THE FLIGHT TRAJECTORY ANALYSIS ON THE EXISTING AIRCRAFT

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ABSTRACT

This thesis presents the flight trajectory analysis for a given aircraft configuration starting with aircraft set at trim condition and after that following by descent for landing. It has been known that the aircraft behaviors during their flight governed by the flight equation of motions. This flight equation of motion consist of 12 first order differential equations which coupling to each other. Those 12 equations described 12 state space variables involving the aircraft position plus aircraft aptitude with respect to the inertial coordinate system and also with respect to their axis body system which is had been used. In the stage of development in developing flight control on board, it is necessary to develop a computer code for solving the governing equation of flight motion for a given aerodynamic characteristics, control surfaces movement and aircraft's mass with inertia properties to obtain their trajectory and also velocity at any instant time. The present work has presented the flight dynamics analysis for two aircraft models. The first aircraft model is Boeing 747 while the second one is the airplane designed to become UAV airplane after appropriate flight controller installed to that airplane. Through this work it can be conclude, in manner how to solve the governing equations are simpler compared to the effort for providing the aerodynamics data or the mass and inertia of the airplane. In the future the control law which represents the governing equation to set the control surface may be introduced in order to keep the airplane at constant speed or at constant altitude. This may the suggestion to modify the present computer code to become design tool for prescribing aircraft flight under a constant speed or constant altitude.

ABSTRAK

Kajian ini berkenaan analisis trajektori pesawat untuk sesuatu pesawat bermula dengan pesawat yang berada dalam keadaan trim dan seterusnya pada keadaan mengufuk sewaktu mendarat. Seperti yang sedia maklum, keadaan pesawat ketika penerbangan dipengaruhi oleh persamaan gerakan. Persamaan ini terdiri daripada 12 persamaan perbezaan tertib pertama yang bersama antara satu sama lain. Kesemua persamaan menerangkan 12 keadaan pembolehubah ruang yang melibatkan keadaan pesawat termasuk kebolehan pesawat keatas system koordinat inersia dan juga keatas sistam paksi badan pesawat yang telah digunakan. Dalam peringkat membangunkan kawalan penerbangan di atas kapal, adalah amat penting untuk menghasilkan satu kod computer untuk menyelesaikan persamaan gerakan pesawat untuk setiap ciri-ciri aerodinamik, kawalan pergerakan dipermukaan dan juga berat pesawat bersama ciri-ciri inersia untuk mendapatkan trajektori dan juga halaju pada sesuatu ketika. Penyelidikan ini membentangkan analisis dinamik penerbangan untuk dua model pesawat. Model yang pertama ialah Boeing 747 manakala model kedua adalah pesawat yang direka untuk dijadikan pesawat UAV selepas kawalan penerbangan yang bersesuaian dipasang kedalam pesawat itu. Melalui penyelidikan ini, kesimpulan yang boleh dibuat ialah dalam menyelesaikan persamaan penerbangan pesawat adalah lebih mudah jika dibandingkan dengan usaha untuk menyediakan data aerodinamik atau berat dan inersia pesawat tersebut. Untuk penyelidikan masa akan datang, undung-undang kawalan yang mana mewakili persamaan untuk menetapkan kawalan permukaan boleh diperkenalkan untuk mengekalkan pesawat pada halaju atau pada ketinggian yang konsisten. Ini mungkin cadangan untuk mengubahsuai kod computer sedia ada untuk dijadikan alat untuk menetapkan penerbangan pesawat dibawah halaju dan ketinggian yang konsisten.

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LIST OF SYMBOLS AND ABBREVIATIONS

AG	- Acceleration of gravity
ALPH	- Angle of attack, **α**
Amass	- Vehicle mass, m
A_T	- Thrust direction cosines relative to X
B_T	- Thrust direction cosines relative to Y
B_w	- Wing span, or reference length
C_D	- Drag coefficient
C_L	- Lift coefficient
CLB	- Coefficient of rolling moment due to beta
CLP	- Coefficient of rolling moment due to roll rate
CLR	- Coefficient of rolling moment due to yaw rate
C_M	- Pitch moment coefficient
CMA	- Coefficient of pitching moment due t o angle of attack
CMAD	- Coefficient of pitching moment due t o angle-of-attack rate
C_{mac}	- Wing mean aerodynamic chord
CMQ	- Coefficient of pitching moment due t o pitch rate
CMO	- Zero lift Pitching moment coefficient
CNP	- Coefficient of yawing moment due to sideslip
CNDR	- Coefficient of yawing moment due to rudder deflection
CNP	- Coefficient of yawing moment due to roll rate
CNR	- Coefficient of yawing moment due to yaw rate
CYP	- Coefficient of side force due to sideslip
C_n	- Yaw coefficient
C_T	- Thrust direction cosines relative to Z
Cy	- Side force coefficient
F	- Force

P	- Angular velocity about X
p	- Roll rate
Q	- Angular velocity about Y
$\dot{Q}$	- Pitching acceleration
q	- Pitch rate
$\bar{q}$	- Dynamic pressure
R	- Angular velocity about Z
r	- Yaw rate
S_W	- Wing or reference area
T_{HR}	- Thrust
$\dot{U}$	- Longitudinal acceleration
U	- Velocity along X-body axis
V	- Velocity along Y-body axis
W	- Velocity along Z-body axis
$\dot{W}$	- Vertical acceleration
W_P	- Elevator servo natural frequency
W_R	- Aileron servo natural frequency
W_Y	- Rudder servo natural frequency
X_E	- Distance relative to inertial X axes
Y_E	- Distance relative to inertial Y axes
Z_E	- Distance relative to inertial Z axes
Θ_0	- Steady-state pitch attitude
Φ	- Roll angle
Θ	- Pitch angle
Ψ	- Yaw angle
α	- Angle of attack
β	- Sideslip angle
$\dot{\beta}$	- Derivative of sideslip angle
CFD	- Computational Fluid Dynamic
NASA	- National Aeronautics and Space Administration
UAV	- Unmanned Aerial Vehicle
UTHM	- University Tun Hussein Onn Malaysia

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CHAPTRE 1

INTRODUCTION

1.1 Introduction

This thesis presents the flight trajectory analysis for a given aircraft configuration starting with aircraft set at trim condition and then following by descent for landing. It has been known that the aircraft behaviors during their flight governed by the flight equation of motions. This flight equation of motion consist of 12 first order differential equations which coupling to each other. Those 12 equations described 12 state – space variables involving the aircraft position and aircraft aptitude with respect to the inertial coordinate system and also with respect to their axis body system had been used. Through solving those 12 equations one can obtain the trajectory of the airplane and also possible to define their trim condition for a given flight speed and flight altitude. For this purposes, the analysis carry out over two aircraft models, they are namely Boeing 747 and UAV model. The data required for analysis aircraft behavior starting from descent to land which are involved the aerodynamics data, mass and inertia of the aircraft and also thrust provided by their propulsion system are available. It is therefore time history of their position, aptitude, linear velocity and as well as their angular velocity can be identified. However it had been realized the comparison with actual flight can be done, since such data are not available.

1.2 Back ground

The flight equation of motion represents the governing equation of flying vehicle which can be used to describe what kind movement of the flying vehicle will be. If one able to control the aerodynamic forces and moments acting on the flying vehicle at any instant time including the capability for controlling the required thrust, it will make such flying vehicle becomes an autonomous flying vehicles. Since through the governing equation of flight motion which normally solved to obtain the aircraft position, aptitude and velocity can be inverted to become the problem of prescribing flight trajectory and control mechanism as its solution. Through these experiences of solving the governing equation of flight motion, it can be expected to give a plat form in developing a particular aircraft to become an Unmanned Aerial Vehicles in the future work. However it had been understood, that design flight control mechanism to allow the airplane able to control its movement arbitrary at various flight condition are so complex and difficult task, it is therefore for only particular flight maneuver the aircraft designed to be autonomous as result various type of UAV had been developed to fulfill different purposes.

In parallel of the advancement of computer technology, material, propulsion system and better understanding on the aircraft stability had made the development of autonomous flying vehicle becomes an attracted matter. The applications of UAV are widely had been recognized whether for civilian or military purposed. The military purposes may the UAV can serve for [1]:

1. Surveillance for peacetime and combat synthetic aperture radar (SAR).
2. Reconnaissance surveillance and Target acquisition (RSTA).
3. Maritime operations (Naval fire support, over the horizon targeting, anti-ship missile deference, ship classification).
4. Meteorology missions.
5. Electronic warfare (EW) and SIGNT (Signals Intelligence).
6. Deception operations.

While for civilian applications, the UAV can be used for:

7. Communications relay. High altitude long endurance UAVs can be used as satellites.
8. Law enforcement. VTOL UAVs can take the role of police helicopters in a more cost effective way.
9. Disaster and emergency management. Arial platforms with camera can provide real time surveillance in hazardous situations such as earthquakes.
10. Research. Scientific research of any nature (environmental, atmospheric, archaeological, pollution etc) can be carried out UAVs equipped with the appropriate payloads.
11. Industrial applications. Such application can be crops spraying, nuclear factory surveillance, surveillance of pipelines etc.

Considering that there are a lot of application can be served through the use of UAV, it is therefore, the ability to develop the UAV based on own design is necessary in order to limit the foreign dependence in this type of technology.

1.3 Problem statements

UAV which stand for Unmanned Aerial Vehicle represents the airplane which designed without pilot onboard. With no pilot on board make the size of the airplane can be reduced to become the size of airplane just for accommodating payload and the required fuel only. As a result the size and weight of aircraft becomes smaller and lighter than ordinary aircraft.

As unmanned flying vehicle, it is means that the aircraft has capability to control their flight path over any kind of disturbance may appear during their flight. Such capability only can be obtained through the use of flight control system placed inside the aircraft. Flight control system represents computer software which required the aerodynamics data for that aircraft in order to allow developing flight mechanism for controlling the aircraft. Flight control system can be considered as inverse problem of solving the governing equation of flight motion. In the stage of development in developing flight control on board it is necessary to develop a computer code for solving the governing equation of flight motion for a given aerodynamic characteristics, control surfaces movement and aircraft's mass and inertia properties to obtain their trajectory and velocity at any instant time.

1.4 Thesis objective

The flight dynamics equations a consist of a complete system equation which can describe the behavior of the aircraft at different flight condition, so the aim of this thesis is to solving the governing equations of flight motion, to get state space variables for a given aircraft configuration. The purpose of this thesis is through developing computer code allowing one to estimate the flight behavior of the existing aircraft. The flight behavior here means for a given an initial state of the aircraft, one can obtain the time history of state – space variables of the aircraft. Here there are 12 state – space variables , they are namely six state variables related to the aircraft position and aircraft aptitude with respect to the inertia frame of reference and another six state – space variable related to the linear and angular velocity with respect to the body axis coordinate system.

1.5 Scope of study

Refer to the objectives of this thesis, the scope of study will be conducted in the present work involves:

- Understanding coordinate system applied to the airplane namely the earth coordinate system, aircraft body axis coordinate system and the aircraft stability coordinate system.
- Understanding in deriving the governing equation of flight motion, included the required aerodynamic model for supporting the governing equation of flight motion becomes solvable equation
- Manner in solving the governing equation of flight motion and so the aircraft behavior for a given initial state can be obtained.

CHAPTER 2

LITERATUR REVIEW

2.1 Mission profile and overview

For any aircraft designed without pilot on board called as unmanned aerial vehicle (UAV). Without pilot on board made the size of vehicle can be reduced significantly but at the same time the ability to maintain their safety flight are highly demanded. In line with the progress of aircraft technology development in respect to the design procedures, material, manufacturing and the rapid progress in electronics, communication system and computing power had made a further effort for UAV's development becomes apparent. The UAV has gained interest for military or civilian users. Military users may look the UAV with a particular design can perform a variety of missions supporting military and intelligence purposes. The list below presents the military applications that UAVs have served up to now [1].

1. Surveillance for peacetime and combat synthetic aperture radar (SAR).
2. Maritime operations (Naval fire support, over the horizon targeting, anti-ship missile deference, ship classification).

3. Adjustment of indirect fire and close air support (CAS).
4. Meteorology missions.
5. Ratio and data relay.
6. Battle damage assessment (BDA).
7. Reconnaissance surveillance and target acquisition (RSTA).
8. Deception operations.
9. Electronic warfare (EW) and SIGNT (Signals Intelligence).
10. Route and landing reconnaissance support.

While from the point of view, civilian users, the Unmanned Aerial Vehicles may be used for the one of following mission [1]:

1. Communications relay. High altitude long endurance UAVs can be used as satellites.
2. Disaster and emergency management. Arial platforms with camera can provide real time surveillance in hazardous situations such as earthquakes.
3. Industrial applications. Such application can be crops spraying, nuclear factory surveillance, surveillance of pipelines etc.
4. Search and rescue. Looking for survivors from shipwrecks, aircraft accidents etc.
5. Research. Scientific research of any nature (environmental, atmospheric, archaeological, pollution etc) can be carried out UAVs equipped with the appropriate payloads.
6. Wild fire suppression. UAVs equipped with infrared sensors can detect fire in forests and notify the fire brigade on time.
7. Border interdiction. Patrol of the borders by aerial platforms.

8. Law enforcement. VTOL UAVs can take the role of police helicopters in a more cost effective way.

In more specific purposes, where the mission condition in civil application is unsafe mission, the UAV can be used to carry out to conduct such mission the mission for:

1. Surveillance over nuclear reactors.
2. Surveillance over Hazardous chemicals.
3. Fire patrol.
4. Volcano patrol.
5. Hurricane observations.
6. Rescue missions over adverse weather conditions.

Above explanation clearly indicated that there are a numerous missions can be performed by the use of UAV. Each mission may require a specific aircraft configuration, payload and size. For a long endurance UAV may require a sufficient size of UAV to accommodate the required fuel.

The UAV which designed for law enforcement by authority body may require the UAV in the form of Helicopter rather than fixed wing aircraft in order to provide the ability to take off and landing vertically in crowded area and hovering over particular region may need to be investigated carefully. A good review on UAV mission for military application may be found in [2].

2.2 Some Examples of UAV Model Already Developed

Unmanned Aerial Vehicles, or UAVs, as they have sometimes been referred to, have only been in service for the last 60 years [3]. UAVs are now an important addition to many countries air defences. Modern UAVs have come a long way since the unmanned drones used by the USAF in the 1940s [4]. These drones were built for spying and reconnaissance, but were not very efficient due to major flaws in their operating systems. Over the years UAVs have been developed into the highly sophisticated machines in use today. Modern UAVs are used for many important applications including coast watch, news broadcasting, and the most common application, defence.

With a growing number of UAVs being developed and flown in recent years there is the problem of classifying these new UAVs. As UAVs are used in a variety of applications it is difficult to develop one classification system that encompasses all UAVs. It has been decided that the UAVs will be classified into the two main aspects of a UAV, their performance specifications and their mission aspects [5].

The specifications of a UAV include weight, payload, endurance and range, speed, wing loading, cost, engine type and power. The most common mission aspects are ISTAR, Combat, Multi-purpose, Vertical Take-off and landing, Radar and communication relay, and Aerial Delivery and Resupply. It is important to have a classification system for UAVs as when a specific UAV is needed for a mission it can be easily chosen from the wide variety of UAVs available for use.

2.2.1 **Predator** [6, 7, 8]

2.2.1.1 Predator Description

Predator is a Medium-Altitude Endurance (MAE) UAV designed to provide battlefield surveillance with a beyond line of sight communications capability. This aircraft is an evolution from the General Atomics Gnat UAV. The Predator program began in 1994 as an Advanced Concept Technology Demonstrator (ACTD). The program transitioned to operational use very early in development [6].

2.2.1.2 Geometry Characteristics

The Predator key geometry characteristics are shown graphically in Figure 2.1, and numerically in Table 2.1.

Figure 2.1: Predator UAV [9]

Table 2.1: Predator Geometry [6]

Description	Value	Source
Wing span	48.7 ft	Jane's [1999]
Aspect ratio	19.25	Jane's [1999]
Sweep (quarter chord)	0^o	Jane's [1999]
Fuselage Length	26.7 ft	Jane's [1999]
Length	27 ft	Jane's [1999]

Table 2.1 (continued)

Description	Value	Source
Height	6.9 ft	Jane’s [1999]
Weight	1,130 lbs (empty)	Jane’s [1999]
Runway (ISA)	Improved,3000 ft * 100 ft	Jane’s [1999]
Max Gross Take-off Weight	2250 lbs	Jane’s [1999]
Fuel	Type: 110 LL avgas ; capacity: 110 lits	Jane’s [1999]

2.2.1.3 Propulsion

Predator uses the Rotax 914 reciprocating engine to drive a pusher propeller. Major engine characteristics are presented in Table 2.2.

Table 2.2: Predator Propulsion Characteristics [6]

Item	Value	Source
Maximum Power (S/L)	105 HP	Jane’s [1999]
BSFC	0.5 lbm/HP-hr	Assumed
Weight	150.4 lbs	Jane’s [1999]

2.2.1.4 Avionics

Predator has a relatively simple avionics suite compared to Global Hawk. Predator is largely a single-sting system with little redundancy. A summary of the Predator avionics weights is presented in Figure 2.2.

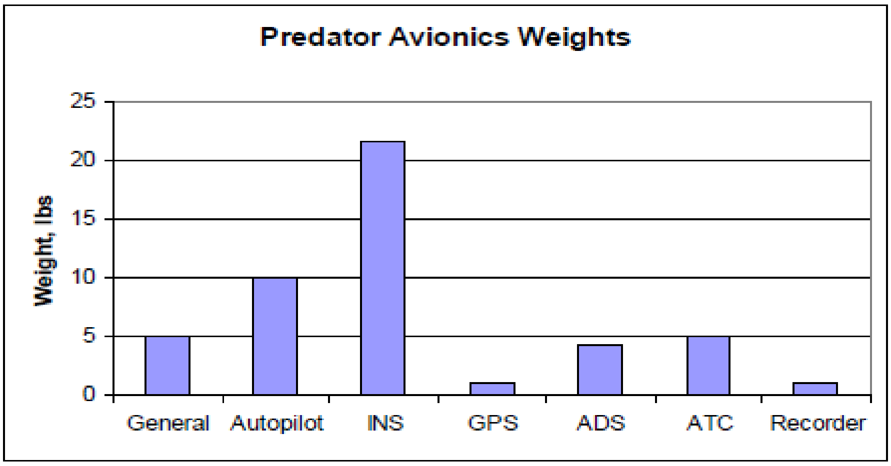

Figure 2.2: Predator Avionics Weights Summary [6]

2.2.1.5 Subsystems

A summary of the Predator subsystems weights is presented in Figure 2.3.

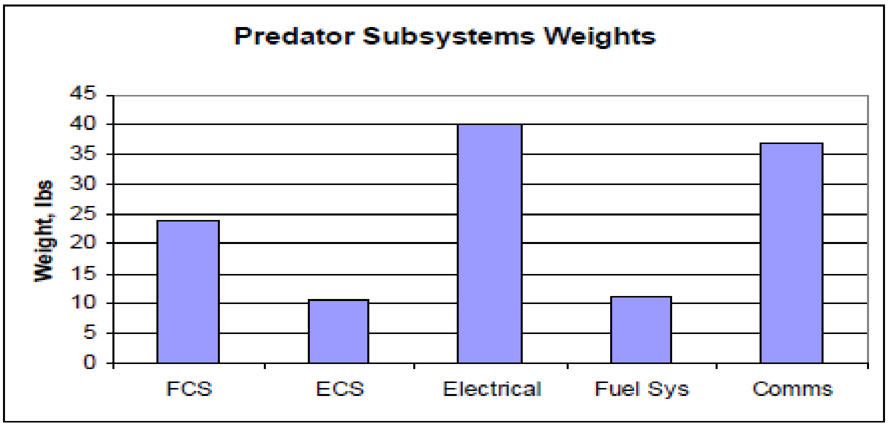

Figure 2.3: Predator Subsystems Weights Summary [6]

2.2.1.6 Structures

The structure is largely made of carbon/epoxy composites [Jane's 1999]. The smaller Gnat UAV in the Predator family is stressed for 6 G manoeuvres at an unspecified weight. Absent of further information, the 6 G loading was applied to the Predator. A summary of the Predator structural weights is presented in Figure 2.4.

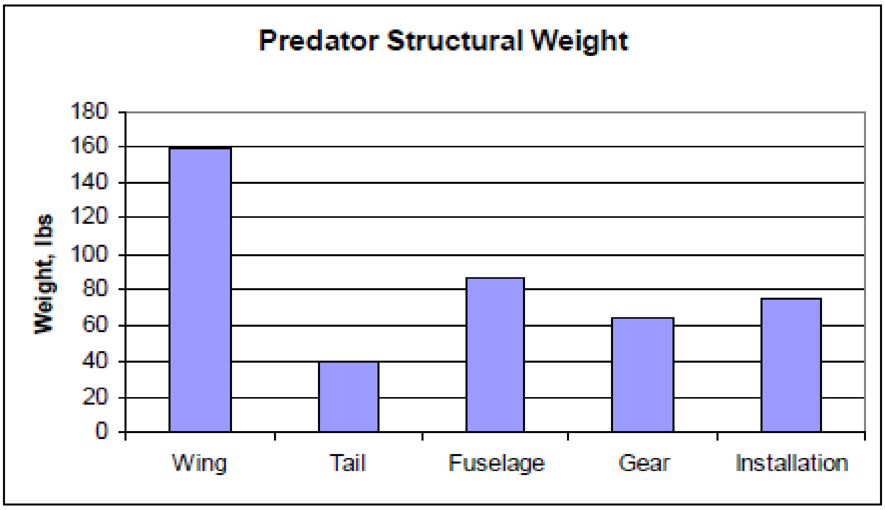

Figure 2.4: Predator Structural Weight Summary [6]

2.2.1.7 Performance

The mission profile for Predator is 24 hours time on station at a 500 nautical mile radius, according to Jane's [1999]. The 2003 General Atomics Predator brochure indicates that the performance is 24 hours time on station at a 400 nautical mile radius. The Jane's [1999] mission profile was used here. The EO/IR-SAR payload combined weight of 181 pounds was used, not the maximum payload capacity. An additional one-hour loiter at sea level is added to account for recovery operations. A ceiling of 25,000 feet was imposed on the mission performance calculation. A climb from sea level to 20,000 feet was included in the ingress segment. The descent from the final loiter point to sea level was included in the egress segment. The Predator altitude and velocity performance is shown in Figure 2.5 and Figure 2.6.

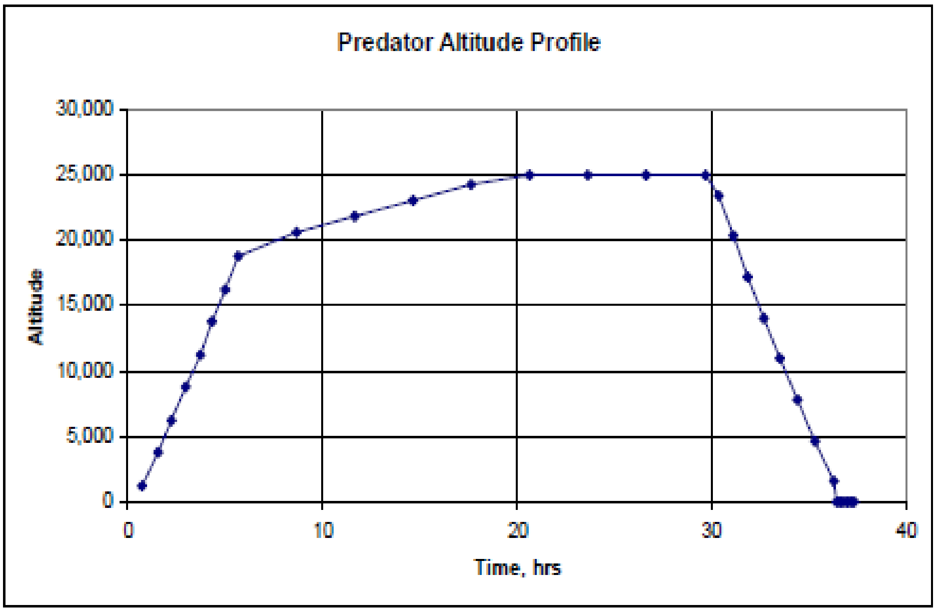

Figure 2.5: Predator Altitude Profile [6]

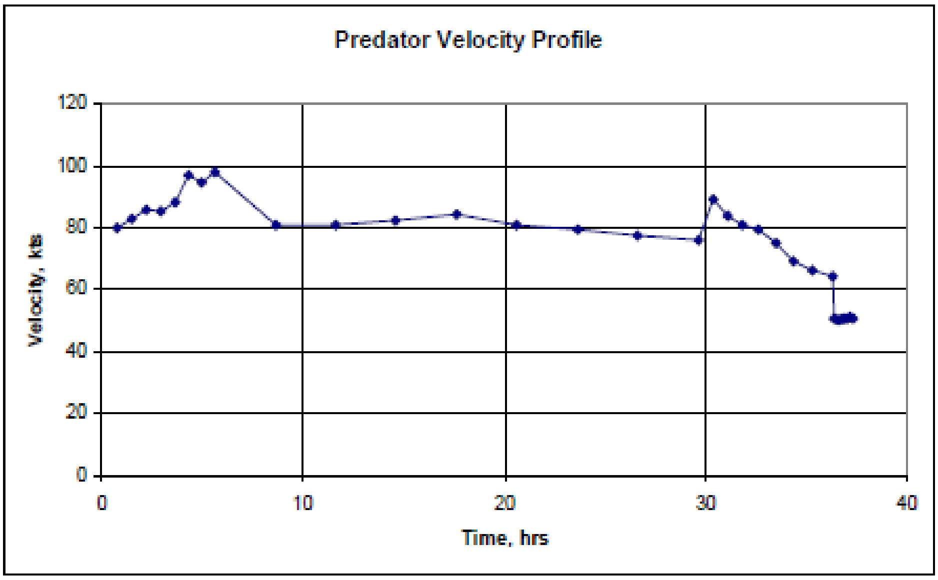

Figure 2.6: Predator Velocity Profile [6]

2.2.1.8 Predator's Design Technology

The weights and performance calibration process resulted design technology levels shown in Table 2.3.

Table 2.3: Predator Design Technology Level [6]

Design Item	Tech Level (0-1)
Volume Efficiency	0.5
Induced Drag	0.4
Interference Drag	1.0
Wave Drag	1.0 (No compressibility impacts)
Laminar Flow	0.4
Factor Of Safety	1.0
Weight Growth	0.75
Installation Weight	1.0

2.2.2 **Global Hawk** [6, 10, 11, 12]

2.2.2.1 Global Hawk Description

The Global Hawk is the first and only operational strategic high altitude UAV. This system began development in 1994 [6]. Global Hawk started as an Advanced Concept Technology Demonstrator (ACTD) with many goals, but the only firm requirements was a fixed Unit Fly-away Price (UFP). Many modifications have occurred to improve the system, and it has experienced operational use in wartime. Therefore, the available performance numbers represent the estimated performance of the vehicle as built, not necessarily as designed. As with nearly any aircraft program, the performance changes over time due to weight growth, system modifications, and other considerations. An attempt is made to calibrate the code against a representative Global Hawk [6].

2.2.2.2 Geometry Characteristics

A rendering of Global Hawk is shown in Figure 2.7 and some important geometrical, weight and other Global Hawk characteristics are shown in Tables 2.4.

Figure 2.7: Global Hawk UAV [13]

Table 2.4: Global Hawk Geometry [6, 14]

Item	Value	Source
Wing span	35.42 m	Jane's [1999]
Length	13.52 m	Jane's [1999]
Height	4.60 m	Jane's [1999]
Wing area	50.2 m^2	Jane's [1999]
Weight MTOW	12111 kg	Jane's [1999]
Aspect ratio	25.09	Jane's [1999]
Equipped empty weight	4177 kg	Jane's [1999]
Take-off weight	11622 kg	Jane's [1999]
Fuel weight	6583 kg	Jane's [1999]
Mission equipment weight	900 - 1000 kg	Jane's [1999]

Detailed geometry characteristics were found through scaling of 3-view drawings. The results were integrated into the detailed geometry input files [6].

2.2.2.3 Propulsion

The Global Hawk engine is the Rolls-Royce 3007H. Major engine characteristics are shown in Table 2.5.

Table 2.5: Global Hawk Propulsion [6]

Item	Value	Source
Thrust (T-O S/L)	8,290 lbs	Jane’s [1999]
TSFC	0.33 lbm/lb-h	Jane’s [1999]
Weight (Dry)	1,581 lbs	Jane’s [1999]
Length	8.88 ft	Jane’s [1999]
Diameter	3.63 ft	Jane’s [1999]

In addition to the engine, an additional 50 pounds of propulsion weight was added to account for the engine control electronics and actuators, as an assumption [6].

2.2.2.4 Avionics

Global Hawk is known to have an extensive electronics suite. Weights for all of the components are not available. Details of some avionics components, such as INS and data recorders, are found in Global Hawk literature and vendor data sheets. The assumed avionics weights use a fragmentary Master Equipment List (MEL), developed from information generated from Altmann [2002] and Janes [1999], as guidance. Figure 2.8 shows the avionics weights determined for the calibration case.

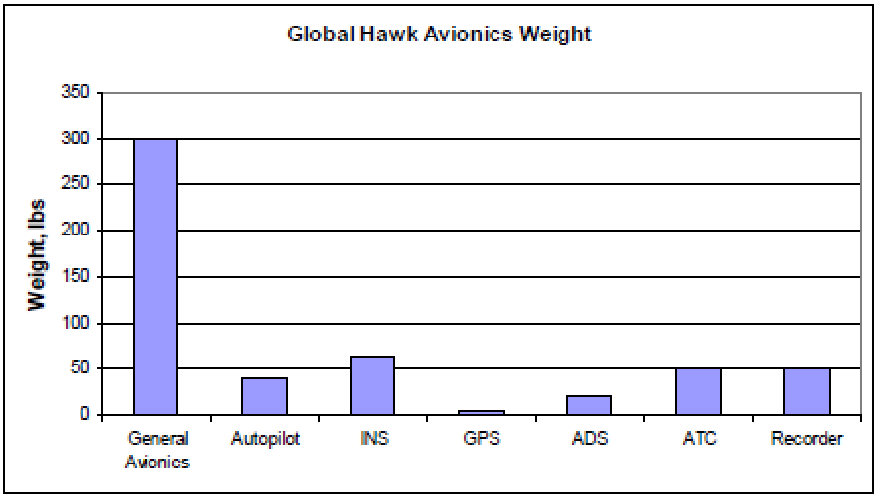

Figure 2.8: Global Hawk Avionics Weights Summary [6]

2.2.2.5 Subsystems

Global Hawk has a complex set of subsystems. A list of known subsystems identified by Altmann and Janes is captured in the simple MEL. Unfortunately, no weights data is available for the subsystems. Therefore, no actual weights were used, only assumed subsystem weights and parametric methods. The resulting subsystems weights are shown in Figure 2.9.

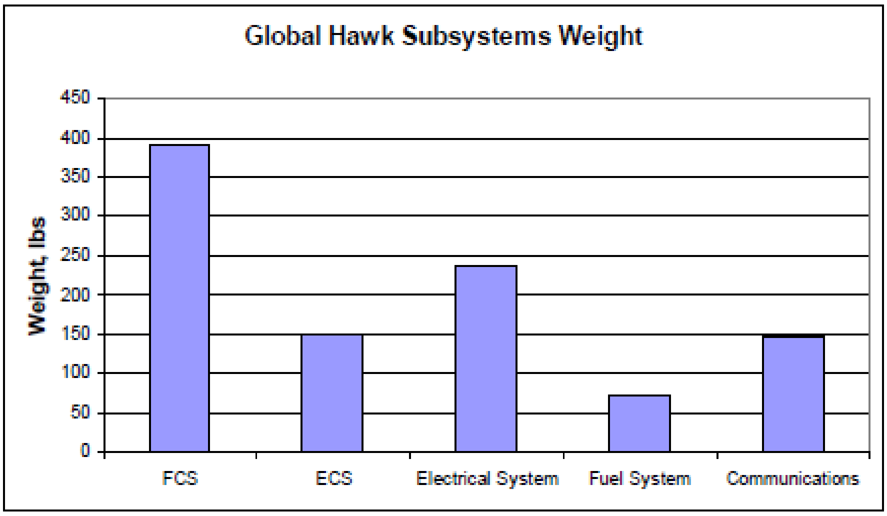

Figure 2.9: Global Hawk Subsystems Weights Summary [6]

2.2.2.6 Structures

The Global Hawk structure consists of the main wing, tails, fuselage, nacelle, landing gear and installation weight. No direct weights data is available for the structure. However, Altmann [2002] provides useful information to describe the structural design drivers and philosophy. The factor of safety for the structure is 1.25. Altmann provides a V-N diagram that indicates that the light weight vertical load is approximately 3.6 G, and the heavy weight vertical load is approximately 2 G. Because the wing weight is calculated at gross weight, the vertical load is assumed to be 2 G. The Global Hawk structural weight is presented in Figure 2.10.

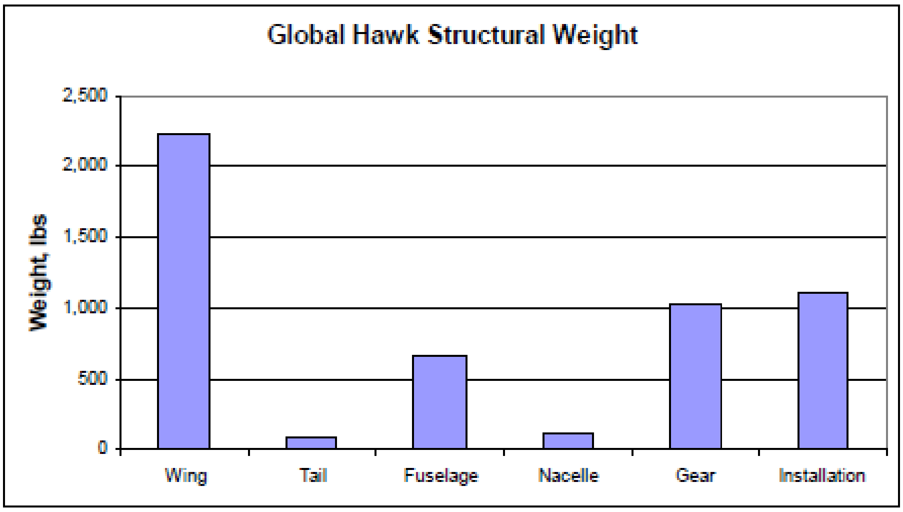

Figure 2.10: Global Hawk Structural Weight Summary [6]

2.2.2.7 Payloads

Global Hawk payloads consist of a Synthetic Aperture Radar (SAR), an Electro-Optical/ Infrared (EO/IR) payload, and the supporting electronics. The supporting electronics include an integrated sensor processor, a receiver/exciter/controller unit, transmitter (for SAR, presumably), and a sensor electronics unit. It is unclear if the elements of the communications architecture, INS, or structure are included in the advertised payload weight of 1,900 pounds [Jane's 1999]. The summation of the listed components comes to 797 pounds [Jane's 1999]. There is no available source that clarified this discrepancy. To satisfy the sizing mission profile, 1,900 pounds was assumed for the total payload weight, with an even weight division between SAR and EO/IR.

2.2.2.8 Performance

Altmann [2002] provides useful information on the Global Hawk performance and flight envelope limitations. The maximum equivalent airspeed is 175 Keas, and the maximum Mach is approximately Mach 0.7 and the characteristics are shown in Table 2.6.

Northrop Grumman advertises the Global Hawk Performance as 24 hours time on station at 1,200 nautical miles radius [Northrop 2003]. This performance estimate was adopted for sizing. Range credit was assumed to be 100 nautical miles for the initial climb to 50,000 feet, and 200 nautical miles from the end of cruise to the final loiter altitude. A half-hour loiter at 5,000 feet was assumed for airfield operations. Altitude and Mach characteristics are shown in Figure 2.11 and Figure 2.12.

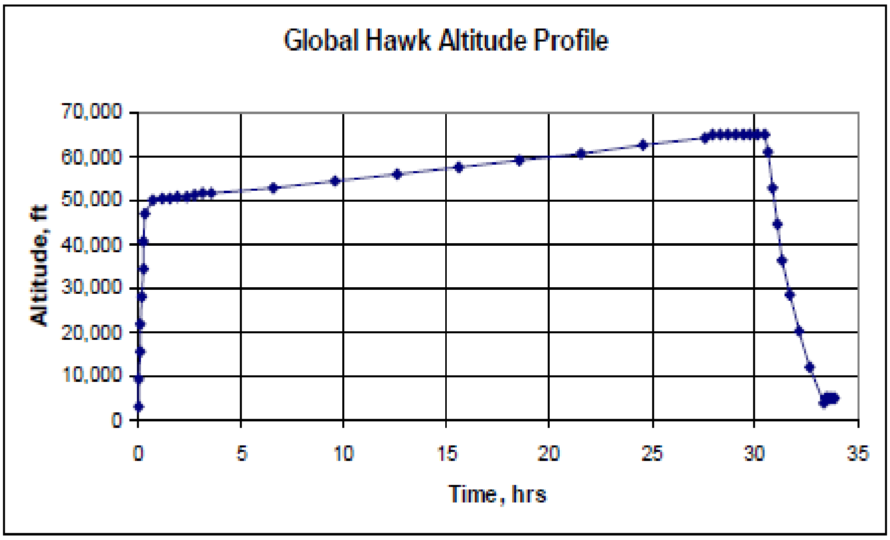

Figure 2.11: Global Hawk Altitude Profile [6]

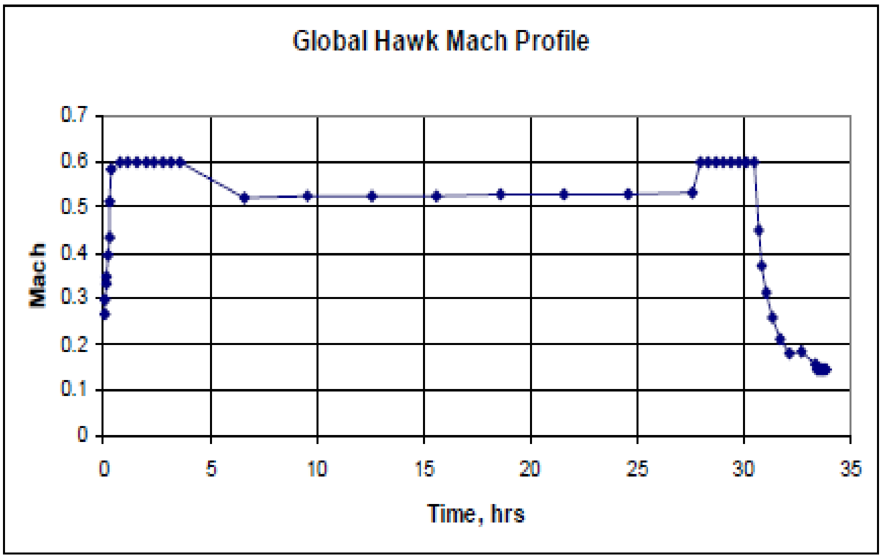

Figure 2.12: Global Hawk Mach Profile [6]

Table 2.6: Global Hawk– selected performances [6, 14]

Item	Value	Source
Stall speed	170 km/h	Jane's [1999]
Loiter speed	650 km/h	Jane's [1999]
Max speed	670 km/h	Jane's [1999]
Ceiling	19.80 km	Jane's [1999]
Rate of climb	17.3 m/s	Jane's [1999]
endurance	38 - 42 h	Jane's [1999]
range	17 000 km	Jane's [1999]
Runway length	1500 m	Jane's [1999]
Take-off thrust	3.13 kN	Jane's [1999]
Wing loading	231.52 kg/m^2	Jane's [1999]
Thrust loading	37.1 kg/N	Jane's [1999]
Max Altitude	65 000 ft	Jane's [1999]

2.2.2.9 Design Technology

The weights and performance calibration process resulted design technology levels are shown in Table 2.7.

Table 2.7: Global Hawk Design Technology Levels [6]

Design Item	Tech Level (0-1)
Volume Efficiency	0.5
Induced Drag	0.31
Interference Drag	1.0
Wave Drag	0.31
Laminar Flow	0.31
Factor Of Safety	1.0
Weight Growth	0.35
Installation Weight	0.5

2.2.3 Shadow 200 [6, 15, 16, 17]

2.2.3.1 Shadow 200 Description

Shadow 200 is a small tactical UAV designed to support line-of-sight battlefield surveillance missions. Initial development began in 1990. However, the technology year was assumed to be 2000 due to the extended development time, significant design evolution, requirements changes, and incorporation of more advanced technologies. Palumbo [2000] is assumed to be the most authoritative source of Shadow 200 data.

Palumbo describes an evolutionary design history beginning in 1990 that has not ended. For example, the wing configuration is driven by a constraint to re-use Pioneer program wing tooling [6].

2.2.3.2 Geometry Characteristics

The Shadow 200 geometry characteristics are shown graphically in Figure 2.13, and numerically in Table 2.8.

Figure 2.13: Shadow 200 UAV [18]

Table 2.8: Shadow 200 Geometry Characteristics [6, 15]

Item	Value	Source
Wing span	12.75 ft	Office of the Secretary of Defence, Unmanned Aircraft Systems Roadmap 2005-2030.
Weight	165 lbs. empty; 328 lbs. loaded	
Length	11.2 ft	
Height	3.0 ft	
Aspect ratio	7.07	
Fuel Capacity	51 lb	
Sweep (quarter chord)	0 º	
Payload Capacity	60 lb	
Ceiling	14,000 ft	

2.2.3.3 Propulsion

The Shadow 200 uses a UEL AR 741 rotary engine. The engine drives a two-blade propeller. The engine weight listed includes the alternator. Major characteristics of the Shadow 200 engine are shown in Table 2.9.

Table 2.9: Shadow 200 Propulsion Characteristics [6]

Item	Value	Source
Maximum Power (S/L)	38 HP	Jane's [1999]
BSFC (Max power, S/L)	0.57 lbm/HP-hr	Jane's [1999]
Propeller Diameter	2.33 ft	Jane's [1999]
Weight	28 lbs	Palumbo [2000]

The thrust and efficiency loss factor was found to be 0.59 through the calibration process. The aerodynamics technologies are already very conservative, so the only remaining performance factor for modification is the propulsion losses [6].

2.2.3.4 Avionics

The Shadow 200 uses a relatively simple avionics suite. There is no indication that any of the avionics components are redundant.

Palumbo does not provide a detailed breakout of avionics weights. The total weight allocated to avionics is 57 pounds, which includes avionics, communications equipment, and elements of the electrical system [Palumbo 2000]. The avionics, at minimum, includes the autopilot and a Mode IV IFF transponder. No further information about the avionics suite is provided by Palumbo. For the purposes of this analysis, 30 pounds was allocated to avionics and 27 pounds was allocated to communications equipment. The electrical system weight was set to 0 pounds, and the alternator weight was included in the propulsion weight. The avionics suite apparently has evolved since 2000 to include more modern equipment. The Shadow 200 is known to use the Tactical Automatic Landing System (TALS), which has an airborne component weighing 3 pounds. The Shadow 200 currently uses the Athena GS-211 Guide Star TM autopilot, which weighs 2 pounds. This autopilot includes INS and air data measurement equipment. The allocated weight of 30 pounds is applied, due to the year 2000 design year assumption [6].

2.2.3.5 Subsystems

An overview of the Shadow 200 subsystems weight results is in Figure 2.14.

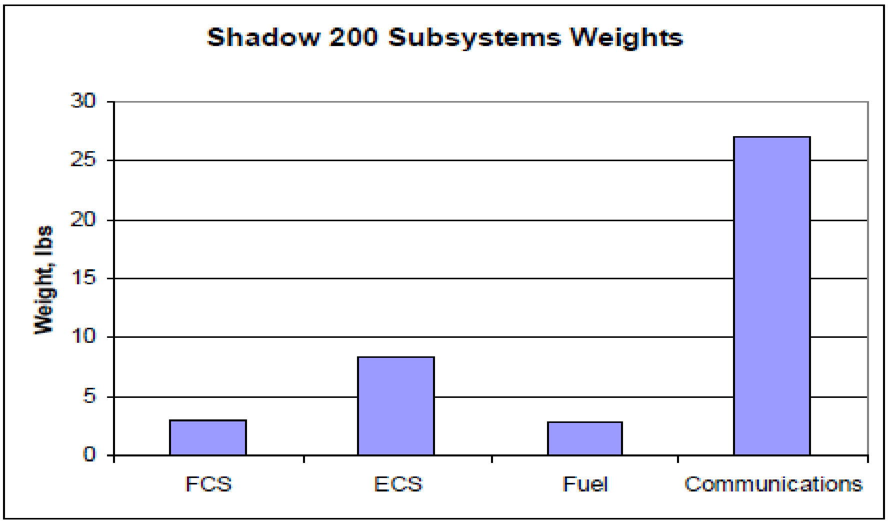

Figure 2.14: Shadow 200 Subsystems Weights Summary [6]

2.2.3.6 Structures

The Shadow 200 structure is 90% composites, which is primarily composed of graphite and Kevlar epoxy [Jane's 1999]. Jane's [1999] lists the limit load at 3.6 G, and Palumbo [2000] lists the limit load at 3.8 G. The limit load of 3.8 G was applied here. This limit was applied directly at the design gross weight condition, since the

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