Modelling and Control of Tethered Kite Systems for Wind Energy Extraction

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Modelling and Control of Tethered Kite Systems for Wind Energy Extraction

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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Dylan Thorpe

______/______/______
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Publications by the Candidate

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Nomenclature

Cable Modelling

\( \phi_j, \theta_j \) \quad \text{\( j^{th} \) cable elemental rotations}

\( a_j \) \quad \text{\( j^{th} \) cable elemental acceleration vector}

\( F_A \) \quad \text{Applied aircraft force}

\( F_{Ag} \) \quad \text{Global referenced applied force}

\( F_i \) \quad \text{\( i^{th} \) elemental externally applied force}

\( F_{qi} \) \quad \text{Generalised inertia forces}

\( F_{qi} \) \quad \text{Generalised active forces}

\( g \) \quad \text{Acceleration due to gravity}

\( J_x, J_y, J_z, J_{xx} \) \quad \text{Values of the aircraft mass moments and products of inertia}

\( l_j \) \quad \text{\( j^{th} \) elemental cable length}

\( el, m, n \) \quad \text{Aircraft aerodynamic moments}

\( \dot{\rho}_j, \phi_j \text{and} \theta_j \) \quad \text{\( j^{th} \) elemental speeds}

\( \ddot{\rho}_j, \ddot{\phi}_j \text{and} \ddot{\theta}_j \) \quad \text{\( j^{th} \) elemental scalar accelerations}

\( m_i \) \quad \text{\( i^{th} \) lumped mass}

\( M \) \quad \text{Aircraft lumped mass}

\( p \) \quad \text{Number of free bodies}

\( P, Q \text{and} R \) \quad \text{Angular velocities of the aircraft body}

\[ q = \omega + xi + yj + zk = \omega + (x, y, z) \]

\( q \) \quad \text{Quaternion vector, e.g.} \omega \text{\ is \ the \ angular \ rotation}

\( (x, y, z) \text{\ is \ the \ axis \ of \ rotation} \)

\( r_j \) \quad \text{\( j^{th} \) elemental position vector}

\( t \) \quad \text{Time}

\( T \) \quad \text{Applied cable tension}

\( u \) \quad \text{Control vector}

\( v_j \) \quad \text{\( j^{th} \) elemental velocity vector}

\( x \) \quad \text{State vector}
Winch Modelling

\[ \alpha \] Motor angular rotation
\[ \dot{\alpha} \] Motor angular velocity
\[ b \] Coefficient of viscous friction
\[ CR \] Capstan radius
\[ GR \] Gear ratio
\[ i_w \] Armature current
\[ J_w \] Winch rotational inertia
\[ K_i \] Motor torque constant
\[ K_e \] Motor back emf constant
\[ l \] Tether length
\[ L_w \] Motor inductance
\[ R_w \] Motor armature resistance
\[ T_w \] Motor applied torque
\[ V_w \] Motor applied voltage

Simulink® Simulation

\[ C_{D0} \] Minimum drag
\[ C_{L0} \] Lift at zero angle of attack
\[ L/D \] Lift to Drag Ratio
\[ I_{peak} \] peak current limitation of the drive motor
\[ I_{cont} \] continuous current limit for drive motor
\[ V_{max} \] Specified maximum voltage of the drive motor

Optimal Control

\[ \epsilon_{[x(t),u(t)]} \] End point penalty for the optimal control problem
\[ C_{\alpha} \] Increase in lift with angle of attack
\[ e^0 \] Initial conditions lower set of box constraints
\[ e^U \] Initial conditions upper set of box constraints
\[ e^L \] Final conditions lower set of box constraints
\[ e^U \] Final conditions upper set of box constraints
\[ f(x(t),u(t),t) \] General function representing system dynamics
\[ g_L \] Lower bound of complex path constraints
\[ g_U \] Upper bound of complex path constraints
\[ J \] Performance index for the optimal control problem
\[ L[x(t),u(t),t] \] Integral penalty for the optimal control problem
\[ t_f \] Final time for the optimal control problem
\[ t_0 \] Initial time for the optimal control problem
\[ u(t) \] Control vector for the optimal control problem
**x(t)**  
State vector for the optimal control problem

**ẋ(t)**  
Time derivative of the state vector

**Design**

\( \beta \)  
Angle of Wrap

\( PCD \)  
Pitch Circle Diameter

\( T_2 \)  
Cable tension low side of capstan

\( T_1 \)  
Cable tension high side of capstan

\( \mu \)  
Coefficient of friction

\( V_{cab} \)  
Velocity of cable leaving capstan (radial velocity)

**Parameter Identification**

\( DATCOM \)  
USAF Stability and Control Digital Data Compendium

\( FDM \)  
Flight Dynamic Model

\( SPO \)  
Short Period Oscillation

\( C_{d0} \)  
Zero-lift drag coefficient

\( g \)  
Acceleration due to gravity

\( I_{xx}, I_{yy}, I_{zz} \)  
Mass moment of inertia about the roll, pitch and yaw axes

\( L_p, L_r, L_n, L_d, L_\delta \)  
Rolling moment due to roll and yaw rate, lateral velocity, aileron, and rudder deflection

\( M_p, M_a, M_q, M_\delta \)  
Moment due to airspeed, angle of attack, pitch rate, and elevator deflection

\( N_p, N_a, N_q, N_\delta \)  
Yawing moment due to roll and yaw rate, lateral velocity, aileron, and rudder deflection

\( p, q, r \)  
Roll rate, pitch rate, and yaw rate

\( T_d, \omega_d, \xi \)  
Damped natural period, damped natural frequency, and damping ratio

\( u, v \)  
Longitudinal and lateral velocity

\( U_0 \)  
Equilibrium free-stream velocity

\( X_p, X_a, X_q, X_\delta \)  
Longitudinal force due to airspeed, angle of attack, pitch rate, and elevator deflection

\( Y_p, Y_r, Y_n, Y_\delta \)  
Lateral force due to roll and yaw rate, lateral velocity, aileron, and rudder deflection

\( Z_u, Z_a, Z_\delta \)  
Vertical force due to longitudinal velocity, angle of attack, and elevator deflection

\( \delta_e, \delta_a, \delta_r \)  
Elevator, aileron, and rudder deflection

\( \phi, \theta, \alpha \)  
Roll angle, pitch angle, and angle of attack

Time derivative of variable
**Experimental Testing**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vs</td>
<td>Storage drive voltage signal</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>tTot</td>
<td>Total time for control schedule</td>
</tr>
<tr>
<td>vs</td>
<td>Storage drive voltage signal</td>
</tr>
<tr>
<td>vm</td>
<td>Main drive voltage signal</td>
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<tr>
<td>Vset</td>
<td>Set voltage signal</td>
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<tr>
<td>ThD</td>
<td>Motor rotational velocity</td>
</tr>
<tr>
<td>Cset</td>
<td>Motor current setting</td>
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<tr>
<td>R</td>
<td>Armature resistance</td>
</tr>
<tr>
<td>Ke</td>
<td>Back emf constant</td>
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<tr>
<td>Vold</td>
<td>Old voltage signal</td>
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<tr>
<td>TD1</td>
<td>Tapped delay 1</td>
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<tr>
<td>TD2</td>
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</tr>
<tr>
<td>Tstep</td>
<td>Simulation time step</td>
</tr>
<tr>
<td>yyold</td>
<td>Old parameter value</td>
</tr>
<tr>
<td>v</td>
<td>Voltage signal</td>
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Abstract
This thesis presents the investigation into modelling, control, simulation and prototype construction of a tethered glider for wind power extraction. Specifically a mathematical model of the proposed system is developed. This model is then used for the development of a Simulink® based simulator, heuristic control, and optimal periodic trajectories for power generation.

It is shown that heuristic control can provide significant power generation that is relatively insensitive to turbulence however; these basic controls are shown to be significantly sensitive to mean wind speed variations. Based on heuristic control (of a conventional glider) certain aspects of the system design are looked at with regard to their impact on power generation. It is shown that the use of a high efficiency drive motor and a two-speed gearbox on the winch can significantly improve power conversion efficiency. Further with the aid of aerodynamic spoilers to reduce the lift generated the glider can be retrieved faster, thus improving average cycle power.

Optimal control methods are then shown to provide a significant increase in power generation (with the use of a gearbox) without the need for additional aerodynamic actuators (spoilers). In fact, maximum power generation and maximum retrieval at minimum power consumption can be achieved for a specific winch design. It is thought that ultimately optimal control methods will play a key part in this emerging technology.

Work on the development of a prototype system is then presented. The result is a working prototype system, which is aimed at being used in future experimental work. Following the design work is an explanation of how the model parameters were identified from the prototype system to match system performance to model performance.

To finalise the work on the system prototype the system is tested in the field and shown to function however no power is generated within this work.
1 Introduction

Climate science tells us that the time to mitigate climate change is fast disappearing. Australia, for example, is becoming both wetter and drier with more extreme weather conditions occurring more frequently [1]. The transition toward renewable energy alternatives from fossil fuels has been put forward as a key step in reducing carbon emissions and in turn mitigating climatic change. While awareness of global warming and the impacts of climate change is now widespread, a culture of consumerism remains unabated with global per capita energy consumption continuing to rise [2]. With energy use likely to continue its upward trend, viable alternatives to conventional (mainly fossil fuel) energy supplies are needed. Wind Energy Extraction has the potential to become one of these viable alternatives.

A literature review in Chapter 2 has been conducted that shows that high altitude wind energy has the potential to provide significant sources of renewable energy. However it also revealed that many gaps still exist within the current body of research, in particular around the question of how this potential can be harnessed. For example most research in the field to date has focussed on tethered surf kites and more conventional wind turbines suspended at altitude. The literature review also revealed that some aspects of high altitude wind energy have had little or no research conducted. These include the use of rigid wing aircraft and ground based winching generators for harnessing high altitude wind energy. It is within this area that research has been conducted and presented in this thesis.

This thesis deals with the question of how to extract high altitude wind energy using a tethered glider. Chapter 3 develops mathematical models to represent the dynamics of the Tethered Glider system as used throughout the research that follows. Initially, the mathematical models are developed in a fairly generic manner with scope to be extended for future investigations before being simplified to the representations used in this work. Ultimately, a single link pendulum model connected at one end to the glider and at the other end a winch is developed and presented. The models are then used throughout the rest of the thesis in design, simulation and control design.

Chapter 4 develops a Simulink® model of the tethered glider system. Controls are then developed which show power generation. In this work (based on a prior publication by the author) the tether is controlled by an acceleration input and control over the glider elevator is used for controlling the pitch and hence tether tension. Using heuristically chosen cable acceleration and pitch set point schedules power generation is demonstrated.

In Chapter 5 the Simulink® model is extended to include winch dynamics, the addition of a two-speed gearbox, a higher efficiency drive motor and the effect of aerodynamic wing spoilers. From the results presented it can be seen that a two-speed gearbox is of high value as are the addition of spoilers (for this type of control) and the use of a high efficiency drive motor. Significant gains in system performance are shown over the initial investigation in Chapter 4.

The work of Chapter 6 presents a simulation of the manual-testing schedule, as close to reality as possible. System sensitivity to various test parameters and wind
disturbances is examined. Chapter 6 reveals some useful information and system characteristics to consider. It is shown that small changes in wind strength have relatively large impacts on the effectiveness of the control design to extracting power efficiently from the wind.

Optimal trajectory generation is the focus of Chapter 7. Optimal trajectories augment the amount of power that can be generated with the system as modelled. Results are shown using:

- Initial system guesses (before the design of the winch was developed)
- The winch design and;
- A winch with two-speed gearbox

Throughout this chapter control over tension is assumed both due to the fact that convergent optimal trajectories for the system including winch model could not be found and because the winch response is fast enough to question the value of doing so. It is shown that with a gearbox optimal control allows the glider to be retrieved at high speed negating the need for drag-increasing/ lift reducing devices. Using a gearbox based on the actual winch design, optimal control indicates a four-fold increase in average power generation for the same conditions used in experimentally based control development.

Chapter 8, describes the design of the prototype tethered glider wind generator. Throughout Chapter 8 the prototype is taken from concept through to physical machine explaining the rationale of key decisions.

Chapter 9 covers the parameter identification of the subsystem components for control, and simulation purposes. This extensive work contains a considerable contribution from colleagues Mr. Michael Williams and Mr. Peter Lapthorne.

Chapter 10 reports the setting up and design of practical experimentation and the results. The first stage of testing demonstrates the function of the prototype with a recorded successful launch. The second and final day of testing shows two more successful launches and the final launch in which the test glider was destroyed. Therefore the demonstration of power generation was never possible however, functionality of the prototype hardware is conclusively demonstrated.

Finally Chapter 11 draws some final overall conclusions and sets out some possible direction for future work. Throughout the conclusions of Chapter 11 the thesis and work as a whole are discussed leading into areas that will require more attention in the future.

1.1 Introduction References

2 Literature Review

2.1 Introduction

Wind energy has long been utilised by humans to perform work. The earliest examples are probably in the form of sail ships used as early as 3400-3000BC [1]. Examples of wind machines populate the history books, the iconic windmills of Holland one of many examples. Most of the uses of wind energy to date have been ground based but there exists a great opportunity to harness higher potential, high altitude winds. At altitude there exists (as shown in the literature and in work later in this chapter) many times the energy potential compared to ground level. This is due to the boundary layer between the air movement and the earth slowing the lower layers of wind. [2]

Many ideas have been proposed to harness this high altitude wind ranging from tethered Roto wings[3], [4], glider carrying generators [5], turbines supported by balloons [6], [7], and various configurations of tethered kite systems [8], [9]. W. Ockels investigated the Laddermill. This work later developed into the pumping mill aimed at using surf kites for tethered wind power extraction [8], [9]. This thesis specifically looks at the pumping type generator using a rigid winged glider as the lifting body. This system has potentially the largest potential of developing energy from wind for the smallest size of plant (as rigid winged gliders have superior aerodynamics to alternatives such as surf kites).

2.2 Wind Resources in Australia

In Australia there are vast quantities of renewable wind energy at altitude over approximately half of Australia. The seasonally variable north edge is near Brisbane and the variable southern edge is near Tasmania [3]. Historical work shows that with an Average Annual Power Density (AAPD) of 10-18kW/m^2, 12 Giga Watts of energy passes annually through a 1 km deep strip 1km north south over South Australia [3]. If we could harness this energy it would be possible not only to meet Australia’s growing energy needs but also expand the yearly energy export.

In examining wind resources in Australia some work was done considering the available wind as measured by the two daily wind measurements over Perth, Adelaide and Melbourne airports. This information is freely available in a raw form from the NOAA/ESRL Radiosonde Database [10]. This raw data was processed to group the available data into altitude bins and average the values. The resulting altitude bin averages were then imported into Matlab® and a centred smoothing average scheme applied (Equation (2.1)) to generate a smooth trend line giving an indication of the wind movement at altitude (Figure 2.1). This smoothing scheme is applied iteratively with appropriate end point assumptions until a reasonable result is achieved.
\[ v_i = \frac{v_{rel} + 2v_i + v_{rel}}{4} \]

Where

\( v_i \) is the velocity at altitude node \( i \)

Figure 2.2 is included to show the quality of the trend line fit. By examining Figure 2.1 it can be seen there is relatively little power at the ground but this increases in a linear fashion to approximately 1kW/m^2 at around 5kms altitude. As we climb there is a large bulge in power between 8kms altitude and 15kms altitude. Here the power does not increase with the cube of velocity as the air density decreases with increasing altitude. The data is fairly noisy and trying to fit a trend suggests further wind studies would be needed to clarify the nature of wind energy at altitude. It can be seen that at altitude there is at least an order of magnitude more energy available, a compelling argument for developing methods of harnessing this power.

Figure 2.1 (wind energy averaged over several years) shows that wind energy at altitude is more consistent where the boundary layer of the earth has a diminished effect. To build a conceptual picture of the nature of winds at altitude one needs to start thinking about the nature of the Earth’s thermal/heating cycle. The equator is hot because most of the sun’s energy falls around the equator. The poles are cold because they receive the smallest fraction of the solar energy incident on the earth. This uneven heating of the earth manifests in rising air at the equator and sinking air at the poles. Air rising from the surface of the equator accelerates as it moves toward the poles to conserve momentum resulting in rotating airstreams about each of the poles [11]. In essence there is a huge heat engine moving heat energy from the equatorial regions to the poles. This natural process leads to a large amount of solar energy being concentrated into winds, which pass directly over a large part of Australia’s land mass. By harnessing a fraction of this energy a large contribution to global energy supply could be made.

Australia is a vast nation with a huge amount of sparsely populated regions, which happen to lie beneath high altitude wind energy reserves. It is entirely possible that with political will some airspace for energy production could be reserved. Locations could be found at or near existing power stations where large grid connection points exist, high altitude wind could power remote operations and with the emergence of hydrogen technologies for energy storage and delivery wind power could be transported, stored and exported.

More recent work [2] explores the seasonal variation with spatial and temporal location of wind resources and may prove valuable to the researcher looking at placing a full-scale high altitude wind generation plant.
Figure 2.1: Trends of wind speed and power over Melbourne, Adelaide and Perth
2.3 Wind Power Concepts

There have been many to look to the sky and contemplate how to get some of the awesome power that moves in bulk, silently above us and hence there have been many ideas on how to do it. While this work does not aim to serve as a review of these concepts a brief overview of important ideas and the work’s contemporaries is presented with mind to placing this research within the bigger picture.

The earliest recorded use of wind power by humans is probably the use of sailboats for sea transport in Egyptian paintings [1]. Wind power has driven windmills that grind grain, pump water and drove many other early industrial processes. Animals use wind power for hunting and transportation. For example, Eagles soaring on uplift at a cliff face or migratory birds using winds to hasten their travel.

Looking to the skies, human use of kites appear dotted through history in various forms, from simple children’s toys to military training devices, cultural symbols, and ingenious fishing devices [12]. The earliest unambiguous recording of a man made kite is in China circa 200BC [12].

Kites have been used in military training for honing the skills of gunners, in war kites have been used to lift spotters to sketch maps of the enemy lines in fact the work of Lawrence Hargrave with kites is arguably a major contribution to the success of the Wrights in developing the first manned, powered flight, a true turning point in western history [12]. Unfortunately the kite has received fairly limited interest in the
last 40 to 50 years until recently with the emergence of Kite Surfing and other Kite based sail sports.

In 1996 Ockels reported the invention of the Laddermill [8], a looped chain of kites driving a ground-based generator. The high angle of attack side develops more lift and pulls the chain up while the low angle of attack side coasts down toward the ground, the tension differential driving the generator. Lansdorp and Ockels (circa 2005) later develop this into the pumping mill concept, essentially half a ladder mill that alternately reels and unreels under low and high lift flight to generate net power. This system has been shown theoretically more efficient in terms of cost per unit generation [9]. Williams has published a number of works on the optimal control of lifting bodies for power generation and towing [13][14].

Lloyd (1980) investigated flying a large tethered aircraft in closed path patterns to increase the apparent wind to onboard turbines [5]. Fletcher and Roberts et al (1979) investigate various turbines suspended in the upper atmosphere transmitting power through a conductive tether [3], [4], with this work continuing at Sky Wind Power in the US [15].

“Sky Sails” developed a commercial sized prototype kite based towing system designed to supplement thrust on ocean going transport vehicles, however there was little documented information available to interested reader beyond a video of operation and an economic discussion [16]. Sequoia Automation have been developing a project called KiteGen to build a kite based generator where the kites tow a carousel about a vertical axis by changing flight patterns to change the force exerted on the carousel arms [17]. The same group has recently (2010) examined a system similar to the technology of Skysails [18]. Makani Power Systems is yet another company working on a high altitude wind power systems [19]. Initially their focus was on kite systems, however this seems to have moved onto something resembling the work of Lloyd (noted earlier).

The work at RMIT essentially investigates a Pumping Mill but with a rigid winged glider. This was chosen as a research path because rigid winged aircraft are well understood and relatively easily modelled, and the Pumping Mill is the best combination of most promising, most simply constructed and most easily scaled. Further, as RMIT’s work aims to interface and couple with the work at TU Delft by Ockels et al. this work picks up an unpursued area of importance in the world of tethered kite generators. To further explain the fact that conventional aircraft are more easily modelled we point to a lack of work on detailed modelling and simulation of surf kites and Para gliders and their dynamical nature. With light flexible structures of this sort it is thought that one cannot neglect the fluid structure interaction problem, this leads to highly sophisticated modelling which would undoubtedly be a PhD thesis in its self.
2.4 Research Questions/ Aims of Research

To date there is very little published work on tethered kite generation systems in general and to the best knowledge of the Author no work on rigid winged aircraft tethered for power generation. Further few winching technologies relevant to the application have been investigated beyond the work of Lansdorp [20]. Thus, the main aim of this thesis is to fill some of this research void, in what is a field of high potential importance.

This document aims to shed some light on the nature of a rigid winged conventional glider tethered to a winching station on the ground with the objective of generating electricity. The key research questions addressed are:

(1) What will a low cost baseline prototype look like for tethered kite power generation?
   -Glider?
   -Tether?
   -Winch? New design?

(2) How will the tethered kite system be modelled?
(3) How will the system be controlled to generate power?
(4) What characteristics of the system are important to overall performance?
(5) How can system models be improved?
(6) How can performance be improved?
(7) How useful are the developed tools/ models for furthering work in this field?
(8) Where should the research head next?

Published work by the Author relevant to and a result of this research can be found in the following references [21,22].

2.5 Conclusions

While many have postulated the use of the immense high altitude wind resources and a few have pursued development of suitable technologies, there is still nothing proven capable of practical and economical operation although it is the desire of the author to see this change. The technological revolution and the resulting low cost electronics are part of the enabling factors allowing this idea to finally grow. However there is much work to be done and a great deal of investment necessary to see the fruits of this research. The author believes that there will be a successful technology to emerge from this research and the time this takes will be a reflection of the resources invested into it. There really is no time to waste in developing alternatives to fossil fuels but it must be acknowledged that at the time of writing there is also a vast array of competing technologies each with its own dedicated team of researchers.

This thesis is intended to help with the development of high altitude power generation by answering research questions about the practical form of a high altitude power generator, including its modelling, performance and control.
2.6 Chapter References


3 Mathematical Modelling

Chapter 3 discusses the mathematical modelling of a tethered glider system which may then be used for control design and design of optimal power generation trajectories. A model using a single pendulum representation of the cable with its length controlled by force coupled to a six degree of freedom non-linear aircraft model is first investigated. A model of the winching station is then developed and this is then integrated with the overall system model. The work here addresses the second of the research questions “How will the system be modelled?”

3.1 Force Controlled Tether, Tethered Glider Model

In this section a mathematical model describing simplified dynamics of the kite wind generator system is developed. The system is modelled in two parts. Conceptually there is a single pendulum model with length controlled by tension that is free to rotate about the ground attachment point. The other end is attached at the centre of mass of a rigid winged aircraft. The aircraft is free to rotate about the end of the pendulum and the mass effects of the cable are assumed only to effect linear translation i.e. no moment coupling effects.

In this model aerodynamics of the cable, cable elasticity and torsion effects are ignored. These simplifications must be noted when using the model in control design in the sense that low or negative tension conditions in the cable cannot be allowed or any other conditions that would make these assumptions seriously flawed.

Although Kane’s equations are not the most efficient way of deriving the equations of motion for a single link pendulum, the process for developing a single link pendulum model with Kane’s equations is exactly the same as for a multi link pendulum. Hence this general approach is followed here to allow higher fidelity modelling to be a straightforward development of this work. According to Kane’s equations of motion, “The generalised inertial forces are equal to the generalised active forces”, as in Equation (3.1). In this simple expression we can define the equations of motion for multi-body multi-degree of freedom systems that can become intractable using other methods.

\[
F_{q_i}^* = F_{q_j}, j = 1,\ldots, p
\]

where

\[
F_{q_i}^* \text{ are the generalised inertia forces,}
\]

\[
F_{q_j} \text{ are the generalised active forces, and}
\]

\( p \) is the number of freebodies.

(3.1)
Equations (3.2) and (3.3) define the generalised inertia and generalised active forces where \( q \) is the generalised coordinate.

\[
F_{a_j}^* = \sum_{i=1}^{p} m_i a_j \frac{\partial v_i}{\partial q_j}, \quad j = 1, \ldots, p \tag{3.2}
\]

\[
F_{a_j} = \sum_{i=1}^{p} F_j \frac{\partial v_i}{\partial q_j}, \quad j = 1, \ldots, p \tag{3.3}
\]

\( F_j \) are the applied external forces.

Consider the pendulum as depicted in Figure 3.1. \( \phi \) is the angle from the cable to the z-x plane and \( \theta \) is the angle in the z-x plane to the z-axis.

![Figure 3.1: Tether Model](image)

Equation (3.4) defines the general position of each lumped mass in the cable system model.

\[
\mathbf{r}_j = [l_j \cos \phi_j, l_j \sin \phi_j, l_j \cos \phi_j \cos \theta_j] + \mathbf{r}_{j+1}, \quad \text{for } j = 1, \ldots, p - 1
\]

\[
\mathbf{r}_n = [l_n \cos \phi_n, l_n \sin \phi_n, l_n \cos \phi_n \cos \theta_n]
\]

where

\( l_j \) is the element length

\( \mathbf{r}_j \) is the element position and

\( \phi_j \) and \( \theta_j \) are the element rotations

Each lumped mass has a local coordinate system attached to the next numbered mass and aligned with the global coordinate system.

The next step is to derive an expression for the nodal velocities. This is done by taking the full time derivative of Equation 3.4 with the results of this operation shown in Equation (3.5).
\[ \mathbf{v}_j = \begin{bmatrix} i_j \cos \phi_j \sin \theta_j - l_j \phi_j \sin \phi_j \sin \theta_j + l_j \phi_j \cos \phi_j \cos \theta_j \\ i_j \sin \phi_j + l_j \phi_j \cos \phi_j \\ i_j \cos \phi_j \cos \theta_j - l_j \phi_j \sin \phi_j \cos \theta_j - l_j \phi_j \sin \phi_j \sin \theta_j \end{bmatrix} + \mathbf{v}_{j+1}, \text{ for } j = 1, ..., p \]

where
\[ \mathbf{v}_j \text{ is the element velocities, and} \]
\[ \dot{i}_j, \dot{\phi}_j \text{ and } \dot{\theta}_j \text{ are speeds} \]

Following the same logic the nodal accelerations are derived (Equation 3.6).

\[ \mathbf{a}_j = \begin{bmatrix} \ddot{i}_j \cos \phi_j \sin \theta_j - 2\dot{i}_j \dot{\phi}_j \sin \phi_j \sin \theta_j + 2\dot{i}_j \dot{\theta}_j \cos \phi_j \cos \theta_j - l_j \ddot{\phi}_j \sin \phi_j \sin \theta_j \\ -l_j \ddot{\phi}_j \cos \phi_j \sin \theta_j - 2l_j \dot{\phi}_j \dot{\theta}_j \sin \phi_j \cos \theta_j + l_j \dot{\phi}_j \cos \phi_j \cos \theta_j - l_j \dot{\phi}_j \sin \phi_j \sin \theta_j, \\ \ddot{i}_j \sin \phi_j + 2\dot{i}_j \dot{\phi}_j \cos \phi_j + l_j \dot{\phi}_j \cos \phi_j - l_j \ddot{\phi}_j \sin \phi_j, \\ \ddot{i}_j \cos \phi_j \cos \theta_j - 2\dot{i}_j \dot{\theta}_j \cos \phi_j \cos \theta_j - 2\dot{i}_j \dot{\phi}_j \sin \phi_j \cos \theta_j - l_j \ddot{\theta}_j \sin \phi_j \cos \theta_j \\ -l_j \ddot{\phi}_j \cos \phi_j \cos \theta_j + 2l_j \dot{\phi}_j \dot{\theta}_j \sin \phi_j \sin \theta_j - l_j \dot{\phi}_j \cos \phi_j \sin \theta_j - l_j \dot{\phi}_j \sin \phi_j \sin \theta_j \end{bmatrix} \]

\[ \text{where} \]
\[ \mathbf{a}_j \text{ is the element acceleration and} \]
\[ \ddot{i}_j, \ddot{\phi}_j \text{ and } \ddot{\theta}_j \text{ are accelerations} \]

The next important step in deriving the cable equations using Kane’s approach is to find the partial velocities, this is done by taking partial derivatives of the velocity vector with respect to the generalised speeds. (In other words we project the velocity vector onto the generalised speeds.) Here the generalised velocities are \( \dot{i}_j, \dot{\phi}_j \text{ and } \dot{\theta}_j \).
In general the partial derivatives of Equation (3.5) with respect to \( \dot{t}_j, \phi_j \text{ and } \dot{\theta}_j \) are as in Equation (3.7).

\[
\frac{\partial v_j}{\partial l_k} = \begin{cases} 
[\cos\phi_k \sin\theta_k \quad \sin\phi_k \quad \cos\phi_k \cos\theta_k] & k \geq j \\
[0 \quad 0 \quad 0] & k < j \end{cases} \quad (3.7)
\]

\[
\frac{\partial v_j}{\partial \phi_k} = \begin{cases} 
[-l_k \sin\phi_k \sin\theta_k \quad l_k \cos\phi_k \quad -l_k \sin\phi_k \cos\theta_k] & k \geq j \\
[0 \quad 0 \quad 0] & k < j \end{cases} \quad (3.7)
\]

\[
\frac{\partial v_j}{\partial \theta_k} = \begin{cases} 
[l_k \cos\phi_k \cos\theta_k \quad 0 \quad -l_k \cos\phi_k \sin\theta_k] & k \geq j \\
[0 \quad 0 \quad 0] & k < j \end{cases} \quad (3.7)
\]

The cable equations for the multi body system following the method of Kane’s equations can now be defined as per Equation (3.1). The left hand and right hand of this expression can be expanded as in Equations (3.2) and (3.3).

Equations (3.2) to (3.7) express a fairly general lumped mass model of a cable. \( F_i \), the external forces encapsulate all effects that one may wish to model. By carefully choosing the applied forces one can model bending stiffness, elasticity, aerodynamic drag, gravity, vortex shedding and any attached bodies, i.e. an aircraft.

In this work the modelled external forces are gravity and that of the aircraft attached at the cable end, as such the external forces are given by Equation 3.8. (Strictly gravity is a body force but it is acceptable to treat it as an external force in this case.)

\[
F_i = F_A + m_i g \quad \text{for } i = 2, \ldots, p
\]

\( F_A \) is the applied aircraft force

\( g \) is acceleration due to gravity and

\( m_i \) is the ith lumped mass

(3.8)

The cable equations of motion can now be formulated by substituting expressions. First the expressions for the inertial forces are expanded and a pattern extracted (Equation (3.9)).
For the \( n \) masses we have

\[
F_{q_i}^* = \sum_{i=1}^{n} \sum_{j=1}^{m} m_j \left( \sum_{k=1}^{p} \sum_{l=1}^{m} \begin{array}{c}
\cos \phi_k \sin \theta_i - 2l_i \phi_k \cos \phi \cos \phi_k \sin \theta_i + 2l_i \phi_k \cos \theta_k \sin \phi_k \sin \theta_i \\
- l_i \phi_k \cos \theta_k \sin \theta_i - l_i \phi_k \sin \phi_k \sin \theta_i - 2l_i \phi_k \sin \phi_k \sin \theta_i - l_i \phi_k \cos \phi \cos \phi_k \sin \theta_i
\end{array} \right)
\]

\[
F_{q_j}^* = \sum_{i=1}^{n} \sum_{j=1}^{m} m_j \left( \sum_{k=1}^{p} \sum_{l=1}^{m} \begin{array}{c}
\cos \phi_k \sin \theta_i - 2l_i \phi_k \cos \phi \cos \phi_k \sin \theta_i + 2l_i \phi_k \cos \theta_k \sin \phi_k \sin \theta_i \\
- l_i \phi_k \cos \theta_k \sin \theta_i - l_i \phi_k \sin \phi_k \sin \theta_i - 2l_i \phi_k \sin \phi_k \sin \theta_i - l_i \phi_k \cos \phi \cos \phi_k \sin \theta_i
\end{array} \right)
\]

\[
F_{p}^* = \sum_{i=1}^{n} \sum_{j=1}^{m} m_j \left( \sum_{k=1}^{p} \sum_{l=1}^{m} \begin{array}{c}
l_i \cos \phi_k \cos \theta_k \\
- l_i \phi_k \cos \phi_k \sin \theta_i - l_i \phi_k \sin \phi_k \sin \theta_i - 2l_i \phi_k \sin \phi_k \sin \theta_i - l_i \phi_k \cos \phi \cos \phi_k \sin \theta_i
\end{array} \right)
\]

The expression for the generalised forces is a little easier. Conceptually one simply projects the applied forces onto the partial velocities for each of the lumped masses. Equations (3.10) and (3.11) show the generalised forces. Note the indices of the generalised forces, which are different to the general expression due to the nature of the partial velocities.

\[
F_{q_i} = \left[ F_A + [0 \quad 0 \quad -m_i g] \right] \frac{\partial v_i}{\partial q_i}
\]

\[
F_{q_j} = \sum_{i=1}^{n} [0 \quad 0 \quad -m_i g] \cdot \frac{\partial v_j}{\partial q_j}, \quad j = 2, \ldots, p - 1
\]

\[
F_{p} = \sum_{i=1}^{n} [0 \quad 0 \quad -m_i g] \cdot \frac{\partial v_p}{\partial l_p} - T
\]

\[
F_{\phi_p} = \sum_{i=1}^{n} [0 \quad 0 \quad -m_i g] \cdot \frac{\partial v_p}{\partial \phi_p}
\]

\[
F_{\theta_p} = \sum_{i=1}^{n} [0 \quad 0 \quad -m_i g] \cdot \frac{\partial v_p}{\partial \theta_p}
\]

where \( T \) is the control tension on the cable.
Equations (3.9), (3.10) and (3.11) can then be equated and rearranged to the common State Space form (Equation (3.12)) for integration with the rest of the system model.

\[ \dot{x} = f(x, u, t), \text{ where} \]

\[ x \text{ is the state vector} \]

\[ u \text{ is the control vector and} \]

\[ t \text{ is time} \]  

(3.12)

These equations, after rearranging according to Equation (3.12), are then coupled with the standard Flat Earth Body Axes 6 degree of freedom equations [1] (Equation (3.13)). In merging these two system models it can be seen that certain information is duplicated. The pendulum equations define the absolute position of the aircraft in global coordinates and hence make the Navigation equations redundant. The Force Equations need rearrangement to yield the applied force to lumped mass 1 in the cable model as shown in Equation (3.14).
Flat Earth, Body Axes 6 Degree Of Freedom

Force Equations
\[ \ddot{U} = RV - QW - g \sin \theta + (X_A + X_T) / M \]
\[ \ddot{V} = -RU + PW + g \sin \phi \cos \theta + (Y_A + Y_T) / M \]
\[ \ddot{W} = QU - PV + g \sin \phi \cos \theta + (Z_A + Z_T) / M \]

Kinematic Equations
\[ \dot{\phi} = P + \tan \theta (Q \sin \phi + R \cos \phi) \]
\[ \dot{\theta} = Q \cos \phi - R \sin \phi \]
\[ \dot{\psi} = (Q \sin \phi + R \cos \phi) / \cos \theta \]

Moment Equations
\[ \Gamma \dot{P} = [J_x - J_y + J_z] PQ - [J_x (J_z - J_y) + J_z^2] QR + J_z el + J_x n \]
\[ \Gamma \dot{Q} = (J_y - J_x) PR - J_x (P^2 - R^2) + m \]
\[ \Gamma \dot{R} = [J_x (J_y - J_z) + J_z^2] PQ - J_z [J_x - J_y + J_z] QR + J_z el + J_x n \]
\[ \Gamma = J_x J_y - J_z^2 \]

Navigation Equations
\[ \dot{N} = U \cos \theta \cos \psi + V (-\cos \phi \sin \psi + \sin \phi \sin \theta \cos \psi) \]
\[ + W (\sin \phi \sin \psi + \cos \phi \sin \theta \cos \psi) \]
\[ \dot{E} = U \cos \theta \sin \psi + V (\cos \phi \cos \psi + \sin \phi \sin \theta \sin \psi) \]
\[ + W (-\sin \phi \cos \psi + \cos \phi \sin \theta \sin \psi) \]
\[ \dot{h} = U \sin \theta - V \sin \phi \cos \theta - W \cos \phi \cos \theta \] (3.13)

where

- \( U \) is body-fixed longitudinal velocity
- \( V \) is body-fixed lateral velocity
- \( W \) is body-fixed downward velocity
- \( N \) is the northern global location
- \( E \) is the eastern global location
- \( h \) is the global height

\[
F_{ab} = \begin{bmatrix}
(RV - QW - g \sin \theta)m_A + X_A \\
(-RU + PW + g \sin \phi \cos \theta)m_A + Y_A \\
(QU - PV + g \cos \phi \cos \theta)m_A + Z_A
\end{bmatrix}, \text{where}
\]

\( F_{ab} \) is the body fixed applied force

\( P, Q, R \) are the rotation rates

\( U, V, W \) are the body fixed velocities

\( \phi \) and \( \theta \) are Euler angles

\( m_A \) is the aircraft mass and

\( X_A, Y_A, Z_A \) are the body aerodynamic forces

The body fixed applied force is then transformed into global coordinates via the direction cosine matrix transformation and applied to the first node, the lumped mass
at the aircraft. Kinematic Equations are, in a mathematical sense, independent from
the translational or Force Equations which are now represented in the cable model.
The model used here uses a Quaternion representation of the aircraft kinematics due
to their computational continuity (as opposed to Euler angles) Equation (3.15).

\[
\dot{q} = \frac{1}{2 \sqrt{q \cdot q}} \begin{bmatrix}
0 & -P & -Q & -R \\
P & 0 & R & -Q \\
Q & -R & 0 & P \\
R & Q & -P & 0
\end{bmatrix} q
\] (3.15)

For the case of a single cable link, Equation (3.5) becomes Equation (3.16), Equation
(3.9) becomes Equation (3.17) and Equation (3.11) becomes Equation (3.18).

\[
\frac{\partial v}{\partial l} = [\cos \phi \sin \theta \quad \sin \phi \quad \cos \phi \cos \theta]
\]

\[
\frac{\partial v}{\partial \phi} = [-l \sin \phi \sin \theta \quad l \cos \phi \quad -l \sin \phi \cos \theta]
\]

\[
\frac{\partial v}{\partial \theta} = [l \cos \phi \cos \theta \quad 0 \quad -l \cos \phi \sin \theta]
\] (3.16)

where

\(l\) is the tether length
\(\phi\) and \(\theta\) are the tether orientations
\(\dot{l}, \dot{\phi}\) and \(\dot{\theta}\) are speeds and
\(\ddot{l}, \ddot{\phi}\) and \(\ddot{\theta}\) are accelerations

\[
F^l_\phi = m \sin \phi \left( \dot{l} \cos \phi \sin \theta - 2 \dot{l} \dot{\phi} \sin \phi \sin \theta + 2 \ddot{l} \dot{\phi} \cos \phi \cos \theta - l \ddot{\phi}^2 \cos \phi \sin \theta \right)
\]

\[
\begin{bmatrix}
\cos \phi \sin \theta \\
-\dot{l} \phi \sin \phi \sin \theta + 2 \dot{l} \phi \phi \cos \theta - l \dot{\phi}^2 \sin \phi + l \dot{\phi} \cos \phi
\end{bmatrix}
\]

\[
F^l_\theta = m \left( \dot{l} \cos \phi \cos \theta - 2 \dot{l} \dot{\phi} \cos \phi \cos \theta - 2 \ddot{l} \phi \phi \sin \theta + 2 \ddot{l} \phi \phi \cos \theta \right)
\]

\[
\begin{bmatrix}
\cos \phi \cos \theta \\
-\dot{l} \phi \sin \phi \cos \theta + 2 \dot{l} \phi \phi \sin \theta - l \dot{\phi}^2 \cos \phi + l \dot{\phi} \sin \phi
\end{bmatrix}
\]

\[
F^\phi_\phi = m \left( \dot{l} \cos \phi \cos \theta - 2 \dot{l} \dot{\phi} \cos \phi \cos \theta - l \ddot{\phi}^2 \cos \phi \sin \theta \right)
\]

\[
\begin{bmatrix}
\cos \phi \cos \theta \\
-\dot{l} \phi \sin \phi \cos \theta + 2 \dot{l} \phi \phi \sin \theta - l \dot{\phi}^2 \cos \phi + l \dot{\phi} \sin \phi
\end{bmatrix}
\]

\[
F^\phi_\theta = m \left( \dot{l} \cos \phi \cos \theta - 2 \dot{l} \dot{\phi} \cos \phi \cos \theta - l \ddot{\phi}^2 \cos \phi \sin \theta \right)
\]

\[
\begin{bmatrix}
\cos \phi \cos \theta \\
-\dot{l} \phi \sin \phi \cos \theta + 2 \dot{l} \phi \phi \sin \theta - l \dot{\phi}^2 \cos \phi + l \dot{\phi} \sin \phi
\end{bmatrix}
\] (3.17)
\[ F_i = (\mathbf{F}_{\chi} + [0 \quad 0 \quad -mg]) \cdot \frac{\partial \mathbf{v}}{\partial \mathbf{r}} - T \]
\[ F_{\phi} = (\mathbf{F}_{\chi} + [0 \quad 0 \quad -mg]) \cdot \frac{\partial \mathbf{v}}{\partial \phi} \]
\[ F_{\theta} = (\mathbf{F}_{\chi} + [0 \quad 0 \quad -mg]) \cdot \frac{\partial \mathbf{v}}{\partial \theta} \]

Equation (3.18)

By taking Equations (3.1), (3.16), (3.17) and (3.18) the system model as described by Equation (3.19) can be developed.

\[
F_i' = m \left[ \begin{array}{c}
\cos \phi \sin \theta \left( \ddot{\theta} \cos \phi \sin \theta - 2 \dot{\theta} \dot{\phi} \sin \phi \cos \theta - \dot{\phi}^2 \cos \phi \sin \theta \right) \\
-\dot{\phi} \sin \phi \sin \theta \left( \ddot{\theta} \cos \phi \sin \theta - 2 \dot{\theta} \dot{\phi} \sin \phi \cos \theta - \dot{\phi}^2 \cos \phi \sin \theta \right) \\
-\dot{\phi} \sin \phi \cos \theta \left( \ddot{\theta} \cos \phi \sin \theta - 2 \dot{\theta} \dot{\phi} \sin \phi \cos \theta - \dot{\phi}^2 \cos \phi \sin \theta \right)
\end{array} \right]
\]

\[
F_{\phi}' = m \left[ \begin{array}{c}
\cos \phi \cos \theta \left( \ddot{\phi} \cos \phi \cos \theta - 2 \dot{\phi} \dot{\theta} \cos \phi \sin \theta - \dot{\phi}^2 \cos \phi \cos \theta \right) \\
-\sin \phi \cos \theta \left( \ddot{\phi} \cos \phi \cos \theta - 2 \dot{\phi} \dot{\theta} \cos \phi \sin \theta - \dot{\phi}^2 \cos \phi \cos \theta \right) \\
-\sin \phi \cos \theta \left( \ddot{\phi} \cos \phi \cos \theta - 2 \dot{\phi} \dot{\theta} \cos \phi \sin \theta - \dot{\phi}^2 \cos \phi \cos \theta \right)
\end{array} \right]
\]

\[
F_{\theta}' = m \left[ \begin{array}{c}
\cos \phi \cos \theta \left( \ddot{\theta} \cos \phi \sin \theta - 2 \dot{\theta} \dot{\phi} \sin \phi \cos \theta - \dot{\phi}^2 \cos \phi \sin \theta \right) \\
-\dot{\phi} \sin \phi \sin \theta \left( \ddot{\theta} \cos \phi \sin \theta - 2 \dot{\theta} \dot{\phi} \sin \phi \cos \theta - \dot{\phi}^2 \cos \phi \sin \theta \right) \\
-\dot{\phi} \sin \phi \cos \theta \left( \ddot{\theta} \cos \phi \sin \theta - 2 \dot{\theta} \dot{\phi} \sin \phi \cos \theta - \dot{\phi}^2 \cos \phi \sin \theta \right)
\end{array} \right]
\]

Equation (3.19)
Equation (3.19) can then be further rearranged collecting accelerations to the left hand side and everything else to the right hand side as in Equation (3.20).

\[
\begin{align*}
\left[ i^2 \left( \cos \phi \sin \theta \cos \phi \sin \theta + \sin \phi \sin \phi + \cos \phi \cos \theta \cos \phi \cos \theta \right) \\
+ \dot{\phi} l^2 \cos \phi \sin \theta \sin \phi + \sin \phi \cos \phi - \cos \phi \cos \theta \sin \phi \cos \theta \right) \\
+ \ddot{\phi} l^2 \cos \phi \sin \theta \cos \phi \cos \theta - \cos \phi \cos \phi \cos \phi \sin \theta \right) \\
= \left( \mathbf{F}_{A_x} + [0 \ 0 \ -mg] \right) \left( \frac{\partial \mathbf{v}}{\partial l} \right) \left( \frac{1}{m} \right)
\end{align*}
\]

\[
\begin{align*}
\cos \phi \sin \theta \left( -2l \dot{\phi} \sin \phi \sin \theta + 2l \dot{\phi} \cos \phi \cos \theta - l\dot{\theta}^2 \cos \phi \sin \theta \right) \\
+ \sin \phi \cos \theta \left( -2l \dot{\phi} \sin \phi \cos \theta - 2l \dot{\phi} \cos \phi \sin \theta - l\dot{\theta}^2 \cos \phi \cos \theta \right) \\
\left[ i^2 \left( l \cos \phi \cos \theta \cos \phi \sin \theta - l \cos \phi \sin \theta \cos \phi \cos \theta \right) \\
+ \dot{\phi} \left( l \cos \phi \cos \theta \sin \phi \sin \theta + l \cos \phi \sin \theta \sin \phi \cos \theta \right) \\
+ \ddot{\phi} \left( l \cos \phi \cos \theta \cos \phi \cos \theta + l \sin \phi \cos \theta \cos \phi \cos \theta \right) \\
= \left( \mathbf{F}_{A_x} + [0 \ 0 \ -mg] \right) \left( \frac{\partial \mathbf{v}}{\partial \phi} \right) \left( \frac{1}{m} \right)
\end{align*}
\]

\[
\begin{align*}
\left( l \cos \phi \cos \theta \cos \phi \sin \theta - l \cos \phi \sin \theta \cos \phi \cos \theta \right) \\
+ \dot{\phi} \left( l \cos \phi \cos \theta \sin \phi \sin \theta + l \cos \phi \sin \theta \sin \phi \cos \theta \right) \\
+ \ddot{\phi} \left( l \cos \phi \cos \theta \cos \phi \cos \theta + l \sin \phi \cos \theta \cos \phi \cos \theta \right) \\
= \left( \mathbf{F}_{A_x} + [0 \ 0 \ -mg] \right) \left( \frac{\partial \mathbf{v}}{\partial \theta} \right) \left( \frac{1}{m} \right)
\end{align*}
\]

\[
\begin{align*}
\left( l \cos \phi \cos \theta \cos \phi \sin \theta - l \cos \phi \sin \theta \cos \phi \cos \theta \right) \\
+ \dot{\phi} \left( l \cos \phi \cos \theta \sin \phi \sin \theta + l \cos \phi \sin \theta \sin \phi \cos \theta \right) \\
+ \ddot{\phi} \left( l \cos \phi \cos \theta \cos \phi \cos \theta + l \sin \phi \cos \theta \cos \phi \cos \theta \right)
\end{align*}
\]
Equation (3.20) can then be simplified and rearranged to arrive at Equation (3.21).

\[
\begin{align*}
\ddot{\theta} &= \left( F_{\lambda_t} + [0 \ 0 \ -mg] \right) \cdot \frac{\Delta V}{\partial \theta} - \left( \frac{1}{m} \right) \left( 2l \dot{\phi} \cos \phi - 2l \ddot{\phi} \dot{\phi} \cos \phi \sin \phi \right) \bigg/ l^2 \\
\end{align*}
\]

Summarising the work so far Equation (3.21) is called the Pendulum Equations. Equation (3.22) states the complete model for the tethered aircraft. Deriving a tether model of higher degree is the same process except that rearranging the tether equations into the state space representation is much more involved and likely to be done numerically.
Pendulum Equations

\[
\ddot{\mathbf{q}} = \frac{1}{2\sqrt{\mathbf{q} \cdot \mathbf{q}}} \begin{bmatrix}
0 & -P & -Q & -R \\
P & 0 & R & -Q \\
Q & -R & 0 & P \\
R & Q & -P & 0 \\
\end{bmatrix} \mathbf{q}
\]

Kinematic Equations

\[
\Gamma = \mathbf{J}_2 (J_z - J_y) + J_{xz} \mathbf{P} \mathbf{Q} - J_{xz} (J_z - J_y) + J_{zz} \mathbf{Q} \mathbf{R} + J_{x2} \mathbf{P} + J_{x1} \mathbf{P} + J_{y2} \mathbf{R} + J_{x1} \mathbf{I} + J_{x2} \mathbf{I}
\]

\[
\mathcal{J} = (J_z - J_y) \Gamma \mathbf{P} - J_{xz} (\mathbf{P}^2 - \mathbf{R}^2) + m
\]

\[
\mathcal{G} = (J_z - J_y) \Gamma \mathbf{P} - J_{xz} (J_z - J_y + J_z) \mathbf{Q} - J_{x2} \mathbf{P} + J_{x1} \mathbf{P} + J_{x2} \mathbf{R} + J_{x1} \mathbf{R}
\]

where

\(l\) is the tether length
\(\phi\) and \(\theta\) are the tether rotations
\(\dot{i}, \dot{\phi}\) and \(\dot{\theta}\) are speeds and
\(i, \dot{\phi}\) and \(\dot{\theta}\) are accelerations
\(P, Q\) and \(R\) are the angular rates
\(e, m, n\) are the aircraft moments
\(\mathbf{q}\) is the Quaternion vector
\(g\) is acceleration due to gravity
\(M\) is the mass
\(J, J, J, J\) are aircraft inertias
\(\mathbf{F}_g\) is the global reference frame applied force

\[\text{(3.22)}\]
3.2 Winch Model

This section of the thesis develops a model of the winching equipment. This model is then integrated with the previously developed system model.

In modelling the winch a few assumptions are made.

1. The plant is sufficiently smooth to ignore vibrational influences
2. The plant can be treated as a geared dc motor with an applied torque
3. The storage drum and drive can be neglected and the storage drive can have the current controlled to keep a set low tension on the cable.

The basic equations of motion for a permanent magnet DC motor are as in Equation (3.23).

\[
\begin{bmatrix}
\dot{\alpha} \\
i
\end{bmatrix}
= \begin{bmatrix}
\frac{-b\dot{\alpha} + K_i j - T}{J_w} \\
\frac{-K_e \dot{\alpha} - R_w i + V}{L}
\end{bmatrix}
\]

where
\(\dot{\alpha}\) is the rotational velocity
\(i_w\) is the armature current
\(K_i\) is the torque constant
\(K_e\) is the back emf constant
\(b\) is the viscous friction coefficient
\(R_w\) is the armature resistance
\(T_w\) is the applied torque
\(V_w\) is the applied voltage
\(J_w\) is the rotational inertia

(3.23)

The equilibrium equations, which will be of use during parameter identification, are as in Equation (3.24). (Equation (3.24) is useful for curve fitting of equilibrium load testing.)

\[
T = -b\dot{\alpha} + K_i i \\
R_i = V - K_e \dot{\alpha}
\]

(3.24)

The winch drive is described functionally as follows. The cable is coupled to the capstan by friction forces, a large number of wraps prevent slip and hence the capstan torque and cable tensile force are directly related. The capstan is coupled to the drive motor with a toothed belt drive. The cable storage drum and associated drive are considered insignificant in modelling system dynamics on the basis that their influence is an order of magnitude less than the rest of the system. The storage cable tension is to be maintained at a minimum during operation of the practical plant.
Winch dynamics are sufficiently represented by a simple permanent magnet DC motor model if the inertia of all the rotating parts are lumped onto the motor inertia and the cable tension is transformed into an applied torque.
3.3 Winch Controlled Tether, Tethered Glider

With the Equations of Motion describing both the winch behaviour and the tethered glider behaviour defined, they can be integrated to give a representation of the winch/cable/ glider system (Equation (3.29)). The modelling framework used allows for future refinement of modelling to include more of the cable dynamics and different winching systems.

It can be seen by inspection of the Equations of motion or by simple modelling that to work as a generator a DC motor must be driven beyond its free speed for a given applied voltage. Hence to derive maximum power from the winch the motor needs to be driven sufficiently above its free speed at maximum applied voltage to drive a negative current (with respect to applied voltage) equal to the maximum allowable for the motor. Another consequence of the inherent behaviour of DC permanent magnet motors is that during retrieval there will be some minimal tension on the cable and hence retrieval speed will be below the free speed at maximum voltage. For a set gear ratio this means the generation cycle will be shorter than the retrieval cycle at maximum power. It is apparent through modelling that a two-speed gearbox would allow superior generation if correctly designed.

If it is assumed that the friction couple between the cable and the capstan drive is ideal then it can be said that motor rotation is directly related to cable movement by the gear ratio and capstan radius (Equation (3.25)).

\[ \alpha = \frac{GR}{CR}, \text{ with} \]
\[ CR = \text{capstan radius} \]
\[ GR = \text{gear ratio} \]
\[ l = \text{tether length} \]
\[ \alpha = \text{motor rotation} \]

(3.25)

Since the ratio between motor rotation and cable length is constant the same factorial relationship exists for the first and second time rate derivatives of the motor rotation and cable length. In fact the inverse of this ratio describes the relationship between motor torque and the applied tension to the tether. If the motor torque equation is rearranged, multiplied by the gear ratio and divided by the capstan radius it can be added directly to the length equations of the cable equations of motion as a tensile force. The cable acceleration term then needs to be moved to the left hand side in the state space representation (Equation (3.26)).
\[ T = -b \ddot{\alpha} + K_i \dot{i}_w - J \ddot{\theta} \times \frac{GR}{CR} = \text{Tension} \]

\[ \alpha = l \times \frac{GR}{CR}, \dot{\alpha} = \dot{l} \times \frac{GR}{CR}, \ddot{\alpha} = \ddot{l} \times \frac{GR}{CR} \]

\[ \therefore \text{Tension} = i_w K_i \times \frac{GR}{CR} - lb \times \left( \frac{GR}{CR} \right)^2 - l \dot{l} \times \left( \frac{GR}{CR} \right)^2 \]

\[ GR = \text{gear ratio} \quad (3.26) \]

\[ CR = \text{capstan radius} \]

\[ \alpha = \text{angular displacement of motor rotor} \]

\[ i_w = \text{motor current} \]

The motor current equation is separable and related to the system by the rotor velocity as already described in the torque equation. (Equation (3.27))

\[ i_w = -\frac{K_i \dot{\alpha} - R_w i_w + V_w}{L_w} \]

\[ \therefore \dot{i}_w = -\frac{K_i \dot{l} \times \frac{GR}{CR} - R_w i_w + V_w}{L_w} \]

\[ R_w \text{ is the armature resistance} \quad (3.27) \]

\[ T_w \text{ is the applied torque} \]

\[ V_w \text{ is the applied voltage} \]
The only equation in the system model affected by the winch model is the equation for the radial acceleration of the cable, Equation (3.21). By substituting the expression in Equation (3.26) for tension in the relevant part of Equation (3.21), Equation (3.28) is obtained.

\[
\ddot{\ddot{I}} = \left( \mathbf{F}_{\text{eff}} + [0 \ 0 \ -mg] \right) \frac{\partial \mathbf{v}}{\partial t} - \left[ i_x \mathbf{K} \times \frac{GR}{CR} \mathbf{i}_b \times \left( \frac{GR}{CR} \right)^2 - \ddot{I} J_w \times \left( \frac{GR}{CR} \right)^2 \right] \left( \frac{1}{m} \right) \\
+ l \dot{\phi}^2 + l \dot{\theta}^2 \cos^2 \phi \\

\therefore \ddot{\ddot{I}} = \left( \mathbf{F}_{\text{eff}} + [0 \ 0 \ -mg] \right) \frac{\partial \mathbf{v}}{\partial t} - \left[ i_x \mathbf{K} \times \frac{GR}{CR} \mathbf{i}_b \times \left( \frac{GR}{CR} \right)^2 \right] \left( \frac{1}{m} \right) + l \dot{\phi}^2 + l \dot{\theta}^2 \cos^2 \phi \\

\therefore \ddot{\ddot{I}} = \left( 1 + J_w \times \left( \frac{\frac{GR}{CR}}{m} \right)^2 \left( \frac{1}{m} \right) \right) \left( \mathbf{F}_{\text{eff}} + [0 \ 0 \ -mg] \right) \frac{\partial \mathbf{v}}{\partial t} - \left[ i_x \mathbf{K} \times \frac{GR}{CR} \mathbf{i}_b \times \left( \frac{GR}{CR} \right)^2 \right] \left( \frac{1}{m} \right) + l \dot{\phi}^2 + l \dot{\theta}^2 \cos^2 \phi 
\]
Taking Equations (3.22), (3.27) and (3.28) the system model including winch dynamics can be summarised as per Equation (3.29). (Non-unique states, for example motor rotation, are derived from other states, in this case cable length.)

**Pendulum Equations**

\[
i = \left( \mathbf{F}_{\text{global}} + [0 \ 0 \ -Mg] \right) \cdot \frac{\partial \mathbf{v}}{\partial t} - \left[ \mathbf{i} \cdot \mathbf{K} \times \frac{GR}{CR} - ib \times \left( \frac{GR}{CR} \right)^2 \right] \left( \frac{1}{M} \right) + l\dot{\phi}^2 + l\dot{\phi}^2 \cos^2 \phi
\]

\[
\dot{\phi} = \left( \mathbf{F}_{\text{global}} + [0 \ 0 \ -Mg] \right) \cdot \frac{\partial \mathbf{v}}{\partial \phi} \left( \frac{1}{M} \right) - \left( 2li\dot{\phi} + l^2\dot{\phi}^2 \sin \phi \cos \phi \right) / l^2
\]

\[
\dot{\theta} = \left( \mathbf{F}_{\text{global}} + [0 \ 0 \ -Mg] \right) \cdot \frac{\partial \mathbf{v}}{\partial \theta} \left( \frac{1}{M} \right) - \left( 2li\dot{\theta} \cos \phi - 2l^2\dot{\theta} \dot{\phi} \cos \phi \sin \phi \right) / l^2 \cos^2 \phi
\]

\[
i = -K_i \dot{\phi} \frac{GR}{CR} - R_i i + V_w
\]

**Kinematic Equations**

\[
\dot{\mathbf{q}} = \frac{1}{2\sqrt{\mathbf{q} \cdot \mathbf{q}}} \begin{bmatrix} 0 & -P & -Q & -R \\ P & 0 & R & -Q \\ Q & -R & 0 & P \\ R & Q & -P & 0 \end{bmatrix} \mathbf{q}
\]

**Moment Equations**

\[
\Gamma P = J_x (J_x - J_y + J_z) PQ - [J_z (J_z - J_y) + J_z^2] QR + J_x el + J_x n
\]

\[
J_y \dot{Q} = (J_z - J_y) PR - J_z (P^2 - R^2) + m
\]

\[
\Gamma R = [J_y (J_z - J_y) + J_z^2] PQ - [J_x (J_x - J_y) + J_x^2] QR + J_x el + J_x n
\]

\[
\Gamma = J_y J_z - J_z^2
\]

where

\[
i \text{is the tether length}
\]

\[
\phi \text{ and } \theta \text{ are the tether rotations}
\]

\[
\dot{i}, \dot{\phi} \text{ and } \dot{\theta} \text{ are speeds and}
\]

\[
\ddot{i}, \ddot{\phi} \text{ and } \ddot{\theta} \text{ are accelerations}
\]

\[
P, Q \text{ and } R \text{ are the angular rates}
\]

\[
e l, m, n \text{ are the aircraft moments}
\]

\[
\mathbf{q} \text{ is the Quaternion vector}
\]

\[
i_w \text{ is the armature current}
\]

\[
V_w \text{ is the applied voltage}
\]

\[
g \text{ is acceleration due to gravity}
\]

\[
M \text{ is the mass}
\]

\[
J_w \text{ is the winch inertia at the motor}
\]

\[
J_x, J_y, J_z, J_{xz} \text{ are aircraft inertias}
\]

\[
\mathbf{F}_{\text{global}} \text{ is the global reference frame applied force}
\]

\[
K_i \text{ is the torque constant}
\]

\[
K_c \text{ is the back emf constant}
\]

\[
b \text{ is the viscous friction coefficient}
\]

\[
R_i \text{ is the motor resistance}
\]

\[
L_i \text{ is the motor inductance}
\]

\[
GR \text{ is the Gear Ratio}
\]

\[
CR \text{ is the Capstan Radius}
\]
3.4 Chapter Conclusions
Throughout this section of the thesis, a mathematical model for the kite system that can leverage an existing aircraft 6-DOF model has been developed and presented. Although the minimum complexity representation has been chosen for this work, the framework for a more complicated representation has also been presented so that future developments can continue from this work. These mathematical models will be used as tools for a great deal of the work that follows in this thesis.

3.5 Chapter References

4 Simulink® Modelling of a Kite Wind Generator

4.1 Introduction

Chapter 4 discusses the implementation of the mathematical model of the tethered glider system in Simulink®. This work is a development of a previous publication [1]. Heuristic controls are developed to demonstrate net power generation by correctly choosing cable controls and glider pitch cycles. It will be shown that approximately 100W of power are generated in this numerical experiment.

The second and third research questions “How will the system be modelled?” and; “How will the system be controlled to generate power?” are explored.

4.2 System Modelling

An existing aircraft model is modified to represent a tethered glider. The original model is taken from the ‘AeroSim Blockset®’[2] for Simulink®. The force equations are replaced with a pendulum model of three degrees of freedom. The pendulum model (as described in Chapter 3, Equation (3.21)) is free to rotate about the ground attachment point and the length is controlled either by direct acceleration control or an applied tension. The aircraft aerodynamic and rigid body model used is the Aerosonde® UAV model included in the Aerosim Blockset® [2]. The pendulum model is reproduced here as Equation (4.1).

\[
\begin{align*}
\ddot{l} &= \left( \mathbf{F}_w \right)^\top [0 \ 0 \ -mg] \frac{\partial \mathbf{v}}{\partial l} - T \left( \frac{1}{m} \right) + \dot{\theta}^2 + l \dot{\theta}^2 \cos^2 \phi \\
\ddot{\phi} &= \left( \mathbf{F}_w \right)^\top [0 \ 0 \ -mg] \frac{\partial \mathbf{v}}{\partial \phi} \left( \frac{1}{m} \right) - \left( 2ll \dot{\phi} \dot{\phi}^2 \sin \phi \cos \phi \right) \left( \frac{l^2}{l^2} \right) \\
\ddot{\theta} &= \left( \mathbf{F}_w \right)^\top [0 \ 0 \ -mg] \frac{\partial \mathbf{v}}{\partial \theta} \left( \frac{1}{m} \right) - \left( 2ll \dot{\theta} \cos \phi - 2l \dot{\phi} \dot{\phi} \sin \phi \right) \left( \frac{l^2 \cos^2 \phi}{l^2} \right)
\end{align*}
\]

where

- \( l \) is the tether length
- \( \phi \) and \( \theta \) are the tether rotations
- \( \dot{l}, \dot{\phi} \) and \( \dot{\theta} \) are speeds and
- \( \ddot{l}, \ddot{\phi} \) and \( \ddot{\theta} \) are accelerations
- \( m \) is the mass
- \( g \) is acceleration due to gravity
- \( T \) is the applied tension

Assuming direct control over tether acceleration, Equation (4.1) is reduced to two equations, with the expression for cable length being defined by a double integral of the cable control input. This equation is then written into a custom Simulink® block for integration with the existing aircraft model (Figure 4.1).
Figure 4.1: Simulink® custom block

The Cable block shown in Figure 4.1 is hidden beneath a mask (in Simulink® the mask effectively created another layer of program abstraction). This block sits within the overall KiteGen block representing the system dynamics (Figure 4.2). The KiteGen block is further hidden beneath a mask and from this block outputs and control inputs are passed as shown in Figure 4.3.
Figure 4.2: KiteGen Block representing system dynamics

Aircraft moment equations

Aircraft force models

Cable Block (Figure 4.1)

Aerodynamic models
Figure 4.3: Kite Simulation Block showing connection between KiteGen dynamic block, input, outputs and controls.
4.3 Stability Control

Once the system model was constructed and simulated it was noted that the tethered glider system was unstable (i.e. without active pitch control the glider would pitch up (exponentially) and drag into the wind losing altitude) and hence some form of stabilisation control was necessary. Using the existing control designs within the Aerosonde® demos available with the AeroSim® Blockset [2] airframe stability was achieved with simple manual tuning. These controls are a PID controller for pitch using the elevator, a PI controller for the roll using the ailerons and a simple proportional controller for heading. By regulating the roll and heading angles to zero the glider remains flying into the wind. The pitch controller is used to regulate the glider pitch about a set point and therefore control the lift generated by the glider. The only additional requirement for stability (in these experiments) is that pitch and cable acceleration inputs are changed smoothly and sufficiently slowly. These controls are shown in Figure 4.4.

Figure 4.4: Inside the Control Block

4.4 Control Settings for Power Generation

Power generation is achieved by coupling cable deployment with high lift conditions and cable retrieval with low lift conditions. In this work, cable deployment speed and pitch settings were chosen by trial and error. Logically the cable deployment speed must be lower than the wind speed powering the system by a significant amount such that the apparent wind is still sufficient to generate lift. Further, since the glider uses linearised aerodynamic models the angle of attack must be limited within the range of model applicability.
4.5 Results

Throughout this section the simulated results are presented and discussed. Out-of-plane motion was regulated to zero and therefore only the relevant variables and results for the two active dimensions are shown. Three-dimensional motions of the glider are much more complicated and due to their high degree of non-linearity, heuristic control is more difficult to implement (and beyond the scope of this work).

The important parameters for this experiment are given in Table 4.1. The wind speed chosen in this work is related to the performance envelope of the glider model used. Although much higher than the wind speed typically encountered at the ground it is reasonable for the wind speeds experienced at higher altitudes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider mass</td>
<td>8.5kg</td>
<td>Cable Linear Density</td>
<td>0.003kg/m</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>22m/s</td>
<td>Wing Area</td>
<td>0.55m²</td>
</tr>
<tr>
<td>Wing Span</td>
<td>2.89m</td>
<td>C_L0 (zero angle of attack)</td>
<td>0.23</td>
</tr>
<tr>
<td>C_D0 (minimum drag)</td>
<td>0.043</td>
<td>L/D</td>
<td>~6</td>
</tr>
</tbody>
</table>

Figure 4.5 shows the time series for both altitude and downwind position of the glider. During deployment the glider climbs and moves downwind as one would expect, as the cable is slowed and the pitch reduced the glider climbs a little more but stops moving downwind. During retrieval the glider rapidly moves upwind until it again reaches a quasi-equilibrium state, due mainly to the change in apparent wind, the wing loading and hence drag. Moving into the second deployment phase the glider drifts downwind as the pitch is increased and the cable begins to deploy. Generally speaking lift is related to pitch and the increased lift has a corresponding increase in drag. Higher drag means the equilibrium position of the glider is further downwind. (Conceptually similar to a heavier glider having more lift induced drag.)

![Figure 4.5: Glider Position Vs Time](image-url)
Figure 4.6 shows the behaviour of tether tension, pitch and the amount of cable deployed over the simulated experiment. The correlation between pitch and cable tension is clearly visible. Care must be taken when designing an experiment to ensure that cable tension remains positive, as a flexible cable cannot support negative tension conditions. This simple experiment shows the glider ranging between approximately 500 and 1000 meters altitude and a similar figure for cable deployment. This suggests that at maximum altitude the glider is approximately directly overhead of the ground station and similarly for minimum altitude.

Figure 4.6: Tether Tension, Pitch and Cable Length with time

Figure 4.7 shows the power generation and work done over the simulation time. The average power generation for this experiment is approximately 100W. By examining the work done it is possible to estimate the amount of energy storage that is necessary so that retrieval is possible before the next deployment phase.

Figure 4.7: Power Generation during simulation time
The simulated performance here shows that with very basic control and a sub-optimal glider design 100W can be generated (for a glider mass of 8.5kg at 1000m). There are many areas for improvement that would yield a greater average power generation with a glider of this size. Optimal control (assuming appropriate winching control is possible) could reduce retrieval time significantly, reduce the transition time in between successive cycles and could increase the power generated during deployment. Further by reducing glider mass much more of the lifting force could be used for generating power.
4.6 Chapter Conclusions

This Chapter presented a model of a tethered glider and simulated its response to heuristic controls. Net power generation has been demonstrated despite using sub-optimal control. This simple system has room for many improvements that would see increases in power generation. It is thought that this work is demonstrative of the real capabilities of using tethered glider for wind power generation.

4.7 Chapter Acknowledgement and Disclaimer

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4.8 Chapter References


5 Simulink® Modelling of a Glider Attached to a Ground Based Winch

5.1 Introduction

This Chapter specifically addresses research questions two, three and four on system modelling, control for power generation and the impact of system parameters on power generation. The model used differs from that used in Chapter 4 (which also addressed research questions two and three) in the following ways:

- The addition of aerodynamic spoilers
- Inclusion of winch dynamics
- Increasing drive motor efficiency of the winch
- Adding a two speed gear box to the winch drive system

5.1.1 System Model

The system model is developed from the previous chapter by including the pendulum model with winch dynamics from Chapter 3 (Equation (3.29)). Figures 5.1 (a) and (b) show the Simulink® implementation of this system model.
Figure 5.1(a): As implemented glider/winch model
Figure 5.1(b): Winch, Cable, Glider model block showing cable model block
Throughout the numerical experiments in the sections that follow the important parameters are shown in Table 5.1. All of the problems use classical PI, PID and P control methods to stabilize the glider, regulate the set point and to control the electric power applied to the winch. Essentially set point values of pitch and cable acceleration are varied manually to achieve reasonable results. These set points are in the form of periodic cycles that are heuristically developed, the cable acceleration set point time history then defines the cable length and hence the cycle altitudes (Figure 5.2). The control methodologies applied here are essentially two dimensional with out-of-plane motions regulated to zero (as in the previous Chapter).

Table 5.1: Glider and Cable Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider mass m</td>
<td>8.5kg</td>
<td>Cable Linear Density</td>
<td>0.003kg/m</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>22m/s</td>
<td>Wing Area</td>
<td>0.55m²</td>
</tr>
<tr>
<td>Wing Span</td>
<td>2.89m</td>
<td>$C_{L0}$ (zero angle of attack)</td>
<td>0.23</td>
</tr>
<tr>
<td>$C_{D0}$ (minimum drag)</td>
<td>0.043</td>
<td>$L/D$</td>
<td>~6</td>
</tr>
<tr>
<td>$J_{x}$</td>
<td>0.7795</td>
<td>$J_{y}$</td>
<td>1.122</td>
</tr>
<tr>
<td>$J_{z}$</td>
<td>1.752</td>
<td>$J_{12}$</td>
<td>0.1211</td>
</tr>
</tbody>
</table>
5.2 Tethered glider power generation (Experiment 1)

This system model is a conventional glider tethered to a winching station on the ground with control over the applied voltage to the winch drive motor and control over the glider aero controls rudder, aileron and elevator. Controls are developed to maximize power generation within the operational limits of the winching station whilst retrieving the glider in a stable manner with minimal power consumption. Table 5.2 shows the relevant model parameters for the winch station.

Table 5.2: Winch Parameters (Experiment 1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ (Viscous Friction Coefficient)</td>
<td>0.00027</td>
<td>$K_e$ (Motor back EMF constant)</td>
<td>0.04434</td>
</tr>
<tr>
<td>$K_t$ (Motor Torque Constant)</td>
<td>0.0491</td>
<td>$J_w$ (rotational Inertia kgm$^2$)</td>
<td>670e-6</td>
</tr>
<tr>
<td>$R_w$ (Armature Resistance)</td>
<td>0.177Ω</td>
<td>$V_{max}$ (maximum voltage)</td>
<td>24V</td>
</tr>
<tr>
<td>$I_{peak}$ (peak current limit)</td>
<td>29A</td>
<td>$I_{cont}$ (continuous current limit)</td>
<td>12.5A</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>71%</td>
<td>$GR$ (Gear Ratio to load)</td>
<td>48/14</td>
</tr>
<tr>
<td>$CR$ (Capstan drive radius)</td>
<td>0.021m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.3 shows the downwind position, altitude and cable length time histories for the simulated experiment. Figure 5.4 gives the time history of tether tension, pitch and cable velocity; the large spikes in tether tension are in part due to the abrupt change in the applied tension to control cable acceleration and, at the end of deployment the large spike is in part due to the large apparent wind velocity as cable retrieval is commenced. This demonstrates one of the challenges of trying to harness wind power with this system. During deployment the cable motion reduces the apparent wind speed and the converse is true during retrieval. Another consideration is that during power generation potential energy is being stored and since there is no way to harness this without on board turbines or optimised periodic orbits, this potential energy must be dissipated during retrieval to prevent the glider moving upstream of the winch.

This experiment shows an average mechanical power generation of 96.3 W, an average electric power generation of 41.7 W with a corresponding mechanical power to electrical power conversion efficiency of 43.3% (41.7/96.3x100%). It can be seen that the effect of losses/inefficiencies in the winching station have a double effect on system efficiency, especially in this case where retrieval is occurring for a significantly longer time than deployment/generation.
Voltage and current are shown in Figure 5.5. Figure 5.6 shows the work done and the instantaneous power generation during operation. Due to the fixed gear ratio retrieval must be slower than deployment as per the nature of permanent magnet brushed DC motors. However the limiting factor in this experiment is the apparent wind speed. As the glider is retrieved, to limit lift, the angle of attack must be reduced and this leads to the glider moving up wind of the ground station. The result is that when the cable is fully retrieved, and it is time to re-commence deployment, the glider must move down wind, leading to a condition where the apparent wind can drop so low that the glider literally drops out of the sky. Methods for avoiding this situation are explored in the following sections.
Figure 5.5: Voltage and Current (Experiment 1)

Figure 5.6: Power Generation (Experiment 1)
5.3 Tethered glider power generation with spoilers (Experiment 2)

The model of the previous section is now extended to include an approximate representation of the effect of spoilers. To allow simple tuning and implementation in the model the spoiler is actuated from 0-100% where the effect at 0% is nil and at 100% lift is zero and drag is doubled with a linear relation in between. As the results in Figures 5.7 to 5.10 show the ability to reduce the lift force and more importantly increase drag means the cable can be retrieved without the glider travelling too far upwind of the ground station, permitting for faster retrieval.

Important parameters for the winch station in this part of the work are as in Table 5.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ (Viscous Friction Coefficient)</td>
<td>0.00027</td>
<td>$K_e$ (Motor back EMF constant)</td>
<td>0.04434</td>
</tr>
<tr>
<td>$K_t$ (Motor Torque Constant)</td>
<td>0.0491</td>
<td>$J_w$ (rotational Inertia kgm$^2$)</td>
<td>670e-6</td>
</tr>
<tr>
<td>$R_w$ (Armature Resistance)</td>
<td>0.177Ω</td>
<td>$V_{max}$ (maximum voltage)</td>
<td>24V</td>
</tr>
<tr>
<td>$I_{peak}$ (peak current limit)</td>
<td>29A</td>
<td>$I_{cont}$ (continuous current limit)</td>
<td>12.5A</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>71%</td>
<td>$GR$ (Gear Ratio to load)</td>
<td>48/14</td>
</tr>
<tr>
<td>$CR$ (Capstan drive radius)</td>
<td>0.021m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The average mechanical power for this experiment is 138 W, and the average electric power generated is 73.3 W with a corresponding conversion efficiency of 53%. Therefore by increasing retrieval speed not only does the average system power increase but so does the energy conversion efficiency, due to less time being spent during retrieval.
Figure 5.8: Spoiler application, Glider Pitch and Cable velocity. (Experiment 2)

Figure 5.9: Tether Tension, Winch Current and Winch Voltage (Experiment 2)
Figure 5.10: Power generation (Experiment 2)
5.4 Tethered glider power generation with spoilers and high efficiency drive motor (Experiment 3)

To further the investigation into how system parameters affect overall performance, the simulation from the previous section is now modified to use a drive motor of much higher efficiency. This is modelled by reducing the armature resistance and viscous friction coefficient in the DC motor model. However, in reality a motor of higher efficiency would likely have different values for all model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ (Viscous Friction Coefficient)</td>
<td>0.00001</td>
<td>$K_e$ (Motor back EMF constant)</td>
<td>0.04434</td>
</tr>
<tr>
<td>$K_t$ (Motor Torque Constant)</td>
<td>0.0491</td>
<td>$J_w$ (rotational Inertia kgm$^2$)</td>
<td>670e-6</td>
</tr>
<tr>
<td>$R_w$ (Armature Resistance)</td>
<td>0.050Ω</td>
<td>$V_{max}$ (maximum voltage)</td>
<td>24V</td>
</tr>
<tr>
<td>$I_{peak}$ (peak current limit)</td>
<td>29A</td>
<td>$I_{cont}$ (continuous current limit)</td>
<td>12.5A</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>90%</td>
<td>$GR$ (Gear Ratio to load)</td>
<td>48/14</td>
</tr>
<tr>
<td>$CR$ (Capstan drive radius)</td>
<td>0.021m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The marked improvement in the power generated (Figs. 5.11-5.14) due to the large improvement in overall efficiency suggests that the use of a Brushless DC motor (Synchronous AC motor) in a practical device may well be of high value. With the improved efficiency the average mechanical power is unchanged on the previous experiment (Section 5.3, Experiment 2) at 137 W, however, the average electric power is 123 W with a corresponding system efficiency of 89%.
Figure 5.12: Spoiler application, Glider Pitch and Cable Velocity (Experiment 3)

Figure 5.13: Tether tension, Winch Current and Winch Voltage (Experiment 3)
Figure 5.14: Power Generation (Experiment 3)
5.5 Tethered glider power generation with spoilers and Winch with Gearbox (Experiments 4&5)

The portion of cycle time devoted to generation in the previous experiments is approximately 50%. Increasing this value would improve the average cycle power of the system. The potential to improve this ratio is now investigated by implementing the ability to change the winch gear ratio from retrieval to deployment. Spoilers allow retrieval speeds greater than deployment and are included in this experiment.

By retrieving the glider fast and with minimal power, more of the cycle time can be spent generating power and hence the mean power generation will increase as retrieval time decreases. As a baseline result for the system with spoilers and a gearbox, the same conditions as used in (Section 5.3) are repeated. The results show an improvement in generation by running the drive motor at higher torque and lower speed. The retrieval speed is then increased to the stable limit (by trial and error) to show how the average cycle power can be increased. Table 5.5 shows the important parameters for these experiments.

Table 5.5: Winch Parameters (Experiments 4&5)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ (Viscous Friction Coefficient)</td>
<td>0.00027</td>
<td>$K_e$ (Motor back EMF constant)</td>
<td>0.04434</td>
</tr>
<tr>
<td>$K_t$ (Motor Torque Constant)</td>
<td>0.0491</td>
<td>$I_w$ (rotational Inertia kgm$^2$)</td>
<td>670e-6</td>
</tr>
<tr>
<td>$R_w$ (Armature Resistance)</td>
<td>0.177Ω</td>
<td>$V_{max}$ (maximum voltage)</td>
<td>24V</td>
</tr>
<tr>
<td>$I_{peak}$ (peak current limit)</td>
<td>29A</td>
<td>$I_{cont}$ (continuous current limit)</td>
<td>12.5A</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>71%</td>
<td>$GR$ (Gear Ratio deployment)</td>
<td>48/14</td>
</tr>
<tr>
<td>$CR$ (Capstan drive radius)</td>
<td>0.021m</td>
<td>$GR$ (Gear Ratio retrieval)</td>
<td>14/48</td>
</tr>
</tbody>
</table>

Studying Figure 5.17 it can be seen that the gearbox introduces much larger spikes in current and tension plots. The control system simply switches gears at zero cable velocity, however the tension in the cable and hence torque on the motor is not zero and neither is the current flowing through the motor hence there is a spike as the winch controller adjusts the applied voltage to maintain the set cable acceleration. Further work would implement improved control to remove this spike, however, in this study the spike is simply truncated to allow better viewing of the results. This spike is also present in the derived instantaneous power generation.

Simply adding a gearbox that reduces the speed of the motor during retrieval yields an improvement in efficiency from 53% to 61% and a corresponding increase in average electrical power from to 73.3 W to 84.3 W (Figures 5.15-5.18).
Figure 5.15: Glider Position and Cable Length (Experiment 4)

Figure 5.16: Spoiler Position, Pitch and Cable Velocity (Experiment 4)
Within the scope of these simplified numerical experiments the system was then driven to the limit of stability by increasing the cable retrieval speed to the maximum stable limit. (It will be shown in Chapter 7 that optimal control techniques allow much faster retrieval speed). In this experiment the retrieval speed is increased to a little over 4 m/s and it should be noted here that this limit is mainly related to the drag that can be applied whilst still maintaining sufficient lift for stable glider retrieval. It is interesting to note that energy conversion efficiency does not improve with the faster retrieval over the baseline test, however, there is a large increase in average mechanical power to 170 W and at 61% efficiency this equates to an average electric power of 104 W (up from 84.3 W) (Figs. 5.18-5.21).
Figure 5.19: Glider Position and Cable Length (Experiment 5)

Figure 5.20: Spoiler Position, Glider Pitch and Cable Velocity. (Experiment 5)
Figure 5.21: Tether Tension, Winch Current and Winch Voltage (Experiment 5)

Figure 5.22: Power Generation (Experiment 5)
5.6 Chapter Conclusions

Throughout this Chapter the development and application of a tethered glider model (including winch) has been demonstrated. The basic model was extended to investigate system properties such as the addition of a two-speed gearbox on the ground station, the use of spoilers and the effect of increasing drive motor efficiency. From this work it can be seen that high drive motor efficiency is important since losses are applied both during generation and retrieval. Further the application of spoilers or another suitable device for reducing lift and increasing drag can significantly increase the speed at which the glider can be retrieved while simultaneously avoiding the problem of the glider travelling upwind of the ground station (and subsequently experiencing very low apparent wind speeds). Finally it can be said that the utilization of a gearbox has two positive effects, first it reduces the speed of the motor during retrieval when loads are low resulting in a improved efficiency due to lower frictional losses and secondly, the use of a gearbox allows for faster retrieval than deployment and hence larger average cycle powers for the same plant by spending a larger proportion of the cycle time in generation.

5.7 Further Work

Further development of more advanced control would allow high-speed retrieval of the glider, utilization of poorer wind resources by flying manoeuvres that increase the apparent wind during deployment and could provide a large margin of stability and robustness. With the utilization of more advanced cable models that allow for zero tension or slack conditions there may be an opportunity to design controls for the system that allow free fall of the glider during retrieval achieving the absolute minimum power consumption and minimum time for this phase of the generation cycle. In addition to the vast body of control and modelling work that needs to be done, practical experimentation needs to mirror simulation efforts and visa versa to examine the validity of the simulation and to uncover new and interesting phenomena.
5.8 Chapter Bibliography


Chapter 6 explores the results of Simulink® testing implementing the same winch control strategies as in Chapter 10 on manual testing. For practical reasons the switch between deployment and retrieval phases of power generation is achieved in a different manner. In the field tests, both the aero controls of the glider and the winch control interface were to be manually controlled. Since this is not the case with the simulation, an alternative schedule is presented that is similar but automated. The motivation of this work is to make some kind of a comparison of performance of the practical control system, to the previous simulations. A logical extension of the work in this chapter is that this control strategy could then be implemented, with the use of an Autopilot, for the first basic automated tests of the prototype.

Throughout this chapter, the sensitivity of this simple control algorithm to changes in wind speed and varying wind properties will also be investigated. This chapter’s work contributes to the seventh research question in demonstrating how the developed tools can be useful and further provides evidence to answer research question eight as to where the research should continue into the future.

As this chapter is quite lengthy and investigates a number of similar scenarios, an outline of each section of the chapter is given in Table 6.1 with the aim to make the information a little easier to navigate.
Table 6.1 Chapter outline

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Simulink® Model</td>
<td>Outlines the Simulink® modelling and control methodology used throughout the chapter.</td>
</tr>
<tr>
<td>6.2</td>
<td>Baseline Simulation of Manual Testing Control</td>
<td>Uses the developed model and control technique with the same test conditions as per previous chapters. This is used for comparison.</td>
</tr>
<tr>
<td>6.3</td>
<td>Simulation with a Main Drive Gear Ratio of 3.33:1</td>
<td>The gear ratio is changed from the previous value of 48/14 (3.43:1) to 10:3 to show the effect of gear ratio on system performance.</td>
</tr>
<tr>
<td>6.4</td>
<td>Simulation with a Main Drive Gear Ratio of 2:1</td>
<td>The gear ratio is changed, this time to 2:1 to examine the effect of gear ratio on system performance.</td>
</tr>
<tr>
<td>6.5</td>
<td>Simulation with differing wind strength</td>
<td>The model of 6.4 is retained and the wind strength is varied to see how the system responds and how the control needs to be altered to generate power.</td>
</tr>
<tr>
<td>6.6</td>
<td>Sensitivity to Yaw Wind Disturbance</td>
<td>Again using the same model as 6.4, random wind is added to the yaw wind component to examine system response.</td>
</tr>
<tr>
<td>6.7</td>
<td>Sensitivity to Pitch Wind Disturbance</td>
<td>The model of 6.4 is retained with a random input to the vertical wind component to examine system response to pitch disturbances.</td>
</tr>
<tr>
<td>6.8</td>
<td>Sensitivity to Wind Strength Disturbance</td>
<td>The model of 6.4 is retained; this time a random component is combined with the wind strength to examine system response to wind strength variance.</td>
</tr>
<tr>
<td>6.9</td>
<td>Sensitivity to Random Strength and Directional Wind Disturbance</td>
<td>Using the model from 6.4 disturbances in all 3 spatial dimensions of the wind is added to the wind vector to examine how the system behaves.</td>
</tr>
<tr>
<td>6.10</td>
<td>Discussion of Results</td>
<td>Here a summary of all the results of this chapter is presented and discussed.</td>
</tr>
<tr>
<td>6.11</td>
<td>Conclusions</td>
<td>Chapter conclusions.</td>
</tr>
</tbody>
</table>
6.1 Simulink® Model

The Simulink® model used throughout this section is essentially the same as that in Chapter 5; the difference being the control algorithm employed for the glider pitch and winch control. Here, instead of a timed schedule as in the previous chapters, a relay switch is used which switches from deployment to retrieval and visa versa, based on the cable length. The work of Chapter 5 was essentially an extension of work performed before the development of the winch model, and was based on acceleration control of the cable. Chapter 5 used this existing control strategy with the winch model. It is therefore reasonable to expect that control based around the winch characteristics will perform significantly better.

Since the model employed ignores the existence of the cable storage mechanism, this part of the winch control from the Chapter 10 on manual testing is ignored also. Further, due to the wiring of the winch electronics the sign convention for the winch current is different (than in Chapter 10) and hence the control algorithm appears different.

Figure 6.1 shows the winch control algorithm representing the manual testing to follow in Chapter 10. The relay is a standard Simulink® Block that is set to switch controls when each of the cable limits is reached (maximum and minimum length).

Figure 6.1: Simulation winch control algorithm
Figure 6.2 shows the embedded code used in the deployment block, which essentially uses the steady state motor equations to choose the applied voltage. This then enforces the set deployment current limit.

```matlab
function Vset = fcn(ThD,CSet,R,Ke)
    if Ke*ThD>CSet*R
        Vset = -Ke*ThD+CSet*R;
    else
        Vset=0;
    end

Figure 6.2: Deployment Control Algorithm
```

Figure 6.3 shows the control used during retrieval of the cable. The Proportional-Integral controller is started when the control is switched (i.e. the integrator is reset). This simply regulates the current flowing through the motor and hence the tension applied to the cable.

```matlab
if u==1
    y=20;
else
    y=1;
end

Figure 6.4: Pitch setting control algorithm

Figure 6.4 shows the code used to control the pitch setting on the glider. Pitch is set to a high value (in this case 20 degrees) for the deployment mode and to a low value during retrieval. As simple as it seems this control strategy is effective in generating power for this simulation.
6.2 Baseline Simulation of Manual Testing Control

To compare this work with other control techniques presented in this thesis, a test of the control technique with the same conditions as in earlier chapters was executed.

From Chapter 5, Tables 5.1 and 5.2 are reproduced as Tables 6.2 and 6.3.

Table 6.2: Glider and Cable Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider mass</td>
<td>8.5kg</td>
<td>Cable Linear Density</td>
<td>0.003kg/m</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>22m/s</td>
<td>Wing Area</td>
<td>0.55m²</td>
</tr>
<tr>
<td>Wing Span</td>
<td>2.89m</td>
<td>$C_l_0$ (zero angle of attack)</td>
<td>0.23</td>
</tr>
<tr>
<td>$C_D_0$ (minimum drag)</td>
<td>0.043</td>
<td>$L/D$</td>
<td>-6</td>
</tr>
<tr>
<td>$J_x$</td>
<td>0.7795</td>
<td>$J_y$</td>
<td>1.122</td>
</tr>
<tr>
<td>$J_z$</td>
<td>1.752</td>
<td>$J_{xz}$</td>
<td>0.1211</td>
</tr>
</tbody>
</table>

Table 6.3: Winch Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ (Viscous Friction Coefficient)</td>
<td>0.00027</td>
<td>$K_e$ (Motor back EMF constant)</td>
<td>0.04434</td>
</tr>
<tr>
<td>Kt (Motor Torque Constant)</td>
<td>0.0491</td>
<td>$J_w$ (rotational Inertia kgm²)</td>
<td>670e-6</td>
</tr>
<tr>
<td>$R_w$ (Armature Resistance)</td>
<td>0.177Ω</td>
<td>$V_{max}$ (maximum voltage)</td>
<td>24V</td>
</tr>
<tr>
<td>$I_{peak}$ (peak current limit)</td>
<td>29A</td>
<td>$I_{cont}$ (continuous current limit)</td>
<td>12.5A</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>71%</td>
<td>$GR$ (Gear Ratio to load)</td>
<td>48/14</td>
</tr>
<tr>
<td>CR (Capstan drive radius)</td>
<td>0.021m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first test showed an average mechanical power generation of 111 W, an average electrical power of 70 W and a corresponding conversion efficiency of 63%. The deployment current was set at 20 A, and the retrieval current 5 A. This control technique shows a significant improvement in power generation and efficiency compared to the approach used in Chapter 5. In Chapter 5, acceleration based set points for the cable control was used under the same conditions, and an average mechanical power generation of 96.3 W, and average electric power generation of 41.7 W (with a corresponding efficiency of 43.3%) was shown. This is quite a substantial improvement. Further, the design of the control is simpler as is the control tuning.

From the results in Figures 6.5-6.8 it is apparent that this form of winch control is much more efficient than that used in Chapter 5. The control demonstrated here shows an almost square wave characteristic to the winch drive current and voltage indicating that power is extracted more efficiently.
Figure 6.5: Cable Length, Altitude and Downwind position time history (Base)

Figure 6.6: Tether velocity, tension and glider pitch time history (Base)
Figure 6.7: Winch Current and Voltage time history (base)

Figure 6.8: Power Generation time history (base)
6.3 Simulation with a Main Drive Gear Ratio of 10:3

This numerical experiment is a simulation based on the winch design used in the first stage of prototype testing with a gear ratio of 10:3. First a simulation with a set deployment current of 25 A, and, a retrieval current of 5 A was run, followed by a simulation with a set deployment current of 20 A. Otherwise the test parameters are identical to the previous section (Tables 6.2 and 6.3).

For a current set point of 25 A during deployment and 5 A during retrieval an average mechanical power of 109 W, an average electrical power 51 W and a corresponding conversion efficiency of 47% is achieved.

Figures 6.9 to 6.12 show a growing oscillation during the first deployment cycle indicating that at the relatively high level of cable loading, the system stability is marginal.

![Aircraft Position/ Cable Length](Image)

![Cable Length, Altitude and Downwind position time history](Image)

*Figure 6.9: Cable Length, Altitude and Downwind position time history (GR3.33, Current 25 A)*
Figure 6.10: Tether velocity, tension and glider pitch time history (GR3.33, Current 25 A)

Figure 6.11: Winch Current and Voltage time history (GR3.33, Current 25 A)
Figure 6.12: Power Generation time history (GR3.33, Current 25 A)
The second experiment used a set deployment current of 20 A. The resulting average mechanical power is 107 W, the average electrical power 67 W and the corresponding conversion efficiency is 63%.

With the lower set current there is an improvement in efficiency and actual power generated. It is thought that this is in part due to lower resistive losses and in part due to the glider interfacing more moving air. By setting the deployment current to a lower point there will definitely be less heating of the motor and hence an improvement in longevity.

Figure 6.13: Cable Length, Altitude and Downwind position time history (GR3.33, Current 20 A)
Figure 6.14: Tether velocity, tension and glider pitch time history (GR3.33, Current 20 A)

Figure 6.15: Winch Current and Voltage time history (GR3.33, Current 20 A)
Figure 6.16: Power Generation time history (GR3.33, Current 20 A)
6.4 Simulation with a Main Drive Gear Ratio of 2:1

During Chapter 10 the modification of the winch to use a smaller gear ratio to increase the maximum cable speed is discussed. This was done to make launching of the system more reliable. Hence, the system is now simulated with a gear ratio of 2:1 as per the gear ratio used in the second phase of field-testing. Several different current set points are investigated to see how they affect power generation and energy conversion efficiency. It is shown that with suitable tuning good power generation results can be achieved.

The first test was run with a set deployment current of 25 A, and, a retrieval current of 5 A. The result is an average mechanical power of 78 W, an average electrical power of 43 W, and a corresponding efficiency of 56% (Figures 6.17 to 6.20).

![Figure 6.17: Cable Length, Altitude and Downwind position time history (GR2, Current 25 A)](image)
Figure 6.18: Tether velocity, tension and glider pitch time history (GR2, Current 20 A)

Figure 6.19: Winch Current and Voltage time history (GR2, Current 20 A)
Figure 6.20: Power Generation time history (GR2, Current 20 A)
The next experiment uses a reduced deployment current of 20 A to achieve an average mechanical power of 65 W, an average electrical power of 40 W, and a corresponding conversion efficiency of 61%. Although the efficiency is higher the actual power generated is reduced. The retrieval time in this experiment is significantly longer than the deployment time suggesting this control strategy is not capturing as much wind as the previous test (Figures 6.21 to 6.24).

Figure 6.21: Cable Length, Altitude and Downwind position time history (GR2, Current 20 A)
Figure 6.22: Tether velocity, tension and glider pitch time history (GR2, Current 20 A)

Figure 6.23: Winch Current and Voltage time history (GR2, Current 20 A)
Figure 6.24: Power Generation time history (GR2, Current 20 A)
In an effort to improve the performance, the retrieval current was reduced to 3 A, the deployment current set to 25 A and the retrieval pitch changed to –3 degrees. The aim was to increase the retrieval speed while simultaneously reducing the power consumed during this phase. The result was an average mechanical power generation of 130 W, an average electric power generation of 80 W, and a corresponding efficiency of 62%. Therefore the decrease in retrieval tension and simultaneous increase in retrieval speed is effective in improving cycle performance (Figures 6.25 to 6.28).

Figure 6.25: Cable Length, Altitude and Downwind position time history (GR2, Current Deploy 25 A, Retrieve 3 A, Pitch -3)
Figure 6.26: Tether velocity, tension and glider pitch time history (GR2, Current Deploy 25 A, Retrieve 3 A, Pitch -3)

Figure 6.27: Winch Current and Voltage time history (GR2, Current Deploy 25 A, Retrieve 3 A, Pitch -3)
Figure 6.28: Power Generation time history (GR2, Current Deploy 25 A, Retrieve 3 A, Pitch -3)
6.5 Simulation with differing wind strength

To gain an understanding of how wind strength affects the prototype system a number of numerical experiments are run at different wind speeds and generation/ control settings. It is shown that this control strategy is relatively sensitive to variations in wind strength.

The first experiment used a wind speed of 20 m/s (as opposed to 22 m/s of the previous sections), a gear ratio of 2:1, a deployment current of 25 A and a set retrieval current of 5 A. The result was an average mechanical power of 76 W, an average electric power generation of 26 W, and a corresponding efficiency of 34%. Interestingly the mechanical power is not significantly different but the electrical power generation is significantly poorer. This is because the drive motor is operating further from its peak efficiency (Figures 6.29 to 6.32).

![Figure 6.29: Cable Length, Altitude and Downwind position time history (GR2, Current 25 A, Wind 20 m/s)](image-url)
Figure 6.30: Tether velocity, tension and glider pitch time history (GR2, Current 25 A, Wind 20 m/s)

Figure 6.31: Winch Current and Voltage time history (GR2, Current 25 A, Wind 20 m/s)
Figure 6.32: Power Generation time history (GR2, Current 25 A, Wind 20 m/s)
Repeating the same experiment with a set deployment current of 20 A, the average mechanical power was further reduced to 70 W, however, the electrical power was increased to 37 W with a corresponding efficiency of 53% (Figures 6.33 to 6.36). This suggests that for the previous experiment the winch was operating in a far from optimum state. Therefore a successful control algorithm needs to take into account the maximum drive efficiency for a given cable loading and speed.

*Figure 6.33: Cable Length, Altitude and Downwind position time history (GR2, Current 20 A, Wind 20 m/s)*
Figure 6.34: Tether velocity, tension and glider pitch time history (GR2, Current 20 A, Wind 20 m/s)

Figure 6.35: Winch Current and Voltage time history (GR2, Current 20 A, Wind 20 m/s)
Figure 6.36: Power Generation time history (GR2, Current 20 A, Wind 20 m/s)
Repeating the experiment with a set deployment current of 15 A the resulting average mechanical power was 60 W, the electrical power 36 W, with a corresponding efficiency of 60%. This is not significantly different from the last experiment except that the efficiency is slightly higher and there is likely to be less heat generated in the drive motor. The results are depicted in Figures 6.37 to 6.40.

Figure 6.37: Cable Length, Altitude and Downwind position time history (GR2, Current 15 A, Wind 20 Am/s)
Figure 6.38: Tether velocity, tension and glider pitch time history (GR2, Current 15 A, Wind 20 m/s)

Figure 6.39: Winch Current and Voltage time history (GR2, Current 15 A, Wind 20 m/s)
Figure 6.40: Power Generation time history (GR2, Current 15 A, Wind 20 m/s)
To further the investigation, the wind speed was changed to 25 m/s, the deployment current to 25 A, and the pitch setting for retrieval 1 degree. The result was an average mechanical power of 56 W, an average electrical power generation of 36 W, and a corresponding efficiency of 65%. It is interesting that the power generation with this higher wind speed is lower than the baseline comparison for control settings from the previous section where an average of 43 W of electrical power was generated. This shows just how important tuning the control strategy is and how sensitive the control performance is to wind conditions. The following four figures show that a large proportion of time was spent in retrieval mode meaning that the extra power available in the stronger winds is not exploited to the full potential (Figures 6.41 to 6.44).

![Aircraft Position/ Cable Length](image)

*Figure 6.41: Cable Length, Altitude and Downwind position time history (GR2, Current 25 A, Wind 25 m/s)*
Figure 6.42: Tether velocity, tension and glider pitch time history (GR2, Current 25 A, Wind 25 m/s)

Figure 6.43: Winch Current and Voltage time history (GR2, Current 25 A, Wind 25 m/s)
Figure 6.44: Power Generation time history (GR2, Current 25 A, Wind 25 m/s)
For retrieval under increased apparent wind it was necessary to increase the proportional gain to ensure stability of the winch controller during the retrieval mode (Figure 6.45). (This controller is also suitable for the other test modes, however it was not developed until it was found necessary.)

Figure 6.45: Retrieval controller for 25 m/s wind speed and a retrieval set pitch of –5 degrees (Proportional gain increased to 10 from 1)

Using the new controller for retrieval as shown in Figure 6.45, with a simulated wind speed of 25 m/s, a set retrieval pitch of –5 degrees and a set deployment current of 25 A gave an average mechanical power of 184 W. The average electrical power generation was 121 W, and the conversion efficiency 65%. The behaviour of this experiment is shown in Figures 6.46-6.49. This is a significant improvement on the previous experiments; however, a great deal of the available wind energy is not captured. Wind power is proportional to the cube of wind speed and the increase in power was not been cubic. Graphically it can be seen a great deal of time is spent retrieving the glider.
Figure 6.46: Cable Length, Altitude and Downwind position time history (GR2, Current 25 A, Wind 25 m/s, Retrieval Pitch -5)

Figure 6.47: Tether velocity, tension and glider pitch time history (GR2, Current 25 A, Wind 25 m/s, Retrieval Pitch -5)
Using this simple control methodology it is apparent that as the wind speed increases there is a greater time spent retrieving the glider and hence the drop in system efficiency.
The final test of wind speed sensitivity found that the maximum wind velocity before instability was unavoidable was approximately 28 m/s. Further it was necessary to modify the pitch control settings to yield any significant power. It is therefore apparent that the system model and existing control is very sensitive to wind speed and that a practical device would need to be capable of continually adapting to changing wind conditions. Figure 6.50 shows the pitch control setting used with the higher wind speed setting. Here ‘y’ is the pitch set point, ‘u’ is the control setting (0=retrieval, 1=deployment) and ‘l’ is the tether length.

function y = Pit(u,l)
if u==1
    y=20;
else
    if 1<270
        y=-1;
    elseif 1<250
        y=-20;
    else
        y=1;
    end
end

Figure 6.50: Pitch control setting algorithm for retrieval at a wind speed of 28 m/s

The resulting mechanical power was 91 W, the electric power generation 52 W, and the conversion efficiency 57% as depicted in Figures 6.51-6.54.

Figure 6.51: Cable Length, Altitude and Downwind position time history (GR2, Current 25 A, Wind 28 m/s)
Figure 6.52: Tether velocity, tension and glider pitch time history (GR2, Current 25 A, Wind 28 m/s)

Figure 6.53: Winch Current and Voltage time history (GR2, Current 25 A, Wind 28 m/s)
It is clear from the results above that to make the most of more powerful winds more advanced and adaptive control techniques and or different hardware combinations will be needed. In these tests the lower limit for wind speed tested was 20 m/s because the Simulink® model had a saturation limits for the apparent wind speed of 15 m/s to 50 m/s. Below a wind speed of 20 m/s and during the transition to deployment from retrieval the apparent wind would drop onto the lower saturation limit. This hard limit could be removed, however, it is thought that the aero-model would be too far from reality and below this apparent wind speed stall is likely. (A summary of the many results in this section is shown in Table 6.4 at the end of the chapter.)
6.6 Sensitivity to Yaw Wind Disturbance

This section investigates the sensitivity of the control strategy to yaw wind disturbance. While not an exhaustive study it does give an indication of the robustness of the system. Figure 6.55 shows the Yaw/Heading to Rudder feedback controller.

![Figure 6.55: Yaw/Heading to Rudder feedback controller](image)

To simulate the effect of random yaw wind disturbances, random white noise is used as an input to the Easterly component of the North, East, Down (NED) wind vector. The winds, and resulting system trajectory are shown in Figures 6.56-6.61. Average mechanical power for the experiment was 79 W, the average electrical power generation was 45 W, and the corresponding conversion efficiency of 57%.

Throughout this test the parameters of the white noise generator block in Simulink® were for a noise power of 0.1 (m/s)²/Hz and a sample time equal to the simulation time. It is interesting to see maximum crosswind spikes of over 5 m/s or approximately 25% and relatively large fluctuations in glider attitude whilst remaining stable. Further, there is actually a marginal increase in power generation over the smooth wind experiment of the same test parameters.
Figure 6.56: North East Down wind time history (Yaw Test)

Figure 6.57: Attitude time history (Yaw Test)
Figure 6.58: Cable Length, Altitude and Downwind position time history (Yaw Test)

Figure 6.59: Tether velocity, tension and glider pitch time history (Yaw Test)
Figure 6.60: Winch Current and Voltage time history (Yaw Test)

Figure 6.61: Power Generation time history (Yaw Test)
6.7 Sensitivity to Pitch Wind Disturbance

Attention is now turned to simulating the sensitivity of the control system to pitch wind disturbance. A random white noise signal is added to the vertical wind component to represent a pitch variation in the winds. Simulation proved that the system became unstable with a noise power of more than approximately 0.02 (m/s)^2/Hz, showing that the system was more sensitive to pitch disturbance than yaw disturbance. This is likely because the upper pitch setting (20 degrees) is actually quite large and a disturbance pushing the pitch significantly beyond this point is likely to compromise system stability.

The average mechanical and electrical power generation were again 79 W and 45 W respectively with a corresponding conversion efficiency of 57%. It is interesting that the generation outcome is again marginally higher than the disturbance free case and almost identical to the previous case.

Figure 6.62: North East Down wind time history (Pitch Test)
Figure 6.63: Attitude time history (Pitch Test)

Figure 6.64: Cable Length, Altitude and Downwind position time history (Pitch Test)
Figure 6.65: Tether velocity, tension and glider pitch time history (Pitch Test)

Figure 6.66: Winch Current and Voltage time history (Pitch Test)
The relatively high sensitivity to pitch variation in the prevailing winds is logical and indicates that control of this is going to be a more challenging factor since the angle of attack is intentionally set high during power generation. Therefore a future research direction should include studying how variable wind conditions are likely to affect lift stability and stall characteristics of the tethered glider.
6.8 Sensitivity to Wind Strength Disturbance

Further investigating the effects of wind disturbance on the tethered glider’s control system, attention is turned to variation in the wind strength. This was implemented by adding a white noise input to the north wind component of the prevailing winds vector. For this test the maximum practical noise power was $0.1 \text{ (m/s)}^2/\text{Hz}$ as at higher intensities the lower apparent wind speed saturation limit is violated and hence the results are not valid. To explore this limit the aero model would need to be improved and extended and or practical tests carried out. From the results presented in Figures 6.68-6.73 it is apparent that the system is relatively insensitive to random variations in wind strength. The average mechanical and electrical power was 78 W and 44 W respectively with a corresponding conversion efficiency of 56%. Interestingly this is the same as the baseline test.

Figure 6.68: North East Down wind time history (Speed Test)
Figure 6.69: Attitude time history (Speed Test)

Figure 6.70: Cable Length, Altitude and Downwind position time history (Speed Test)
Figure 6.71: Tether velocity, tension and glider pitch time history (Speed Test)

Figure 6.72: Winch Current and Voltage time history (Speed Test)
Potentially the biggest risk imposed by variations in the wind strength is the fatigue loading on the system. The magnitude of the load variation on the system is proportional to the square of wind speed and hence the wind speed variation will have a squared effect on the fatigue loading.
6.9 Sensitivity to Random Strength and Directional Wind Disturbance

Finally sensitivity to a combination of randomness in all wind directions is investigated (without investigating rotational disturbances). As one would expect the combinational influence of random variations in all three dimensions of the wind is greater and hence stability can only be maintained with smaller disturbances. The implemented control is tuned in a heuristic manner and therefore other control techniques would likely offer a greater margin of stability. In this test there was a white noise input on each of the North, East, Down wind directions of 0.05, 0.05, and 0.005 (m/s$^2$/Hz respectively. The resulting behaviour of the system is presented in Figures 6.74-6.79.

![Figure 6.74: North East Down wind time history (Random Wind Test)](image)
Figure 6.75: Attitude time history (Random Wind Test)

Figure 6.76: Cable Length, Altitude and Downwind position time history (Random Wind Test)
Figure 6.77: Tether velocity, tension and glider pitch time history (Random Wind Test)

Figure 6.78: Winch Current and Voltage time history (Random Wind Test)
As with the previous sensitivity tests, the power generation is relatively unaffected by the variation in the wind properties. The average mechanical and electrical power generation was 79 W and 45 W with a corresponding conversion efficiency of 57%.
6.10 Discussion of Results

Table 6.4 summarises the results from all of the tests/experiments in this chapter. It is clear that the control is particularly sensitive to mean wind speed variations but not particularly sensitive to higher frequency random variation about this mean. The system was most sensitive to pitch variation in wind velocity, however, the fact remains that mean wind speed changes have a much more profound influence on generation outcomes. When the mean wind speed increases by 1m/s there is a large impact on the control necessary to extract power. The actual power generated is highly sensitive to control tuning. If the control settings are poorly chosen, even by a small factor, the power generated can be reduced by a factor of two.

It is apparent that the system is sensitive to low frequency wind vector variations and relatively insensitive to high frequency disturbance (provided the system remains stable). This realisation comes from the results in section 6.8 and the fact that system performance is highly sensitive to steady state changes in wind speed. A logical conclusion is that as the frequency of wind speed variations approaches a similar magnitude to the power generation cycle frequency (from higher to lower frequencies), the system becomes more sensitive to the variations. If wind forecasting was sufficiently accurate this could be used to benefit the system. For example if the wind strength was varying at a suitable frequency or the gusts reasonably well predicted the generation phase could be coupled with the wind strength peaks and retrieval with the wind strength troughs.

It can, however, be said that provided the apparent wind stays inside the performance envelope of the glider and the pilot is sufficiently skilled, power generation can be achieved with simple control.
Table 6.4: Summary of Results

<table>
<thead>
<tr>
<th>Wind m/s</th>
<th>Gear Ratio</th>
<th>Retrieval Current</th>
<th>Deploy Current</th>
<th>Retrieval Pitch</th>
<th>Mechanical Power</th>
<th>Electric Power</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>3.43</td>
<td>5</td>
<td>20</td>
<td>1</td>
<td>111</td>
<td>70</td>
<td>63</td>
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<td>25</td>
<td>1</td>
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<td>51</td>
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<td>5</td>
<td>20</td>
<td>1</td>
<td>107</td>
<td>67</td>
<td>63</td>
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<td>2</td>
<td>5</td>
<td>25</td>
<td>1</td>
<td>78</td>
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<td>20</td>
<td>1</td>
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<td>8</td>
<td>25</td>
<td>1, -1, -20</td>
<td>91</td>
<td>52</td>
<td>57</td>
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</tbody>
</table>

(for the above test see Figure 9.46 for the pitch schedule)

<table>
<thead>
<tr>
<th>Wind m/s</th>
<th>Gear Ratio</th>
<th>Retrieval Current</th>
<th>Deploy Current</th>
<th>Retrieval Pitch</th>
<th>Mechanical Power</th>
<th>Electric Power</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>2</td>
<td>5</td>
<td>25</td>
<td>1</td>
<td>79</td>
<td>45</td>
<td>57</td>
</tr>
</tbody>
</table>

(the above test is the result for yaw sensitivity)

<table>
<thead>
<tr>
<th>Wind m/s</th>
<th>Gear Ratio</th>
<th>Retrieval Current</th>
<th>Deploy Current</th>
<th>Retrieval Pitch</th>
<th>Mechanical Power</th>
<th>Electric Power</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>2</td>
<td>5</td>
<td>25</td>
<td>1</td>
<td>79</td>
<td>45</td>
<td>57</td>
</tr>
</tbody>
</table>

(the above test is the result for pitch sensitivity)

<table>
<thead>
<tr>
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<th>Gear Ratio</th>
<th>Retrieval Current</th>
<th>Deploy Current</th>
<th>Retrieval Pitch</th>
<th>Mechanical Power</th>
<th>Electric Power</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>2</td>
<td>5</td>
<td>25</td>
<td>1</td>
<td>78</td>
<td>44</td>
<td>56</td>
</tr>
</tbody>
</table>

(the above test is the result for wind strength sensitivity)

<table>
<thead>
<tr>
<th>Wind m/s</th>
<th>Gear Ratio</th>
<th>Retrieval Current</th>
<th>Deploy Current</th>
<th>Retrieval Pitch</th>
<th>Mechanical Power</th>
<th>Electric Power</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>2</td>
<td>5</td>
<td>25</td>
<td>1</td>
<td>79</td>
<td>45</td>
<td>57</td>
</tr>
</tbody>
</table>

(the above test is the result for random disturbance)
6.11 Chapter Conclusions

The control as designed is functional and in certain conditions can be quite effective at generating power. However, away from design conditions, the control can be relatively ineffective and small changes in mean wind conditions can lead to a very large reduction in the power generated. As the frequency of wind variation increases, the system becomes less sensitive to this disturbance, provided it is not so severe as to push the system beyond its stable limits. Overall, the control is relatively robust, however a practical system would need a great deal of adaptability in the control to manage varying wind conditions.
Chapter 7 presents optimal trajectory development for power generation using a glider tethered to a ground based winching station. The mathematical model from Chapter 3 (Equation (3.22)) is applied in the formulation of an optimal control problem describing periodic flight patterns for maximal power extraction from prevailing winds. The optimal control problem is solved in Matlab™ using the software package DIRECT. This work develops tools to improve upon the controls developed in previous chapters. The flight dynamic model (FDM), for an Aerosonde™ UAV is freely available with the AeroSim Blockset®. Optimal solutions for a number of different periodic cycle times are investigated and the average cycle power compared. It is shown that by correctly controlling the winching of the tether and the aerodynamic control surfaces on the glider, significant net power can be generated. In fact, optimal control provides up to four times the best generation result from the previously presented heuristic control strategies. This chapter is based on a previously published conference paper [1] by the author, and developed to explore optimal power generation for the problems similar to those in previous chapters (Chapters 4 and 5). The work of this chapter addresses research questions three and four of how power can be generated and how system parameters affect the performance.
7.2 Mathematical Model

Here the work of Chapter 3 is utilised again. The model used throughout is that given by Equation (3.22) reproduced here as Equation (7.1) representing a tethered glider with the tether length controlled by an applied force. This model is implemented with the flight performance data (modelling parameters) of the Aerosonde UAV™ available with the Aerosim Blockset®, by transcribing the Simulink model used in Chapters 4 and 5 to a “State Space” type script for integration with the DIRECT software package. Attempts were made to use models including winch dynamics and/or aerodynamic spoilers, however, no convergent optimal control problems were found.

\[ \ddot{\vec{l}} = \left( \vec{F}_{A} + \begin{bmatrix} 0 & 0 & -Mg \end{bmatrix} \right) \frac{\partial \vec{v}}{\partial \vec{l}} - T \left( \frac{1}{M} \right) + l\dot{\phi}^2 + l\dot{\theta}^2 \cos^2 \phi \]

\[ \ddot{\phi} = \left( \left( \vec{F}_{A} + \begin{bmatrix} 0 & 0 & -Mg \end{bmatrix} \right) \frac{\partial \vec{v}}{\partial \phi} \left( \frac{1}{M} \right) - \left( 2li\dot{\phi} + l^2\dot{\theta} \sin \phi \cos \phi \right) \left/ l^2 \right. \right) \]

\[ \ddot{\theta} = \left( \left( \vec{F}_{A} + \begin{bmatrix} 0 & 0 & -Mg \end{bmatrix} \right) \frac{\partial \vec{v}}{\partial \theta} \left( \frac{1}{M} \right) - \left( 2li\dot{\theta} \cos \phi - 2l^2\dot{\phi} \theta \cos \phi \sin \phi \right) \left/ l^2 \cos^2 \phi \right. \right) \]

**Kinematic Equations**

\[
\dot{\vec{q}} = \frac{1}{2\sqrt{\vec{q} \cdot \vec{q}}} \begin{bmatrix} 0 & -P & -Q & -R \\ P & 0 & R & -Q \\ -R & 0 & 0 & P \\ R & Q & -P & 0 \end{bmatrix} \vec{q} 
\]

**Moment Equations**

\[
\Gamma \dot{P} = J_{z_{\xi}} \left[ J_{\xi} - J_{z_{\xi}} + J_{\xi} \right] P - \left[ J_{z} \left( J_{\xi} - J_{z} \right) + J_{z}^2 \right] Q - J_{z} \dot{e}_{l} + J_{\xi} n \\
\Gamma \dot{Q} = \left( J_{z} - J_{\xi} \right) P R - J_{\xi} \left( P^2 - R^2 \right) + m \\
\Gamma \dot{R} = \left[ J_{z} \left( J_{\xi} - J_{z} \right) + J_{z}^2 \right] Q - J_{z} \left[ J_{z} - J_{\xi} + J_{\xi} \right] Q R + J_{\xi} \dot{e}_{l} + J_{\xi} n \\
\Gamma = J_{z} J_{\xi} - J_{z_{\xi}}^2 \\
\text{where,} \\
\begin{align*}
\vec{l} & \text{ is the tether length} \\
\phi & \text{ and } \theta & \text{ are the tether rotations} \\
\dot{i}, \dot{\phi}, \text{ and } \dot{\theta} & \text{ are speeds and} \\
\ddot{i}, \ddot{\phi}, \text{ and } \ddot{\theta} & \text{ are accelerations} \\
P, Q \text{ and } R & \text{ are the angular rates} \\
el, m, n & \text{ are the aircraft moments} \\
& \text{ are the aircraft inertias} \\
F_{A} & \text{ is the global reference frame applied force} \\
T & \text{ is the applied tension} \\
g & \text{ is acceleration due to gravity} \\
M & \text{ is the mass} \\
& \text{ are aircraft inertias} \\
\end{align*} 
\]

Control over the cable tension is assumed and based on the results of winch testing (see Chapter 8) this is a reasonable assumption.
7.3 Optimal Control Problem

The problems solved here are the general set of optimal control problems described below. These are solved using the DIRECT software package, an optimal control problem solver. The non-restrictive framework it encompasses solves a large set of engineering problems.

The control problem is stated as follows: find the state control pair \( \{x(t), u(t)\} \) and possibly the final time \( t_f \) that minimise the performance index;

\[
J = e[x(t_f), t_f] + \int_{t_0}^{t_f} L[x(t), u(t), t] dt
\]  
(7.2)

subject to the non-linear state equations;

\[
x(t) = f(x(t), u(t), t)
\]  
(7.3)

the end point conditions,

\[
e^0_L \leq e[x(t_0), t_0] \leq e^0_U
\]

\[
e^0_L \leq e[x(t_f), t_f] \leq e^0_U
\]  
(7.4)

the path constraints,

\[
g_L \leq g[x(t), u(t), t] \leq g_U
\]  
(7.5)

and the box constraints,

\[
x_L \leq x(t) \leq x_U
\]

\[
u_L \leq u(t) \leq u_U
\]  
(7.6)

This general formulation allows the user to prescribe as few or as many end point conditions as they please, as many linear/ non-linear possibly time varying path constraints as they please and the more conventional state and control box constraints.

There are however a number of common problems that can be encountered, first it may be that there is no feasible solution. In which case there is definitely no optimal solution. Second there may be an infinite set of solutions. Perhaps this wouldn’t present too much difficulty with analytic solutions but with numerical methods this causes problems with convergence. One method for working around this problem is to constrain solutions to remove solution symmetry. In this work a small non-symmetrical wind component is added and initial conditions for the problem start the glider off centre.

The optimal control problems that follow use periodic end point conditions \((x_0 = x_f, u_0 = u_f)\), non-linear state equations as presented in Equations (7.1), non-linear path constraints on the quaternions such that the glider remains belly down and flying forward (Equation (7.9)), box constraints as shown in Table 7.1 and the
performance index given in Equation (7.7). Further, extra states were introduced to represent the controls with control input defined as the time rate change of the new states. This was done to obtain smoother solutions and to avoid control changes that are too fast to be realised. The control inputs are thus as shown in Equation (7.8). The performance index instructs DIRECT to find maximum power generation. Table 7.2 shows the key glider and cable parameters.

\[ J = \int_0^t -x_{\text{cable_tension}} \times x_{\text{cable_velocity}} \, dt \]  

(7.7)

\[ x_{\text{cable_tension}}(t) = u_1(t) \]
\[ x_{\text{flap}}(t) = u_2(t) \]
\[ x_{\text{elevator}}(t) = u_3(t) \]
\[ x_{\text{aileron}}(t) = u_4(t) \]
\[ x_{\text{rudder}}(t) = u_5(t) \]

(7.8)

\[-\frac{\pi}{2} \leq \tan^{-1}\left(\frac{2(q(3)q(4) + q(2)q(1))}{q(1)^2 - q(2)^2 - q(3)^2 + q(4)^2}\right) \leq \frac{\pi}{2}\]
\[-\frac{\pi}{2} \leq \sin^{-1}\left(2(q(3)q(1) + q(2)q(4))\right) \leq \frac{\pi}{2}\]
\[-\frac{\pi}{2} \leq \tan^{-1}\left(\frac{2(q(2)q(3) + q(1)q(4))}{q(1)^2 + q(2)^2 - q(3)^2 - q(4)^2}\right) \leq \frac{\pi}{2}\]

(7.9)

with

\[ q(1), q(2), q(3), q(4) \text{ quaternion components} \]

Table 7.1: Box Constraints

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Length</td>
<td>50 m</td>
<td>200 m</td>
</tr>
<tr>
<td>( \phi )</td>
<td>(-\frac{\pi}{4}) radians</td>
<td>(\frac{\pi}{4}) radians</td>
</tr>
<tr>
<td>( \theta )</td>
<td>(-\frac{\pi}{4}) radians</td>
<td>0 radians</td>
</tr>
<tr>
<td>Cable Speed</td>
<td>-10 m/s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Cable Tension</td>
<td>5 N</td>
<td>1500 N</td>
</tr>
<tr>
<td>Cable Tension Rate Change</td>
<td>-1000 N/s</td>
<td>1000 N/s</td>
</tr>
<tr>
<td>Flap</td>
<td>-15 degrees</td>
<td>15 degrees</td>
</tr>
<tr>
<td>Elevator</td>
<td>-15 degrees</td>
<td>15 degrees</td>
</tr>
<tr>
<td>Aileron</td>
<td>-15 degrees</td>
<td>15 degrees</td>
</tr>
<tr>
<td>Rudder</td>
<td>-15 degrees</td>
<td>15 degrees</td>
</tr>
</tbody>
</table>
Table 7.2: System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider Mass</td>
<td>13.5 kg</td>
</tr>
<tr>
<td>Drag Coefficient (zero angle of attack)</td>
<td>0.0434</td>
</tr>
<tr>
<td>Lift Coefficient (zero angle of attack)</td>
<td>0.23</td>
</tr>
<tr>
<td>$C_{la}$ increase in lift with angle of attack</td>
<td>5.6106</td>
</tr>
<tr>
<td>Wing Span</td>
<td>2.8956 meters</td>
</tr>
<tr>
<td>Wing Area</td>
<td>0.55 square meters</td>
</tr>
<tr>
<td>Cable linear density</td>
<td>0.003 kg/m</td>
</tr>
</tbody>
</table>

In an effort to identify some general trends, average power generation and the resulting trajectory for a number of cycle times and wind speeds are examined in the following sections.
7.4 Results Part 1

To examine how optimal control systems will work, optimal control problems have been solved for a number of cycle times. To permit comparison several problems were solved for different wind speeds. Table 7.3 shows cycle time, wind speed, average cycle power and cable length range. Some time histories of states and controls are shown and one of the resulting trajectories (Figures 7.2 to 7.7).

Table 7.3: Average Power Generation Results

<table>
<thead>
<tr>
<th>Cycle (seconds)</th>
<th>Time (m/s)</th>
<th>Wind Speed (m/s)</th>
<th>Average Power (kW)</th>
<th>Power Cable Length Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>0</td>
<td>152-152 (0)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>1.2472</td>
<td>159-164 (5)</td>
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</tr>
<tr>
<td>2</td>
<td>20</td>
<td>2.4943</td>
<td>107-117 (10)</td>
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</tr>
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<td>2</td>
<td>25</td>
<td>2.4943</td>
<td>124-134 (20)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>3.1803</td>
<td>50-64 (14)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>4.6759</td>
<td>180-200 (20)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>4.6721</td>
<td>146-165 (19)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>4.6771</td>
<td>50-74 (24)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>5.5912</td>
<td>166-200 (34)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>5.5927</td>
<td>81-114 (33)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>6.0747</td>
<td>114-153 (39)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>6.2274</td>
<td>153-197 (44)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>6.3561</td>
<td>114-163 (49)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>6.3572</td>
<td>151-200 (49)</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>6.7279</td>
<td>126-200 (74)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.3 shows a general trend that as the cycle time increases, the average cycle power tends to increase. This was a result of the assumption of the maximum rate of change of cable tension and to a lesser extent control surface deflections. Longer cycle times resulted in a lower percentage of cycle time being spent in turn around between power generation and plant retrieval modes of the generation cycle. There was also an increase in tether length variation with longer cycle times. These trends are shown in Figure 7.1. The wind speeds used in these tests are higher than what is typically experienced at these altitudes, however, their choice was related to the glider model used and its limitations.
Figure 7.1: Trends in power generation and cable length variation with cycle time and wind speed
Figure 7.1 shows that as cycle time increased average power output tended to asymptote and change in cable length tended to increase more or less linearly. Due to the nature of the optimal control problem it is likely that if cycle time was continually extended the state bounds of the cable length would become a limiting factor and therefore one would expect the solution to contain multiple short cycles. The operating limits used here were an estimate of likely practical control limits.

Looking more closely at the results the optimal trajectory for a cycle time of 3 seconds and a wind speed of 25m/s is presented.

*Figure 7.2(a): State Control Set for a cycle time of 3 seconds and a wind speed of 25m/s*
Figure 7.2(b): State Control Set for a cycle time of 3 seconds and a wind speed of 25m/s

Figure 7.3 shows that the controls were quite active; this could be problematic and could be addressed by including a penalty on control inputs in the statement of the optimal control problem. Further, it is apparent that although the average cycle power was 3.2kW, the peak power output was 12.3kW (the set limit was 15kW). This indicates an approximate duty cycle of 25%. Another point is that if the rate change of tether tension could be increased, the average power generation could be increased. With the motor operating at approximately 25%, it would be acceptable to have peak power settings significantly above allowable continuous power. Peak power during retrieval is 5.6kW, interestingly, close to the average cycle power.

The Aerosonde UAV on which the model here was based, was relatively heavy due to the fitment of an engine. The Spirit 100 Sailplane planned for use in the prototype had a similar wingspan, and a fully laden mass of approximately 6kgs (approximately half the Aerosonde’s mass). However, for this particular optimal control problem mass was not a limiting factor and would likely not make a significant difference. It was thought that the lower mass would allow maximum generation with less powerful winds since less wind power would be used lifting the aircraft mass.

Figure 7.3 shows the flight path for a 3 second cycle time at a wind speed of 25m/s. (The aircraft image used is a representation and not the actual glider.) It can be said that the result is quite non-intuitive. Showing trajectories for every problem solved in Table 7.2 would be quite repetitive, however, the author notes that they are all slightly different, becoming wobblier with increasing cycle time. Many of the trajectories
developed show this wobbly nature. It is thought this is due to the optimisation algorithm working along the edges of the box constraints for maximum power.

Figure 7.3: Trajectory cycle time of 3 seconds and a wind speed of 25m/s

The consequence of cycle time on the winch requirements is presented in Figures 7.4 to 7.7. Peak cable powers for each problem are shown in Table 7.4.
Figure 7.4: Cable controls for a 5 second cycle time with a wind speed of 20m/s

Figure 7.5: Cable controls for an 8 second cycle time with a wind speed of 20m/s
Figure 7.6: Cable controls for a 10 second cycle time with a wind speed of 20m/s

Figure 7.7: Cable controls for a 15 second cycle time with a wind speed of 20m/s
Table 7.4: Peak Cable Power

<table>
<thead>
<tr>
<th>Cycle Seconds</th>
<th>Time</th>
<th>Maximum Retrieval Power kW</th>
<th>Maximum Generation Power kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>24.3587</td>
<td>9.5968</td>
</tr>
<tr>
<td>4</td>
<td>6.7545</td>
<td>15.000</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6.4286</td>
<td>15.000</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6.0650</td>
<td>15.000</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6.5081</td>
<td>15.000</td>
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</tr>
<tr>
<td>9</td>
<td>6.0628</td>
<td>15.000</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6.4634</td>
<td>15.000</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>6.3785</td>
<td>15.000</td>
<td></td>
</tr>
</tbody>
</table>

Peak cable power for a wind speed of 25m/s at various cycle times

<table>
<thead>
<tr>
<th>Cycle Seconds</th>
<th>Time</th>
<th>Maximum Retrieval Power kW</th>
<th>Maximum Generation Power kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.1941</td>
<td>4.8131</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.4151</td>
<td>9.6532</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5.5930</td>
<td>12.272</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6.6895</td>
<td>15.000</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6.0650</td>
<td>15.000</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6.4549</td>
<td>15.000</td>
<td></td>
</tr>
</tbody>
</table>
Maximum Retrieval Power and Maximum Power Generation Vs Cycle Time

Figure 7.8: Maximum Retrieval Power and Generation Power for various conditions
Studying Figures 7.4 to 7.8 and Table 7.4 reveal that the winch requirements were approximately the same regardless of cycle time. The gain in power with increasing cycle time was due to the transition time between power generation and retrieval. Longer cycle times resulted in a larger percentage of time spent in generation and retrieval. Clearly there is a trade off between the length variation of the cable and average power generation in this problem.
7.5 Results Part 2

This section presents work representing the specific prototype system developed in this work and solutions to control problems similar to those of Chapters 4 and 5. The work in Chapter 9 will indicate that the winch response was sufficiently fast, that direct control over cable tension would be a realistic assumption. In fact, the rate of change of cable tension assumed in the earlier part of this chapter was overly conservative (1000N/s). Chapter 10 will show that the rate of change limit chosen for the cable tension in these optimal control problems was appropriate.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
<th>Parameter</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Acceleration</td>
<td>1.9 (m/s²)</td>
<td>Max Cable Tension</td>
<td>150 (N)</td>
</tr>
<tr>
<td>Cable Velocity Out</td>
<td>3.3 (m/s)</td>
<td>Cable Velocity In</td>
<td>2.9 (m/s)</td>
</tr>
<tr>
<td>Min Cable Tension</td>
<td>5 N</td>
<td>Max Tension Rate Change</td>
<td>7400N/s</td>
</tr>
</tbody>
</table>

Generating optimal trajectories using this model and software proved time consuming, and hence a selection of solutions was generated to show the influence of the physical limitations of the proposed prototype. General trends are shown that can guide future work.

Initially, a 5 second cycle time was investigated, with the control limitations as per Table 7.5. In Figure 7.9 the control surface deflection time histories are shown. Figure 7.10 shows the time history of the tether length and tension, and the instantaneous power. The average power generation is 217 W. Recalling from Chapter 5 that the best that could be achieved utilising aerodynamic spoilers, a gearbox (two additional performance enhancing devices) and manual tuning was 170 W. Optimal control, therefore, provides a significantly higher energy yield with a simpler mechanical system.
Figure 7.9: Control Surface time history (5 second cycle)

Figure 7.10: Tether length, tension and instantaneous power generation (5 second cycle)
Figure 7.11 shows as an example trajectory, the cable is joins the winch to the glider at its down wind position.

Additionally a 15 second cycle was examined, generating an average of 220 W. This was not significantly different to that achieved with a 5 second cycle, suggesting that for a set gear ratio, a short cycle time could be better, in that cable wear may be limited to a smaller section of cable. Figures 7.12 and 7.13 show the time histories of the control surfaces and tether variables. Figure 7.14 shows a representation of the actual trajectory.
Figure 7.12: Control Surface time history (15 second cycle)

Figure 7.13: Tether length, tension and instantaneous power generation (15 second cycle)
Compared to the manually tuned control utilised in Chapter 5, optimal control strategies can achieve a two-fold increase in power generation (assuming a single gear ratio). Further, if one studies the resulting trajectories, it would suggest that the optimisation routine negates the need for drag flaps or spoilers since the trajectory can be shaped so that the potential energy gained during climbing can be converted to kinetic energy during descent and then recaptured at the beginning of deployment.
7.6 Results Part 3

In this third set of optimal control solutions, the results in “Part 2” are revisited with the allowable cable retrieval speed set much higher. This represents the fitment of a two-speed gearbox to the main winch drive. The two-speed gearbox takes advantage of the glider’s ability to dive; an inherent strength of rigid winged gliders for tethered power generation.

Investigating the resulting optimal trajectory for a 5 second cycle with a two-speed gearbox allowing retrieval at 20 m/s, an average power generation of 410 W was achieved. The minimum tension constraint of 5N was maintained during retrieval. In comparison to the work in the previous section, fast retrieval resulted in a further two-fold improvement in average cycle power. Therefore this system was four times more effective than the manually tuned baseline using a two-speed gearbox. However, at 410 W the drive motor is being driven beyond its design rating, it may therefore be necessary to supply additional cooling in a practical system.

Figure 7.15: Control Surface time history for a 5 second cycle with gearbox
To further investigate the performance of a system with gearbox, results for optimal power generation for a 15 second cycle have also been generated. The result was an average power generation of 405 W. Curiously this was less than for the 5 second cycle by 5 W suggesting that shorter cycle periods could be beneficial. However, the gearbox would be changing gears three times more frequently with the shorter cycle time and hence this small penalty may be worth a reduction in system wear. Figures 7.17 to 7.19 show the results of the optimisation routine.
Figure 7.17: Control Surface time history for a 15 second cycle with gearbox

Figure 7.18: Tether length, tension and instantaneous power for a 15 second cycle with gearbox
Figure 7.19: Representation of actual trajectory calculated for the 15 second cycle
7.7 Chapter Conclusions

The numerically generated optimal trajectories presented in this chapter showed that, for the first set of assumptions (as per Table 7.1) a larger cycle time lead to higher average power generation. This trend asymptotes as the transition time became insignificant compared to the cycle time. It is apparent that the limiting factor for power generation was the winch control parameters.

In the second set of results, the actual performance of the prototype winching system was modelled (faster response, lower speeds and lower loadings) and for the third set of results a hypothetical situation representing the addition of a two-speed gearbox was modelled. The actual performance (Chapter 9) showed that transient response of the winch was fairly negligible, due to the inherently low inertia of the design, and hence optimal power generation is fairly independent of cycle time. With a two-speed gearbox the power the system was capable of generating was four times the best results of manually tuned trajectories.

7.8 Chapter Acknowledgements

The author would like to acknowledge Dr. Paul Williams, the developer of the DIRECT package, RMIT University for supporting the research, and Valerio Scordamaglia for the use of his Matlab code, which was modified for this particular application to show glider motion.

7.9 Chapter References


7.10 Chapter Bibliography


8 Design of a Prototype Kite Generator

8.1 Introduction

Chapter 8 presents the development of the prototype Kite Wind Generator. The conceptual design, construction and design revision, of the winch and winch components are examined. The winch design overcomes the limitations that make existing winch technologies unsuitable for this application and results in an easily controlled, simple, compact and innovative machine.

To put this work in the context, Researchers at Delft have been investigating the pumping laddermill with various inflatable, flexible type aircraft for some time. There exists little published research into rigid winged systems. Further, an alternative winch system is developed to fit the budget and scale of this project. This chapter’s work addresses the first research question of what form the prototype will take.

8.2 Design Objectives

The design of the winch for the tethered glider generator had a number of specific requirements.

- The winch needed to control the deployment and retrieval of a tether with a reasonable amount of precision whilst keeping to a minimalist design for the reduction of cost and complexity.
- During operation, the cable could make two angles to the winch, an angle between the cable and the ground plane, and an angle of rotation about the vertical axis, dependent on the direction of the wind. The design of the winching system needed to account for cable rotations.
- The system prototype used a tethered two-metre wingspan glider and hence the load requirements of the winch were based on heuristic approximations of what the glider performance. The maximum load on the tether was estimated to be 100 N and the maximum speed of ascent at this load, 5 m/s. These approximations indicate a winch power of approximately 500 W.
- The winch needed to be computer controlled to enable the implementation of autonomous control. Hence, direct computer control over the applied voltage and reading of the sensory feedback was required to control and capture winch dynamics. Finally,
- The prototype had to be easily portable and set up in at the airfield for testing.
8.3 Winch Conceptual Designs

There were a number of concepts investigated to meet the requirements of the winching system for a kite wind generator. The type of winch used to tow Sailplanes by model aircraft enthusiasts (Figure 8.1), is simply a driven drum with a tether wrapped around it. The tether is reeled and unreeled directly from the drum as it rotates.

![Sailplane winch and capstan](image)

*Figure 8.1: Sailplane winch (left) [1] and a capstan (right) [2]*

The second basic kind winch uses a capstan type drive (Figure 8.1). The cable is wrapped around the capstan several times to transfer the tensile force to the drum as a moment by friction. From these two basic concepts machines capable of meeting the design criteria could be developed.
8.3.1 Conceptual Design of Single Drum Winch

Figure 8.1 shows a basic single drum winch on the left. A more sophisticated version of this type of winch has been developed Lansdorp et al. [3]. The basic design as per Figure 8.1 functions the same as many commercial winches, be they for hauling land vehicles ships or otherwise. Cable is wrapped under tension on the drum and layered on top of its self as the cable is retrieved. This system works well while the cable is pulled in under high tension and pulled out under low tension. However, when this cycle is reversed a problem exists, especially with synthetic cables, which can have a significant amount of stretch. When the cable is continually reeled out under high tension and reeled in under low tension (as is desirable with a Kite Wind Generator) the cable becomes loosely packed on the winch drum. Under deployment at high tension the cable can then pull between the loosely packed layers of cable on the drum resulting in high friction and high rates of wear if not complete tangling and binding of the cable.

To overcome this problem Lansdorp et al. [3] proposed that the cable should be only a single layer on the winching drum. The drum can then be moved underneath the cable guide or the cable guide can be moved over the drum to ensure single layering of the cable. One such design is shown below in Figure 8.2.

Figure 8.2: TU Delft Conceptual Winch Design [3]
8.3.2 Conceptual Design of Capstan Winch

Figure 8.1 shows a basic capstan on the right. The working principal is that the maximum ratio of tension between each end of the cable before it begins to slide is related by the number of wraps around the capstan drum and the coefficient of friction between the cable material and the capstan surface. This ratio increases exponentially with the number of wraps. By using a capstan drive the cable can be stored and deployed on a secondary storage drum under a constant low tension.

By examining commercial capstan designs a common design trait was identified (Figure 8.3), either there is a low number of cable wraps and; a bell shaped end or a concave surface profile.

![Figure 8.3: Commercial Capstan Designs [4]](image)

If a cable is wrapped around a parallel-sided cylinder as per Figure 8.1 and the cylinder is rotated to feed the cable, the cable “screws” along the cylinder in much the same manner as a screw thread. The minimum pitch of the cable as it moves axially along the capstan is its diameter. The same friction force that binds the cable to move with the capstan resists axial movement. At the end where cable is being added to the capstan it lays next to the existing cable. A large numbers of wraps means a large axial force to push the cable along the cylinder. There is hence a significant limitation on achievable tension ratios with a single capstan.

To overcome this problem the concept of multiple capstans with a low number of wraps and a concave profile was developed. Figure 8.4 shows two concepts employing multiple capstans into a single drive. The concept on the left shows a single driven shaft with multiple capstan profiles and a number of passive pulleys to transfer the cable between each profile. The right of Figure 8.4 shows a single driven shaft and a single passive shaft both with multiple capstan profiles, arranged to allow passing of the cable between the two. Figure 8.4 shows a single cable wrap, however, a low number of full wraps is possible for each capstan profile.
The concepts in Figure 8.4 addressed the problem of screwing and allowed for an arbitrary number of capstan wraps. The concept to the right in Figure 8.4 can have as many cable wraps as desired with only two moving parts. Using this concept, a simple design was developed that allowed for the high tension ratios needed.
8.3.3 Conceptual Design of Winch Cable Guide

In relation to the winching station, the glider could be at any location above the ground. A mechanism was needed to guide the cable through two rotations onto the winch drive. The cable needs to be guided from the vertical axis of the winch to the downwind location of the Kite, and Kite elevation to the winch drive as depicted in Figure 8.5.

![Figure 8.5: Schematic of cable to winch angles](image)

To achieve the two rotations there are a number of possibilities. The simplest method would have a simple bell mouth entrance above the winch/ capstan drive over which the cable slides as depicted in Figure 8.6.

![Figure 8.6: Bell mouthed cable guide](image)
Another possibility was to use two pulleys to guide the cable from its elevation onto the winch and to allow these two pulleys to rotate on a vertical axis into the downstream wind much like a weather vane. This design was labeled the roller guide. See Figure 8.7.

![Figure 8.7: Twin pulley articulated cable guide (roller guide)](image)

The concept shown in Figure 8.7 required the addition of a bell mouth type guide to keep the cable on the guide pulleys. (Figure 8.8)

![Figure 8.8: Slot bell mouthed guide for roller cable guide (Figure 8.7)](image)
8.4 Comparison of Winch Design Options

This section compares the benefits of each of the design concepts leading to the choice of a capstan based winch design with a pulley based cable guide.

8.4.1 Capstans Winch versus Drum Winch

The concept employed by Lansdorp et al. [3] used a single drum winch with a single layer of cable that is moved underneath the cable guiding system. It is referred to here as configuration 1.

The second concept investigated here used a single winch drum with the cable guide moving above it to maintain a single layer of cable, configuration 2. The third concept used a multi-capstan drive, positioned below a cable guide, with cable layered under low tension onto a drum.

The essential functions of configuration 1 were:
- The winch drum was driven by the primary motor/generator,
- The winch drum was moved in a timed manner so that the cable is laid onto the winch drum in a single neat layer

Since this concept stored the cable in a single layer its physical size would be linearly related to the length of cable used.

Configuration 2 differed from configuration 1 in that instead of moving the winch drum in a timed manner it moved the guiding structure. The downside with this was that cable loading would in some instances be adding to the loading of the cable guide drives, meaning, it would likely be less efficient and require heavier duty secondary drives.

The essential functions of configuration 3 were:
- A multi-capstan drive, and
- A secondary drive to apply a small tension to the cable storage drum during both deployment and retrieval.

No traversing mechanism was needed since the cable was stored under low tension. Further, by separating drive and storage functions, changes in maximum cable length would be relatively easy and the overall system more compact since the cable could be layered on its self, leading to an exponential increase in cable storage with winch size. (Hence for very long cables this winch would be much smaller alternative designs.) Another possibility existed with this system; if a fast joining method were available additional reels of cable could be added/ subtracted during operation. This would be advantageous when seasonal variation of wind resources dictated it necessary to change cable length or the lower part of the cable needed replacing due to wear.
Due to the operational advantages, compactness and the simplicity of the concept; a multi-capstan based drive was pursued. The simplicity allowed a small prototype to be built in house with conventional tooling.

To ensure the cable was stored under minimal tension, while allowing maximum tension conditions on the cable, a large tension ratio (ratio between cable inlet tension and cable outlet tension) needed to be achieved. Using Equation 8.1 and assuming a coefficient of friction between the cable and the capstan of 0.1 (approximate value for Nylon on Aluminium) Figure 8.9 was generated.

\[ T_2 = T_1 e^{\mu \beta} \]

where
\( \mu \) is the coefficient of friction and
\( \beta \) is the angle of wrap

![Figure 8.9: Tension Ratio Vs Number of Wraps](image)

Figure 8.9 shows the exponential relationship between the number of cable wraps and tension ratio. It was thought that a relatively large number of wraps would be needed. It was desirable to exceed the minimum number of required wraps by a good margin given that the coefficient of friction was estimated and is, in reality, dependant on operating conditions and the presence of contaminations like dirt and lubricants. Hence the capstan design should be a multi-capstan design permitting many numbers of cable wraps. The capstan concept to the right of Figure 8.4 best met the design criteria of multiple cable wraps and a minimum number of parts.
8.4.2 Bell Mouth Cable Guide versus Roller Cable Guide

There were two main competing concepts for guiding the cable onto the winching mechanism. The simplest was a bell mouth as shown Figure 8.6. Clearly the advantage of this concept was the simplicity, no moving parts and a single component. The drawback however was that this concept would likely result in high wear rates, friction and heating.

The second concept (the roller guide) consisted of two pulleys, which could rotate freely about the vertical axis, and rotate into the down wind position with minimal friction. This mechanism had the advantage of lower friction and lower wear at the cost of higher system complexity.

For this prototype the roller guide concept pictured in Figure 8.7 was pursued.
8.4.3 Winch Conceptual Machine

The basic conceptual design developed was;

- A capstan drive to transfer tension from the cable to the drive system
- A secondary drum to store the cable under low-tension (of the form shown to the right of Figure 8.4), and
- An articulated cable guide to guide the cable from any direction above the winching station onto the capstan

Figure 8.10: Capstan based winch concept

This concept was thought to best meet the requirements of a small-scale prototype Kite Wind Generator. The discussion that follows develops this concept into a detailed design for construction.
8.5 Winch Subsystem Components

The purchased components and/or subsystems are investigated throughout this section of the Thesis. This includes the choice of the drive motors/generators, cable, and power transmission components.

8.5.1 Winch Main Power Drive

The key attributes of the main power drive should be:
- Approximately 500 W,
- Easily controlled,
- Capable of running continuously for periods long enough for testing (possibly hours), and
- Low cost.

With this in mind there were a number of choices (Table 8.1). Only electric drives were considered since the system was to be portable and battery energy storage preferred.

<table>
<thead>
<tr>
<th>Drive Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent Magnet brushed DC motor</td>
<td>Cheap, easy to control, self exciting for generation</td>
<td>Relatively high wear, less efficient</td>
</tr>
<tr>
<td>Wound field brushed DC motor</td>
<td>Cheap, easy to control, easily sourced from an automotive recycler</td>
<td>Not self-exciting so regeneration is more difficult, relatively high wear, less efficient.</td>
</tr>
<tr>
<td>Brushless DC motor</td>
<td>Efficient, high power density, very low wear</td>
<td>Control more complicated to drive, more expensive</td>
</tr>
<tr>
<td>AC Induction motor</td>
<td>Cheap, robust</td>
<td>Requires polyphase voltage and frequency control, low starting torque, non-linear properties.</td>
</tr>
</tbody>
</table>
For this prototype a relatively low power drive was required and ease of control was very important. Either a brushed or brush less DC motor was most suitable for the application. Brushless DC motors are becoming standard in model aircraft and cost is reducing as a result. A permanent magnet brushed DC motor is easy to control, easy to model, and robust but has the drawback of wearing brushes and lower efficiency. Cost was a deciding factor in choosing between the designs. Preslite Drive Technologies® donated a suitable permanent magnet brushed DC motor and supplied load testing results (which were invaluable in developing the application and modelling the winch). Hence the resulting main drive chosen was a Preslite® 14000052 permanent magnet DC motor.
8.5.2 Winch Storage Drive Motor

Section 8.5.1 discussed the relative benefits of various drive types for the main power drive. These relative benefits also apply to the storage drive. The storage drive was only required to provide enough torque for accelerating the storage drum and the cable wrapped upon it whilst maintaining a small tensile force on the cable.

During deployment, it was thought that friction would be sufficient to provide the necessary tension on the storage side of the capstans. During retrieval, a small tension needed to be maintained on the cable as it was wrapped around the storage drum. For this task a brushed DC permanent magnet motor was chosen, suitable motors were readily available from local electronics suppliers.

8.5.3 Winch Power Transmission

The drive motor needed gearing to match its performance characteristics to the appropriate speed range of the capstan drive. In an experimental device, it may be necessary to change the gear ratios at a later date, and hence the use of belts and pulleys or chain and sprockets was thought appropriate. An important factor was positive location between the motor drive and the capstan drive to avoid slippage, which could be detrimental to efficiency and accurately sensing system variables. A synchronous belt drive was the preferred drive type due to its smoothness and compactness.

8.5.4 Cable

Although not specifically part of the winch the cable needed to be chosen to facilitate design of the winch. The cable is both large and expensive.

The cable should be:

- Low stretch
- High strength
- Compact
- Hardwearing
- Flexible, and
- Low weight

The cable that best met these criteria and was available for purchase was a polypropylene fibre sheathed in a polyester cover like Spectraspeed®, the sheathing not only gives better wear characteristics but increases the coefficient of friction for tension transfer. Spectraspeed® was specifically designed for rigging in marine environments and would likely meet the performance criteria of the application. A 2 mm cable was the smallest available and had an average break load of 295kg, which should far exceed the requirements of this application.
8.6 Final Winch Design

Throughout this section the detail design of the winch system is discussed.

8.6.1 Winch Virtual Prototype

Throughout the design process a focus was minimising cost while maintaining the required performance and to avoid designing/ fabricating any custom parts where a standard/ salvaged part can be used. The first such example was the use of a recycled bicycle wheel as the cable storage drum. The hub of the wheel was used for its bearings and mountings.

The winch was to be used in the field and stored in the office and hence needed to be easily portable. For this reason the size of the winch was limited to something that could be easily moved by one person either manually or using a trolley. The amount of cable to be stored directly influences the size of the winch and it was likely that a few hundred meters of cable would be sufficient. The design specification was for approximately 500m of cable to fit on the storage drum. Winch stability was achieved by anchoring the structure to the ground with steel pegs the same way the winches used by sailplane enthusiasts are anchored. Looking closely at Figure 8.1 there are small holes in the bottom of the frame of the commercial glider winch to allow pegging into the soil.

Figure 8.11: Detail virtual winch design, view 1
Figure 8.11 shows the detail design of the winch (3D model) from which the design drawings were developed for construction. Figure 8.11 shows how the cable would be wrapped around the capstan to achieve the large tension ratio required.

Key design points are as follows:

- The winch has holes in the bottom of the frame for anchoring pegs.
- The cable guide is designed for construction out of plate materials and round bar.
- Welding has been avoided where possible to avoid problems with distortion.
- The plate to which the motor mounts and to which the frame supporting the cable storage drum is attached supplies the structural rigidity.
- The motor bracket is a simple plate bent into shape with a clearance block.
- A threaded rod is clamps the motor in place.
- The cable storage drive is mounted on the frame in line with a large pulley integrated into the storage drum assembly and is driven by a timing belt.
- The large pulley uses a rubber band to enhance friction in the place of teeth but instead (Figure 8.12).

Figure 8.12 does not show the storage drive motor as its fitment was communicated verbally.

Figure 8.12: Detail virtual winch design, view 2
8.6.2 Winch Drive Ratio Selection

This section presents the design of the cable storage drum drive and main capstan drive gear ratios and the resulting pulley sizes. To correctly select the gear ratios for the respective drive motors it was important to understand the performance characteristics of the motors. A permanent magnet brushed DC motor generates a back emf proportional to its rotational speed. This is better understood by studying the equations of motion for a brushed DC motor (Equation (8.2)).

\[
\begin{bmatrix}
\dot{\alpha} \\
i
\end{bmatrix} = \begin{bmatrix}
\frac{-b\dot{\alpha} + K_i i - T}{J} \\
\frac{-K_e\dot{\alpha} - Ri + V}{L}
\end{bmatrix}
\]

where

- \(\dot{\alpha}\) is the rotational velocity
- \(b\) is the viscous friction coefficient
- \(i\) is the armature current
- \(R_i\) is the armature resistance
- \(K_t\) is the torque constant
- \(T_w\) is the applied torque
- \(K_e\) is the back emf constant
- \(V_w\) is the applied voltage

Equation (8.2) shows that when the back emf exceeds the applied voltage, there will be a reversal of current flow; this is the condition under which the motor is acting as a generator. It can also be thought of as the condition where the motor is driven beyond its free speed by the applied torque. If the battery is treated as an ideal voltage source the speed at which current will reach its maximum value for generation can be calculated. Maximum generation power is at maximum applied voltage and maximum reverse current. Parameter identification of the motor showed an armature resistance of \(R_i=0.177\ \Omega\) and back EMF constant of \(K_e=0.0491\ V/(rad/s)\) (see Chapter 9 for details). Equation (8.2) was used to calculate the rotational speed at 24 V and a current flow of \(-12\ A\) (the maximum continuous rating for the motor as per manufacturers specifications) (Equation (8.3)).

\[
\begin{bmatrix}
\dot{\alpha} \\
i
\end{bmatrix} = \begin{bmatrix}
\frac{-b\dot{\alpha} + K_i i - T}{J} \\
\frac{-K_e\dot{\alpha} - Ri + V}{L}
\end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \text{(Steady State)}
\]

\[
\therefore \dot{\alpha} = \frac{-R_i + V}{K_e} = \frac{-0.177\times-12 + 24}{0.0491} = 532 \ \frac{rad}{s} = 5080\ rpm
\]

It is important to note that this is an idealisation, in reality a lead acid battery (as was used here) would exhibit internal resistance and the effective applied voltage would increase as the energy being stored in the battery increased. This means that maximum power generation would occur at a higher motor rpm than was estimated here.

The next step was to examine how the motor performance would relate to the necessary cable speeds and loadings. The work of Lansdorp et al. suggested that a minimum winch or capstan diameter of twenty times the cable diameter should be
used to minimise the cable wear and fatigue due to bending. It was also thought that small radius bends would be difficult for the cable to comply to and hence reduce the friction force since cable bending stiffness would become important. Based on this recommendation the minimum capstan diameter for the chosen cable was 40 mm. A direct drive from the motor to a capstan of this diameter would result in a deployment cable velocity of approximately 10 m/s. It was thought that this value was excessive and would require extreme winds to generate any power. Hence gearing was required.

Another consideration with the winch was the tension applied to the cable. For example, if the glider/kite could be loaded more heavily and the cable pulled out slower while still achieving maximum generation, there would be the potential to exploit slower winds. The glider to be used was a Spirit 100 Sailplane weighing between 2-3 kgs when equipped with control hardware. The Spirit 100 was designed to be launched by a winch and is quite robust. It was thought that the glider should resist approximately 100 N or 10 kgs of loading. At 12 A and 24 V the steady state maximum power the drive motor can generate was only 288 W, much less than its peak value of 480 W. Since power is the product of force and velocity, a cable load of 100 N and power of 288 W suggests a cable velocity of approximately 2.88 m/s. As suggested earlier this was likely an estimate on the lower side of the ideal deployment speed (due to ideal voltage source assumptions). Based on the desired cable speed, loading and capstan diameter a gear reduction ratio of $\frac{532 \times 0.02}{2.88} = 3.69$ from the motor to the capstan was deemed appropriate.

Initially recycled bicycle drive parts were used. The closest gear ratio available was by using two sprockets with 48 and 14 teeth respectively. This yielded a gear ratio of 3.42, a reasonably good match for the design target.

The storage drive motor chosen was a 12 V brushed DC permanent magnet motor with a no load speed of 11,800 rpm. Without performing dynamic parameter estimation only the parameters present in the steady state DC motor equations could be estimated from the motor specifications. Following the same process used to derive the gear ratio for the main drive; the relevant parameters were the armature resistance, $R_a=0.4615 \ \Omega$, and the back EMF constant $K_e=0.0094 \ \text{V/(rad/s)}$.

There are two important criterions to meet for the storage drive gear ratio.

- The storage drive must not be run beyond maximum speed during deployment otherwise it would generate sufficient back EMF to cause current overload and burn out the motor.
- The gear ratio must be such that the storage motor could apply a small torque during retrieval of the cable at full speed.

While the cable is accelerating in the deployment sense, inertia will increase the primary cable tension and during acceleration from deployment to retrieval the storage driver must supply sufficient torque to overcome the inertia of the cable plus drum, however, the mass of the stored cable would be at a minimum when the tether is deployed.
During deployment it was calculated that the cable velocity would be approximately 2.88 m/s. To be conservative, a cable speed of 3 m/s was chosen as the maximum deployment speed. Maximum storage drum speed would be when the cable was down to a single layer on the storage drum, so, as a worst case the maximum rotational speed of the cable drum would be (3 m/s) / (0.025 m) = 120 rad/s since the radius of the cable drum was 25 mm. Again employing Equation 8.3 the maximum speed of the storage motor was calculated using an assumed maximum current of 5 A (Equation (8.4)). (Maximum efficiency occurred with a current of 4.7 A, from motor specifications, and this type of motor usually has maximum efficiency close to maximum allowable current.)

\[
\dot{\alpha} = \frac{-R_i + V}{K_e} = \frac{-0.4615 \times -5 + 12}{0.0094} = 1522 \frac{rad}{s} = 14530\text{rpm} \quad (8.4)
\]

For ease of manufacture the pulley on storage drive was made to a pitch circle diameter (PCD) of 166 mm to achieve a suitable gear ratio with the available pulley sizes for the diameter of the motor shaft. Using this information the PCD of the storage motor pulley can be calculated using Equation (8.5).

\[
PCD = 166(\text{mm}) \times 120(\text{rad/s}) / 1522(\text{rad/s}) = 13\text{mm} \quad (8.5)
\]

A PCD of 13 mm for the storage motor drive was in fact the minimum. The other extreme to consider was whether during retrieval the storage drive could continue to apply a tension to the cable. Again, the maximum speed would be under similar conditions, instead during cable retrieval. The maximum speed of retrieval using the main drive free speed (4605 rpm) and the gear ratio chosen earlier in this section yielded a cable retrieval speed as per Equation (8.6).

\[
V_{\text{cab}} = 4605(\text{rpm}) \times \frac{2\pi}{60(\text{rad/s}/\text{rpm})} / [3.42(\text{Gear Ratio})] \times 0.02(\text{m})
\]
\[
= 2.82 m / s \quad (8.6)
\]

The retrieval velocity calculated in Equation (8.6) was an absolute maximum. Using Equation 8.7 the minimum PCD for the retrieval case is calculated.

\[
PCD = 166(\text{mm}) \times \frac{2.82 / 0.025(\text{rad/s})}{[11800 \times 2\pi / 60](\text{rad/s})}
\]
\[
= 15\text{mm} \quad (8.7)
\]

The PCD in Equation (8.7) matches the free speeds at the point where the storage drum speed would be at a maximum. Using available timing pulleys the largest pulley available without a pilot hole exceeding the size of the motor shaft had a PCD of 17.6 mm. This size was thought to give a sufficient safety margin over the maximum allowable speeds while still providing sufficient torque for acceleration. (Pulley specifications and resulting gear ratio are shown in Table 8.2.)
Table 8.2 Winch pulley size and gear ratio

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage motor pulley PCD</td>
<td>17.6mm</td>
</tr>
<tr>
<td>Storage drum pulley PCD</td>
<td>166mm</td>
</tr>
<tr>
<td>Capstan drive reduction ratio</td>
<td>3.42</td>
</tr>
</tbody>
</table>

The preceding discussion covered the critical design details and it is felt that the rest of the design information (without providing detail drawings) would be best presented visually.
8.6.3 Winch Prototype as Built

The final as built prototype winch is presented in Figure 8.13.

![Figure 8.13: Final prototype as constructed](image)

During the set up process two 100m rolls of tether had to be spliced together in such a way as to retain strength without creating a large change in diameter or a long rigid pellet that would not conform to the capstan surface. An important future innovation would be an efficient and strong method of quickly coupling the cables, permitting the cable storage drum to be changed during operation thus greatly increasing the range of cable lengths capable of being used by this winch.
8.7 Winch Computer/ Control Interface

Throughout this section the interface between the winching machine, the control hardware and the computer is presented. Each part of the electrical hardware, the resulting system and finally the software interface are discussed.

8.7.1 Capstan Position Sensing

An optical encoder was mounted to the rear of the drive motor (Figure 8.14).

![Optical Encoder Mounting](image-url)

The output of the optical encoder was two pulsed signals; a quadrature encoder interface board read these two signals. A Phidget® High Speed Encoder interface was chosen for a number of reasons. Phidgets® offered an API interface for their products that could be used in a number of different programming languages with documentation and support. Given that Matlab® was one supported language this was a very useful feature.

The encoder was a US Digital S5 Optical Shaft Encoder, ball bearing, 1024 cycles per revolution yielding a high precision measurement of the motor shaft location.
8.7.2 Winch Voltage and Current Sensing

To estimate the cable tension both between the storage drive and the capstan, and the tension in the deployed cable, measurements of battery voltage and the current flowing through each motor were needed.

A Phidgets® “PhidgetInterfaceKit 8/8/8 w/6 Port Hub” was chosen with two current sensor input boards and one voltage sensor input board. The key reason for choosing this board (as opposed to a cheaper interface without a USB hub) was so that a single USB cable could connect the computer to all of the USB input/output devices.

8.7.3 Winch DC Motor Drivers

To complete the winch electrical hardware, two motor drivers were needed to control the main drive motor and the storage motor. To permit as much freedom for future work as possible and to allow the utilisation of the vast array of model building components available a Phidgets® Advanced Servo – 8 Motor USB interface was chosen. The advantage of this being that, the drive motor could be replaced with a brush less DC motor and appropriate driver without changing any other hardware if future needs dictated this necessary. Further, should any guiding components or additional drives be needed, there are six spare servo outputs, which can be easily accessed.

The 12 Volt storage motor and the 24 Volt Main Drive motor, are driven by a Sabertooth® 2x25 regenerative driver. Details are:

- 2 motor drive outputs
- Absolute maximum voltage of 30 V
- Nominal voltage of 24 V
- 25A output current per channel
- 50A peak current per channel
- Current limiting and thermal overload protection.
8.7.4 Winch Electrical Hardware Assembly

The electronics were mounted inside a sealed project box, as seen in Figure 8.15. The 24 Volt sealed lead acid battery pack is externally connected.

*Figure 8.15: Electronic Control Box*
8.7.5 Winch Software Interface

It was necessary to develop a software interface between the supplied Dynamically Linked Library (DLL) Application Programming Interface (API) and the control software, Matlab®/Simulink®. A sample of this code used for setting up the interface environment is shown in section 8.14 Appendix 1.

Ultimately the Simulink® simulation environment was used to develop and implement the winch control algorithms. Figure 8.16 shows an example Simulink® block for this work. Custom blocks were written for this model to call the DLLs and form the bridge between the control boards and Simulink®.
Figure 8.16: Simulink® Interface block (early prototype)
8.8 Winch System Testing

Once the control interface was completed, the first task was to run a series of square wave response tests on the main drive. From the recorded results, an estimate of the viscous damping coefficient was made from the free speed and then used in simulation. The simulated results were compared to the measured results as a measure of modelling accuracy. For this the steady state current equation was used with a negligible loss in accuracy over the use of dynamic current equations.

![Figure 8.17: Applied voltage time history](image-url)
Figure 8.18: Simulated vs Measured Current

Figure 8.19: Simulated vs Measured Motor Velocity
It was apparent that the simulated and measured responses were acceptably close to give confidence in the model parameters. It could also be seen in the test results that there was a significant amount of noise in the system. A limitation with this set-up was sampling at a rate that allows the code to run to approximate real time (10Hz), and consistent with the controller response times (~50Hz). When the motor was running at its free speed (~4600rpm /76 revolutions per second), there would be approximately eight revolutions of the motor shaft between each sample. This makes it impossible to resolve any vibration/ noise accurately. To make accurate speed estimation possible from discrete encoder measurement the vibration/ noise in the signal needed to be removed. This lead to a number of possible solutions:

- If adequate control could be achieved without a speed estimate then the system could function in its existing state.
- If a speed estimate would be required then:
  - A slow lag filter could have been used.
  - The chain drive could be replaced with a smoother toothed belt drive.
  - A dedicated interface system could be developed which performs state estimation on board at a much higher rate than is achievable with the current system.
8.9 Further Winch Modification

From the results in the previous section it was decided to replace the chain drive with a toothed belt drive as a possible solution to the noise. To stay close to the original gear ratio; a 18-tooth pulley and a 60-tooth pulley were chosen to give a gear ratio of 3.33:1 (2.7% lower than before). While this reduced the operating performance margin for the storage drive to meet maximum speed requirements it did not affect its ability to perform the job (this can be shown by running through the original design process again). The winch with the toothed belt drive is shown in Figure 8.20.

Figure 8.20: Winch with toothed belt drive fitted
The previous tests were then rerun and the same noise was present in the measured signals. It can thus be concluded that there is a significant amount of noise in the electronic control hardware. The consequence of this was that control methodologies based on lag filters were employed. If there were scope within this project then an investigation into developing an optimal observer could have been made.

After the first series of tests (discussed in chapter 10) it was decided that a change in the capstan drive ratio was needed to increase the cable free speed, hence the capstan drive ratio was changed to 2:1 from 3.33:1 by changing the motor pulley to a 30 tooth pulley. There was the possibility that the cable storage drive would no longer be capable of operating at the required velocity however it is noted that there was sufficient cable on the storage drum most of the time to avoid this limitation. To maintain the same ratios it was calculated that the storage drum could be packed up with foam 16mm thick which would have the effect of increasing the minimum cable velocity by a factor of 5/3, similar to the change in the capstan drive ratio.
8.10 Glider Selection

For practical reasons the glider should be cost effective, easy to construct, readily available (so that it can be replaced), and data on the glider should be easily accessible. The glider should also house the Micropilot™ MP2028™ Autopilot system board (40mm x 100mm), as it was already used within the research group, along with the necessary antennae and batteries.

Other work in the area of tethered wind power extraction [5] showed that power extraction was related to the lift-drag ratio of the glider with higher L/D ratios leading to the ability to extract more power for a given wing area. Hence a glider would be the most appropriate type of airframe as they are designed to have a high L/D ratio (at the expense of manoeuvrability) to minimise the glide angle. Another point to consider is that gliders usually have to make a trade-off between ultimate L/D ratio and the penetration speed. High penetration speeds could be of use in this application as it allows the glider to dive fast during the retrieval process.

To minimise cost, a model glider was chosen and hence consultation with an experienced supplier of model aircraft was made. This led to the selection of a Great Planes Spirit 100 Sailplane (model glider, Figure 8.21).

The key factors of the Spirit 100 were:

- Inexpensive (~$250AUD),
- Common
- Easy to replace
- Had Rudder, Elevator, Aileron, Flap, optional Spoilers
- Came “Almost Ready to Fly” (ARF)
- The gliders fuselage had sufficient room for the necessary hardware
- Constructed of Glass Fibre Reinforced Polymer, balsa wood, aluminium, plywood and MonoKote™ film makes for easy modification and repair as they are all common materials
- The flight simulator Real Flight™ had a model of the Spirit 100, aiding experimental work in that the pilot could practise in Virtual Reality. (This product leads to the possibility of directly sourcing a flight dynamic model of the Sailplane. Unfortunately the manufacturer was unwilling to share this information.)

Kit construction was straightforward and simply a matter of following the included instructions [6]. Fitting the Micropilot™ was a matter of fixing two beams inside the space under the wing mounting, approximately 180mmx45mm by 45mm deep.
Figure 8.21: The Spirit 100
8.10.1 Glider Modification

In order to permit safe reliable testing of the prototype kite wind generator a number of modifications were necessary. Important modifications included the fitment of:

• Mounting points for electronics
• A Pitot tube (on the rudder in Figure 8.24), and
• A controllable cable release

The controllable cable release allowed the cable to be securely connected to the glider at or near the centre of gravity (preferably in front if not right on the centre of gravity), and in the case of emergency allowed a reliable method of disconnecting the cable so that the glider can be brought down safely.

A cable release mechanism (used on other aircraft within the research team) was modelled on the cable release mechanism for full-scale gliders (generally towed up by tug aircraft). (Figure 8.22.)

![Figure 8.22: Cable release mechanism 1](image)

The cable release shown in Figure 8.22 attached under the fuselage with the right end pointed forward. A ring on the end of the cable sat on the hinged gate at the bottom of Figure 8.22. The release catch is to the left of the figure and when rotated clockwise it allowed the gate to swing open and the cable ring to slide off.

A simpler design using a sliding gate and a ball seat was suggested by RMIT Technician Mr. Gilbert Atkins and, as a result the device shown in Figure 8.23 was developed.
The function of the cable release shown in Figure 8.23 was such that the slide pin was pulled out from the left hand end of the image. This allowed the half ball to drop through the bottom of the mechanism. Actuation was controlled by a servo inside the glider.

This design was chosen since it was much easier to construct than the design of Figure 8.22. A potential weakness was that increased cable loading may bind the release mechanism or that high loading may force the release open. This behaviour would depend on the frictional properties of the mating materials and on the angle of the cable with respect to the glider. (However, there were no issues encountered during the testing of Chapter 10.)
8.10.2 Glider Control Interface (Manual Control)

The Pilot control interface for the Spirit 100 was an off the shelf digital 9 channel 2.4GHz system. The specific make was a DSX9 (~$2000) by JRPROPO®. This devise made programming in fail-safe control positions, custom set ups and trimming relatively quick and easy. The receiver had a second redundant circuit to prevent accident due to radio failure.

The required channels were:
- 2 flaps
- 2 ailerons
- 1 rudder
- 1 elevator
- 1 spoiler
- 1 cable release drive

With this in mind the DSX9 met the requirements and had one spare channel should this be required in future testing.
8.10.3 Glider Control Interface (Automatic Control)

The interface for the aerodynamic platform was the MP2028™ Micropilot™ since there was knowledge of these systems within the research team. The specifications for the autopilot systems were as stated below in Table 8.3.

The Micropilot™ MP2028™ autopilot system was a compact, lightweight system with a full suite of sensing and inbuilt autopilot functions.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flight Control Computer with GPS receiver, GPS antenna connector kit and 1 servo board.</td>
</tr>
<tr>
<td>1</td>
<td>Software Development Kit</td>
</tr>
<tr>
<td>1</td>
<td>2.4 GHz Extended Range DL Base</td>
</tr>
<tr>
<td>1</td>
<td>2.4 GHz Extended Range DL Remote</td>
</tr>
</tbody>
</table>

Table 8.4 shows the manufacturers specification list for the MP2028™ UAV autopilot hardware.
### Table 8.4: Specifications - MP2028g [7]

<table>
<thead>
<tr>
<th>Servos &amp; Mixing</th>
<th>MP2028g</th>
<th>Control System</th>
<th>MP2028g</th>
</tr>
</thead>
<tbody>
<tr>
<td>elevon</td>
<td>yes</td>
<td>inner loop update rate</td>
<td>30 hz</td>
</tr>
<tr>
<td>flaperons</td>
<td>yes</td>
<td>gain scheduling for optimum performance</td>
<td>yes</td>
</tr>
<tr>
<td>4 servo flap/aileron</td>
<td>yes</td>
<td>rudder aileron feed forward for improved turn performance</td>
<td>yes</td>
</tr>
<tr>
<td>separate flaps</td>
<td>yes</td>
<td>aileron elevator feed forward for improved altitude hold during turns</td>
<td>yes</td>
</tr>
<tr>
<td>y-tail</td>
<td>yes</td>
<td>autonomous takeoff and landing</td>
<td>yes</td>
</tr>
<tr>
<td>x-tail</td>
<td>yes</td>
<td>user definable PID feedback loops (for camera stabilization etc)</td>
<td>16</td>
</tr>
<tr>
<td>split aileron</td>
<td>yes</td>
<td>user definable table lookup functions</td>
<td>8</td>
</tr>
<tr>
<td>rudder throttle</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>split rudders</td>
<td>yes</td>
<td>airspeed sensor range (kph)</td>
<td>500</td>
</tr>
<tr>
<td>number of servos</td>
<td>8/16/24</td>
<td>altimeter range (meters above launch point)</td>
<td>12000</td>
</tr>
<tr>
<td>servo update rate</td>
<td>50 hz</td>
<td>pitch, Roll, and Yaw Gyros</td>
<td>yes</td>
</tr>
<tr>
<td>separate servo and main battery power supply</td>
<td>yes</td>
<td>y-accelerometer to co-ordinate turns</td>
<td>yes</td>
</tr>
<tr>
<td>separate voltage monitor for main and servo battery power supplies</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>integrated RC override</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>servo resolution</td>
<td>11 bit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>extra ADC channels and 3-axis magnetometer</td>
<td>optional</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 8.4: Specifications - MP2028 [7] (Continued)

<table>
<thead>
<tr>
<th>Navigation</th>
<th>MP2028⁸</th>
<th>Ground control station</th>
<th>MP2028⁸</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Hz GPS update rate</td>
<td>yes</td>
<td>HORIZON⁹⁹ ground control software included with system</td>
<td>yes</td>
</tr>
<tr>
<td>move servo at waypoint</td>
<td>yes</td>
<td>MP2028⁸ autopilot simulator for operator training</td>
<td>yes</td>
</tr>
<tr>
<td>change altitude at waypoint</td>
<td>yes</td>
<td>ground control station developer's kit</td>
<td>yes</td>
</tr>
<tr>
<td>change airspeed at waypoint</td>
<td>yes</td>
<td>gains can be adjusted in-flight</td>
<td>yes</td>
</tr>
<tr>
<td>user definable holding patterns</td>
<td>yes</td>
<td>change waypoints in-flight</td>
<td>yes</td>
</tr>
<tr>
<td>user definable error handlers (loss of GPS, low battery etc.)</td>
<td>yes</td>
<td>payload servos controlled from ground station</td>
<td>yes</td>
</tr>
<tr>
<td>RPV and UAV modes</td>
<td>yes</td>
<td>fly in RC mode via datalink (both stabilized and normal)</td>
<td>yes</td>
</tr>
<tr>
<td>supports DGPS accuracy</td>
<td>yes</td>
<td>point and click waypoint editor</td>
<td>yes</td>
</tr>
<tr>
<td>waypoints</td>
<td>1,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Telemetry, Datalog & Video**

<table>
<thead>
<tr>
<th>MP2028⁸</th>
<th>Physical Characteristics</th>
<th>MP2028⁸</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight (including GPS receiver, gyros, and sensors)</td>
<td>28 gm (not including GPS antenna)</td>
<td></td>
</tr>
<tr>
<td>telemetry update rate</td>
<td>5Hz</td>
<td>supply Voltage (volts)</td>
</tr>
<tr>
<td>size of onboard datalog</td>
<td>1.5 MB</td>
<td>size - length (cm)</td>
</tr>
<tr>
<td>datalog update rate</td>
<td>5Hz</td>
<td>size - width (cm)</td>
</tr>
<tr>
<td>video overlay (number of user definable fields)</td>
<td>16</td>
<td>size - height (cm)</td>
</tr>
<tr>
<td>video overlay uses low cost industry standard video overlay boards</td>
<td>yes</td>
<td>software upgradable in the field</td>
</tr>
<tr>
<td>pressure altitude and pressure airspeed available on video overlay</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>
The specification list in Table 8.4 shows that aircraft control could be implemented efficiently via onboard hardware. The ground-based station could then be used as a parent control, with control updated based on wind predictions and system performance. This would require custom control code for the hardware as the existing control methodologies were suitable for waypoint navigation but not for tight closed path periodic orbits [8]. For this, the Horizon control software (produced by Micropilot™) and the Extender™ package would be required. In its self this would be a significant project and was beyond the scope of this work.
8.11 Chapter Conclusions

This Chapter presented the design and construction of a prototype Kite Wind Generator. Alternate concepts, design problems and solutions were solved to demonstrate the rationale behind the resulting systems and models. It is thought that the resulting solution is a novel, robust design concept that will serve not only the experimental workers at RMIT, but also act as a guide to designers of winches with similar design requirements and kite generator systems in general. This prototype should prove useful during experimental work on the problem of extracting high altitude wind energy.

8.12 Chapter Acknowledgements

The author would like to acknowledge the significant contribution made by Mr. Gilbert Atkins during the redesign of the prototype winch. His availability and willingness to discuss this work lead to a simpler, cheaper solution that meets the necessary performance criteria. Further the assistance of fellow student Mr. Peter Lapthorne with the practical side of the flying equipment was of high merit.

8.13 Chapter References

8.14 Appendix 1

```
%% Script to interface the winch control with Matlab/ Simulink
% Dylan Thorpe 2009

% Phidgets need to be initialised in this block ready for simulink
calls to
% read their values.

if ~libisloaded('phidget21')
loadlibrary('phidget21', 'phidget21Matlab.h');
end

ptr = libpointer('int32Ptr', 0);
calllib('phidget21', 'CPhidgetAdvancedServo_create', ptr);
%ptr points to a CPhidgetServoHandle sturcture but we use it's int
%for control functions - handle
handle_1 = get(ptr, 'Value');

%-1 states open any phidget, this can be replaced with the serial
number
calllib('phidget21', 'CPhidget_open', handle_1, 98473);

if calllib('phidget21', 'CPhidget_waitForAttachment', handle_1, 2500) == 0
    disp('Opened servo')
    % set up all the servos that we'll use
    % Set which servo to use and then engage it.
    calllib('phidget21', 'CPhidgetAdvancedServo_setEngaged',
            handle_1, 4, 1);
    % Set position velocity and acceleration bounds
    calllib('phidget21', 'CPhidgetAdvancedServo_setPositionMax',
            handle_1, 4, 1.75*375/4-23); %12V motor
    calllib('phidget21', 'CPhidgetAdvancedServo_setPositionMin',
            handle_1, 4, 1.25*375/4-23);
    calllib('phidget21', 'CPhidgetAdvancedServo_setVelocityLimit',
            handle_1, 4, 6400);
    calllib('phidget21', 'CPhidgetAdvancedServo_setAcceleration',
            handle_1, 4, 320000);
    % Speed Ramping (Doesn't seem to work)
    % calllib('phidget21', 'CPhidgetAdvancedServo_setSpeedRamping',
    %        handle, 4, 0); %0 false, 1 true
    % Set which servo to use and then engage it.
    calllib('phidget21', 'CPhidgetAdvancedServo_setEngaged',
            handle_1, 3, 1);
    % Set position velocity and acceleration bounds 24V motor
    calllib('phidget21', 'CPhidgetAdvancedServo_setPositionMax',
            handle_1, 3, 2*375/4-23); %2ms pulse
    calllib('phidget21', 'CPhidgetAdvancedServo_setPositionMin',
            handle_1, 3, 1*375/4-23); %1ms pulse
    calllib('phidget21', 'CPhidgetAdvancedServo_setVelocityLimit',
            handle_1, 3, 6400);
    calllib('phidget21', 'CPhidgetAdvancedServo_setAcceleration',
            handle_1, 3, 320000);
    % center the servo
    calllib('phidget21', 'CPhidgetServo_setPosition', handle_1, 3,
            1.5*375/4-23);
    calllib('phidget21', 'CPhidgetServo_setPosition', handle_1, 4,
            1.5*375/4-23);
```

184
else
    disp('Could not open servo')
end

ptr1 = libpointer('int32Ptr', 0);
calllib('phidget21', 'CPhidgetInterfaceKit_create', ptr1);
handle_2 = get(ptr1, 'Value');
calllib('phidget21', 'CPhidget_open', handle_2, 84416);

if calllib('phidget21', 'CPhidget_waitForAttachment', handle_2, 2500) == 0
    disp('Opened InterfaceKit')
else
    disp('Could not open InterfaceKit')
end

ptr2 = libpointer('int32Ptr', 0);
calllib('phidget21', 'CPhidgetEncoder_create', ptr2);
handle_3 = get(ptr2, 'Value');
calllib('phidget21', 'CPhidget_open', handle_3, 54757);

if calllib('phidget21', 'CPhidget_waitForAttachment', handle_3, 2500) == 0
    disp('Opened Encoder')
else
    disp('Could not open Encoder')
end

% center the servo (for some reason it doesn't work in the other loop)
calllib('phidget21', 'CPhidgetServo_setPosition', handle_1, 3, 1.5*375/4-23);
calllib('phidget21', 'CPhidgetServo_setPosition', handle_1, 4, 1.5*375/4-23);
9 Parameter Identification

Throughout this chapter parameter identification of the generator prototype is presented. This work complements the efforts of modelling and making some predictions as to how the system may behave. First, the identification of modelling parameters to represent the dynamic response of the winch is investigated. This is followed by work identifying key modelling parameters for the Spirit 100 Sailplane. This work addresses the second research question on how to model the system by fitting the developed mathematical models to the physical equipment.

9.1 Winch Parameter Identification

The winch was essentially a geared DC motor applying tension to the cable. The basic equations defining the behaviour of the winch (as per Chapter 3) are:

\[
\begin{bmatrix}
\dot{\theta} \\
i
\end{bmatrix} = \begin{bmatrix}
- \frac{b \dot{\theta} + K_e i - T}{J} \\
- \frac{K_e \dot{\theta} - R_i V + V_e}{L}
\end{bmatrix}
\]

where

\(\dot{\theta}\) is the rotational velocity
\(i_w\) is the armature current
\(K_e\) is the torque constant
\(K_e\) is the back emf constant
\(b\) is the viscous friction coefficient
\(R_i\) is the armature resistance
\(T_w\) is the applied torque
\(V_e\) is the applied voltage

and the equilibrium equations:

\[
\begin{align*}
T_w &= -b \dot{\theta} + K_e i \\
R_i i_w &= V_e - K_e \dot{\theta}
\end{align*}
\]  

(9.1)

Preslite Industries® provided a motor free of charge, and a set of equilibrium load test results. The tests were at constant voltage and measured current, speed and torque. By plotting speed versus current it was possible to fit a straight line and extract both armature resistance and back emf constant (Figure 9.1).

The resulting straight-line equation was:

\[y = -0.2764x + 135\quad R^2_{value} = 0.9988\]  

(9.3)

The resistance and back emf constants were extracted by equating Equation (9.3) with the current equation from Equation (9.2).
Next a linear regression analysis on the torque equilibrium equation (Equation (9.2)) was performed. Using the Linest function in Excel and setting the offset to be zero the following results were achieved.

\[ b = 0.00027808 \text{ Nms} \]

\[ K_r = 0.044344 \text{ Nm/A} \]  

(9.5)

\[ R^2 = 0.9998 \]

Note that the \((R_{value})^2\) value is a measure of fit with 1 being a perfect fit and 0 no correlation.

To demonstrate the success of parameter identification the measured performance curves were plotted against the simulated results (Figure (9.2)). These plots show a good fit of the simulated equilibrium test to the actual test data.
Figure 9.1: Current versus rotational speed for a constant voltage load test of the winch drive motor

\[ y = -0.2764x + 135 \]

\[ R^2 = 0.9988 \]
**Figure 9.2:** Simulated versus measured load, torque and efficiency curves
To complete the characterisation of the winch model the motor inertia and inductance needed to be determined. The inertia of the Capstan, Chain Drive, Emergency Brake and associated components were lumped onto the motor inertia for the model. There were a number of ways of achieving this:

- The components designed in Solid Works could simply have the property values calculated and exported (i.e. Capstan, Capstan Axel)
- The off the shelf components, brake, chain drive and chain sprockets required additional work to either:
  - Draw all of the components and use Solid Works to calculate inertias (However this would require disassembly of the winch plant which would be undesirable.) or;
  - Experiment:
    - A pendulum experiment could be set up with a pendulum attached to the motor and period and amplitude measured (However there were problems with backlash in the main drive and magnetic cogging of the drive motor at low speeds.)
    - An experiment whereby the plant is excited by a known voltage input and, displacement and current are measured. A model-based output-matching algorithm can then be used to tune the response by altering parameters.

One method of parameter identification via fitting of test data to computational model response was to use DIRECT. DIRECT functioned exactly the same for parameter identification as it did solving optimal control problems, except that the cost function became the mean square deviance of the states. In addition to the requirements of the optimal control problems it requires measured experimental data, which needs to be loaded, and assigned to the appropriate variables before parameter identification could begin. It was thought that if the parameters could be derived within approximately 10% of their actual value a controller could be designed for the winch.

The inductance was measured directly using an inductance meter. Averaging the inductance of the motor coils, a value of L=347μH was derived. As a starting point, the rotational inertia of the winch system was approximated, using the property output data from solid works for the winch components. 10% was added as an approximation for the unknown components. When considering that the reflected inertia at the motor is reduced by a factor of $(14/48)^2$ the approximation error is reduced. The motor inertia was estimated using a solid copper cylinder (approximately the same size as the rotor). The resulting inertia was $640 \times 10^{-6}$ kgm$^2$ for the rotor plus $30 \times 10^{-6}$ kgm$^2$ for the other rotating parts. As will be seen in the testing section, the motor inductance is not necessary and this approximate value for inertia was sufficient for the work here.
9.2 Winch Test Results

Throughout this section the no load testing of winch is discussed. It will be shown that electrical dynamics are not relevant for the testing done here as they were much faster than the dominant inertial effects. Figures 9.3-9.5 show the measured response of the winch main drive to a known input. For the simulated response, the viscous damping was derived from the steady state speed and current data using the steady state current motor equations. This level of accuracy was considered sufficient since the measured results match the simulated results within approximately 10%. (The simulation was also run with the full current model equations with no appreciable difference in accuracy.)

![Winch test applied voltage](image)

*Figure 9.3: Winch test applied voltage*
Figure 9.4: Winch test simulated versus measured current

Figure 9.5: Winch test, simulated versus measured motor velocity
9.3 Glider Parameter Identification

Parameter identification for the Spirit 100 Sailplane was no trivial task and cannot be considered complete due to inconclusive results. The work that follows is based on a paper submitted to American Institute of Aeronautics and Astronautics (AIAA). Further the developed model has not proven useful to the numerical side of the research (except in showing some similarity to the Aerosonde® performance) because the resulting model caused instability in the Simulink® models, which has not been successfully remedied, and no convergent optimal control problems were found using the model. Regardless, the work that has been done in identifying key modelling parameters for the Spirit 100 is summarised here as it may guide future investigations.

A large enough wind tunnel was not available at RMIT for testing the glider without complicating effects of sidewall influence on the aerodynamics. While it is possible that other arrangements could have been made, the decision was made to attempt dynamic flight-testing designed specifically for model parameter identification. Ideally this allowed the identification of dynamic performance derivatives without complicated apparatus. The downside was that significant sources of error are present. From atmospheric turbulence and localised variations in air properties to sensor drift and measurement inaccuracy. With more sophisticated equipment, some of these problems could have been avoided. Further, due to time constraints, only limited testing was possible, leading to a small amount of data to analyse for the underlying performance characteristics. A thorough investigation would include many hours of flight test data to allow statistical analysis to supplement the work and overcome the uncertainties associated with flight-testing.

The development of the flight dynamic model of the Spirit 100 glider used the following methodology:

1) Obtain a priori values of longitudinal and lateral-directional stability and control derivatives
2) Use the a priori derivatives to define a flight test schedule suitable to excite the longitudinal and lateral-directional dynamic modes of the glider
3) Use parameter estimation techniques to extract stability and control derivatives from the flight test data
4) Investigate the novel application of DIRECT, a solving package for full non-linear optimal control problems, to parameter estimation using the full non-linear equations of motion for the glider.
5) Compare the performance of DIRECT for this application against the more traditional methods.
6) Modify an existing Simulink®-based flight dynamic model (FDM) to represent the identified flight dynamic properties of the glider
9.3.1 DATCOM Analysis

The United States Air Force (USAF) Stability and Control Digital Data Compendium (DATCOM) is a computer program used to estimate an aircraft’s stability and control derivatives based on geometric information and flight conditions (Table 9.1) [1].

Derivatives were evaluated for Mach numbers corresponding to velocities between 10 and 20 m/s at an altitude 250 m. These velocities covered the range expected of the glider in an equilibrium glide, whereas the altitude was limited by Civil Aviation Safety Authority (Australia) regulations for model flight at the given site without special permission. The angle of attack ranged from -12° to +12°. ASYFLP and SYMFLP cards were used to model ailerons and an elevator respectively. NACA cards were used to define the respective aerofoil sections.

The DATCOM results include stability and control derivatives for each angle of attack and Mach number. These results were imported to the MATLAB® workspace, from which plots of the lift curve, moment curve, centre of pressure position, and drag polar were generated (Figure 9.6).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>2.08 kg</td>
</tr>
<tr>
<td>Span</td>
<td>2.52 m</td>
</tr>
<tr>
<td>Chord</td>
<td>0.246 m</td>
</tr>
<tr>
<td>Area</td>
<td>0.615 m²</td>
</tr>
</tbody>
</table>

9.3.2 Flight Test Design

Using the DATCOM stability and control derivative estimates, a flight test schedule was designed such that the applicable longitudinal and lateral-directional dynamic modes were excited. The frequency response function of each dynamic mode was first identified, following by the exact control inputs required to excite those frequencies.
9.3.2.1 Optimal Frequency Range

The following linearised longitudinal and lateral-directional state space models were used to analyse the frequency response of the glider. In Equations (9.6), \( u, \alpha, q, \) and \( \dot{\theta} \) correspond to the aircraft's longitudinal speed, angle of attack, pitch rate, and pitch angle respectively. For the lateral-directional case of Equations (9.7), \( v, p, r, \) and \( \phi \) refer to the aircraft's lateral speed, roll rate, yaw rate, and roll angle respectively. The \( \delta \) symbol refers to respective control surface deflections, \( g \) is the acceleration due to gravity, and \( I \) is a derived mass property defined in Equations (9.8) – (9.10). The remaining variables are dimensional stability and control derivatives.

\[
\begin{bmatrix}
\dot{u} \\
\dot{\alpha} \\
\dot{q} \\
\dot{\theta}
\end{bmatrix}
= 
\begin{bmatrix}
X_u & X_\alpha & X_q & -g \\
Z_u/U_0 & Z_\alpha/U_0 & 1 & 0 \\
M_u & M_\alpha & M_q & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
u \\
\alpha \\
q \\
\theta
\end{bmatrix}
+ 
\begin{bmatrix}
X_\delta \\
Z_\delta \\
M_\delta \\
0
\end{bmatrix}
\delta, \\
(9.6)
\]

\[
\begin{bmatrix}
\dot{v} \\
\dot{p} \\
\dot{r} \\
\dot{\phi}
\end{bmatrix}
= 
\begin{bmatrix}
Y_v/m \\
Y_p/m \\
Y_r/m \\
Y_{\phi}/m - U_0
\end{bmatrix}
\begin{bmatrix}
v \\
p \\
r \\
\phi
\end{bmatrix}
+ 
\begin{bmatrix}
1/m & 0 & 0 & \tan \theta \\
0 & 1/I'_{xx} & 0 & 0 \\
0 & I'_{xx} & 1/I'_{xx} & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
Y_\delta \\
Z_\delta \\
L_\delta \\
N_\delta
\end{bmatrix}
\delta, \\
(9.7)
\]

\[
I'_{xx} = (I_{xx}I_{zz} - I_{xz}^2)/I_{zz}, \\
(9.8)
\]
\[ I'_{zz} = \left( I_{xx} I_{zz} - I_{xz}^2 \right) / I_{xx} \]  
(9.9)

\[ I'_{xz} = I_{xz} / \left( I_{xx} I_{zz} - I_{xz}^2 \right) \]  
(9.10)

The longitudinal results showed two pairs of complex conjugates, with one pair belonging to the short period oscillation (SPO) mode, and the other representing the phugoid mode. The lateral-directional results indicated only the dutch roll mode was present, with the dynamics of the spiral and roll damping modes both being critically damped. Table 9.2 gives the damped natural frequency, \( \omega_d \), damped period, \( T_d \), and damping ratio, \( \xi \), of the SPO, phugoid, and dutch roll modes respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPO Mode</th>
<th>Phugoid Mode</th>
<th>Dutch Roll Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_d ) (rad s(^{-1}))</td>
<td>3.998</td>
<td>0.732</td>
<td>3.807</td>
</tr>
<tr>
<td>( T_d ) (s)</td>
<td>1.576</td>
<td>8.584</td>
<td>1.650</td>
</tr>
<tr>
<td>( \xi )</td>
<td>0.955</td>
<td>0.284</td>
<td>0.156</td>
</tr>
</tbody>
</table>
9.3.2.2 Optimal Control Input Design

Control inputs were designed based on the requirement that the damped natural frequencies of each mode be excited with adequate energy. The energy spectrum and magnitude of any control input are inversely related. If large energy content were required, this energy would be concentrated around a narrow frequency band. Hence, a compromise was made between selecting a control input with high energy content (such that the mode will be excited with sufficient amplitude), and a broad energy spectrum (to increase the confidence that the input will excite the mode). Plots of the normalized frequency distribution for a variety of common flight test manoeuvres were used to extract the normalized frequency of the peak energy content. Control input time steps were then determined based on this normalized frequency. Multistep, pulse, and doublet manoeuvres were selected to excite the SPO, phugoid, and dutch roll modes respectively (Table 9.3).

Table 9.3: Dynamic Mode Control Input Sequences

<table>
<thead>
<tr>
<th>SPO Mode</th>
<th>Phugoid Mode</th>
<th>Dutch Roll Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Input Sequence</td>
<td>3-2-1-1 elevator multistep</td>
<td>Elevator pulse</td>
</tr>
<tr>
<td>Time step (s)</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>
9.3.3 Flight Testing and Instrumentation

In order to achieve the goals of this work an experimental system was needed that would allow measurement and logging of system states during flight, be physically small and light enough to be incorporated into the aircraft, provide an automated control option, and be compatible with commercial model radio equipment. The Micropilot Systems already in use within the research team meet these criteria and are hence applied to this work. The MP 2028g system employed here consists of components as described in Figure 9.7 (including a commercial radio). In addition a Pitot tube was added to the aircraft to allow a measurement of airspeed (Figure 9.8).

![Micropilot + RC system block diagram](image1)

![Glider with Pitot tube fitted](image2)
In the basic test procedure the glider was accelerated at launch using a modified car starter motor. This towed the glider to approximately 250m in elevation before a steady descent to the ground. Flight testing manoeuvres were performed using manual control inputs with the MicroPilot autopilot recording system variables at a rate of 5Hz (Figure 9.9). The angle of attack and angle of sideslip were not recorded directly, but derived from inertial accelerations [2],[3].

Following the set control inputs, the glider’s free response was recorded for at least 3 periods of the excited dynamic mode (Figure 9.9). In total, 6 flights were conducted yielding data relevant to 11 flight test manoeuvres.

Following flight-testing, the recorded data was reconstructed in FlightGear via a MATLAB animation object. This functionality was found to be useful when interpreting the recorded data, allowing for a “visual reconstruction” of the flight.

![Figure 9.9: Rudder Doublet Input and Resulting Sideslip Response](image)

It was found in flight test that manual control input was not accurate enough to provide repeatable results and that further work should incorporate automated flights (an existing capability of the Micropilot). Another issue with the testing method was that without the on-board telemetry fitted, certain measurements could not be obtained meaning derived values had to be used. Based on already noisy data this introduced more uncertainty into the results. As such it is recommended that future work include the on-board telemetry to enable recording of all flight variables in addition to automating the test procedure.
9.3.4 Parameter Estimation

Three time-domain parameter estimation methods were employed to estimate derivatives from the recorded flight test data. In each case, the initial values of the estimated parameters were set to the a priori values from the DATCOM analysis, as to provide consistency between estimations. The first two methods, one using a traditional and well documented output error method and the second using Simulink’s Parameter Estimation toolbox are based on linearised equations. These are then compared with DIRECT’s capability to utilize the full non-linear equations of motion.

9.3.4.1 Gauss-Newton Output Error

The first method used MATLAB m-files developed by Jategaonkar [4]. This approach used a Gauss-Newton output error optimization method with 4th order Runge-Kutta numerical integration. Figure 9.10 compares the actual and estimated pitch rate response of an SPO manoeuvre.

![Figure 9.10: Measured vs. Simulated SPO Pitch Rate Response](image)

9.3.4.2 Simulink Parameter Estimation Toolbox

The second method used Simulink to relate a recorded control surface deflection to a corresponding recorded variation in a measured variable. Transfer functions containing stability and control derivatives were adjusted by Simulink’s Parameter Estimation Toolbox so as to minimize the cost function describing the difference between the estimated and recorded response. This method used a non-linear least squares optimisation routine with 4th order Runge-Kutta numerical integration for the linearised equations of motion.

As an example of the results obtained from the Simulink-based method, Figure 9.11 shows the comparison between the flight test and estimated results for the phugoid airspeed data following an elevator pulse input.
The simplicity of the Simulink® method proved to be an advantage, with minimal changes to one model allowing for estimations of many dynamic modes. It was also evident that the transfer functions were able to identify even weak derivatives, ultimately allowing for improved convergence. However, derivatives obtained via the first method appeared to be more valid than those of the second method, as indicated by larger variations of the same derivatives between flight tests, and larger differences when compared to the DATCOM approximations. Further, the Simulink® optimisation routine was more computationally intensive than that of the first method, resulting in more time-consuming estimations.

9.3.4.3 DIRECT Parameter Identification

The third method used for Parameter Estimation for a flight dynamic model of the glider was a software package developed at RMIT (DIRECT). DIRECT is a generic solver of optimal control problems that may have many non-linear aspects as described in many prior publications [5,6]. DIRECT allows the use of non-linear equations of motion in the state estimation and is capable of solving a parameter estimation problem where the cost function to be minimized is a mean square sum of state errors.

The nature of the linearised equations of motion employed in the previous parameter estimation problems makes them sensitive to measurement noise. The basic assumption in deriving the linearised equations of motion is that the aircraft is operating at equilibrium conditions with small perturbations about the equilibrium. Therefore if a random absolute noise of 10% is encountered and the perturbation about equilibrium is 5% there is more noise than the disturbance we are trying to measure, further only a small amount of the recorded data can be used, as most flight test data for a small glider will not be under equilibrium conditions. By using the full
non-linear equations of motion these problems could be addressed in that non-equilibrium flight test data with larger variations could be used which would be more tolerant of measurement error.

The problem was posed by modelling the motion of the glider with a six-degree of freedom rigid body aircraft model. This used the standard Force, Moment and Navigation Equations [7]. In the place of the Euler Equations, Quaternions were utilized for their computational continuity. DIRECT then solved the following problem.

Find the state-control pair \( \{x(t), u(t)\} \) and possibly the initial and final times, \( t_0 \) and \( t_f \), as well as the vector of unknown parameters \( p \) that minimize the performance index

\[
J = \sum_{k=1}^{n_{dx}} v^T \left( x_k - x(t_k) \right)^2 \tag{9.11}
\]

subject to the non-linear state equations;

\[
\dot{x}(t) = f(x(t), u(t), p(t), t) \tag{9.12}
\]

the end point conditions,

\[
\begin{align*}
e^0_L & \leq e[x(t_0), t_0] \leq e^0_U \\
e^I_L & \leq e[x(t_f), t_f] \leq e^I_U
\end{align*} \tag{9.13}
\]

the path constraints,

\[
g_L \leq g[x(t), u(t), t] \leq g_U \tag{9.14}
\]

and the box constraints,

\[
\begin{align*}
x_L & \leq x(t) \leq x_U \\
u_L & \leq u(t) \leq u_U \tag{9.15}
\end{align*}
\]

The cost function was a least squares sum of the state errors, i.e. the difference between the measured and computed response, which was minimized by altering the problem parameters \( p \). In this work the mass properties were measured in the previous sections. The parameters \( p \) represents the stability derivatives estimated and were substituted into the aero model in the state calculation. Selected stability derivatives are presented in Table 9.4.
Table 9.4: Selected Stability Derivative Estimates

<table>
<thead>
<tr>
<th>Derivative</th>
<th>DATCOM (A Prior)</th>
<th>Simulink</th>
<th>DIRECT</th>
<th>Gauss-Newton Output error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{\alpha}$</td>
<td>0.4090</td>
<td>N/A</td>
<td>0.1685</td>
<td>0.6928</td>
</tr>
<tr>
<td>$C_{D_\alpha}$</td>
<td>0.0029</td>
<td>N/A</td>
<td>0.0423</td>
<td>-2.3959</td>
</tr>
<tr>
<td>$C_{D_\beta}$</td>
<td>0.0360</td>
<td>N/A</td>
<td>0.0525</td>
<td>1.4275</td>
</tr>
<tr>
<td>$C_{\delta_\alpha}$</td>
<td>0.1146</td>
<td>0.0054</td>
<td>0.2680</td>
<td>N/A</td>
</tr>
<tr>
<td>$C_{\delta_\beta}$</td>
<td>-0.0885</td>
<td>-3.3914</td>
<td>-0.4980</td>
<td>N/A</td>
</tr>
<tr>
<td>$C_{L_\delta}$</td>
<td>0.4125</td>
<td>0.3432</td>
<td>0.1820</td>
<td>1.2616</td>
</tr>
<tr>
<td>$C_{\delta_\gamma}$</td>
<td>5.7004</td>
<td>8.4287</td>
<td>3.3744</td>
<td>1.7412</td>
</tr>
</tbody>
</table>

The measured data is presented with the simulated response based on the derived stability derivatives and the initial guesses, Figures 9.12-9.15. The red line is the simulation based on the guess or seed values of the stability derivatives, the blue line on the derived stability derivatives and the green line is the measured response.

![Figure 9.12: Measured Body Fixed Velocities](image)

![Figure 9.13: Quaternions derived from measured data](image)
By looking at the derived stability derivatives for this method it was seen that the values were within a reasonable range of the other estimates and particularly the DATCOM values (Table 9.4). This gave some kind of confidence in the results. In examining Figures 9.12-9.15 it was seen that the simulated response appears to have only a loose correlation with the measured response, a good indication that more work was needed in filtering the data and choosing optimisation conditions to achieve a better result. A problem encountered in this work was drift and errors in the accelerometer recorded data and the low rate of sampling, more accurate results could be obtained with better data and would give more confidence in the results.

Due to inherent measured data flaws the data had to be massaged to remove offsets in the accelerometer calibration and in integrating the accelerometer to reveal body velocity data. Further improvements could be made by using on-board telemetry to record the body velocities directly and or by using the parameter fitting results to feed back into the model. Building a Kalman filter for the data to better estimate the system states may have provided more useful results. This process could then have been iterated using further testing data sets for a best estimate of modelling parameters. Finally much better results could be expected with a higher rate of data capture, while 5 Hz may be sufficient for very large aircraft, for a small glider it was likely to miss the higher rate dynamics.
9.3.4.4 Parameter Estimation Limitations

An analysis of the results showed that all the parameter estimation methods were unable to provide consistently reliable and valid approximations of stability and control derivatives. There are five broad reasons for this: i) the limited quantity of flight test data, ii) atmospheric interference, iii) the coarse data sampling rate, iv) the noise in the data measurements and v) control input inaccuracies.

It was apparent from the results that the estimated parameters obtained from each set of flight test data varied widely, despite individual estimations producing relatively good convergence. This variation was similar to that witnessed by Seanor [5], who calculated the mean of each particular derivative. Only six flight tests were conducted in this study, with each occurring on the same day. This is compared to the 14 flight tests of Seanor [5], with multiple manoeuvres completed within each flight. Additional flight test data would have allowed for more reliable and valid averages to be obtained.

The second source of error was a result of atmospheric interference. Wind gusts of even the smallest magnitude disturbed the dynamics of the large, light glider with these interferences recorded by MicroPilot as changes in attitude, velocities and accelerations. The changes were subsequently incorporated into the non-dimensional derivatives, often resulting in what would appear to be gross exaggerations of the actual dynamic properties.

It has already been mentioned that the MicroPilot hardware logged all information at the rate of 5Hz. Although acceptable in terms of the Nyquist frequency, advisory literature suggested a rate of at least 20Hz when performing such flight tests [4]. Considering the relatively high natural frequency characteristics of the glider, this requirement takes on an extra importance. The specific MicroPilot hardware available for use with the project did not support these higher rates. In addition large quantities of noise appear to be present in the recorded data making it difficult for any parameter estimation method to achieve satisfactory results.

Finally, unavoidable inaccuracies in the manual application of control inputs may have resulted in insufficient energy being contained within the control input to excite the required dynamic frequency. If this were the case, the ability of any parameter estimation technique to obtain valid estimates of derivatives would be significantly hindered.

As a result of these observations, it was decided to build the FDM using derivatives obtained from parameter estimation methods and DATCOM values, rather than select the results of one method in their entirety.
9.3.5 Flight Dynamic Model

9.3.5.1 Development

The glider’s FDM was based on the work of Rauw [6], using Simulink® to relate the aerodynamic forces and moments with the resulting motion of the glider. The model contains 5 top-level blocks representing pilot inputs, the environment, airframe, motion conversion and FlightGear inputs respectively.

The stability and control derivatives from the parameter estimation phase were incorporated into the FDM by referencing workspace variables. One of the differences when compared to the model in [6] is the addition of several scopes allowing for real-time plotting of, for instance, control surface deflections, roll, pitch, and yaw angles (Figure 9.16). This functionality was added so as to facilitate validating the simulated dynamics.

![Figure 9.16: FlightGear Simulation and Simulink® Scopes](image-url)
9.3.5.2 Validation

Validation of the FDM was demonstrated in two ways. The first was via a comparison of the flight-test-based frequency response with the model-based frequency response. Elevator and rudder pulses identical to those applied during flight-testing were applied to the simulator by referencing the flight test-recorded control surface time histories. The resulting dynamic response was recorded via the simulation scopes. The comparisons indicate an approximate 20% difference between the flight-test and simulated longitudinal and lateral-directional damped natural frequencies (Table 9.5). While seemingly large, this difference is thought to be reasonable for the first of a series of iterations during the development of a flight simulator. Further flight-testing was expected to decrease this difference.

Table 9.5: Flight Test and Simulated Dynamic Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phugoid Mode</th>
<th>Dutch Roll Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A Priori</td>
<td>Flight test</td>
</tr>
<tr>
<td>( \xi ) (rad s(^{-1}))</td>
<td>0.732</td>
<td>1.013</td>
</tr>
<tr>
<td>( T_\xi ) (s)</td>
<td>8.584</td>
<td>6.200</td>
</tr>
<tr>
<td>( \xi )</td>
<td>0.284</td>
<td>0.118</td>
</tr>
</tbody>
</table>

The second method by which the simulator was validated was more heuristic, and attempted to visually compare the simulated and flight test response of the glider to a common set of control inputs. The flight test response was entered into MATLAB® as an animation object via a .csv file containing the variation of the six degrees of freedom with respect to time. The exact control input used during the flight test example was applied to the simulator with the resulting simulated response recorded by FlightGear. This recording was then imported into MATLAB® and superimposed with the flight test animation object (Figure 9.17). This technique allowed researchers to appreciate how the derivative uncertainties were manifested in a physical reconstruction of a flight, although it did not provide any assessment of how the derivatives differ.
Figure 9.17: FDM Validation via MATLAB® Animation Object
9.4 Chapter Conclusions

This work described the development of a flight simulator representing the flight dynamic properties of an unmanned glider. The work is considered to represent an important step in the development of a mechanism to extract energy from the jet stream. Future research efforts should build on this initial simulator platform, focusing on improving the validity through additional flight testing and incorporating autonomous control capabilities into the FDM. However, as mentioned earlier, the developed FDM did not prove directly useful for numerical work due to problems with instability.

9.5 Chapter References

10 Experimental testing of the Kite Wind Generator

Chapter 10 presents the testing of the prototype generator; from the development of controls suitable for manually controlled flight, to the field-testing and results of the testing. The initial aim was to achieve automated optimal control, however, it became apparent that this was not feasible to achieve within the project time lines. Therefore the work presented in this chapter will be based on manually/semi automated testing of the system. While successful operation of the equipment was demonstrated, unfortunately the glider was destroyed before power generation was achieved. This chapter addresses research question seven, by testing the prototype, its usefulness can be assessed.

10.1 Winch Conceptual Control Design

The start point for the set up of a test for the prototype system was to build a conceptual picture of how the winch would need to behave during different phases of the testing.

A logical control sequence would be:

- A launch strategy that could ramp the winch up to maximum speed as quickly as possible without significantly overloading the two drives.
- Following launch the cable needed to transition smoothly to deployment mode.
- The deployment mode of control needed to be simple for the pilot. During generation the applied drive voltage should be such that the current flow was regulated not to exceed the maximum. That is, as the glider pulls the cable off the winch faster, the applied voltage needed to increase to maintain maximum safe current flow at that particular cable deployment speed.
- The suggested generation control would allow the pilot to transition the system to a stand still at any time by reducing the lift the glider is generating. (i.e. reducing the glider’s angle of attack)
- Once the system had been stabilised by the pilot the cable needed to be retrieved. Again to simplify control actions by the pilot, a simple tension was to be maintained giving the pilot full control of decent.
- With the cable fully retrieved the pilot could simultaneously start increasing the angle of attack as the winch control switches from retrieval to deployment mode.

In addition to the four main phases mentioned above there needed to be a stop function that could bring the winch to rest for idle time and for emergency situations.
10.2 Winch Performance Limits

The first step in designing winch control was evaluating the winch performance. The launch phase would be limited by the smallest of the maximum accelerations of the glider and the two winch drives.

The winch parameter identification in Chapter 9 revealed that the main drive took approximately 0.3 seconds to ramp up to maximum speed from rest as seen in Figure 10.1.

![Figure 10.1: Step response of winch main drive (24 volts applied at 0.1 seconds)](image)

However, the cable storage drive was observed to accelerate much slower when loaded with the 200 m of cable. Since, during launch, the storage drive needs to supply a small tension to the cable to ensure a good friction couple is maintained, this would limit the winch’s acceleration. By observing how long the current took to drop to steady state levels, the time to reach maximum speed could be estimated. Further, since the storage drive was a 12 V motor and there was 24 V available to drive it, the possibility existed to overdrive the storage drive for a short period during acceleration.

Figure 10.2 shows a controlled ramp up of the fully loaded storage drum (200 m of cable). Ramp up took 1.5 seconds. It may have been possible to reduce this further, however it was desirable not to run the drive motor to destruction. The result shown is a manually tuned ramp up at maximum acceleration (i.e. estimated maximum burst current) to the 12 V free speed. (Note that speed was not measured, as there was no position sensor on the storage drum.)
Figure 10.2: Storage drum ramp up with full load of cable.
10.3 Winch Control Design

As was mentioned in Chapter 9 Simulink® was used for the interface between the winching system and computer. With the Simulink® winch interface already developed for initial testing, the Simulink® model needed to be developed to include the winch control for testing. As discussed in section 10.1 there were four distinct phases of control. The following sections follow the same logical framework.

10.3.1 Launch Control

As discussed in the conceptual control design, the launch control should ramp up to the maximum cable retrieval speed as soon as possible. However, provision should be made to tune this in the field should it prove that this method was too aggressive. Another parameter that would need tuning in the field was the duration of launch winching time as it would be dependent on weather conditions. (i.e. if the wind is strong enough a launch phase might not be required at all.)

The performance of the storage drive was such that it could be run at 12 V for the first 0.2 seconds, at which point the current had dropped enough to ramp up to 24 V over the following second. The voltage then dropped back to the design voltage of 12 V. This control strategy pushed the limits of the winch, however, the overload was limited to one second. Over the 1.5 seconds the storage drive took to ramp up under this control, the main drive had the voltage setting ramped up to 24 V from 0 V. The Matlab® code for this control is shown in Figure 10.3.

```matlab
function [vs,vm] = launch(t,tTot)
if t>=0 && t<1.5
    vs=-12;
    vm=-24*(t)/1.5;
    if t>0.2 && t<1.2
        vs=-12-12*(t-0.2);
    end
elseif t>=1.5 && t<tTot-5
    vs=-12;
    vm=-24;
elseif t>=tTot-5 && t<tTot
    vs=-12+12*(t-(tTot-5))/5;
    vm=-24+24*(t-(tTot-5))/5;
else
    vs=0;
    vm=0;
end
```

*Figure 10.3: Launch Control Code*

Examination of Figure 10.3 shows that launch began at time = 0 meaning there needed to be some logic conditioning to generate the time trace beginning at the moment launch control was activated. To explain this, the final control design is examined; it is thought that the big picture of the winch control will help the reader to make sense of each control component. Figure 10.4 shows the top level of abstraction of the developed controller. Within this figure it can be seen that a number of manual switches were used for selection of the control algorithm. Essentially a number of
constants define which control mode is active. To reset the timing function for each controller, where appropriate, the control constant previously mentioned was passed through a derivative, which created a spike when the control algorithm was switched. This spike was used to drive an external reset on an integrator (that integrates unity) giving a reset-able time trace that started from zero each time the control regime was changed. See Figure 10.5.
Figure 10.4: Winch test controller
Further examination of the code in Figure 10.3 reveals that there is an external input defining the total time for launch. The reason for this was so the launch time could be tuned in the field. The total launch time would depend on how high one aims to launch the glider, how much cable is deployed for launch and the wind conditions of the day. It is likely that in high winds, only a small launch time will be needed or, if the terrain was such that there was significant wind flow disturbance at ground level, a large deployment time may be necessary to climb above the turbulent air flow. As such the Launch control block is shown in Figure 10.6.
10.3.2 Deployment Control

Assuming a successful launch, the cable should come to rest once the set launch time has expired. At this point it would be safe to switch to deployment control. Since the target of this control algorithm was to pass most control of the test to the pilot the deployment was of a passive nature. The storage drive was regulated to a set current (which could be easily adjusted in the field) to maintain minimum tension on the cable between the storage drive and the capstan drive. The main drive control voltage was set to zero or to a value that would regulate current flow to the set value. The deployment control block is shown in Figure 10.7.

![Figure 10.7 Deployment control block](image)

The current regulation in the storage drive was simply a proportional-integral controller with unity gain. This proved adequate during preliminary testing. The capstan drive control was embedded in the “Voltage Setting” block (Figure 10.7). Figure 10.8 shows the code within this block (embedded Matlab®).

```matlab
function Vset = fcn(ThD,CSet,R,Ke)
if Ke*ThD>-CSet*R
    Vset = Ke*ThD+CSet*R;
else
    Vset=0;
end
```

![Figure 10.8 “Voltage Setting” block code](image)

The code in Figure 10.8 calculates the back emf, and if it is larger than the voltage drop due to the set current flow, the voltage is set to achieve the desired current flow. Otherwise the voltage is clamped at zero. Since the motor drive hardware was a regenerative driver, clamping the voltage at zero drives the motor current into the battery. The maximum value of set current should be approximately 12 A.
10.3.3 Retrieval Control

Once the cable had reached its extreme during deployment the pilot should level the glider to reduce the tether tension and retrieval should be commenced. To give the pilot maximum control, retrieval should be of a relatively passive nature. With this in mind simply regulating the capstan drive torque (or equivalently current) to an appropriately low level should suffice. The current set point for retrieval was set as a constant in the main controller block to allow quick adjustment in the field. The control methodology employed to regulate the retrieval current is a classical, manually tuned Proportional, Integral controller.

![Figure 10.9: Cable retrieval control block](image)

Similar to the storage drive controller for deployment, Figure 10.9 shows the two Proportional-Integral controllers for regulating the current set-points during retrieval. The two integral components are shown with an external reset driven by the change in control logic to prevent integrator wind up during other control modes.
10.3.4 Stop Control

In the event that something goes wrong or the launch time is not set correctly there needed to be a stop control to ramp the drives from whatever condition they were operating at, to a stop.

![Stop control block](image)

Figure 10.10: Stop control block

Figure 10.10 shows the same block time signal as earlier described in section 10.3.1, along with a block to supply the previously applied voltage signals and the stop block; the two latter being embedded Matlab functions. The tapped delays provide the voltage signal for the two drives for the last 100 sample times.

```matlab
function Vold = sam(t,tstep,TD1,TD2)
    ind=round(t/tstep+3);
    if ind<101
        yyold=[TD1(ind),TD2(ind)];
        Vold=yyold;
    else
        yyold=[TD1(100),TD2(100)];
        Vold=yyold;
    end
```

![Old voltage signal block](image)

Figure 10.11 Old voltage signal block

In Figure 10.11, \( t_{step} \) is a user defined constant corresponding to the fixed step size as defined in the configuration parameters of Simulink\textsuperscript{®} defining the integration step size. The code takes the voltage setting from three samples ago unless it is 100 samples into the stop control algorithm in which case it holds the 100\textsuperscript{th} sample. Figure 10.12 shows the code for the stop algorithm.
function v = stop(t,Vold)
    % Ri=V-KeThd => i=(V-KeThd)/R => V=Ri+KeThd
    v=[0,0];
    if t<1.5
        v(1)=Vold(1)-Vold(1)*t/1.5; %ramp down over 1.5 secs
        v(2)=Vold(2)-Vold(2)*t/1.5; %ramp down over 1.5 secs
    elseif t>=1.5 && t<3
        v=[0,0];
    else
        v=[Vold(1),Vold(2)];
    end

Figure 10.12: Stop block embedded code

In Figure 10.12 the old applied voltage setting is held and the applied voltage is ramped from whatever this value is to zero in 1.5 seconds. This control algorithm was limited in that, one sample time there held a zero second setting on both voltage controls, resulting in a single sample kick but no noticeable change in drive velocity. This did not affect the function of the control block.

10.3.5 Control Block

Figure 10.13 shows how the various control algorithms are integrated to complete the controller. The user input is passed as a logic signal, which triggers the timers for each controller (where relevant) and defines which of the controllers is connected to the output to drive the two DC motors. The inclusion of the scopes was to aid diagnostic work during performance testing of the controller.
Figure 10.13: Control Block
10.3.6 State Estimation

To complete the controller it was necessary to estimate the unmeasured system states. Applied voltage, current and motor displacement were measured, leaving the other system variables, such as the cable or motor velocity, to be estimated. It was thought that the ideal way to do this would be with optimal Kalman filtering since the plant model was linear. However, after various attempts using a continuous time observer with Kalman feedback gains based on guesses for the covariance values, no adequate response was seen. The noise in the system measurements posed a significant challenge to achieve a useable result with a Kalman Filter and hence this approach was not pursued.

Rather, a different approach was taken. Simple lag filters (just slow enough to smooth out the measurement noise) and an approximate derivative to calculate the motor velocity were used. This derived value of velocity was also smoothed with a low pass filter. This technique had the drawback of introducing delays into the system and slowing the response, however, the initial testing indicated that functionality was adequate.

Figure 10.14 shows the Simulink® block for state estimation. It shows the blocks to read the sensors, the data conditioning, application of appropriate conversion factors and an estimation of the cable tension. It was originally desired to control the cable tension directly, however this is a no trivial task since, based on the equations of motion for a DC motor, the torque depends on motor acceleration. Acceleration can be derived taking multiple derivatives of the displacement signal. This measurement was already noisy and differentiating it would lead either to a large lag or large calculation errors. Hence, regulating the current flow was chosen to control cable tension since this was simpler and likely to be more robust. Measuring the cable tension directly would result in a better performing control system and is left as a topic of future work.
The resulting controller addresses the winching side of practical testing for the prototype.
10.4 Prototype Testing Results

Testing was conducted on two separate test days at Riddell Airfield, Riddell’s Creek Victoria, Australia with the support of colleague Peter Lapthorne. The first day provided some useful data and resulted in some reworking of the software and hardware with two successful Glider launches. The second day there was a successful test launch, one launch with attempted power generation followed by a launch resulting in a catastrophic accident that destroyed the glider. Testing is summarised in Table 10.1.

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Number</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/02/10</td>
<td>1</td>
<td>Successful launch with no data recorded due to software fault.</td>
</tr>
<tr>
<td>06/02/10</td>
<td>2</td>
<td>Successful launch with data recorded. Cable jettisoned after launch (launch testing was the aim).</td>
</tr>
<tr>
<td>06/02/10</td>
<td>3</td>
<td>Unsuccessful launch, glider failed to ascend.</td>
</tr>
<tr>
<td>26/03/10</td>
<td>1</td>
<td>Successful launch, data recorded. Cable jettisoned after this first test.</td>
</tr>
<tr>
<td>26/03/10</td>
<td>2</td>
<td>Successful launch with data recorded. Attempt at power generation however the glider over shot the winching station and failed to pull up on the cable.</td>
</tr>
<tr>
<td>26/03/10</td>
<td>3</td>
<td>Failed launch; Aircraft rolled at launch wrapping the cable around its self; destroying the aircraft.</td>
</tr>
</tbody>
</table>

*Table 10.1 Flight Testing Outcomes*

*Figure 10.15: Riddell Airfield [1]*
10.4.1 Test Results Day 1 (06/02/2010)

The initial round of testing was aimed at determining if the prototype system would launch and if the system functions were functional under test conditions. The most challenging aspect of testing was that it not only required suitable weather conditions but also the availability of the research team. With the control and initial testing having been completed in early December 2009 it wasn’t until February 6th, 2010 before both weather and researchers were available.

A further consideration was that the first series of tests were the most risky and hence the minimalist glider configuration (i.e. without Micropilot® and associated instrumentation) was used.

On the test day the wind speed was predicted to be approximately 10m/s although no measurements were taken (a lack of available equipment). At the actual airfield (Riddell Airfield, Riddell’s Creek Victoria, Australia) the airflow at the ground was contained a small amount of turbulence and hence was a little variable due to the deep valley that runs around one edge of the test site (Figure 10.15). An initial test was run and the glider was successfully launched with the winch. The glider climbed rapidly as expected and the cable was successfully jettisoned with the cable release control. The glider was then safely landed.

Unfortunately no data was collected for this first flight (an oversight due to the many revisions of the controller). To rectify this, the Simulink® model was quickly modified in the field to record the relevant data, however, the time trace was missed as was the battery voltage. Further, since saturation was not accounted for in the motor driver, the effect of voltage sag under load cannot be analysed. Within these limitations a qualitative analysis of the data was possible. The final control block showing the data capture is shown in Figure 10.16 and the block in which the applied voltage was calculated is shown in Figure 10.17.
Figure 10.16: Winch control model showing data capture
The second launch was also successful with the cable jettisoned once the glider had risen to a position above the winch with data recorded for later analysis. Further first day testing failed to result in takeoff. To determine the reason for the change in performance the successful recorded launch and one unsuccessful launch are compared.
Figure 10.18: Applied Capstan Drive voltage of a successful and an unsuccessful launch

Figure 10.18 shows the applied capstan voltage for both the successful and unsuccessful launch as recorded. The spike and different ramp gradient in the failed launch were due to aborting the launch as the glider was being pulled along the ground. Otherwise the two time histories are very similar.

Figure 10.19 shows the same comparison for the storage drive applied voltage, again a spike where the launch was aborted but otherwise the profiles were very similar. Figure 10.20 shows the time history of the main drive current. The motor current was a good indication of cable tension and Figure 10.20 indicates that during the failed launch the glider was held until more tension had built in the cable. Up until four sample time units there was no significant difference, however, soon after, the successful launch shows the tension building but not in the failed launch. Visually this corresponded to the point in time where the glider began to pitch up and lift into the wind (or not).

Figures 10.21 to 10.23 show that the storage drive current, cable position and cable velocity time histories were all very similar for both the successful and failed launch. This left the question of how the cable tension could be the only thing that is different?
Figure 10.19: Storage Drive applied voltage for a successful and unsuccessful launch

Figure 10.20: Main Drive Current for a successful and unsuccessful launch
Figure 10.21: Storage drive current time histories for a successful and unsuccessful launch.

Figure 10.22: Cable Position time histories for a successful and unsuccessful launch
The only logical conclusion to be drawn from these results was that perhaps as the day progressed, the wind strength reduced, this wasn’t perceived on the test site but without a measurement of wind speed at the launch location, this is difficult to prove either way. However, if the wind were a little weaker the apparent wind on the glider would have been lower and perhaps the first two successful launches were marginal and lucky ones. Historical data from the flight-testing of the glider indicates that the lower glide speed was around 15 m/s. If this were the lower end of the flight envelope, a launch cable speed of approximately 3 m/s would require a wind of 12 m/s for take off. Once the glider begins to climb the glider velocity builds as the flight path makes a larger angle with the cable and the wind, further increasing apparent wind.

With the previous test experience in mind it was decided to change the capstan drive motor pulley to achieve a gear ratio of 2:1 and an approximate maximum cable retrieval speed of 5 m/s. The trade-off was that the maximum cable tension was reduced by approximately 40%, limiting the loading on the glider.

There is more to be extracted from the data; Figure 10.20 shows that a maximum of 25 A is seen during the successful launch where the motor driver was limiting the current. This indicates that the glider comfortably sustained the maximum tensile load. The load test results supplied with the drive motor show that at 25 A the motor was generating approximately 1 Nm of torque. Using Equation 10.1 this equates to an approximate cable tension of 150 N.
\[ Tension = \frac{\text{torque} \times \text{gear\_ratio}}{\text{Capstan\_Radius}} = \frac{1 \times 60 / 18}{0.022} = 151.5 N \quad (10.1) \]

This was approximately 15 kg or, for the glider as tested weighing a little less than 2 kg, approximately 8g (8 times the at rest gravitational force). From this it can be concluded that the glider structure is more than capable of driving the winch to its limits, leaving the possibility that perhaps future winch drive motor upgrades may be justified.
10.4.2 Test Results Day 2 (26/03/2010)

The results that follow were captured on the second day of testing. These include:

- The first successful test launch
- The second launch (in which the glider overshot the winch and failed to safely drift downwind to begin generating power before releasing the cable and landing), and
- The third and final test (where the glider responded unexpectedly during launch, stall rolled and had its wing destroyed by the cable faster than the pilot could respond).

Since this was the second day of preliminary testing with the prototype set-up, the glider was not instrumented to minimise risk to equipment, and hence there is no data to represent the apparent wind or even prevailing wind conditions. The forecast wind was for approximately 36 km/hr or 10 m/s and as an estimate (based on heuristic approximation) the wind would have been a little stronger than this but not sufficient at ground level to lift the glider at zero cable velocity.

Following the second day of field-testing it was apparent that no further testing would be possible since the glider was destroyed and further time and resources were not available to perform more tests.

Figures 10.24-10.32 show the recorded and derived data for the three tests arranged such that first to third tests are top to bottom in each of the figures. The first test, as stated earlier, was a test launch to ensure everything was working as expected. The second test was much longer. After the glider was launched, the winch control was switched to deploy or generation mode. However, the glider flew (as far as could be measured by the eye) directly above the winch and gradually glided down with a ground speed of approximately zero. Since the glider overshot the ideal angle range for generating power of about 45 to 60 degrees from the ground, and the wind was a little too slow to move the glider downwind of the winch without stalling the glider, the test was aborted. This was reflected in the recorded data by the fact that the winch did not move the cable; visually the cable was slack and bowing down wind. The third test was aborted approximately 6 seconds after launch when the glider violently rolled wrapping the cable around itself before crashing into the ground. With the glider destroyed there was no possibility of further testing.

The applied voltage in Figure 10.24 is calculated from the signal sent to the motor driver and the recorded battery voltage. The subscripts \( t1, t2, t3 \) here are for the 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} tests.
Figure 10.24: Main Drive applied voltage for tests 1, 2 and 3

Figure 10.25: Main Drive current for tests 1, 2 and 3

Figure 10.25 shows that during launch the current limit of the motor driver (25 A) was reached and hence the motor driver would have been internally regulating the applied
voltage to limit the current. This indicates that the calculated voltage in Figure 10.24 was only accurate when the current was not being limited.

Figure 10.26: Main Drive power for tests 1, 2 and 3

Figure 10.27: Storage Drive applied voltage for tests 1, 2 and 3
Figure 10.27 displays the storage motor applied voltage for the three launches. The main point of interest is the deployment phase depicted in the second test where the controller’s efforts in regulating the cable tension on the storage side of the capstan can be seen. The current flow setting for these tests was set at 4 A, which was chosen by experiment to ensure the cable storage drive kept the cable just taught during all modes of operation.

*Figure 10.28: Storage Drive current for tests 1, 2 and 3*
Cable length is negative in Figure 10.29 because the cable was pulled to the launch position before the winch was prepared for operation and hence the encoder started at zero count once the cable was already beyond the launch start point.

Cable velocity was generated using a lag differentiator applied to a lag-filtered signal of the cable displacement and hence is only approximate and will clearly have a significant time lag (Figure 10.30).

The tension estimate in Figure 10.31 was based on differentiated and lag filtered values and hence contains inaccuracies, the magnitude of the tension and the shape of the motor current plot are the best estimate of cable tension behaviour during the tests.
Figure 10.30: Cable velocity for tests 1, 2 and 3

Figure 10.31: Approximate cable tension for tests 1, 2 and 3
Here Figure 10.32 is included to show how the size of the batteries may affect the winching system. Clearly there was appreciable voltage sag during launch related to the storage batteries ability to supply the current demand. The maximum sag experienced was approximately 20%.
10.5 Discussion of Testing Results

The testing presented in this work has shown some useful results. The capability of the winch and control devices was shown to be adequate. The modifications made after the first round of testing proved effective in making the launching of the system more reliable. Unfortunately there was no successful test to show power generation. Perhaps the piloting skill of the researchers was not sufficient to adequately control the experiment and therefore it may have been wiser to involve a more skilled model aircraft pilots. The relative difficulty in using the system as designed may also indicate that for initial testing, a different aircraft design suitable for slower winds and characteristically slower and more stable behaviour would have been appropriate. Milder winds and slower dynamics, even if coupled with inferior energy generation performance would be easier to achieve and generate more useful and complete results.

With reference to the research questions, this Chapter demonstrates the development of a useful prototype system both in design and in practise. It is the hope of the Author that the lessons learned and the tools developed here can be used for future work in this research area.

10.6 Chapter Conclusions

There are clearly many areas where improvements could be made in the prototype system that may yield the results so keenly pursued by the Author. Electrically, the winch electronics could be improved to decrease the level of noise, and a higher sampling rate would lead to improved control designs. More importantly a champion pilot and or a much slower glider should be chosen to facilitate testing in milder conditions with lower demands on the pilot’s skills.

Winch function and the function of the cable release mechanism have proven reliable and effective. Hence, even without a successful demonstration of power generation, at least part of the prototype system has been proven effective and, with a little more work, could be updated with a different glider to achieve many more results.

10.7 Chapter References


10.8 Chapter Bibliography

11 Conclusions, Future Work and Comments

In this chapter some final conclusions are drawn from the work presented throughout the thesis. How the work and this document address the research questions is explained. Further, the eighth and final research question, “Where should the work head next?”, will be addressed in this chapter.

The first research question asked what a low cost prototype system would look like and, it is believed that Chapter 8 on the design of the prototype system answers this question. Although the prototype system failed to generate electricity due to mishaps during testing, the hardware designed and built has proven cost effective, simple, robust and functional.

- The cable used was a Spectraspeed® sheathed parallel core cable and represented one of the major system costs,
- The glider was an “off the shelf” model sailplane purchased from a local model shop.
- The winch for the prototype was designed by the author and constructed at RMIT University.

The winch testing results of Chapter 9 demonstrated the fast response of the winching system, due to the characteristically low rotational inertia of the capstan-based design. Modelled optimal power generation solutions from Chapter 7 show the positive impact of fast winch response. The low inertia means fast transition from deployment to retrieval and hence a higher percentage of the available wind energy can be extracted. With the developed design there was minimal penalty for shorter cycle periods as could be necessary when harnessing winds in the jet stream where the wind layers may be thinner. (At the time of writing, high altitude wind energy resources were an active area of research.)

The capstan type winch concept created here and developed into a working prototype had further advantages.

- The cable can be stored at constant tension, resulting in neat packing without the need of additional mechanisms to guide the cable.
- The main power drive had relatively low inertia, allowing rapid acceleration of the system.
- Compact system scaling as the capstan diameter was linearly related to the cable diameter but not cable length.
- Separate storage and drive functions permit the cable to be deployed/retrieved in sections (assuming an appropriate joining method is available).

At minimum cable deployment length the cable storage mechanism has its maximum inertial load requiring larger drive power, however, electrical drives have an inherent ability to be overloaded by a factor of 2 or 4 for short periods, enabling the storage drive system to be sized for the lower loads of deployment and retrieval. A modern high strength cable of a 10mm diameter would be capable of generating approximately 200kW. The required capstan diameter would be 200mm, resulting in a
compact design where, the drive motor itself is likely to be bigger than the capstan drive and gearbox. Separate storage and drive functions would allow seasonal variation of the cable length or replacement of worn sections, without having to bring the glider back to ground. It is the belief of the author that this design has many significant advantages over other winch designs for this particular function, including the likelihood of lower cost.

The second research question of how to model the system was explored in Chapter 3. The system was modelled in a generic manner prior to simplification for the work that followed. The reason for starting with a complex model and then simplifying was that, future development of higher fidelity models, should be a continuation of the work already done. The model used in the remainder of the thesis was essentially a pendulum with its length controlled by the ground-based winch, free to rotate about the attachment point. The other end of the pendulum was attached to the centre of mass of the glider, with the glider allowed to pivot freely about this attachment point. Chapter 9 outlined how to fit the practical performance of the prototype to the dynamic model. A significant amount of work was done identifying model parameters for simulating the system. It is believed that the performance of the winch model was sufficiently close to reality, to have confidence in these simulation results. A great deal of work also went into the development of a flight dynamic model of the glider used in the prototype. The results of this were unfortunately less successful, in part due to limited testing time, and in part due to the limitations of the equipment used. The results of the flight dynamic modelling of the glider are believed to be representative, however, the model proved unstable in simulation and thus progress with this model was discontinued.

The fifth research question, “How to improve the modelling?”, leads from the previous discussion. Firstly, the quality of the Flight Dynamic Model of the glider used would need to be improved and developed in a systematic nature that would allow fast reproduction of this work for different glider designs. Next, the cable model had significant room for improvement. Utilising a model of multiple cable elements to allow slack conditions in the cable would be one such worthwhile development. This way a broader set of possible operating conditions could be investigated (although optimal trajectory solutions may prove more difficult to find). Further improvements would include the effects of wind drag on the cable, vibration from vortex shedding, cable rigidity and stretch.

The third, fourth and sixth research questions, “How to control the system?”, “What system parameters most effect performance?”, and “How to improve the performance?” were addressed in Chapters 4, 5, 6, 7 and 10. Significant effort has gone into modelling and simulating the prototype system, along with the generation of optimal trajectories for wind energy generation. The modelling used in simulation has given indications as to certain design characteristics that may yield the best system. Optimal trajectory generation was included in this work and showed general trends in how these systems may perform. Most importantly, it would seem that a practical plant would have a design that allows for very rapid retrieval of the deployed components and slower deployment at high wing loadings/ lift forces. It was apparent that the winching system could be optimised with the use of a two-speed or indeed multi-speed gearbox. This would speed up retrieval and reduce losses, whilst being able to load the motor/generator at maximum efficiency during deployment. Perhaps
a continuously variable transmission (CVT) would be worthwhile to allow optimal loading of the winch drive motor. Optimal trajectories suggested that aero-braking was not necessary (counter to results in Chapter 5 based on heuristic controls) with high retrieval speeds and hence a design similar to a glider, which has both a high lift to drag ratio and good penetration speed, should work well. This of course relies on the ability to control such a high speed system.

Simulating the system used for practical testing revealed further challenges for the working prototype. For a given set of steady wind conditions it was relatively easy to design control to generate a significant amount of power with respectable efficiency (relative to the efficiency of the main drive). However, when the mean wind conditions changed even by a relatively small amount, it was necessary to make significant changes to the control algorithm to ensure stability and reasonable power generation. As wind speeds increased, stability of the system during retrieval become more challenging as did the ability to retrieve the glider in a reasonable time without expending a great deal of energy. As wind speeds decreased, the risk of stall during transition from retrieval to deployment increased because the apparent wind speed drops sharply while the glider drifts downwind. Problems with stability and apparent wind would be addressed with optimal control methodologies, as shown in Chapter 7 but it should be kept in mind that these simulations were based on a linearised aero model and pushing the limits of this model may lead to violations of the assumptions used in deriving the model. Further, there are likely to be un-modelled non-linear effects as a result of the relatively fast manoeuvres.

The practical limitations identified above opened up considerable scope for refinement to the tools generated in this research. For example, highly developed non-linear aero models would be necessary to push the bounds of control since there are likely to be tight periodic manoeuvres necessary in at least some modes of operation. Other questions arising include:

- What is more important for a versatile and efficient system?
- Is a large aspect ratio aircraft, like a glider, capable of generating good lift at relatively low airspeeds and able to penetrate winds better? Or
- Is a lower aspect ratio aircraft capable of tighter manoeuvres and more radical flights paths better?
- Which will intercept more wind?
- Which will prove more versatile with a broader range of operating conditions?
- Perhaps reconfigurable aircraft would be ideal, changing performance characteristics between deployment and retrieval and for differing wind conditions.
- On the other hand, is the expense and complication of a reconfigurable aircraft going to be worthwhile? Could a simpler cheaper system perform better economically?

In spite of a crash and loss of aircraft, testing has shown that the design of the winch was successful and practical. However, with a lack of time and resources to continue the research, power generation with the practical system was still to be proven. There are a number of indications with simulation and the functionality of the prototype that this was entirely possible if not probable. The destruction of the second glider in testing, led to the conclusion that, a less ambitious prototype should have been
pursued first. It may be that difficulties in proving power generation with the prototype as built, due to the high performance nature of the glider, could have been avoided. Since the sailplane needed significant wind strength and was fairly sensitive and responsive to control inputs, the characteristic dynamics were fairly fast, perhaps too fast for an operator of average skill. A key point that can be learned by this is that choosing a glider that would work in lower strength winds of 5-10m/s would not only make a greater range of testing days available but would allow the pilot/winch operator to gain experience in milder conditions. Further, it is likely that a glider designed for slower winds would be inherently more stable and slower to respond and therefore easier to control. Developing an in house design for lower wind speeds, modularity, high structural integrity, construction simplicity and high relative stability would mean, not only could the glider be reproduced/ repaired more cost effectively, but it could be tailored to the application and requirements of the initial “Proof of Concept”.

To answer the seventh question of “How useful the tools developed in this research are?” one needs to reflect on the document as a whole. Some useful mathematical models and simulation tools have been developed which, due to a reasonably modular nature, can be improved upon in future work. The modelling and simulation tools have provided more insights than the practical testing, as they were able to be more rapidly deployed and refined (and were not damaged in a crash). Simulation and control development has provided clues as to performance trends and key performance parameters, which should guide workers as to where to look in the next series of investigations. Further, a number of methodologies have been presented for the parameter identification of the system for simulation, giving future researchers a good start on building and simulating new systems.

The development of the capstan based winch for this research should prove to be a significant contribution to the field. The design and the testing prove that the concept is strong, simple and cost effective with a number of inherent advantages over drum winch type systems as discussed earlier. It is hoped that the winch will be a useful tool for this research into the future.

The final research question, “Where should the work head next?” is fairly open-ended. There are many aspects of simulation and modelling that would benefit from refinement:

- The flight dynamic modelling and cable modelling could be developed to look at broader test results and to investigate potential problems with vibration, limit cycles etc.
- Further work should be done with the prototype to demonstrate power generation. It was felt that power generation was close to realisation, only beyond the time permitted for this researcher. Being able to repeatedly and reliably demonstrate power generation for significant periods of time is a critical step in garnering support to further this technology.
- More needs to be done finding the optimum glider design, which will no doubt affect over all system design. Using the glider to drive the winch increases the wing loading and therefore the glider design needs to be optimised for this. Perhaps bridling the glider or blending wing and body will yield the best overall performance and allow further increases in glider loading.
Resource permitting, a reliable scale pilot plant should be developed. A scale plant, operating full time, would yield a wealth of information and weight to the work. A test bed of this nature would build a great deal of confidence in the technology, and could be gradually developed, and refined, as the technology is deployed and its niche in the renewable energy market developed.

Given that (as stated in the literature review) wind resources at altitude contain approximately an order of magnitude more energy per unit area than at the ground, if the technological requirements to make the system work are met there is a potential to produce electricity at $1/10^{th}$ the cost of conventional wind turbines. Further, the visual impact would be far reduced in that the cable would only be visible by beacon lights and aircraft markers.

While there is much work to be done and the potential for much refinement the author feels that the project objectives have been met. A great deal of ground has been covered and many aspects of a practical system dealt with. It is hoped that this work can act as a basis for future work. This document provides many ideas, new information, and answers for some aspects of High Altitude Tethered Wind Power Extraction. Equally it can be said that it reveals as many questions. In addition to those already raised in this chapter the following practical challenges should be addressed with future investigations:

- Lifetime and fatigue problems
- Security, risk and safety ethics of this system
- Similarity and scaling of such a project
- Legal considerations of wind power generation
- Economics of wind energy of such a design
- Development and funding of this project
- Electrical generation and grid system integration

There are promising results, enough for the author to recommend that it is well worthwhile pursuing this area of research. It is, in the author’s opinion, completely feasible that tethered glider can autonomously generate electricity and this is reinforced by the growing interest and investment in the field in other research institutions.
12 Bibliography


13 Notes for researchers/ workers in the field

Anyone interested in further explanation, supporting documents, Simulink models, coding or general support please contact me. I am happy to give for academic purposes. Ultimately I would prefer to see a technology like this prosper and grow rather than be inhibited by the small personal gains to be had by hording the information.

At this point in my life a mailing address is probably only going to be accurate for a short period of time hence the best bet is my personal email dylan.thorpe@gmail.com or looking me up via the wonderful world wide web.

Finally, I would also be happy to engage in future collaborations based on this work whether they are here in Australia or abroad. While currently on a different part of my journey working in Engineering Consultancy, there is some part of me that feels I will take the business sense I am currently learning and bring it to this research in the future.

Good luck with your pursuits!