Parafoil Control for STRAPLEX

João Luís Granja da Costa

PROVISIONAL VERSION

Mestrado Integrado em Engenharia Electrotécnica e de Computadores

Orientador: Sérgio Reis Cunha (PhD)

March 19, 2013
Abstract

In the context of the course "Preparação da Dissertação" of the year 2012/2013, this document will present the initial approach to the dissertation.

In the beginning, the objectives and the previously structure of the dissertation will be presented. The schedule of the project shows the several phases of the project which will be developed during the dissertation.

In the second section, the STRAPLEX project is explained as well as its actual state. In particular, this description will be focused on the "Autonomous paraglider for STRAPLEX" dissertation which was developed in the last year by Mário Martins de Sousa [2]. Then the state of the art of the topic under discussion is addressed with special attention to the research of the autonomous paraglider and the identification process for this type of system.

Finally, a simple description of the system involved in the project is made and a first approach to the mathematical model is presented, through the kinematic and dynamic equations analysis.
Contents

1 Introduction
   1.1 Objectives .......................................................... 1
   1.2 Preview contents of the dissertation .......................... 1
   1.3 Project Schedule .................................................... 2

2 STRAPLEX
   2.1 STRAPLEX project ............................................... 3
   2.2 Actual status ...................................................... 5
   2.3 The STRAPLEX project next step .............................. 7
   2.4 State of the art .................................................. 7

3 Mathematical model
   3.1 Parafoil-Payload System ......................................... 13

References ............................................................... 16
List of Figures

1.1 Project Schedule .................................................. 2
2.1 STRAPLEX ascension flight test .............................. 4
2.2 STX MATLAB center .............................................. 6
3.1 STRAPLEX components ....................................... 13
3.2 Parafoil-payload system ....................................... 14
Chapter 1

Introduction

1.1 Objectives

The paraglider is a promising flying vehicle in great development on modern aviation. It has many potential for autonomous transportation by its low-cost and space efficiency. In our work, the paraglider system is constituted by a canopy, a payload, a special module named main STRAPLEX capsule and a transponder. Its behaviour is non-linear and the canopy is a non-rigid wing shaped structure. Furthermore the unpredictable wind disturbance and the possible double pendulum effect due to the presence of the main STRAPLEX capsule in addition to the canopy control payload, make the paraglider control a non trivial issue.

The goal of this dissertation is to analyse the paraglider motion mathematically and study its regime of stability in order to develop control loops to perform automatic landing of STRAPLEX from high altitude (e.g. 40 kilometres) until reaching the ground. To do that it is essential to know some characteristics of the system (e.g. the payload and the canopy aerodynamic coefficients) which will be estimated through the identification process from the already collected flight data.

The spiral motion during the descent trajectory is the new path following problem which will be addressed. The ultimate target is to make the autonomous paraglider autonomously land on the launching point.

1.2 Preview contents of the dissertation

The previous dissertation may be divided into six chapters. On the first one the dissertation objectives will be explained together with its organization and the project schedule. Next, it will be present the STRAPLEX project and its actual status. The third chapter will contain the analysis of the mathematical model of the paraglider and also its stability regimes. A dynamic system identification procedure will be also included. The next chapter will be devoted to the detail at the control theory and at the implementation and at tuning control loops for the system. It is also planned to programme the autonomous spiral motion. The fifth chapter will present the flight test results and finally, the last one will finish with the final remarks and future work.
1.3 Project Schedule

The previous work to be done during the first and second semester for this dissertation is showed on the following Gantt. During the first semester, which finished on thirteen of February, the study and the analysis of the already performed works were done. The mathematical model has also started as planned. For the second semester it is expected to finish the mathematical modelling and to perform estimation method to important parameters of the system. After that it will be interesting to put the previous work into practice making flight tests.

![Figure 1.1: Project Schedule](image)

The work done on the first semester occurred on course and for the author there are great expectations that the project runs smoothly in the second semester.
Chapter 2

STRAPLEX

2.1 STRAPLEX project

STRAPLEX (STRAtospheric PLatform EXperiment) is a program by the University of Porto, Portugal in collaboration with the Education Projects Division of the European Space Agency (ESA) [1]. This program began at 2005 and offers the scientific community the possibility to make experiences in the stratosphere. It is possible to make tests such as on the specific space environment because the stratosphere has near-space conditions. So STRAPLEX is an interest opportunity to send experiments in the stratosphere on low cost and flexible way.

The near-space conditions is interpreted by the scientific community as the near vacuum conditions which are good conditions to make following experiments:

- **Experiments related to Stratospheric Balloon design**: Archimedes force, Balloon principles, Ascent velocity, Parachute system, Helium utilisation, etc;
- **Experiments related to the Atmosphere**: Temperature environment, Pressure environment, Atmosphere density, Humidity, sound propagation, pollution, etc;
- **Experiments related to radiation**: Solar radiation flux, solar energy, cosmic ray, etc;
- **Experiments related to tele-detection**: Albedo, colour photography, black and white photography, digital photography, video, data transmission, etc;
- **Experiments related to biology**;
- **Landing systems**;
- **Detachable capsules** (including specific localisation and recovery system).

The STRAPLEX launch vehicle is essentially composed by five main components: a capsule for payload accommodation, a parachute system, an helium balloon, a transponder and a cutdown
Figure 2.1: STRAPLEX ascension flight test

system. The four first components can be viewed on the figure 2.1 which was taken on last launch experiment.

The capsule carries both the scientific experiment and the control system and is reached up high altitude through the balloon filled with Helium. Depending on the mass of the experiment, STRAPLEX can reach up to 40 km altitude. The parachute system is activated in the descent movement to stabilize and control the trajectory. The cutdown system is used to separate safely the balloon of the others components. This enables the possibility of in case of emergency shorten the mission duration.

The STRAPLEX mission can be divided in four main phases:

1. Launch;
2. Ascent trajectory;
3. Descent trajectory;
4. Land.

In the first phase, the balloon is filled with helium until its lower density make the system up. After that the balloon raise up the capsule and the other components until the stratosphere. Indeed, the air pressure decreases with altitude such that into the stratosphere the air pressure is very low and the helium expands until the latex of which it is made reaches its rupture point, bursting the balloon. The platform starts the descent trajectory aided by the parachute system, meanwhile, the balloon is separated of the system by the cutdown system. Finally the last operation is the land in which the land point depends of the wind effect. There isn’t any type of control on the land operation. Due to difficult recovery and possible mistake on the equipment, wooden area and water bodies should be avoided. So this phase should be controlled to increase the security operation and to avoid mistakes on the equipment due to unwanted land point.

In all phases of the mission, the capsule is in constant communication with a fixed ground station.
through redundant types of RF communications. Information such as air pressure, humidity, temperature (in and outside the capsule), position, velocity and other relevant information required can be sent to the ground station. In the ground, the station receives the flight informations and stores to future analysis. When it is necessary the station can send some action to the capsule such as cutdown action. Moreover a mobile station follows the platform descent in order to recover the capsule as soon as it lands.

The STRAPLEX launch is normally carried out from the Évora launch site. The moderate climate, the regular air and considerably flat region are good reasons to the success of the launch and land missions.

## 2.2 Actual status

As stated in above section, the descent trajectory is only aided by a round parachute so the point landing is very influenced by the wind. The lack of landing control already led to some problems on the rescue process in realized experiments. In one experiment the capsule transcended the border with Spain due to a west wind, thus affecting the Spanish traffic and complicating the recover operation. In another experiment the capsule landed on the Alqueva dam, which is near Évora. This caused a large waste of time on the rescue process and some equipment inside the main capsule was damaged.

In order to avoid unwanted landing site, the engineering student Mário Martins de Sousa oriented by the teacher Sérgio Reis Cunha developed a solution based on a controlled ram-air parachute situated between the round parachute and the capsule [2]. The control of the canopy is assured by a special capsule called Drone. It is composed by actuators, navigation and guidance system and is attached by four lines to the canopy. Two main cables can triggered in differential mode to change the lift of the canopy. The two others lines are the breaks which can triggered at same type decreasing the glide ratio or using independently making an roll movement pursued by an yaw movement of the canopy.

The main goal of the student’s dissertation was to create a solution that be able to follow a given path till the landing. He implemented 2 types of flight modes: manual or autonomous modes. In the first one, the user maneuvers the parachute using a joystick with the help of the real time video of the capsule. The joystick movements are interpreted by a ground station software, named STX center, that sends actions to Drone where the actuators act accordingly. In the autonomous mode, the Drone controls the descent path resorting to a algorithm control implemented on its software. This algorithm was implemented to the paraglider follows a specific path oriented by:

- A given heading;
- A given course;
- A spacial point (localizer) and an arrival angle;
- Two spacial points.
The ground and flight tests validated the control systems and the obtained results could be analysed to improve the control algorithm. However it was verified that some drawbacks greatly influence the landing point such as the wing effects, twist lines and the double pendulum effect. During all phase of the STRAPLEX trajectory some flight information measured on board (on Drone or capsule) are transmitted to ground station for control loop and posterior analysis. For example, the video data are essential in manual mode to control the paraglider when it isn’t in line of sight(LOS). The capsule has the video camera and reports its position to the ground station by automatic packet reporting system (APRS) or using a dedicated GPS receiver. For better the data acquisition Drone also incorporates a GPS receiver and an attitude and heading reference system (AHRS). The capsule and the Drone have sensors of temperature, humidity, pressure and power monitoring. The GPS provides information to the position and velocity; the AHRS which is composed by 3-axis accelerometer, magnetometer and a gyro, provides the pitch, yaw and roll angle using a Kalman filter; the pitot tube uses an absolute and differential pressure sensor to calculates the airspeed; the internal sensors have a significant role to ensure the good processing and monitoring of the microcontrollers.

The STRAPLEX reliability was improved by a strong communication protocol with redundant channels implemented between the platform and the ground station. The redundant channels is based on a GFSK, a 5DPSK and a DTMF modulation. An aviation transponder is installed in the platform to increase the air traffic control. The ground station has the main objective to monitor the platform during the flight. It is essentially composed by a computer which gathers the received flight information and transmits the control action through transceivers. Its interface with the operator is a MATLAB graphic user interface (GUI) named STX center, visible in the following picture.

Figure 2.2: STX MATLAB center

Version 0.92 (March 19, 2013)
In the left part of this interface it is possible to see the most important flight information (coordinates, attitude velocity, course, etc), GPS information and some sensor status. In the center, we can see the wind forecast, some Drone options and the actuators position. In the right side, we have the autonomous control part where it is possible to download or upload important parameters to the control (heading/course, sink rate, etc). The last part is constituted by some buttons which allow for example to see the platform part on Google Earth and choose the operating control mode. Mario also improved the cutdown system making it more reliable and efficient using a mechanical approach instead a pyrotechnic method. The cutdown system has the function of separate the helium balloon from the capsules. This device has a crucial function on the experiment success because if the balloon doesn’t separate of the capsule, after on the descent phase the balloon, already busted, it will compromise the paraglider control. After some test, it was proved that the cutdown system played successfully its function.

2.3 The STRAPLEX project next step

The controlled paraglider developed by Mario showed to be a reliability solution with great stability and maneuverability mode of operation. However during the flight tests the paraglider doesn’t reach the default destination because of the wing effects and on some case of the double pendulum effect which isn’t take account on the algorithm control. In order to overcomes these issues and in this way to reach the desired landing point, a better control action should be implemented. A mathematical model of the system is a good support to analyse the domains of asymptotic stability of the system motion and synthesize control regimes. The parafoil and payload aerodynamic coefficients and some others important coefficients of the system can be determined through a identification process from the already collected flight data. After a good characterization of the system, a spiral motion is possible to implement in the system. The ultimate target of control issue is the landing point be the same that the launching point.

2.4 State of the art

Since the appearance of the ram-air parafoils many researches and studies have been carried out proving its great advantages on autonomous flight such as the stability, controllability and maneuverability. For a dynamic motion analysis of the parafoil system, the aerodynamic coefficients (lift \(C_L\), drag \(C_D\)) should be known and therefore estimated. The articles [3-5] analyse these coefficients at small size models of the canopy up to 300\(ft^2\) and at low-aspect ratio parafoil up to 3.0. At [3] the maximum obtained lift-drag ratios of the wings varied from about 1.9 to 2.7 and the maximum obtained lift coefficients ranged from 0.9 to 1.1. Moreover Burk analysed the canopy stability and concluded that the tested parafoils were statically longitudinally stable over the entire test angle-off-attack range of 0\(^\circ\) to 70\(^\circ\).
Nikolaides presented results of the aerodynamic coefficients and of the velocity in various direction obtained from ascending flights and manned jumps from aircraft tests [4]. The results are showed graphically or in tables for various aspect ratio (1.0-3.0). A comparison of the predicted flight performance of the parafoil with the measured flight performance of the parafoil, as obtained from ascending flight and glide tests and from jump tests, has been made concluding that the agreement between the predicted performance and the measured performance was good.

Lingard discussed the performance and design of ram-air parachutes for the Precision Aerial Delivery System (PADS) [5]. He made a briefly general description of the ram-air parachute and analysed the aerodynamic characteristics of ram-air wings. The theoretical drag and lift coefficients and L/D ratio are plotted, versus incident angle for aspect ratios 2.0-4.0. Analysing the previous results it should be noted that the lift curve slope increases with increasing aspect ratio, but the drag coefficient at a given incidence varies little with the aspect ratio. In relation to the L/D ratio it improves with the increasing of the aspect ratio. A comparison of the experimental and theoretical drag and lift coefficients and L/D ratio is showed for the aspect ratio 3.0. Some little differences are observed mainly on the lift coefficient results where upper 10 degree of the incident angle, the experimental and theoretical plots are very different. For the analysis of the aerodynamic characteristics ram-air parachute, the effect of line length is verified on wing lift coefficient and on L/D ratio. He also presented the forces equation on the system horizontally and vertically in order to analyse the ram-air parachute flight performance. Its longitudinal static stability is analysed showing the effect of the trailing edge deflection on the pitching moment, drag and lift coefficients, L/D ratio, attitude and flight velocity for the standard system. The response of ram air parachute to trailing edge deflection measuring the attitude and flight velocity is plotted in way to analyse the longitudinal dynamics of ram-air parachutes for different mass ratio. The effect of a 7.5m step tail gust on the standard large system is also shown.

A more complex mathematical model of the paraglider system is presented on the articles described below. The models mainly differ on the number of degrees of freedom (DoF). Some models consider the paraglider-payload as a rigid system and therefore their dynamic analyse concern on the center of mass. Others consider the relative motion between the paraglider and payload, increasing the DoF number. The general modelling approach is to determine the system kinematics and dynamic equations. In the first one is present the position, velocity and acceleration equations of the system, while in the second it is determined the force and moment equations of the system.

Toglia et al. [6] presents two models, one with nine DoF and another with six DoF. On the first one, she takes account the effect of the payload twisting and therefore uses three DoF to characterize the inertial position of the joint point and six DoF to describe the parafoil and payload attitude motion, using the three Euler angles. The forces applied on the system are: the aerodynamic force, the weight force and the reaction exerted at the joint point to the payload and the aerodynamic, the
weight, the reaction and the apparent force to the parafoil. On the other model the relative motion is neglected and the analyse is made only on the global center of mass, being the inertial position and the attitude motion the six DoF. On this case the forces (total weight force, both aerodynamic forces and the apparent force) are applied on the center of mass. On both models, the control is applied on the flaps deflection with the symmetrical term $\delta_s$ and the asymmetrical term $\delta_a$ which is given by the differential flaps deflection. After setting the kinematics and dynamic equations, it is derived the global system motion equation with the effect of the flap deflection. Using the MATLAB tool, the two models were simulated to a free dynamic trajectory and a spiral motion, analysing the flap deflection effect and the payload twist effect (this only on the nine DoF model). Through the results we can concluded that the six DoF model presents a delay in turning to the spiral motion and has less oscillations due to the lack presence of relative motion caused by the payload influence.

A control algorithm for autonomous paraglider was been proposed by [7]. The first step was to modulate the kinematic and dynamic equations of the paraglider and payload system considering six DoF (the relative motion of the parafoil and the payload were neglected) and the flap deflection as the control input. Really this model is similar of the six DoF model in [6]. In order to reduce the model complexity, a simplified model was proposed, neglecting some features of the system (apparent force, payload drag, etc). Through the dynamic equation of the simplified model, an equilibrium point is founded for a linear path in the XY plane and a input-output feedback control is designed. In way to test the performance of the control input, two path following task (a pure line and a polygonal path) are simulated. On the second path, which represents more interests for us, the system converges to the reference path for each segment in about 50 s. The stabilization of the system along a polygonal path was achieved using lateral directional control input within acceptable real values.

A different point of view of a powered paraglider system is described on [8]. Beyond the payload has a propeller motor, the system dynamic equations are determined on the basis of the state variables. The system is analysed accounting the relative pitching and twisting motion of the payload which represent two DoF that more six DoF of the parafoil characteristic totals eight DoF of the system. Through the DoF of the system it was defined twelve state of variables: three canopy velocities, 3 canopy angular velocities, payload pitch and yaw angular velocities relative to the canopy, payload pitch and yaw angles relative to the canopy and canopy roll and pitch angles. Regarding the control variables, we have the propelling force, the symmetric and the asymmetric brake deflection of the canopy. A nonlinear state equation is achieved taking account the weight, aerodynamic, inertial and cable tensions forces. In order to simply the model, a state equation linearization is made and evaluated its effect through numerical simulation results applying an individual impulse of the control input. Gathering the output results of the simulations, it was acceptable conclude that the linearization effect is minimum. Watanabe and Ochi also implemented a state feedback control system using a Kalman filter for enhance the damping characteristics of
the canopy and the payload oscillation due to wind disturbance. For this it is necessary an observer which requires the system to be observable and controllable. The controllability and the observability were proved separating the linear model on the longitudinal and lateral-directional models. After that a closed-loop system with a state feedback system and wind disturbance was described.

Slegers and Costello analysed the effect of small brake deflections parafoil-payload on the directional control [9]. They presented the combined system of the parafoil canopy and payload modelled with nine DoF including three inertial position components of the joint as well as the three Euler orientation angles of the canopy and the payload. After the determination of the kinematic and dynamic equations for the payload and parafoil, the system of equations is solved using LU decomposition and the equations of motion are numerically integrated using a fourth-order Runge–Kutta algorithm to generate the trajectory of the system from its point of release. Although this procedure was omitted. Simulations under different conditions are performed so that the performance of the controllable parafoil and payload system can be evaluated. Simulating the effect of small brake deflections parafoil-payload, it was observed that the parafoil and payload systems exhibit two basic modes of directional control: skid and roll steering.

The relative pitching and yawing motion of a payload with respect to a parafoil are studied using an eight DoF model for the parafoil-payload system [10]. The eight DoF included the three inertial position components of the joint as well as the three Euler orientation angles of the parafoil system and two Euler orientation angles of the payload with respect to the canopy. The kinematic and dynamic equations for the parafoil and payload systems were determined. Using estimated aerodynamic and apparent mass coefficients, it is presented the response to a constant brake deflection observing the angular rates and the system yaw, roll and pitch angles. It was shown that relative payload motion had little effect on the predicted ground track. However, using a turn rate controller common in precision placement algorithms it was demonstrated that relative yawing motion of the payload can result in persistent oscillations of the system. These oscillations can be eliminated by reduction of feedback gains, but the resulting tracking performance was poor.

A different approach of the model development is presented in [11]. The article addresses a six DoF model of a low-aspect ratio controllable parafoil-based delivery system, where the model was derived using general equations of fluid dynamics. The simulation results are obtained recording through the MATLAB tool. In the first step it is simulated the effect of the angle of attack on the lift, drag and side-force coefficients and on the rolling moment, pitch moment, and yawing moment coefficients for some aspect ratios and some symmetrical flaps deflections. Next the model response of control inputs is presented, illustrating the longitudinal response. A parameter identification technique including employment of the multicriteria optimization and zero-order Hooke-Jeeves method was applied to tune the initial aerodynamic dependences and apparent mass terms as well. A comparisons of the flight test data with the tuned and non-tuned model are presented and discussed.
Two mathematical models of the payload-parachute system are presented and detailed in [12]. The payload is considered as a rigid body with six DoF and the parachute canopy acts as a rigid body and they are connected by a single riser. The system of differential equations that describes the parachute-payload system can be broken into sections, six rigid body equations of motion, four quaternion equations, three position equations, and the velocity and displacement of the parachute. In this way the most simplest model is based on euler angles orientation beside the other is based on quaternions. A simulation software is used to observe the differences between these two models on the trajectory profile. The major discrepancy between the two models was the level of dynamic stability of the modal response. Some differences can also been observed between the second model simulation results and the flight tests.

An identification problem consists to find the dimension of the system and the space state system matrices (A, B, C, D), up to similarity transforms. As mentioned in [13] to resolve this problem we can have two different type of data: a sequence of impulse responses of a discrete-time LTI system or an input-output data. In parafoil-payload system, generally we have only input-output data by sensors presented on the payload system. So, the identification problem for parafoil-payload system is through input-output data to identify the dimension of the system and the system matrices (A, B, C, D), up to similarity transforms. In order to solve this problem, Katayama presented two identification method. On both methods it is utilized the LQ decomposition and the SVD theory which also are explained in [13]. After method description, it is summarized an algorithm with steps to resolve the problem. Some examples where the algorithms are applied are illustrated.

The system identification results for a commercial powered parafoil vehicle are described by Valasek and Hur [14]. They analysed the controllability and observability of the system and applied an observer/kalman filter identification method for the system identification. Initially Markov parameters and observer Markov parameters are developed. These parameters are very useful to identify mathematical models, thus with them we can obtain the Hankel matrix and through this matrix it is possible to find the matrices (A, B, C, D). Identification results are showed and it is made a comparison between the identification model results and the nonlinear model simulations. The results demonstrated that the identification method can identify the dynamic system effectively and accurately.

A more complex and realistic identification technique is presented in [15]. Unlike the previous identification technique, which is base on one single criterion, Yakimenko et al. studied a multicriteria parametrical identification technique. In addition to by their nature, applied identification problems are multicriteria problems, there are many several groups of parameters, with different nature, which should be identified. Therefore several adequacy criteria are suggested to be used. The identification problem is studied and differences between these two identification technique
are showed. The multicriteria identification is developed from the multicriteria optimization and its results are discussed. The parafoil trajectories are showed with respect to the real drop and to different criteria. The criteria numbers are two describing the closeness of the horizontal and vertical projections of the trajectories, and three relating to the adequacy of the natural eigenvalues (power spectrum) for all channels (roll, pitch and yaw). Analysing the results it was concluded that not much difference was observed between the several criteria and the real drop.

In order to improve the parafoil-payload system control, a model predictive control strategy is described [16]. The optimal input which minimize the cost function is presented using a discrete system described in state-space form. Identification of aerodynamic coefficients is performed using a recursive weighted least-squares method. The model predictive control strategy is described for a simplified six DoF model. Three autonomous flight tests showed that model predictive control is an effective way to control autonomously the trajectory of a parafoil-payload system.
Chapter 3

Mathematical model

In this chapter the already work done on the formulation of the mathematical model for the parafoil-payload system will be presented. Initially the key components of the system which affect the behaviour of the system during the flight will be mentioned.

3.1 Parafoil-Payload System

After the balloon bursting, a circular parachute opens to reduce substantially the velocity of the system. When the system achieves more stable mass air, it’s more easy to maneuver a parafoil, so the parachute is released of the system by a cutdown system and the parafoil is inflated. The control implementation can be now activated on the parafoil canopy in order to forward a predefined path. An overview of the all components of the system is showed on the following picture.

Figure 3.1: STRAPLEX components
The components to consider on the controllable descent phase are:

- Parafoil;
- Drone (payload);
- Satellite;
- Transponder.

The parafoil is constituted by a green canopy which was adapted from a common recreational power kite and has three square meter. This canopy is made of a thin fabric composed of the small sections called cells. The Drone is connected to the canopy by four suspended lines. Two main cables, which support the majority Drone weight, are used in a differential mode to deflect the canopy. The two others cables are the breaks which can be used independently and mainly allow to create an yaw movement. Besides the Drone, there are also the satellite and the transponder which are connected to the Drone as it is possible to see in right side of the figure 3.1. Although these two last components affect the motion and the behaviour of the system, its effects will be initially neglected, simplifying the analyses. In this way, the parafoil-payload system which will be initially studied is showed on the figure 3.2.

![Figure 3.2: Parafoil-payload system](image)

This system will be modulated as a eight DoF model with three DoF used to describe the inertial position of the joint point, and three Euler angles for the parafoil and two DoF to describe the yaw and pitch relative motion of the payload with respect to the parafoil. In this case the roll relative motion of the payload with respect to the parafoil is neglected on the mathematical modelling. Indeed, the roll relative motion is caused by the control input breaks.
The mathematical modelling will be began with the determination of the kinematics equation for the parafoil and payload. The dynamics equations for the payload and parafoil lets to know the system dynamics. With both kinematics and dynamics equations, we can determine the motion equation of all system and obtain a nonlinear state equation of the form:

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

Where the \( x(t) \) is a state variables vector of the motion equations and \( u(t) \) is the input vector. In our case, the input is composed by two terms: a symmetrical term \( \delta_s \) and a asymmetrical term \( \delta_a \) of the flaps deflection. \( \delta_s \) varies the roll and yaw moments, which make the system turn, while \( \delta_a \) change the lift and drag aerodynamic force of the canopy.

For the kinematic equations, we need to determine the position, velocity and acceleration of the parafoil and the payload system considering that we have two reference frame: the inertial reference frame and the body fixed reference frame. These two reference frame are correlated by a rotation matrix which corresponds to a rotation with Euler angles.

For the dynamic equation we have to consider the all forces applied on the system. For the payload we have mainly three forces: the payload weight force, the aerodynamic force (drag force) and the tension cable force. On the other hand, for the parafoil, we have four forces: the parafoil weight force, the aerodynamic force (drag and lift force), the tension cable force and the apparent force which has potential influence on the equation motion. Indeed when an object moves through the medium, it causes the fluid to move on opposite direction. This effect is weight in the apparent force.
References


