inherent safety in the event of a crash compared to rigid wing solutions.
2. Use of a control-pod actuation method to avoid additional drag of multiple tethers trailing to a ground station.
3. Independently actuated steering implemented on the control pod where the steering lines are actuated separately and together form a longitudinal and lateral control input, using symmetrical and asymmetrical line displacements, respectively.
4. A pumping-mode winching ground station that uses separate, dedicated electrical machines for the power generation and recovery tasks. Each machine is appropriately sized for the task it performs.

Through field tests, the suitability of the flexible kite, control pod, and distributed control system are examined. The field-testing is aimed at both the testing of suitable control system hardware required to fly tethered kites and the development and testing of estimation and control algorithms for AWE kites.

2. SYSTEM DESCRIPTION

Pumping mode airborne wind energy uses a tethered wing to extract power from the wind. Operating in a periodic pumping cycle, the tethered wing is flown in a high-lift periodic orbit about the wind vector. This produces high tension in the tether, which pays out from a tether drum. Thus, mechanical power is produced on the ground station drive shaft. At the maximum tether length, the power phase ends and a recovery phase begins where the wing is flown in a low-lift configuration and is winched in to the starting tether length, using a fraction of the previously generated power. This cycle continues, somewhat analogous to a slow-moving long-stroke piston engine. At the ground station, electrical power takeoff is performed by a generator connected via a drivetrain to the tether drum, as shown outlined in Figure 1 (Coleman, Ahmad, Pican, & Toal, 2014).

A tethered kite control system requires a distributed control system. The control system can be divided into three main subsystems: the ground station, the control pod, and the wing. The ground station anchors the system and manages the tether while performing the electromechanical power takeoff operations, launch, and recovery process. The control pod houses the sensors, actuators, and processors necessary to control the flight of the kite. The wing is fitted with sensors to enable feedback control.

2.1. Parafoil Kite

A parafoil kite is a tethered, ram-air inflated wing whose geometry is defined through the dimensions of its fabric panel elements and through the system of tensioning rigging lines (Lingard, 1995). The fabric elements form an upper and lower airfoil surface, which is divided into sections along the span by ribs. The ribs divide the parafoil into discrete
cells. The fabric is a high-strength, nonporous, rip-stop nylon weave. The cell divisions are formed from fabric ribs, which act in tension to maintain the airfoil section geometry. The cells may be cross-braced to provide additional rigidity. The parafoil maintains its aerodynamic shape by ram-air pressurization through vents in the leading edge of the foil. The oncoming airflow stagnates within the foil, causing the foil to inflate, as internal pressure is now greater than the local atmospheric pressure. The stagnation pressure of the flow is equal to the total pressure ($P_o$) of the flow as in Eq. (1), where $V_a$ is the freestream airspeed, $P_s$ is the static pressure of the flow, and $\rho$ is the density of air,

$$P_o = P_s + \frac{1}{2} \rho V_a^2.$$  \hspace{1cm} (1)

Cross-port vents in the ribs ensure pressure distribution along the span of the wing. The aerodynamic forces developed on the foil are distributed through the system of branched lines, which form the rigging of the kite. These lines act in tension to maintain even wing loading and thus the foil geometry. The rigging lines are connected to the lower surface of the parafoil along the ribs, converging below the kite to four flying lines: two symmetrical “power” lines and two steering lines. The power lines carry the force developed by the foil to the control pod, where they merge onto the main tether. The foil is controlled by adjusting the relative length of the steering lines, also called brake lines. The steering lines run to the trailing edge of the foil, one on each side, and the relative shortening of these lines deflects the trailing edge downward on a given side. This has the effect of increasing the camber of the foil locally where the deflection occurs, changing the local lift and drag profile of the foil. By the symmetric positive deflection of brake lines, the lift of the foil is increased; however, this will also increase the drag. Asymmetric deflection of the brake lines will induce a coupled yaw and roll output, enabling steering. In the brake-line zero position, the control lines are very lightly loaded, with increasing tension as the deflection increases. To minimize airborne weight, extremely high strength-to-weight ratio polymers such as Dyneema braided rope (Bosman, Reid, Vlasblom, & Smeets, 2013) are used in the kite rigging lines and main tether. Figure 2 illustrates the basic operation of the brake lines on a parafoil kite.

### 2.2. Kite Sensors

A variety of sensors are required to provide feedback for the control system and to measure system parameters for analysis. The kite is fitted with an inertial measurement...
Figure 2. Steering mechanism on foil kite during brake line inputs (viewed from below, leading edge forwards).

Figure 3. IMU and GPS enclosure mounted on Flysurfer 12 m² kite upper surface during kite launch.

The core of this system is a National Instruments single-board RIO (sbRIO) (National Instruments, 2010) real-time (RT) processor, which interfaces to hardware through the IO of a field-programmable gate array (FPGA). The sbRIO communicates with the kite mounted IMU/GNSS microcontroller using a serial connection. The servo motor drives are controlled via FPGA generated pulse width modulation (PWM) signals. Additional sensors interfaced through the FPGA include the following:

- Load cell on the tether, which determines the tension generated by the wing.
- Current monitors for each servomotor.
- Battery voltage monitors.

The pod also contains an embedded computer (Intel, 2012) running a real-time operating system (Phar Lap ETS) (National Instruments, 2004). The real-time PC (RTPC) is used to solve complex algorithms with low latency and a high level of determinism. The RTPC and the sbRIO are interfaced via an Ethernet switch, which also provides communications to the ground station via a radio link. Figure 5 outlines the hardware and communications architecture of the distributed control system.

### Table I. Inertial measurement unit and global navigation satellite system sensor specifications.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Model</th>
<th>Range</th>
<th>Resolution</th>
<th>Sampling rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometers</td>
<td>MPU-6000</td>
<td>±8 g</td>
<td>2.44 × 10⁻⁴ g</td>
<td>100</td>
</tr>
<tr>
<td>Gyroscopes</td>
<td>MPU-6000</td>
<td>±1,000 deg/s</td>
<td>0.0305 deg/s</td>
<td>100</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>HMC5883L</td>
<td>±8 G (G)</td>
<td>5 mG</td>
<td>100</td>
</tr>
<tr>
<td>Barometer</td>
<td>MS5611</td>
<td>10–1,200 mbar</td>
<td>0.012 mbar</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Model</th>
<th>Accuracy</th>
<th>Output rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS</td>
<td>LEA-6H</td>
<td>Horizontal accuracy (SBAS aided): 2 m</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Course accuracy: 0.5 deg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity accuracy: 0.1 m/s</td>
<td></td>
</tr>
</tbody>
</table>
2.3.1. Steering Actuators

The kite is steered by two geared servomotors. The motors are brushed dc machines, powered by a dual-channel motor drive. A reduction gearhead is fitted to the motor output. Nylon spools attached to each gearhead output form small winches for each steering line, which control the length of the left and right steering lines. Position feedback and speed estimation are provided by incremental encoders fitted to

![Control pod subsystem.](image)

![Functional diagram of the distributed control system architecture.](image)
Figure 6. Steering line actuator fairlead and passive level winding.

each motor shaft. Bidirectional current is measured on each motor input to enable closed-loop torque control and analysis of the loads and power consumption during various flight maneuvers. Consideration must be made to the suitable routing and guidance of the steering lines on the actuator reel. A simple fairlead with offset attachment to the actuator reel provides a simple passive level winding effect of the steering lines, as shown in Figure 6.

The governing equations for the servomotors are given as follows:

\[ P_e = V I = \omega (\tau_m + \tau_f), \]  
\[ \eta = \frac{P_m}{P_e}, \]  
\[ \sum T = J \dot{\omega} = \tau_m - \frac{\tau_t}{G} - \tau_f, \]  
\[ T_l = F_l r, \]

where \( \tau_m \) is the mechanical torque developed by the motor, \( \tau_t \) is the torque on the pulley from the actuation load, \( G \) the gear ratio of the gearhead, \( \tau_f \) is the total torque produced by frictional effects (Coulomb & viscous damping), and \( J \) is the effective inertia seen by the motor shaft. The motor speed, \( \omega_r \) (rad/s), is determined by the voltage induced in the winding (\( V_{ind} \)) and the speed constant \( k_w \):

\[ \omega_r = V_{ind} k_w. \]  

Similarly, the mechanical torque developed by the motor is determined by the torque constant \( k_T \) and the armature current:

\[ T_m = I_a k_T. \]

The key motor properties are given in Table II from the manufacturer data (Maxon Motor, 2012).

A disadvantage of the implemented arrangement is that the motors draw current to hold position in the presence of an opposing load. An alternative arrangement using fast-acting electromagnetic brakes on each motor would possibly reduce the motor power consumption, but only when no position change is demanded. Other actuation arrangements have been developed, notably that of van der Vlugt et al. (2013), where the steering function is provided by one motor and the longitudinal input is provided by a second motor. This configuration may allow for reductions in actuator power consumption if the longitudinal motor could largely remain in a braked, low-power condition. The advantage of the implemented configuration is that the steering line lengths can be directly and independently controlled, which to the authors’ knowledge is novel. Other control-pod arrangements either do not provide longitudinal depower control (Fritz, 2013), or they provide longitudinal depower and lateral steering control through individual servos and thus cannot actuate the steering line lengths independently (van der Vlugt et al., 2013).

2.3.2. Control Mixing

As the same two control surfaces and actuators must perform two separate control actions, a suitable method of mixing these signals is required. A software control mixing function performs this task by superimposing the symmetric longitudinal (\( \delta_l \)) offset value on the asymmetric lateral-directional control input (\( \delta_a \)) and converting them.

<table>
<thead>
<tr>
<th>Table II. Maxon (RE 40) graphite brushed motor with gearhead (GP42) and encoder.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power nominal ( P_{nom} )</td>
</tr>
<tr>
<td>Voltage nominal ( V_{nom} )</td>
</tr>
<tr>
<td>Speed no load ( n_{ral} )</td>
</tr>
<tr>
<td>Torque nominal ( T_{nom} )</td>
</tr>
<tr>
<td>Torque stall ( T_{stall} )</td>
</tr>
<tr>
<td>Current nominal ( I_{nom} )</td>
</tr>
<tr>
<td>Motor mass</td>
</tr>
<tr>
<td>Gearhead mass</td>
</tr>
<tr>
<td>Gearhead reduction</td>
</tr>
<tr>
<td>Torque constant ( k_T )</td>
</tr>
<tr>
<td>Speed constant ( k_w )</td>
</tr>
<tr>
<td>Speed constant ( k_n )</td>
</tr>
<tr>
<td>Terminal resistance ( \Omega_t )</td>
</tr>
<tr>
<td>Terminal inductance ( L_t )</td>
</tr>
<tr>
<td>Motor efficiency</td>
</tr>
<tr>
<td>Gearhead efficiency</td>
</tr>
<tr>
<td>Gearhead backlash</td>
</tr>
<tr>
<td>Encoder resolution</td>
</tr>
</tbody>
</table>
to nondimensional left and right motor position set points \((\delta_{bl},\delta_{br})\):

\[
\delta_{bl,br} = \delta_e + \delta_a. \tag{8}
\]

These commands are then dimensioned to degrees of gearhead output by a steering line displacement variable \((\delta_{\text{max}})\) and sent to each servo position controller as a position set point.

### 2.3.3. Lateral-directional Control

Lateral-directional control authority is provided by the asymmetric displacement \(\delta_a\) of the steering lines. This command ranges from \(-1\) to \(+1\), where right is positive. The shortened line deflects one side of the trailing edge producing asymmetric lift across the wing, inducing a roll-yaw coupled moment. During manual control, moving the joystick between the left and right limits provides the lateral input. A trim setting enables the lateral input to be offset, which is useful in trimming out small asymmetries in the rigging setup without requiring a continuous stick deflection.

### 2.3.4. Longitudinal/Depower Control

Symmetric deflections of the steering lines produce a symmetric deflection of the trailing edge region of the wing; this pitches the wing upward while also changing the coefficient of lift through airfoil changes similar to the action of an aircraft plane flap. The longitudinal depower inputs are made using the joystick throttle setting, as this input is generally held constant with infrequent changes.

### 2.3.5. Communications

The RT processors are interconnected on an Ethernet network. An Ethernet switch in the control pod connects the RT processor and RTPC and allows additional components to utilize the network, e.g., camera systems or additional sensors. The link to the ground station is made using a 2.4 GHz IEEE 802.11 wireless point-to-point (PtP) transmission. Similarly, an Ethernet switch at the ground station provides access to the network for all necessary components, such as the winch, control PC, display, and visualization.

### 2.3.6. Power Supply

The control pod is powered by two 24 V (nominal) lithium polymer batteries, which enable operation for approximately 2 h. The batteries are positioned such that they can be exchanged easily in the field. Future developments of the system may incorporate a dc supply through the tether, although smaller batteries would be retained to provide an uninterruptable supply sufficient to land the system in the event of a power loss, e.g., due to a conductor in the tether breaking. Voltage monitoring of the batteries is implemented to estimate the remaining battery charge and endurance of the system; this is also required for accurate estimation of the servo motor power consumption. The control electronics have been measured to draw a continuous current of 0.7 A at 24 V (16.8 W). Due to the varied loads experienced by the actuators, the power draw is best measured in terms of a peak and an average during flight time. The 3.3 A-h battery was found to provide an actuator endurance of approximately 1-h flight time. Instantaneous actuator current is measured and logged with peak values of up to approximately 10 A occurring in each motor. The motor current control loop constrains the maximum current to 10 A, while a resettable fuse will activate if a sustained current at greater than 10 A occurs to prevent motor winding burnout.

### 2.4. Ground Control System

#### 2.4.1. Control PC

The control PC provides the link between the airborne components of the system and the ground system. The control PC is connected to the control network via an Ethernet switch. Custom LabVIEW virtual instruments provide display and human interface consoles. Audible tones are generated by the PC to alert the operator to any caution or alarm conditions. Further audible tones are used to provide simple feedback to the operator, without breaking eye contact with the wing. A data log of the network data stream is recorded onto the control PC hard drive.

#### 2.4.2. Joystick Input

A USB joystick connected to the ground control PC is used by the operator manually to control the kite and to enable and disable automatic controllers. During manual control, the longitudinal and lateral inputs are provided by the human pilot. As shown in Figure 7, the left to right movement
of the joystick provides the manual lateral input ($\delta_a$) while the longitudinal input ($\delta_e$) is provided by the “throttle” lever of the joystick, as this input is not frequently changed. Fine adjustment to the lateral trim ($\delta_{a,trim}$) is provided by the joystick hat switch. Automatic controllers can be overridden by pulling the joystick trigger, reverting to manual control.

2.4.3. Ground Winch Station

The ground winch controls the tether length and speed and performs the mechanical to electrical power conversion. The tether enters the winch through a fairlead, which ensures correct alignment with the tether drum. The tether drum holds the excess tether, and its radius provides a lever arm, converting the tether tension into mechanical torque on the driveshaft. The winch prototype (Figure 8) has three driveshafts: the main low-speed shaft where the tether drum is mounted, a high-speed recovery and brake shaft, and a further high-speed power takeoff shaft, which terminates at the generator. A direct drive power takeoff topology has also been proposed in Coleman et al., (2014), however due to budgetary constraints a geared solution with higher-speed electrical machines was required in the prototype.

The winch is controlled by a programmable logic controller (PLC) with human interface and access to the distributed control variables provided by the ground control PC. The PLC receives inputs from various switches and sensors on the winch, such as the low-speed shaft position and speed, the generator current and voltage, and a barometer enabling the electronic altimeter on the parafoil to be referenced to ambient ground barometric conditions (see Section 2.4.4). PLC outputs control various elements of the winch, such as the electromagnetic clutch, brake, dump load relays, and the recovery motor drive communications over a Modbus port. An encoder is fitted to the low-speed shaft providing a measurement of tether length and speed. The encoder is also required to provide closed-loop position and speed control in the tether recovery phase. An electromagnetic brake provides an emergency stop function and enables the kite to be flown on fixed tether lengths. The winch is powered by a single-phase 230 V ac supply, which can be provided from a mains connection or a portable generator. Appropriate electrical safety devices are installed to ensure the safe operation of the electrical system. The winch front panel provides a low-level human interface to the winch system. An emergency stop button when activated rapidly stops the recovery motor drive, applies the electromechanical brake, and switches in the full generator dump load. The tether recovery function is performed by a dedicated three-phase induction motor connected to a variable frequency drive (VFD), as detailed in Table III.

The mechanical power is delivered through the drive train for electrical power takeoff by a dedicated permanent magnet dc generator, detailed in Table IV. The generator dump load provides a power sink circuit for the generator. Three 2.2 kW 1.2 $\Omega$ resistors are connected to the generator via electromagnetic relays. These relays are controlled by the PLC. The dump resistors are switched parallel such as

<table>
<thead>
<tr>
<th>Table III. Induction motor specifications.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor power</strong></td>
</tr>
<tr>
<td><strong>Current nominal</strong></td>
</tr>
<tr>
<td><strong>Winding connection</strong></td>
</tr>
<tr>
<td><strong>Voltage nominal</strong></td>
</tr>
</tbody>
</table>
Table IV. Permanent magnet dc generator specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power nominal</td>
<td>7.22 kW</td>
</tr>
<tr>
<td>Torque constant</td>
<td>4.88 A/Nm</td>
</tr>
<tr>
<td>Current max</td>
<td>110 A</td>
</tr>
<tr>
<td>Resistance at terminals</td>
<td>0.016 Ω</td>
</tr>
<tr>
<td>Voltage constant</td>
<td>0.22 V/RPM</td>
</tr>
<tr>
<td>Inductance at terminals</td>
<td>0.019 mH</td>
</tr>
</tbody>
</table>

that when an additional resistor is activated, it is switched in parallel with the existing load, which increases the electrical load.

2.5. Estimation and Control Algorithms

2.5.1. Definition of Axes and Coordinate System

A right-handed, Cartesian, body-fixed coordinate system is defined to describe the airborne system orientation. For the purposes of orientation and position definition, the parafoil is assumed rigid with six degrees of freedom. Three body-fixed axes (X_p, Y_p, Z_p) are defined with the origin on the estimated aerodynamic center (midspan, quarter chord) of the parafoil. As illustrated in Figure 9, the x axis is positive forward through the leading edge, the y axis is positive moving out the starboard wing, and the z axis is on the plane of symmetry of the wing, downward positive. Roll, pitch, and yaw Euler angles are positive when clockwise about the x, y, and z axes, respectively, observing the common aeronautical convention (Stevens & Lewis, 2003).

Fixed Earth axes (X_E, Y_E, Z_E) are defined with the origin fixed to the tether anchor position, i.e., the point at which the tether exits all fairleads and guides. The Earth-fixed axes have the x axis aligned with magnetic north, the y axis with east, and the z axis down along the Earth spheroid normal. From the magnetic heading, a wind axes system is defined by rotating the Z_E axis by the wind direction \( \Psi_w \), such that X_E aligns with the wind vector \( V_w \).

2.5.2. Roll and Pitch Estimation

A complementary filter adapted from Lai, Jan, & Hsiao (2010) and Dongwon & Tsiotras (2007) is used to provide roll and pitch estimation from the accelerometer and gyroscope data. The complementary filter first estimates the roll (\( \Phi_\text{acc} \)) and pitch (\( \Theta_\text{acc} \)) angles based on accelerometer data (\( x_{\text{acc}}, y_{\text{acc}}, z_{\text{acc}} \)):

\[
\Phi_\text{acc} = \text{atan2}\left( \frac{y_{\text{acc}}}{z_{\text{acc}}} \right), \quad (9)
\]

\[
\Theta_\text{acc} = \text{atan2}\left( \frac{x_{\text{acc}}}{\sqrt{y_{\text{acc}}^2 + z_{\text{acc}}^2}} \right). \quad (10)
\]
The gyroscope data are used to provide an estimate of the roll and pitch angular rates using the previous iteration estimate of roll and pitch and the current iteration gyroscope data:

\[
\begin{bmatrix}
\dot{\Phi}_{est} & \dot{\Theta}_{est}
\end{bmatrix} =
\begin{bmatrix}
1 & \cos\Phi_{est}\tan\Theta_{est} \\
0 & \cos\Phi_{est} \sin\Phi_{est}
\end{bmatrix}
\times
\begin{bmatrix}
x_{gyro} \\
y_{gyro} \\
z_{gyro}
\end{bmatrix},
\]

where the estimated roll and pitch angles are given by

\[
\begin{bmatrix}
\Phi_{est}(k) \\
\Theta_{est}(k)
\end{bmatrix} =
\begin{bmatrix}
(\Phi_{est}(k-1) + \dot{\Phi}_{est} dt) \\
(\Theta_{est}(k-1) + \dot{\Theta}_{est} dt)
\end{bmatrix}
\times
\begin{bmatrix}
a \\
1 - a
\end{bmatrix}.
\]

In Eq. (12), \(a\) tunes the complementary filter with a filter period, \(t_f\):

\[
a = \frac{t_f}{t_f + dt}.
\]

### 2.5.4. Altitude Estimation

To determine altitude from barometric pressure, two pressure measurements are required, one at the altitude to be measured and a second reference pressure that can be sea level (QNH) or at a field elevation (QFE). During short duration flights, the pressure can be measured by the wing-mounted barometer while it is still on the ground. This measurement can be stored as the reference pressure (QFE) and used to perform altitude calculations. However, if the atmospheric conditions at ground level change, the altitude determined using an invalid stored reference would be inaccurate. Traditionally in aviation, this problem is overcome by verbal and information system radio signals, communicating the updated reference pressure for the field. Locating a barometer at the winching station provides measurements of the local atmospheric pressure at the field elevation (QFE) at a high rate, and this can be transmitted via the communications network to enable live updates of the reference pressure. Thus, the altitude can be accurately measured even during changes in local atmospheric conditions. Altitude \(h\) is determined from two static pressures according to the following equation (Kayton & Fried, 1997):

\[
h = \frac{p_0}{\rho_0 \log_{10}(e)} \left( \frac{T_0}{T} \right) \log_{10} \left( \frac{p}{p_0} \right),
\]

where \(T_0\), \(p_0\), and \(\rho_0\) are the reference temperature, pressure, and density at sea level, respectively.

The measurement of altitude above a reference point is calculated as a function of the ratio of the reference pressure to the observed pressure at altitude. Aircraft altimeters require the reference pressure to be manually inputted; different reference pressures are used based on the current flight segment and the local aviation regulations. For the AWE application, the altitude most useful for control systems is the altitude above ground level at the tether anchor point.

### 2.5.5. Wind Profile Estimation

A log law estimating the wind velocity at the wing altitude is implemented. The law outlined by Archer (2013) provides estimates of wind speed at a given altitude based on a reference wind speed \(V_{w,ref}\) measured at a reference height \(h_{ref}\):

\[
V_{w,h} = V_{w,ref} \frac{10}{10} \left( \frac{h}{z_0} \right),
\]

where \(V_{w,h}\) is the wind at altitude \(h\), \(V_{w,ref}\) is a wind speed measurement at reference altitude \(h_{ref}\), and \(z_0\) is the surface roughness length, which accounts for the impact of local terrain features and obstacles. In Archer (2013), open farmland with windbreaks more than 1 km apart has a roughness...
length of 0.1 m, while farmland with many windbreaks has a value of 0.4 m. An intermediate value of 0.2 m is implemented, as sites with 1 km between windbreaks are not common in the testing region.

2.5.6. Downwind and Crosswind Position Estimation

The ground station is set up facing into the wind with the soil anchor forming the origin of a wind axis. The downwind and crosswind position of the kite are calculated relative to the position of the tether anchor. The position of the tether anchor is determined by GPS and stored in the control system as a reference value. In general terms, the distance between two sets of coordinates \((\text{lat}_1, \text{lon}_1)\) and \((\text{lat}_2, \text{lon}_2)\) can be determined using the haversine method (Sinnott, 1984). The first step of this method requires that the difference between the longitudes and the latitudes is calculated, and then intermediate values \(a\) and \(c\) are calculated. Finally, from the intermediate values the distance between the points, \(d\), is calculated. For use in the following formulaz, the longitudes and latitudes must be converted to radians.

\[
\delta\text{lat} = \text{lat}_2 - \text{lat}_1, \quad (18)
\]

\[
\delta\text{lon} = \text{lon}_2 - \text{lon}_1, \quad (19)
\]

In the tethered wing case, the anchor reference position is inserted into \(\text{lat}_2\) and \(\text{lon}_2\), such that \(\text{lat}_2 = \text{lat}_{\text{ref}}\) and \(\text{lon}_2 = \text{lon}_{\text{ref}}\),

\[
a = \sin^2 \left( \frac{\delta\text{lat}}{2} \right) + \cos(\text{lat}_1) \cos(\text{lat}_2) \sin^2 \left( \frac{\delta\text{lon}}{2} \right), \quad (20)
\]

\[
c = 2 \tan^{-1} \left( \frac{\sqrt{a}}{\sqrt{1 - a}} \right). \quad (21)
\]

\[
d = R c, \quad (22)
\]

where \(R\) equals 6,371 km, the mean radius of Earth for the WGS84 ellipsoid. The bearing between the points \((\text{lat}_1, \text{lon}_1)\) and \((\text{lat}_2, \text{lon}_2)\) is given by

\[
B_T = \tan^{-1} \left( \frac{\sin(\delta\text{lon}) \cos(\text{lat}_2)}{\cos(\text{lat}_1) \sin(\text{lat}_2) - \sin(\text{lat}_1) \cos(\text{lat}_2) \cos(\delta\text{lon})} \right), \quad (23)
\]

where \(B_T\) is the bearing from true north to the kite about the anchor point in a range of \(-180^\circ\) to \(+180^\circ\). As illustrated in Figure 10, the angle between the bearing \((B_T)\) and the wind direction \((B_W)\) is defined as the kite to wind angle \((\gamma_{KW})\) and can be used to calculate the crosswind and downwind distances of the kite from the anchor position. The crosswind and downwind distances to the wing from the anchor in a Cartesian frame are given by the wing to wind angle and the distance \(d\) calculated in Eq. (22),

\[
d_{\text{cross}} = d \sin(\gamma_{KW}), \quad (24)
\]

\[
d_{\text{down}} = d \cos(\gamma_{KW}). \quad (25)
\]

2.5.7. Azimuth and Elevation Estimate from Cartesian Position Estimates

Using the altitude estimate \((h)\) and the crosswind and downwind distances, azimuth \((\phi)\) and elevation \((\theta)\) angles between the wing and the anchor point, as defined in Figure 11, are estimated as follows:

\[
\phi = \tan^{-1} \left( \frac{h}{d_{\text{down}}} \right), \quad (26)
\]

\[
\theta = \tan^{-1} \left( \frac{d_{\text{cross}}}{d_{\text{down}}} \right). \quad (27)
\]

The wind window

Human kite pilots naturally reference the kite position in a qualitative spherical coordinate system known as “the wind window” shown in Figure 11. The wind window 12 o’clock position is aligned with the wind direction, with the 9 and 3 o’clock positions forming the left and right constraints of where a wind-powered tethered wing can be flown. Low elevation and azimuth angles maximize the crosswind flight power of the wing (Loyd, 1980), resulting in a high tether
tension and mechanical power, yielding a region of the wind window known as the “power zone.” At larger angles of elevation and wind speed, dynamic crosswind maneuvers are not possible and so the wing airspeed and hence tether tension is lower. The zenith position over the anchor point is a useful position in which to “park” the wing, facing into wind with little or no groundspeed. This is also a useful position in which to initialize and handover to automatic controllers in a relatively steady condition compared to other positions during a dynamic maneuver.

2.5.8. Point-to-point Heading Controller

A simple point-to-point heading controller has been designed with the objective of flying an oscillating pattern about the wind vector with a fixed magnitude oscillating steering input. Figure 12 outlines the operation of this controller. The controller is initialized with the wing steady and level on the “into-wind” heading. When the controller is activated, a constant steering input is applied until the first “out-of-wind” heading is reached. Upon reaching the first heading target, the negated constant steering input is applied until the negated out-of-wind angle is reached. Thus, the wing flies in an oscillating pattern about the wind heading, bounded by the symmetric out-of-wind heading angles. This controller uses a single output from the orientation estimation algorithm: the magnetic heading. Three data inputs are required prior to activation: the wind direction, the desired out-of-wind angle, and the steering input magnitude. In the example, flight data presented that the wind was from the south (183°) with the out-of-wind angle set point at 50°. A steering input of nondimensional magnitude 0.8 was used.

2.5.9. Data Stream and Logging Parameters

Data logging is an important part of the system. Post-test data processing can be performed to evaluate the system performance and the impact of iterative design changes. The data logging function is performed by the ground-based control PC. An application on this PC receives data from the control pod and the ground winch and saves this to file at 15 ms intervals. The data are transferred using buffered network streams, ensuring lossless transfer. Table V outlines the parameters recorded by the data logging program. The data are stored in a human readable (.txt) format, using approximately 36 kB per second of operation. This is nonoptimal from a data storage efficiency perspective; however, it is a convenient human readable format for a quick overview and plotting of results.

3. FIELD SETUP AND TESTS

The control system detailed herein was deployed in numerous field trials in southwest Ireland during 2013 and 2014. The field trials were carried out in a range of wind conditions at several different sites. To facilitate rapid deployment with minimal logistical requirements, the system has been designed to operate without the electrical winch when necessary. No modifications are required to facilitate the changeover between winched operations and static tether operations. The typical setup for flight-testing without the power takeoff winch is displayed in Figure 13. Such an arrangement is suitable for much of the initial controller testing and system analysis, and for what is essentially a special case of winched operations where the tether velocity is constrained to zero and operation is with short tether lengths (20–35 m). A shorter tether length also represents a more challenging flight control problem, as with a shorter tether, the period of maneuvers about the wind decreases, requiring more frequent changes from the control system.

The setup during field tests consists of the following steps:

- Wind speed and direction are measured and recorded. Wind direction determines the layout of the test setup, such that the anchor aligns with the wind direction.
- A secure soil anchor is established that removes the vertical force components from the tether. Anchor position is recorded in the control system.
- A winching anchor is established that counters the tension in the tether without slippage or lifting of the anchor station. This is typically several meters upwind of the soil anchor position.
- A tether is deployed with appropriate routing through fair leads; secure connection of tether to control pod tension connection.
- Kite and kite control lines are deployed.
- Power and test control system.
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System time</td>
<td>2. X acceleration (m/s²)</td>
<td>3. Y acceleration (m/s²)</td>
<td>4. Z acceleration (m/s²)</td>
<td>5. X gyroscope (deg/s)</td>
</tr>
<tr>
<td>6. Y gyroscope (deg/s)</td>
<td>7. Z gyroscope (deg/s)</td>
<td>8. X magnetometer (mG)</td>
<td>9. Y magnetometer (mG)</td>
<td>10. Z magnetometer (mG)</td>
</tr>
<tr>
<td>16. Longitude (GPS) (deg)</td>
<td>17. Ground speed (GPS) (m/s)</td>
<td>18. Course (GPS) (deg)</td>
<td>19. Altitude (GPS) (m)</td>
<td>20. GPS time</td>
</tr>
<tr>
<td>31. Tether speed (m/s)</td>
<td>32. Tether length (m)</td>
<td>33. Tether tension (kN)</td>
<td>34. Motor 1 speed (deg/s)</td>
<td>35. Motor 2 speed (deg/s)</td>
</tr>
<tr>
<td>36. Motor 1 current (mA)</td>
<td>37. Motor 2 current (mA)</td>
<td>38. Crosswind distance (estimate) (m)</td>
<td>39. Downwind distance (estimate) (m)</td>
<td>40. Distance over ground to kite (m)</td>
</tr>
<tr>
<td>41. Bearing to kite (deg)</td>
<td>42. Tether drum position (rev)</td>
<td>43. Tether drum speed (RPM)</td>
<td>44. Recovery motor current (A)</td>
<td>45. Recovery motor power (kW)</td>
</tr>
<tr>
<td>46. Generator current (A)</td>
<td>47. Generator voltage (V)</td>
<td>48. Generator power (kW)</td>
<td>49. Barometer on ground (mbar)</td>
<td>50. Winch clutch state</td>
</tr>
<tr>
<td>51. Winch brake state</td>
<td>52. Load relay 1 state</td>
<td>53. Load relay 2 state</td>
<td>54. Load relay 3 state</td>
<td>55. Tether azimuth (estimate) (deg)</td>
</tr>
<tr>
<td>56. Tether elevation (estimate) (deg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As the testing system was designed to be mobile but not necessarily vehicle-mounted, as is the case with many AWE prototypes, a two-part anchoring arrangement is deployed that eliminates the vertical force component from the tether tension. The anchoring arrangement resolves the tether forces into the vertical and horizontal components and anchors these separately. This arrangement alleviates the requirement of the winch to counter the vertical force.

**Figure 13.** Flight-testing setup in the field with kite in zenith position.
component by passing the tether through a pulley attached to the vertical soil anchor, as shown in Figure 14. This resolves the tether tension into a horizontal vector, requiring the winch anchor to counter this horizontal force only, rather than a large lifting component. An opposing pair of meter-long steel spikes are driven into the ground, as illustrated. These spikes form the vertical anchor to which the tether pulley block is attached. This pulley constrains the tether tension into the horizontal axis, which is anchored by additional steel pegs passing through the winch baseplate.

3.1. Flight Maneuvers

3.1.1. Zenith Position Hold

It is possible to hold the wing steady facing into the wind, with as little departure from the zenith position as possible. This position is a low-lift configuration compared to when the kite is undergoing dynamic maneuvers. This position hold is useful as a method of “parking” the kite overhead during non-power-generating periods or for the recovery of the system. This position hold capability is also useful for alternative or complementary applications of tethered wings, such as commutations relays or sensor platform. Such applications are not likely to be feasible if the system is rapidly maneuvering, as is required for power production.

3.1.2. Dynamic Maneuvers

The maximum tether tension is produced when the kite flies in a crosswind motion, which increases the airspeed over the foil, thus increasing lift. The tension profile produced by the wing depends largely upon the trajectory followed during the dynamic maneuvers. The trajectory is centered about the wind vector and typically traces either a figure-of-8 orbit or a circular orbit. If the tether is unwound, such as during power production, these trajectories result in helical flight paths. Figure 15 displays an example of a crosswind flight maneuver where the wing is flown perpendicular to the wind direction, which results in a large airspeed and tether tension, which is required for power takeoff applications.

4. RESULTS AND PERFORMANCE

4.1. Manual Control

The manual flight of the kite using the human operated joystick established the performance of the system and enabled a shakedown of the system over several test days, where issues such as the best rigging arrangements of
the steering and power line attachment to the control pod were determined. Through iterative adjustments and flight-testing, the required lengths of the control-pod power-line attachment line and the length of the steering lines were found. Figure 16 provides video capture from two of the many such test days.

As the steering lines also provide the longitudinal input that controls the kite geometry and hence the lift coefficient, the steering lines must be sufficiently long such that at the zero deflection position they are just slack, in a “depower” condition. In this condition, the kite is at minimum lift (possibly zero lift, depending on kite design). The servomotor maximum deflection range was set such that with a full longitudinal input, the kite was brought to a stall. The required displacement for this was found to be 2,750 deg or 1,056 mm for the 12 m² kite employed. It was thought initially that the pulley passive winding might not function well at full servo speeds, particularly during reel out where the steering line may not have sufficient tension to clear the released line from the pulley spool and fairlead. The initial field tests found that the aerodynamic drag acting on the steering line was indeed sufficient to increase the servo speed to the maximum possible speed (i.e., motor-rated speed).

In addition to the line displacement range and maximum speed, the behavior of the servomotors is modified by tuning the PID gains of the motor position and current control loops. These were set in the laboratory initially and adjusted in the field to provide a behavior similar to a human pilot, providing rapid set-point tracking for large position errors without being overly stiff during small position errors. Bracing lines, which balance the orientation of the control pod, were also adjusted to minimize control-pod twisting about the tether axis. Following these tests and adjustments, the radio communication, data logging program, servo performance, anchoring and rigging arrangement, control-pod mechanical load bearing, kite, and kite sensors were found to perform reliably.

The following figures illustrate a subset of the data from one of these short trial flights. In Figure 17, the servo actual position is seen to closely track the set point except during large actuation loads exceeding the torque capability of the servomotor. This condition occurs during tight turns when the foil is flying at a large airspeed. Large airspeeds require increased actuator force to displace the control surface of the kite due to the increased aerodynamic forces on the control surface. The servo position errors can be seen where the current loop of the servo position controller reaches the maximum allowable current (10A) and saturates at that level. Recalling that the servomotor is a brushed dc machine, the current is directly proportional to the torque output [see Eq. (7)]. This results in a steady-state actuator position error until the actuator load reduces. The maximum allowable current must be traded off against the requirements to meet the actuator load with the current limitations of the motor windings. Sustained currents above the rated maximum will overheat the motor with possible winding burnout occurring.

4.2. Point-to-point Heading Controller

The sequence begins with the wing under manual control, as can be seen by the initial varying steering input with the wing heading approximately southerly. When the controller is activated, the initial constant steering input (−0.8) is applied until the southwesterly (233° = 183° + 50°) heading target is crossed. The opposite steering input (+0.8) is applied by the controller until the southeasterly (133° = 183° − 50°) heading target is crossed. As the heading controller requires the target heading to be crossed, an overshoot occurs; it can be seen in Figure 18 that the overshoot is approximately 20°–30° with a maximum of 70°. The wing position during
4.3. Dynamic Maneuver Data: Speed and Tension

During the dynamic maneuvering of the wing, the tension produced by the wing varies according to the airspeed. While a direct measurement of airspeed has not been implemented, the GPS ground speed of the wing, in addition to the measured wind speed, can provide an approximation of the airspeed, especially when using short tether lengths and hence lower altitudes, where the wind measurement at ground level is indicative of the wind condition at the wing. Figure 20 shows the correlation between wing groundspeed and tether tension. The optimization of tether tension and hence mechanical power production, through the control of flight path trajectories and hence airspeed, is a key step to facilitate airborne wind energy as a practical power-generation method.

4.4. Steering Actuator Performance

The performance of the steering motors during the controller test flight is shown in Figure 21. The alternating sequence of steering inputs can be seen as the square wave of
position set points, dimensionalized here from the nondimensional input $\delta_a$ to meters of steering line displacement. The directly measured current drawn by each motor is overlaid. Both left and right motors experienced approximately equal loads during this sequence, which is to be expected from a roughly symmetrical flight about a steady wind vector. From the current measurements, the torque as seen by the steering line pulley can be estimated.

The steering line forces are not directly measured, but an equivalent force to that of the pulley radius is estimated, however it should be noted that this estimate is only valid when the motor is in a steady state, when the current drawn is only that needed to counter the pulley torque. The large force spikes seen are caused by inrush current during the step change in input to the position controller, and they are not steering line forces; however, it is useful to observe the force estimate when the position set point has been reached. In this condition, the motor is at low or zero speed and the current is proportional to the torque required to counter the steering line force and pulley torque (recalling that the steering motors are brushed dc machines). The force estimate is expressed in kilograms equivalent (kgf), as this allows for an intuitive comparison of the line loads for human kite pilots. For example, at time 783 s, motor 2 is seen to have a steady state current of 1.4 A at the position set point, which equates to a pulley torque of 0.6 N m and a steering line force of 3 kgf.

5. CONCLUSION

The robotic system developed to facilitate research in the automated flight of a tethered parafoil has been outlined with
a focus on suitability to the field of airborne wind energy. Further, potentially complementary applications of the system are possible, such as the addition of airborne sensors and communications systems, which leverage the low-cost access to altitude afforded by wind power aerial platforms. The prototype development and early testing has been detailed, including an in-depth description of the key sub-systems, components, and the implemented estimation and control methods. The system has been tested under a variety of wind conditions, and such tests are continuing with future work focused on reducing the human operator involvement by implementing automatic control algorithms, and a greater focus on the power-producing operation of the system. The two- and three-dimensional plot displays give an overview of the flight trajectory of the kite. The development of an augmented reality tool with three-dimensional position and orientation overlay is another focus of future work. This provides a useful operator display with the full position and orientation data incorporated, and it provides a visual method for the replay of logged data for postflight analysis. The flight-test results verify the performance and suitability of the system parameters and components, such as the joystick to servo control mapping, actuation load and handling, kite lines to control pod interaction and rigging, wireless communications range and interference, battery endurance under real operating conditions, and actuator loads.

Challenges identified during the testing program have been discussed, including the solutions resolving these issues, which may be beneficial during future kite robot design and test cycles. One key challenge identified during the testing was the actuator forces required to fly large ram-air kites. A tradeoff exists between the torque capabilities of motors and their weight. Thus, the servomotor torque-to-weight ratio is a most important consideration in designing kite robotic systems. While the installed motors have been capable of flying the 12 m² kite, there have been brief motor current saturations beyond the design rating of the motors. Larger kites may require a motor upgrade, including the weight and battery endurance penalty that would result.

A simple point-to-point heading controller maintained the wing in a stable oscillating flight about the wind vector, emulating the action of a human pilot flying the kite in a gentle pattern about the wind, near the zenith position. The test flight data collected will enable the identification of various system properties, such as roll and heading responses to the steering input, which will be used in control design techniques and controller development, and they will remain the focus of further work. Data presented, such as actuator position ranges, current and torque loadings experienced by the motor, kite speed and tension profiles, and the wing turn rate response, offer valuable insight into the requirements of a kite control system, and they will be beneficial to future kite-control system designs.

ACKNOWLEDGMENTS

This research is funded by the Irish Research Council Postgraduate Enterprise Partnership Scheme [RS/2010/2632] with Bord Gáis as an enterprise partner and the Irish Research Council Postdoctoral Enterprise Partnership [EPSPD/2011/56] with Analog Devices as an enterprise partner. The experimental and testing work has also been supported in part by MMRRC, UL support and by Science Foundation Ireland MaREI (Marine Renewable Energy Ireland Research Centre) funding [12/RC/2302].
Figure 21. (a) Left steering actuator performance data during heading controller flight. (b) Right steering actuator performance data during heading controller flight.

REFERENCES


