Rafael Coronel Bueno Sampaio

**Novas Morfologias para Robôs Aéreos: Projeto para
Aplicações de Campo**

Tese de Doutorado apresentada ao Programa de Pós-Graduação em Engenharia Mecânica da Escola de Engenharia de São Carlos da Universidade de São Paulo, como parte dos requisitos para obtenção do título de Doutor em Ciências

Área de Concentração: Dinâmica das Máquinas & Sistemas
Orientador: Prof. Assoc. Marcelo Becker

São Carlos
2015

**ESTE EXEMPLAR TRATA-SE DA VERSÃO CORRIGIDA. A VERSÃO
ORIGINAL ENCONTRA-SE DISPONÍVEL JUNTO AO DEPARTAMENTO DE
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Cn Coronel Bueno Sampaio, Rafael
Novas Morfologias para Robôs Aéreos: Projeto para
Aplicações de Campo / Rafael Coronel Bueno Sampaio;
orientador Marcelo Becker. São Carlos, 2015.

Tese (Doutorado) - Programa de Pós-Graduação em
Engenharia Mecânica e Área de Concentração em Dinâmica
de Máquinas e Sistemas -- Escola de Engenharia de São
Carlos da Universidade de São Paulo, 2015.

1. Robô Aéreo. 2. Drone. 3. Quadrotor. 4. MAV. 5.
Novas Morfologias. 6. Controle e Estabilidade. 7.
Controle Robusto. 8. Hibridização Robótica. I. Título.

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**Novel Morphologies on Flying Robots: Design for Field
Application**

Thesis presented to the University of São Paulo at São Carlos
School of Engineering, as part of the requirements to obtain
the Doctoral degree in Mechanical Engineering

Main Area: Dynamics of Machines & Systems
Advisor: Prof. Assoc. Marcelo Becker

São Carlos
2015

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FOLHA DE JULGAMENTO

Candidato: Bacharel **RAFAEL CORONEL BUENO SAMPAIO**.

Título da tese: "Novas morfologias para robôs aéreos: projeto para aplicações de campo

Data da defesa: 27/03/2015

Comissão Julgadora:

Resultado:

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Dedicatória / Dedication

To my beloved wife Tati and our daughters Lica & Naná.

Agradecimentos / Acknowledgment

I am truly grateful to my advisor, Prof. Dr. Marcelo Becker, for his trust and confidence and for his dedicated supervision. I'm specially thankful to his care to my personal welfare and development, for his friendship and support, which have considerably eased my work.

I am also greatly indebted to Prof. Dr. Adriano A. G. Siqueira (USP/EESC/SEM), Prof. Dr. Davide Scaramuzza (University of Zurich), Prof. Dr. Fernando M. Catalano (USP/EESC), Prof. Dr. Marco A. Terra (USP/EESC), Prof. Dr. Paulo C. Greco (USP/EESC), Prof. Dr. Marcel Bergerman (Carnegie Mellon University), Dr. Samuel S. Bueno (Centro de Tecnologia da Informação Renato Archer/CTI) and Prof. Dr. Luiz Marcos G. Gonçalves (UFRN) for substantial contributions to the improvement of this thesis.

I am thankful to my dear friend André Carmona Hernandez, for his true friendship and specially for believing this work as well as for always being supportive during my research. I'd also like to thank friends Eduardo Cazarini and Rômulo Rodrigues for the valuable contribution and participation in key points of this work.

My deep appreciation goes to undergraduate students Marcelo Montanher, Leonardo W. Freschi, Fabio "Bala" Zanin, Joao "Suple" Entringer, Caio "BP" Martins and Andre Rittner, whose contributions were determinant to the development of this work.

A special thank goes to Elson Rosalis and Leandro Berti for the important technical support. I big thanks goes to BAJA/Formula automotive teams for the valuable workshop support. I'm also indebted to Maurício Nakai, Raphael Montanari and Willian Leão (USP/EESC/SEL/LASI) for the technical support with the ©VICON system set up.

Thank you to my wife Tati and my daughters Lica and Naná for understanding and (unconditionally) supporting my professional career.

Thank you to my parents, Luiz and Cirila, without whom I would never have reached educational opportunities.

I would also like to express all my gratitude to my dear friends Henry Guerrero Borrero and Kelen Vivaldini for their friendship.

Finally, I thank CAPES and FAPESP for the financial support to carry on this project.

“Inventions are, above all, the result of an obstinate work.”

Alberto Santos-Dumont, Brazilian aviation pioneer

Abstract

SAMPAIO, R. C. B. **Novel Morphologies on Flying Robots: Design for Field Application.** 2015. Thesis (PhD.) - Engineering School of São Carlos, University of São Paulo, São Carlos, 2015.

Energetic limitations in low scale Unmanned Aerial Vehicles (UAVs) sometimes turns outdoor field applications impractical, which restricts the realization of several tasks that could potentially be improved or benefited from its sounding characteristics. Depending on the mission, Mini Aerial Vehicles (MAVs) energetic resources may be mostly wasted during the round trip from launching base and target point around which a given mission must be accomplished. In this sense, the initial deployment problem becomes prominent, raising new opportunities on how aerial robots may be launched/deployed. This work presents a novel perspective in morphological adaptations for aerial robotics that may potentially minimize initial deployment problem issues. From that perspective, we present three novel morphologies. First refers to a hybrid fixed-wing/quadrotor aiming in-flight launching possibilities. Still looking at in-flight launching, second MAV regards to a new morphology for a quadrotor whose center of gravity is shifted in order to improve passive static stability. Third one relates to a hybrid MAV that combines a watercraft and a quadrotor. The aircraft may navigate on water with low energetic cost through a specially designed structure. It also presents static stability in air and over the ground. We present all details concerning new concepts, development, analysis, design and flight simulation for all three novel platforms. A concise and robust validation of stability control is firstly performed with the ©VICON vision system. Finally, on-the-field evaluation for all three morphologies are extensively carried out, presenting optimistic experimental results of our findings.

Keywords: Aerial robots. Drone. Hybrid Robots. MAV. Morphology. Control and Stability.

Resumo (Portuguese)

SAMPAIO, R. C. B. **Novas Morfologias para Robôs Aéreos: Projeto para Aplicações de Campo**. 2015. Tese (Doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2015.

As limitações energéticas em robótica aérea de campo muitas vezes levam à sua não utilização em tarefas que poderiam se beneficiar substancialmente de suas vantagens. Dependendo da complexidade da missão, os recursos energéticos podem ser despendidos prematuramente ainda durante o traslado ao ponto de interesse. Nesse contexto, se evidencia o problema do lançamento inicial de robôs, o que faz surgir novas possibilidades para o desenvolvimento de novas maneiras de lançá-los. Este trabalho propõe uma nova perspectiva para adaptações morfológicas para robótica aérea as quais podem significativamente contornar os efeitos das limitações energéticas. Sob essa ótica, são propostas três novas morfologias. A primeira consiste de um robô aéreo híbrido asa fixa/quadrotror visando a possibilidade do lançamento em voo. A segunda consiste de uma aeronave de asa rotativa na configuração quadrotrora morfolologicamente adaptada para reposicionamento do seu centro de gravidade. O aumento da estabilidade estática passiva da aeronave também visa o seu lançamento durante o voo. A terceira se refere a um veículo aéreo híbrido que combina uma estrutura naval e um quadrotror, capaz de navegar em cenários aquáticos com baixo custo energético. O desenho mecânico resultante permite sua operação no ponto ótimo tanto para a navegação aérea quanto aquática, oferecendo estabilidade estática em todos os cenários (terra, ar e água). São apresentados todos os detalhes de conceito, concepção, análise, projeto e simulação em voo das três novas plataformas. Uma validação robusta dos sistemas de controle e estabilidade é realizada por sistema de visão ©VICON. Por fim, ensaios em campo apresentam resultados experimentais otimistas para a aplicação das três novas morfologias.

Palavras-chave: Robôs Aéreos. Drone. Robôs Híbridos. MAV. Novas Morfologias. Controle e Estabilidade.

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1. **SAMPAIO, R. C. B.** ; HERNANDES, A. C. ; BECKER, M.. Nova Morfologia para Aumento de Estabilidade Global em Voo Omni-Direcional a Baixas Velocidades de Aeronave Quadrotora Elétrica; *INPI Process # BR120141288518-8*, 2014

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Acronyms

<i>Term</i>	<i>Description</i>
AFCS	Automatic Flight Control System
ART	Aerial Robots Team
EV	Electric Vehicle
FVMS	Flight Variables Management System
ICAO	International Civil Aviation Organization
MAV	Mini Aerial Vehicle
MUAV	Mini Unmanned Aerial Vehicle
μ -AV	Micro Aerial Vehicle / Mini Aerial Vehicle
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial System
FAA	Federal Aviation Administration
ANAC	Agência Nacional de Aviação Civil
ART	Aerial Robots Team
CoG	Center of Gravity
C#	<i>C Sharp</i>
MSFS	Microsoft Flight Simulator
SiL	Softwarwe-in-the-Loop
HiL	Hardwarwe-in-the-Loop
MiL	Man-in-the-Loop
H-STOL	Horizontal Short Take-off and Landing
V-STOL	Vertical Short Take-off and Landing
ROV	Remotely Operated Vehicles
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial System
GPS	Global Position System

<i>Term</i>	<i>Description</i>
SUAV	Small Unmanned Air Vehicle
HALE	High altitude long endurance
MALE	Medium altitude long endurance
NAV	Nano Air Vehicles
RPH	Remotely Piloted Helicopter
VTUAV	vertical take-off UAV
UCAR	Unmanned Combat Rotorcraft
3D-IPM	3D Inverted Pendulum Mode
CFD	Computer Fluid Dynamics
VLM	Vortex Lattice Method
ESDU	European Security and Defense Union
XPS	Extruded Polystyrene
NP	Neutral Point
GUI	Graphical User Interface
DoF	Degree of Freedom
UA	Unmanned Aircraft
ROA	Remotely Operated Aircraft
COA	Certificate of Authorization
AGV	Autonomous Ground Vehicle
AUVSI	Association for Unmanned Vehicle System International

List of Symbols

<i>Symbol</i>	<i>Description</i>	<i>Unit</i>
$[u, v, w]^T$	CG velocity vector	m/s
$[p, q, r]^T$	Body angular velocity vector	rad/s
$[\phi, \theta, \psi]^T$	Tait-Bryan CG orientation angles	rad
$[x_G, y_G, z_G]^T$	CG displacement	m
m	Quadrotor mass	Kg
$\tilde{I}$	Quadrotor Inertia Tensor	Kgm^2
b	Thrust factor	-
d	Drag factor	-
l	Motors lever	m
K	Force-to-moment ratio	-
$c_{W1..6}$	Body drag coefficients	—
$\Omega_{1..4}$	Rotor speed	rad/s
$[F_x, F_y, F_z]^T$	External applied forces	N
$[M_x, M_y, M_z]^T$	External applied torques	Nm
$[U_{1..4}]^T$	Control action vector	-
$[F_{1..4}]^T$	Thrust vector from propellers	N
I_M	Rotors Inertia	Kgm^2
Ω_r	Residual motors velocity	rad/s
μ	Fluid viscosity	m^2/s
p	Pressure	Pa
p_{atm}	Atmospheric pressure	Pa
$\forall$	Volume	m^3
ρ	Fluid density	Kg/m^3

<i>Symbol</i>	<i>Description</i>	<i>Unit</i>
G_{ap}	Augmented plant	-
T_{zw}	T.F. between w e $z_{1,2}$	-
W_e	Error weighting function for G_{ap}	-
W_u	Control weighting function for G_{ap}	-
S	Sensibility function	-
R	Sensibility function	-
L	Open loop T.F.	-
γ_{max}	γ Maximum value	-
C_d	Drag coefficient	—
C_l	Lift coefficient	—
C_m	Moment coefficient	—
ω_n	Natural frequency	rad/s
ξ	Damping ratio	—
M_w	Moment of the wing	Nm
M_{acw}	Moment of the wing in the aerodynamic center	Nm
L_w	Wing lift	N
D_w	Wing drag	N
α_w	Wing angle of attack	rad
a_w	Lift-curve slope of the wing	—
$C_{L\alpha w}$	Airplane lift-curve slope (elevator fixed)	—
h	CG position, fraction of mean chord	m
h_{nw}	neutral point of the wing-body combination	m
C_{mw}	Coef. of Moment of the wing	—
C_{lw}	Lift coefficient	—
C_{dw}	Lift coefficient	—
$\bar{c}$	Lift coefficient	—
C_{mp}	Moment of the wing	Nm
$C_{m\alpha}$	Moment of the wing —	—
K_n	Static margin	—
δ_e	Elevator deflection	—
δ_T	Thrust level	—
A_{lat}	Lateral dynamic matrix	—
B_{lat}	Lateral control matrix	—

<i>Symbol</i>	<i>Description</i>	<i>Unit</i>
A_{long}	Longitudinal dynamic matrix	—
B_{long}	Longitudinal control matrix	—
F_{lat}	Lateral force	N
F_{long}	Longitudinal force	N
θ_p	Pendulum pitch	rad
ϕ_p	Pendulum roll	rad
f_{px}	Pendulum correction force in x	N
f_{py}	Pendulum correction force in y	N
Re	Reynolds number	—
F_d	Drag force	N
F_l	Lift force	N
A	Area	m^2
F_B	Buoyancy force	N
$\forall_i$	Volume of immersed body	m^3
$\forall_b$	Volume of entire body	m^3
d_b	Draft of buoyant body	m
B	Center of Buoyancy	m
T	Thrust force	N
W	Weight force	N
T_r	Period of oscillatory mode	s
$BrMd$	Hull width	m
η	Lateral force	N
γ_{opt}	Optimal value for γ	-
γ_{min}	Minimal value for γ	-
M_s	Peak sensibility	-
γ	Open loop T_{zw} minimization norm	-
$M_{1..2}$	Motor number	—
G_{ap}	Augmented plant H_∞	-
T_{zw}	Open loop between w e $z_{1,2}$	-

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Chapter 1

Introduction

Flying is one of the most fascinating achievements that man has ever accomplished. The capability to artificially overcome gravitational force is an amazing discovery which has led mankind to outstanding new conquests. More than a simple revelation, the ability to build little (smart however) devices that are put together to mold big, complex and stunning machines that cross the skies reflects an exceptional state of knowledge. In nature, in most of the time birds, bugs and other insects fly instinctively through our eyes almost imperceptible. Because flying is a genuine ability of such living beings (which humans absolutely are not provided with) this has been a quality that we have been obstinately pursuing since our very beginnings. Even today, when technological advances have overcome most of the biggest challenges of physics, there are still much to be done. As well as birds and insects, whose evolutionary development has never stopped not for one single second, we may surely say that the study of flying robotics is still in its embryonic stage. This has been an obstinate work. However, it is just a small contribution to a huge field that still remains completely unexplored.

1.1 Motivation & Objectives

The potential usage of low weight electric aircraft has exponentially grown in the last years. Low scale UAVs (Unmanned Aerial Vehicles) best known as Mini Aerial Vehicles (MAVs or MUAVs), or still popularly known as “drones”, are highly maneuverable, offers good stability and are relatively easy to be controlled. Altogether, those qualities are attractive for utilization in precision missions - e. g., in highly constrained environments. Besides, the advent of ultra high energy density batteries, micro-electronics (and advances in micro sensing) and low-density and resistant composite materials have also aided small scale electric flying vehicles to be compact and still extremely light.

Nevertheless, from the operational point of view, MAVs offer many advantages over medium and large UAVs in determined missions - *e.g.*, precision tasks when a high level of maneuverability/controllability is required. Furthermore, in most cases constructive/geographic constraints may detract the quality of the mission turning it difficult to a medium/large aircraft to operate appropriately. In that sense, a low scale UAV (a MAV) may offer superior operational features.

Even after significant advances in chemistry and materials engineering, current high efficiency batteries still present low energy-to-density/weight ratio. In practical terms, the more batteries offer energetic density, heavier they become. That represents major and prominent drawback for Electric Vehicles (EVs). Regarding flying electric robots, energetic resources become even more critical since energy capabilities decrease as project requirements demand more payload. Typically, current commercial batteries allow electric MAVs to perform an average flight time of fifteen minutes at the most, which drastically restricts the list of missions that could benefit from MAV potentials. Battery deadline, however, may occur earlier depending on the mission and on the environment. Flight time may go up to 20 minutes indoor while it may drastically drop to less than 10 minutes outdoor in a severe windy day. We have broadly carried out field experiments with the ©AscTec Pelican quadrotor, a state-of-the-art equipment, both indoor and outdoor to attest the above numbers.

In the best of the worlds, the full accomplishment of missions should happen before battery go dead. Several works on control, mission planning and navigation strategies have been proposed in attempt to maximize energetic capabilities. However, the initial deployment of mobile robots still has not been fully addressed. The way a MAV is deployed out to a given mission is paramount and directly impacts over energetic outgoing. When it comes to the success of a mission, first thing that comes into mind is placing the robot at the precise location at which it

is destined to execute a determined task. Regarding present medium range MAVs (e.g., those for search and surveillance), main drawback is the considerable waste of energy during the round trip during the mission. Perfect outline is that 100% percent of battery charge would be fully employed to the mission itself. However, reality is even more tough, and this is nothing more than the idealist portrait of a perfect scenario in field robotics. In the best of cases, if the robot reaches the target, it needs to preserve energy for the back trip. In the other hand, MAVs poor energetic efficiency opens many windows and brings light to the development of novel techniques on building aerial robots through which novel ways to deploy them may be achievable.

A possible solution to the issue is the in-flight-launching of MAVs from a carrier/mother-aircraft as the launching platform. The carrier may be either a manned or an unmanned aircraft with plenty of autonomy. In-flight launching may be performed after some mechanic adaptations, where a MAV may be modified and/or adapted to meet such mission demands. Morphological adaptations may improve MAV flight mechanics. The robot may be molded to feature some desired characteristics in order to be planted as near to the interest point as it is possible. In example, hybridization between a helicopter and a fixed-wing aircraft may produce interesting aerodynamic results that may potentially turn it feasible to achieve larger range tasks. Another possibility aiming the in-flight-launching is modifying the CoG (Center of Gravity) of a multi-engine helicopter in order to increase passive stability during descend (as a slung-payload). Other interesting possibility is to endow a quadrotor MAV with watercraft features. A MAV with such hybrid characteristics may raise novel perspectives to multi-environment applications (water, air and ground). It may use much less energy to navigate in water or it may remain in the water for a long period while batteries may be recharged (*e.g.*, through solar panels).

Whatever is the scope a MAV is designated to act in, it surely demands design to be very well grounded and carefully analyzed. This thesis aims to provide a novel overview in the construction of MAVs with a substantial theoretic background on the modeling, simulation, construction and control of novel morphologies for aerial robots. However, our main focus, which is the last stage of this work, relies on-the-field experimentation of novel possibilities for mission, as those described above.

1.2 Goals & Original Contributions

1.2.1 Novel Outlook on the Initial Deployment of MAVs

The first contribution of this thesis, with a strong inspiration in the motivations of Section 1.1 is presenting novel possibilities on the deployment and launching of MAVs. Until the present date, we haven't known of any work with a straight research line with this aim.

1.2.2 Full Design & Control of Hybrid/Morphologically Adapted MAVs

Secondly, biggest contribution of this thesis is presenting the complete development of three novel concepts of MAVs, with a strongly focus on the novel outlook of Section 1.2.1:

- a hybrid quadrotor/fixed-wing aircraft;
- a morphologically adapted quadrotor;
- a hybrid quadrotor/vessel aquatic MAV;

As far as we know, this has been the very first work that deeply sketches all stages that heads the successful maiden launching of three MAVs with such characteristics.

1.2.3 Robust Control Design

We designed an optimal H_∞ robust controller to fit the three platforms with no gain scaling. We make use of the robust control theory to ensure that the same controller could take care of stabilizing three distinct aircrafts. Novelty lies in the validation of our controller in a novel flight simulation framework that we have developed during the accomplishment of this thesis.

1.2.4 A Novel Flight Simulation Framework

During the development of this thesis, we have developed a software framework named FVMS (Flight Variables Management System), through which we may interact to MSFS (Microsoft Flight Simulator). FVMS allow the full closed loop validation of a great variety of algorithms. We successfully reproduced the three MAVs dynamics in flight simulation and the control of each one as well.

1.2.5 Visual Motion Tracking Validation

After designed, constructed and fine tuned, the controllers of each platform were first evaluated and validated with the aid of a ©VICON System, a visual motion tracking system through which we may trace the quality of the stability system of our MAVs.

1.2.6 Academic Contributions

Up to this date, the present work has resulted in one patent pending and one industrial design registry to INPI (2015). We also have achieved one publication in the ABCM Symposium Series on Mechatronics Journal (2012), one publication (front cover) in *Ciência Hoje* Brazilian national magazine (2013), five works in the IEEE/AIAA Aerospace Conference (2013 and 2014), one paper in the IEEE ICIT (2013) and one publication in IEEE ROBOCONTROL (2014).

From the development of this thesis, the following research works related to aerial robotics could be supported in the Aerial Robots Team group (USP/EESC/ART):

- 02 PhD;
- 03 MSc;
- 06 Undergraduate Programs/Scientific Initiation;

1.3 State-of-the-Art

A very few number of works may be listed regarding novel morphologies for flying robots. When it comes to combining in-flight and V-STOL capabilities, as for novel morphologies involving hybridization of helicopters, airplanes and ships, new propulsion systems and/or novel ways of operation, relevant researches are even more scarce. Table 1.1 brings a list of MAVs developed during this thesis while Tab. 1.2 refers to other MAVs developed abroad.

Table 1.1: Novel morphologies for MAVs developed during this thesis.

Project Name	Organization	Figure
Sharky I	USP, Brazil
Sharky II	USP, Brazil
SquidCop I	USP, Brazil
SquidCop II	USP, Brazil
H ₂ Omni	USP, Brazil

Table 1.2: Abroad related works on novel morphologies for MAVs.

Project Name	Organization	Figure
OATAO	Onera, France
Latitude	Latitude Eng., USA
Quadshot	GeorgiaTech Univ., USA
Cycloidal	Nanchang Univ., China
Sky Tote	AeroVironment Inc., USA

1.4 Organization

This thesis is basically organized in five parts. Each one contains chapters, aiming to better organize the work flow. Every chapter is followed by a conclusion of our findings.

1.4.1 Chapter 2

This chapter aims to clarify the UAV/UAS subject. A brief time line on UAV milestones and remarkable facts is outlined, leading to MAVs birth. Functional features and possible configurations of unmanned aircrafts and systems are later presented and detailed. This is a good ground from which novel possibilities may rise.

1.4.2 Chapter 3

The initial deployment problem is addressed and elucidated. Novel possible morphologies and MAV adaptations are presented with focus on field applications. In-flight launching possibilities are illustrated as well as hybridization of MAVs and multi-environment applications are presented and reviewed. Preliminary design results are exposed.

1.4.3 Chapter 4

A novel hybrid fixed-wing/quadrotor MAV named Sharky is presented and outlined in details. We present project requirements, main features and functionalities of the resulting MAV.

1.4.4 Chapter 5

A morphologically adapted quadrotor MAV named SquidCop is presented and outlined in details. The static stability improvements of a novel frame architecture for a multi-rotor helicopter is addressed.

1.4.5 Chapter 6

A hybrid multi-environment quadrotor/watercraft MAV named H₂Omni is presented and described. We bring naval engineering concepts so the MAV hull meets in-water static stability.

Still, the MAV presents aerodynamics features such that it may perform both aerial and water navigation at the optimal point.

1.4.6 Chapter 7

Control fundamentals are presented with focus on the robust control theory. An optimal H_∞ controller is synthesized. At the end we validate the controller in a novel flight simulation framework with Software and Hardware-in-the-Loop simulation.

1.4.7 Chapter 8

A novel flight simulation framework named FVMS (Flight Variables Management System) is presented, through which the three platforms are first evaluated. Resulting graphic and dynamic representations of the three MAV provide users with an outstanding feedback of the real behavior of our platforms.

1.4.8 Chapter 9

Embedded stability controllers are double validated using visual motion capturing (MOCAP) with the ©VICON system and embedded IMU sensors. This is an important stage as the pre-flight validation for the on-the-field flight test.

1.4.9 Chapter 10

Exhaustive on-the-field experimental evaluation is run outdoor while all three proposed MAVs are in real operational situation, subject to wind disturbances and gusty conditions. In the case of H₂Omni, besides of flight tests, the platform has been extensively put into practice in water evaluation.

Chapter 2

Unmanned Aircraft Systems

Federal Aviation Administration (FAA) defines an UAV/UAS as any unmanned aircraft (UA) and all of the associated support equipment, control station, data links, telemetry, communications and navigation equipment, etc., necessary to operate the unmanned aircraft (ADMINISTRATION (2014)). According to FAA, an UA is the flying portion of the system, flown by a pilot via a ground control system, or autonomously through the use of an on-board computer, communication links and any additional equipment that is necessary for the UA to operate safely. In other words, an UAS is a system. Simple like that. Main contribution of this chapter is to offer a complete and wide overview of all existing morphological, structural and functional possibilities to UAVs (or systems) as well as to provide readers with an up-to-date review of worldwide legal aspects and regulations about the subject (AUSTIN (2010)).

2.1 Growth of the Potential Market for UAVs: A Realistic Perspective

The unprecedented growth of market possibilities and demands for a wide set of sectors for UAVs have never been so notable. The 2011 AIAA/Aerospace America Global Roundup reports that 226 manufactures distributed in 44 countries were producing about 675 different unmanned aircrafts in that year. In the 2013 report, the list brings 57 nations and 270 different companies. Altogether, such companies are currently producing 960 distinct aircrafts. That represents an increasing of 20% in the number of companies, 30% for countries and 40% for the number of UAVs in production (AMERICA (2013)). An important market analysis conducted by a respected agency has predicted that the UAV commerce would produce total sales that could easily reach US\$ 61.37 billions in the period between 2011 and 2020 (US\$ 7.31 billions only in 2020) (FROST E SULLIVAN (2012)). The USA leads the top list of manufactures followed by Israel which is the largest exporter with a list of 49 countries as main customers.

The current and promising market for UAV began in the military field, with successful battlefield operations - e.g., Iraqi's Desert Storm, when emerging improvements in electronics/-computing, communication and navigation systems led to the so-called "Decade of the Robot" (just after the 9/11 terrorist attacks). At that occasion, US/Israel Predator UAVs have deployed Hellfire missiles in the Middle East, showing UAVs potentialities. At that time, UAVs were mostly used as low-level law enforcement and environmental monitoring by USA government. Meanwhile, with the popularization of robotic equipments, several commercial robotic products were launched and have begun to be used by civilians. Consequently, UAVs potentials started to be aimed by other sectors like precision agriculture, wildlife monitoring, remote-area medicine delivery, etc. The increasing use of aerial robots by civilians made governments to increase spendings with security (as commercial systems started to offer outstanding capability, reliability and good prices). That is starting to force nations to adapt legislation over the usage of UAV worldwide. Countries that delay adaptations to such brand new scenario will have to rely in imports (MAPLE (2013)).

In Latin America, the use of UAVs used to be primarily focused on border control/surveillance, security, law enforcement and drug cartels restraint. Brazil's Army and Navy main interests used to lie in the previous mentioned missions in a recent past. Nowadays, Brazil leads Latin America list of UAV producers. About 30 distinct UAVs are currently being developed in

the country. A kind of common sense is gradually beginning to become prominent regarding the potentials of UAVs in covering huge territories for agricultural based economy countries (Brazil included). Distinct and Potential markets for UAVs are tremendous and very promising.

The Association for Unmanned Vehicle System International (AUVSI) predicts that in any time the agriculture market for UAVs will be 10 times larger than safety in the United States (AUVSI (2013)). Still, another important and relevant social aspect pointed by the AUVSI research states that more than 100.000 new job opportunities may be created from opening the civil airspace for the application of UAVs in the next decade incorporating more than US\$ 100 billion in the economy. Naturally, in a global scenario, such numbers may be extended to agro-industry based potential countries, likewise Brazil and most countries in the Latin American continent and beyond.

An important and recent change in airspace regulatory laws may be labeled as a landmark in Brazilian civil aviation. The National Civil Aviation Agency (ANAC) has recently granted an UAV private company with the very first certification for an UAV to experimentally fly in Brazilian airspace. The company (XMobots) is located in São Carlos (São Paulo State) and currently tele-operates the Nauru A-500 UAV for imagery in remote areas over Amazon and other remote agro-industrial based areas in the country.

2.2 Brief UAV Time Line & Relevant Facts

It is indispensable to walk through a brief history of UAVs to verify the evolution of flying unmanned vehicles, its impact over the history to better understand the incoming future of flying autonomous robots. Historically speaking, UAS/UAV development first occurred in the early XX century. Curiously, neither military nor civil aviation may be considered precursors of autonomous flight isolate. The prelude of unmanned guided flight origins begins in 1917 (World War I) with the French attempt to produce autonomous bombs using gyroscopic and barometric stabilization systems. In the next year, Germans quit the development of guided weapons. Still in 1918, “Kettering Bug”, a biplane aircraft morphologically adapted by Dayton Wright company to contain a torpedo flies for the first time (Fig. 2.1). The 45 minutes circle coordinate flight was a landmark at that time. Consequently, it secured an order of 75 unities which were delivered to Army Air Corps (USAAC) (WERRELL (1985)) (ORDWAY E WAKEFORD (1960))(NEWCOME (2004)). That was the start of military and civil aviation joint venture on

the interest by UAS (GUNSTON (1979)).

Figure 2.1: Kettering Bug UAV.

The history of modern UAV begins right after the end of World War II. In the early decade of 1950 Air Force Major General David Baker publicly predicts that manned combat aircraft would become obsolete in the future for certain types of missions. In early 1960, an American U-2 spy airplane was shoot down by Russians over soviet territory. The incident became prominent since both airplane and pilot had been captured (Fig. 2.2-(a)). Subsequently to the incident, US intelligence office has signed a contract to the development of an UAS named Oxcart, posteriorly named SR-71 Blackbird (Fig. 2.2-(b)), a new reckoning airplane. However, the project was vetoed due to the elevate budget regarding its construction. Concomitantly, a notable growth in the interest for UAV technologies was perceived. Furthermore, satellite technologies started to be improved and implemented for imagery, surveillance and communication which in a long term would make it feasible to future UAVs to be guided by the well-known GPS technology.

(a)

(b)

Figure 2.2: The New York Times front cover clipping from May'1960 featuring the U-2 Russian incident (Tye NYT archive) and the Sr-71 Blackbird

Next, "Program D" was started by US National Reconnaissance Office, aiming low-rate modifications to manned airplanes. The project leaded to the development of Teledyne Ryan Model 147A "Fire Fly". The main goal was to construct an UAV that was capable to be in-flight deployed for imagery purposes. On Oct'1962 one Fire Fly was deployed over Cuba, as the Cuban Missile Crisis started. Later, the Fire Fly UAV was improved to the new version named "Light-

ning Bug”. Main application of the Bug became notable in 1972, during Vietnam War. Also, the new UAV was an important war tool in Korea. At that time, it was best-known as 147TE “Fire Bee” (AQM-34Q) (see Fig. 2.3)-(a), endowed with a more powerful engine, real-time data equipment and NSA (National Security Agency) package. The 147TE UAV was able to real-time transmit image data to a satellite that, in turn, was capable to process that and retransmit to the US Air Force base center. That represents a considerable and remarkable stage on UAV technology.

Still in means of 1970 decade, a prominent rise in many fields of technology has contributed to a quick evolution that led to UAV improvements. Altogether, the advent of micro-electronics, microprocessors, composite materials, communication (GPS), led to the development of lighter, digital, fly-by-wire, low-detectable (stealth), automatic flying machines. Figure 2.3-(b) shows the AQM-34Q on display at the National Air Force Museum at Wright-Patterson Air Force Base.

Figure 2.3: Firebee (a) and AQM-34Q UAV (b). (San Diego Air and Space Museum Archive/- Courtesy: National Air Force Museum)

In 1980 the new-elected President Reagan began to grant US intelligence with more than US\$ 1.5 billion per year on the development long-range/endurance high altitude remotely operated stealth reconnaissance aircrafts. Consequently, UAV industry started to benefit from the governmental investment. The most important (and historical) reflex of the joint venture between military and civil industry culminated in the production of the BQM-145A, a new UAV that operated in joint with a F-16R. The idea was to put a manned and unmanned aircrafts to work with data linkage, exchanging information and working in cooperative mode. However, as the BQM-145A was able to embed the whole system for the mission, the program was abandoned later since it was underutilized.

After that, a period of silence was experienced as only very few relevant UAV projects were seriously run. As a consequence, such a short number of initiatives were transferred to Defense Airborne Reconnaissance Office (DARO). At that very time, new projects were basically

influences by Israel designs - e.g. Pioneer, Predator family, and Global Hawk (2.4). That may be considered the start of the new era for UAVs as we currently know. Posteriorly, a great variety of programs were started. In example, the well-known Predator was built in a joint venture between TRW, General Atomics, DARO, and Defense Airborne Reconnaissance Program (DARP).

After the consolidation of unmanned systems for real scale aircrafts and with the advent of micro/nano technologies, a great variety of projects started to be developed involving mini/micro aircrafts as well as medium-range and high altitude UAVs (used in very specialized and tactical missions) has notably been increasingly funded by governmental agencies. Brazilian company AVIBRAS have also successfully developed the Falcão UAV (Fig. 2.4-(d)).

Figure 2.4: Pioneer (a), Predator (b), Global Hawk (c) and Falcão UAVs (d).

2.2.1 MAVs Birth

Differently from UAV, the term MAV (Mini Aerial Vehicle) is subject to different interpretations. Although the attempt of many authors to brand/label both the acronym and the definition, MAVs started to gain headway and become popular in the 1990s. Due to a notable advance in computational power, electronics miniaturization and improvements in battery technology, a clear transition between large and low scale UAVs was assuredly noted. Besides, embedded electronics that was formerly restricted to military is now accessible to academia/civil, which greatly contributed to many new low scale flying machines to be designed and constructed.

At the very beginning, a MAV used to be denoted as μ -AV (Micro Aerial Vehicle) and referred to any small scaled UAV whose dimensions not exceed 15cm and up to 140g of weight (MOTAZED et al. (1998)) (KROO et al. (2000)) (HEIN E CHOPRA (2007)). The work of (PINES E BOHORQUEZ (2006)) defines technical specifications regarding size, weight, range, endurance, speed, payload and cost. However, such categorization definition is still far from being achieved. Hence, the term MAV may not be longer effectual since miniaturization is still a concern. Furthermore, from academia, private corporations and military, MAVs dimensions and

weight may drastically vary (from one dozen of grams to 5 kilograms) which makes the acronym ambiguous and dubious. Hereafter, the term MAV shall be referred to Mini Aerial Vehicle in this thesis.

Quadrotor Shaped MAVs

Quadrotors had become an attractive flying solution due to symmetric aspects. Besides, it is dynamically easy to be understood and low-cost. Moreover the omnidirectional nature of its dynamics plus high controllability allows the quadrotor to navigate without constraints with high precision even in indoor narrow/small sites.

Back to decade of 1990, some sound and relevant works have introduced important advances in the newly-designed four-engine helicopter well-know today as quadrotor. At that time, modeling, control and miniaturization issues begun to take place. However, although battery/electronics advances were notable, there was still a long journey to effective achievements in minimizing dimensions and maximizing range and flight time.

From the second half of the 90s Stanford have presented the impressive Mesicopter (Fig. 2.5-(a)) which may be considered one of the precursors of the quadrotor design and that most approximated to the -UAV concept. Later, OS4 (Fig. 2.5-(b)) started to be developed at EPFL (BOUABDALLAH et al. (2004b))(BECKER et al. (2012)). Concomitantly, many other relevant works brought considerable contributions to the quadrotor development, among which most significant are Stanford Starmac (Fig. 2.5-(c)) and microDrones GmbH ©MD4-200 (Fig. 2.5-(d)) (HOFFMANN et al. (2004)).

Figure 2.5: Some of the most relevant works involving quadrotors: Mesicopter (a), OS4 (b), Starmac (c) and MD4-200 (d).

As a consequence of the diffusion of the quadrotor technology, some commercial versions of the MAV started to emerge. Although most of them bring relative high technology embedded to the product, sometimes they referred as toys. Shortly after quadrotors rasing, a great varia-

tion of multi-engine helicopter configuration raised, such as tri/hexa/octa-rotors configurations. Regardless of the classification, most common commercial quadrotors are endowed with HD cameras, IMU, autopilot, Wi-Fi communication (Apple ©and Android compatible). Figure 2.6 show the Parrot ©Ar.Drone 2.0 and the Draganflyer ©X-6, respectively.

Figure 2.6: Parrot ©Ar.Drone 2.0 (a), Draganflyer ©X-6 (b) and ©AscTec Falcon (c).

Airplane Shaped MAVs

Popularization of small computers, electronics and low weight materials plus the well succeeded use of medium/large UAVs in the airplane configuration for military purposes, small unmanned airplanes took place. Still in the military field, some backpack hand-launched SUAV (Small Unmanned Air Vehicle) started to be used in the battlefield. Basically, the airplane may be disassembled and reassembled whenever it is required. The operator may manually throw the little craft upwards in the air so that it get impulsed to the mission.

Figure 2.7 show some of the most popular SUAVs used by armies worldwide. The AeroVironment RQ-11 Raven (Fig. 2.7-(a)) is the most widely used SUAV in the world. It is a lightweight solution designed for rapid deployment and high mobility for military applications requiring low-altitude surveillance and reconnaissance intelligence. Figure 2.7-(b) shows the RQ-20A Puma AE, one of the precursors of the hand-launched SUAVs. Figure 2.7-(c) shows the a Lockheed Martin Desert Hawk. Finally, Figure 2.7-(d) shows ASN-15, a Chinese defense and reconnaissance SUAV.

2.3 Functional Aspects, Airframe Configurations & Morphologies

Due to the huge technological development involving UAVs in general plus the sequent raising in the number of unmanned aircrafts of all sizes and sorts, categories have suffered subdivisions.

Figure 2.7: Some of the most relevant works involving UAV airplanes: AeroVironment RQ-11 Raven (a), RQ-20A Puma AE (b), Lockheed Martin Desert Hawk (c) and ASN-15 (d).

Such categories may vary according to constructive parameters (dimensions, weight, payload, etc.), operational matters (autonomous or teleoperated) and mission nature.

However, there is not ultimately a commonly accepted categorization of UAS. Figure 2.8 is an attempt to provide readers with an infographic that may aid to position UAVs and MAVs into a bigger set of categories.

Figure 2.8: UAVs and MAVs categorization (adapted from Northrop).

- *HALE* High altitude long endurance. Over 15 000 m altitude and 24+ hr endurance. They carry out extremely long-range (trans-global) reconnaissance and surveillance and increasingly are being armed. They are usually operated by Air Forces from fixed bases.
- *MALE* Medium altitude long endurance. 5000-15 000 m altitude and 24 hr endurance. Their roles are similar to the HALE systems but generally operate at somewhat shorter ranges, but still in excess of 500 km. and from fixed bases.
- *TUAV* Medium Range or Tactical UAV with range of order between 100 and 300 km. These air vehicles are smaller and operated within simpler systems than are HALE or MALE and are operated also by land and naval forces.

Close-Range UAV used by mobile army battle groups, for other military/naval operations and for diverse civilian purposes. They usually operate at ranges of up to about 100 km and have probably the most prolific of uses in both fields, including roles as diverse as reconnaissance, target designation, NBC monitoring, airfield security, ship-to-shore surveillance, power-line inspection, crop-spraying and traffic monitoring, etc.

- *MUAV or Mini UAV* relates to UAV of below a certain mass (yet to be defined) probably below 20 kg, but not as small as the MAV, capable of being hand-launched and operating at ranges of up to about 30 km. These are, again, used by mobile battle groups and particularly for diverse civilian purposes.
- *Micro UAV or MAV* - The MAV was originally defined as an UAV having a wing-span no greater than 150 mm. This has now been somewhat relaxed but the MAV is principally required for operations in urban environments, particularly within buildings. It is required to fly slowly, and preferably to hover and to perch i.e. to be able to stop and to sit on a wall or post. To meet this challenge, research is being conducted into some less conventional configurations such as flapping wing aircraft. MAV are generally expected to be launched by hand and therefore winged versions have very low wing loadings which must make Introduction to Unmanned Aircraft Systems (UAS) 5 them very vulnerable to atmospheric turbulence. All types are likely to have problems in precipitation.
- *NAV* Nano Air Vehicles. These are proposed to be of the size of sycamore seeds and used in swarms for purposes such as radar confusion or conceivably, if camera, propulsion and control sub-systems can be made small enough, for ultra-short range surveillance.

Some of these categories possibly up to the TUAV in size can be fulfilled using rotary wing aircraft, and are often referred to by the term remotely piloted helicopter (RPH) see below.

- *RPH*, remotely piloted helicopter or VTUAV, vertical take-off UAV. If an air vehicle is capable of vertical take-off it will usually be capable also of a vertical landing, and what can be sometimes of even greater operational importance, hover flight during a mission. Rotary wing aircraft are also less susceptible to air turbulence compared with fixed-wing aircraft of low wing-loading.
- *UCAV and UCAR*. Development is also proceeding towards specialist armed fixed-wing UAV which may launch weapons or even take part in air-to-air combat. These are given the initials UCAV for unmanned combat air vehicle. Armed rotorcraft are also in development and these are known as UCAR for Unmanned Combat Rotorcraft.

However, HALE and MALE UAV and TUAV are increasingly being adapted to carry air-to-ground weapons in order to reduce the reaction time for a strike onto a target discovered by their reconnaissance. Therefore these might also be considered as combat UAV when so equipped. Other terms which may sometimes be seen, but are less commonly used today, were related to the radius of action in operation of the various classes. They are:

- *Long-range UAV* replaced by HALE and MALE
- *Medium-range UAV* replaced by TUAV
- *Close-range UAV* often referred to as MUAV or midi-UAV.

2.4 Airframe Configurations

Airframes employed in UAVs are quite diverse and may assume different shapes and configurations. Basically, airframes are divided in three major groups, as it is discussed next.

2.4.1 Horizontal take-off and landing Architecture (HTOL)

With rare exceptions, all UAVs in HTOL configuration present rear mounted power plant to allow a free of obstacle wide and clean front view of cameras. Besides, equipment is also installed in the front portion of the aircraft. Aerodynamically speaking, in the case of using propellers, the induced air velocity ahead does not significantly increase friction drag of the fuselage. It is known that the same effect may not be neglected in front mounted power plant aircraft since propellers air stream increases friction drag.

Figure 2.9 shows the four variations of HTOL airframe configurations. Basically, aircrafts with HTOL airframe are divided by four distinct groups, based on its stability, controllability and their means, listed below:

- *Main Wing Forward with Control Surfaces Aft* - Also called “tailpane aft”, such configuration comprehends tail-aft on fuselage and tail-aft on booms. First one is commonly seen in HALE and MALE for long-range missions, since fuselage volume must be widening for carrying more payload (equipment and fuel). The second is arranged in a twin boom shape and is most commonly used in short/medium tasks. The twin boom shape allows the motor group to be installed between the wing the control surface. That is interesting from many aspects. Flight mechanics is improved once engine acts near from the aircraft CoG which reduces inertia for pitching and yawing. Also, the proximity of the motor group

from elevators and rudders is favorable on control power enhancements. Another point is that parallel booms offer, somehow, protection for propellers. In both configurations, the power plant acts as a pusher.

- *Canard* - Also named “tailplane forward”, canard is a horizontal stabilizer that is mounted right at the forward position of the wing. Since canard generates positive lift (as well as the main wing) and the aircraft CoG is also after main wing, stability in horizontal plane is achieved. For the same very reason, the aircraft in such configuration presents higher aerodynamic efficiency compared to tailplane after one. Another advantage of this configuration lies in the fact that, at high angles of attack, the foreplane stalls before the main wing. Result is a minimum loss in general lift and, consequently, a small pitch down recovering moment. Main disadvantage is that the elevator arm is reduced since CoG is rearward. That may be minimized by adding a certain sweep-back angle whose wing tips are endowed with fins to increase the moment arm.
- *Flying Wing* (“tailless”) - Generally, flying wings are also crafted with a considerable wing sweep-back in order to increase the tail-arm that produces torques. However, limitations in pitch and yaw are observed. Advantages are that, since the sweep-back is present, as the aircraft nose rises, the center of lift moves rearward. Practical effect is a restoring moment to the aircraft stable attitude. Another positive point of tailless aircrafts is that the absence of horizontal stabilizers aid reducing drag. However, negative point is that negative lift may be observed at the wing tips, leading to induced drag and, as a consequence, tip stall.
- *Delta Wing* - Likewise the flying wings, delta wings suffer the same effects of induced drag. Main disadvantage is the quick loss of energy specially in turns caused by tip induced drag. Main advantages, however, lies in an augmented stall angle, simplicity of manufacture, elevated inner volume for embedding payload, among others. Another advantage is the reduced gust response. The delta shaped structure offers highly rugged resistant airframe, which protects payload and airframe itself.

2.4.2 Vertical take-off and landing Architecture (VTOL)

Helicopters configure almost the plenty of aircrafts in such architecture. Accordingly, the main characteristic intrinsic to VTOL airframe configurations is that the counter-torque of main rotor must to be handled and canceled at the equilibrium point.

Figure 2.10 shows the four variations of VTOL airframe configurations, which are listed as

Figure 2.9: Some of HTOL UAVs architecture.

follows:

- *Single Main Rotor* - This architecture comprehends the great majority of helicopters. At the same time main rotor produces lift forces, a secondary side-thrusting propeller counteracts the natural counter-rotating tendency generated by main rotor. Main disadvantage lies in high asymmetry which demands complicated control algorithms to act over the frame. Furthermore, tail rotor is completely exposed, which may offer risk of collision to obstacles.
- *Tandem Rotor* - Tandem configuration is not appropriate to UAVs since as the small payload does not require a long fuselage, rotor would need to be attached to extensors (extended pylons). That turns the application structurally inefficient.
- *Coaxial Rotor* - Oppositely to manned coaxial aircrafts, UAVs in such configuration are compact, tailless (free of collision), are almost symmetric (facilitating AFCS algorithms). Experiments in early 1980s have shown that this configuration uses less power than single main rotor. Besides of not using extra power for counter torque cancellation, less power is wasted in energy being left in rotor downwash.
- *Tri-rotor* - This is a raising configuration. First tests were unsuccessfully run in 1940. However, some works report that this set up present some advantages over quadrotors. At the best of the author's knowledge, none of current works that addresses such configuration has already finished programs regarding this configuration.
- *Quadrotor* - Most popular in University scope, a quite great number of works recently

appeared addressing this configuration most for indoor applications. Main advantage of quadrotor configuration lies in mechanical simplicity. Unlike the previous configurations, a quadrotor does not demand mechanical transmissions to work. All four motors are strategically positioned upwards. A couple of opposite propellers run in the same rotating sense. The other two run in the counter-sense. That cancels torques. The correct combination of angular speeds allows the 6 DoF maneuvers. Control systems for quadrotors are quite difficult to be synthesized. Regularly, due to the highly coupled dynamics, quadrotors are more sensitive to gust and may offer a time lag response. However, if controllers are well-synthesized, quadrotors may offer optimal stability response.

Figure 2.10: Some of VTOL UAVs architecture.

2.4.3 Hybrid V/H-TOL Architecture

Hybrid V/H-TOL aims to combine the advantages of both HTOL and VTOL features. Briefly speaking, in the design of hybrids, it is desired to achieved the outstanding performance of a helicopter, its hovering capabilities for precision flight at any point over the Earth. Concomitantly,

it is also a goal that, for feasibility of the application, the aircraft is able to cruise in high speed to the interest point. Thus, many attempts to hybridize both architectures have been reached.

- *Convertible Rotor Aircraft* - Maybe this is the most successful architecture up to now. It consists in attaching rotors onto each wing. This configuration is divided in two. First, named “tilt-rotor” is when the wing remains fixed and rotors tilt forward 90°. Second, named “tilt-wing” consists in mounting both wings and rotors in the same assembly and then being hinged on the upper fuselage. That is, the whole assembly tilts as the aircraft switches between HTOL and VTOL and vice-versa.
- *Tilt Wing Body* - Consists in a puller propulsion system attached to the forward position of the aircraft. This configuration requires the whole aircraft to tilt, in order to achieve the transition between HTOL/VTOL and vice versa. Main and sound problem in this configuration lies in the transition between HTOL to VTOL (transition down). It is necessary to keep airflow attached over the wing as well as a good pitching control. Pitching moment is more difficult to be achieved. As the aircraft increases angle of attack, airflow over the wings decreases, leading the loss of altitude. That will demand more power from the power plant. Transition between VTOL to HTOL (transition down) is less critical but no less complex. As the aircraft is hovering, it must climb at positive speed rate so that the airflow over the wing reduces the risk of stall. Transition down may be optimized by elevating lift loading ratio (ratio between disc loading of the rotor and wing loading of the wing). However, this requires a larger wing and more powerful engines, which may detract the overall aircraft efficiency. A possible solution may be choosing a suitable airfoil section (of low aspect ratio) and/or appropriate flow attachment devices.
- *Ducted Fan Aircraft* - This configuration consists in enclosing the thruster in a duct. Thruster is composed by two counter rotating blades that may produce thrust by varying rotational speeds. When such blades rotate in different speeds and rotations are achieved by tiltable vanes in the slipstream. Lack of force in the vanes may be a major drawback, which directly impacts over attitude control.
- *Jet-Life Aircraft* - In this configuration, the aircraft is lifted in hovering mode by one or more jets of air. Smaller jet vanes are positioned on the wing tips so that the appropriated combination of air flow produces resultant moments that may vary the aircraft attitude. That was proved efficient in large aircrafts (e.g., V-STOL Harrier) because of the high quantity of fuel demanded, as well as large engine and duct fans. It is not appropriated to low/medium UAVs nor to low speed aircrafts for the above mentioned reasons.

Figure 2.11: Some of hybrid HTOL/VTOL UAVs architecture..

2.5 Potential Fields of Outdoor Application for MAVs

From the previous discussed raising perspectives, potential fields of applications which may benefit from MAVs/MUAVs capabilities are, but not limited to:

- *Precision Agriculture* - activities like imagery, monitoring and sowing may significantly be improved if MAVs are inserted in plantation. That may save time, improve the quality of results and be cheaper than traditional means;
- *Urban Surveillance* - high manobrability of small scaled UAVs may fit navigation through restricted urban areas, top of buildings and the dynamics of great urban centers;
- *Wild Life Observation* - silent electric MAVs may penetrate dense forests and glades in order to capture images and small samples where other medium/large UAVs may not be able to get to.
- *Law Enforcement* - routine aerial surveillance with MAVs may restraint criminal activities in determined areas - e. g., urban centers and neighbors;
- *Atmospheric Monitoring* - a MAV may perfectly be used to get samples in the atmosphere for research purposes - e. g., ozone density and pollution monitoring.
- *Hazardous Environments* - a MAV may be deployed over volcano areas for monitoring and sampling, where the aircraft may be expendable or may be recovered.
- *Sea Water Measuring/Collecting* - A MAV may be strategically deployed overseas in order

to acquire samples from water to salinity, pollution, microorganisms studies.

- *Military/Border Control* - Critical areas, like borders and war zones may make use of MAVs for monitoring and imagery without the need to put human lives in danger.
- *Remote areas Medicine Delivery* - Remote areas, like mountains and deep forests may benefit from MAVs which may transport medicines, vaccines and bring human samples (urine, blood, etc.) to big cities.

2.6 Outline of the Current Regulations on the Use of UAV/UAS

Internationally speaking, the UAV issue is brand new regarding wide civil utilization. First FAA policy decisions occurred only in 2005. In 2012, FAA performed a series of adaptations, among which the non-acceptance of COA (Certificate of Authorization) applications for civil UAV operations. Less than one year later, FAA agreed to receive applications under some conditions (ADMINISTRATION (2014))(ICAO (2013)). Today, 2015, regulations still remain unclear in most countries.

In Brazil, ANAC (National Civil Aviation Agency) regulations are still being adapted to constantly follow international rules. Up to this date, ANAC regulations state that any ROA (Remotely Operated Aircraft) must be considered as a subcategory of an UAV and does not include full autonomous aircrafts. There is not whatsoever any registration nor any application for COA for a full autonomous aircraft in the country by the present time. Additionally, ANAC also addresses that ROAs operation must be followed by a special certification, which categorizes the aircraft as experimental. As for commercial purposes applications, the ROA may not be categorized as experimental aircraft. In this case, a special certification must be submitted to ANAC in order to describe the operation intentions, security level, among others. However, as ANAC affirms, there is not any specific and official regulation related to the ROAs for commercial purposes and submissions are currently analyzes by a special commission that decides about granting or overruling the application (ANAC (2015)).

2.7 Autonomous *vs.* Teleoperated Flight

One important remark regarding the application of UAV/UAS lies in the nature of its operation. International regulations are extremely restrictive about the autonomous operations with UAV/UAS. In some countries, the complete absence of legislations on autonomous vehicles

derails any attempt to put autonomous equipment into operation.

In Brazil, for instance, ANAC regulations does not cover operations with autonomous vehicles. They refer to them as ROV (Remotely Operated Vehicles). By definition, a ROV is a machine that may navigate with no human operator into it. However, a human operator must necessarily be in charge of guiding it by remotely sending decision commands.

2.8 Conclusions

This chapter offers a wide and illustrative overview from historic facts that have leaded the development of Unmanned Aerial Systems. It also presents valuable information concerning architectural aspects on the construction of aircraft from the morphological perspective. All these information aims to open readers mind to novel perspectives on the utilization of hybridization and morphological adaptations to be used in low scale MAVs. This chapter shapes the base lines for the next chapter, where we start to mold our aircrafts.

Part I: A Novel Concept on MAVs & Applications

First part of this thesis offers a new perspective on how to meet ideal frames, shapes, architectures, morphologies and adaptations for MAVs with a strong look at novel platforms for field robotics applications.

Chapter 3

Novel MAV Morphologies for Field Applications

In this chapter we address new morphological possibilities on the design of MAVs looking at a new perspective for field application and to the way they are deployed. We take a look in the initial deployment problem from the perspective of the low energetic efficiency in flying robotics. We present the hybridization and adaptation of MAVs for fitting specific deployment missions strongly aiming constructive requirements. Main contribution of this chapter is to present three novel MAV platforms which are the main object of study in this thesis. Moreover, it is intended to provide readers with a new outlook on the applicability for hybrid and modified aerial robots.

3.1 Problem Formulation

Major concern regarding the utilization of electric machines in mobile robotics essentially lies in serious energetic limitations imposed by low efficiency of current batteries. All outstanding possibilities of usage and potential improvement of a great variety of mission involving MAVs, as it was previously presented in Chapters 1 and 2, may be seriously detracted, limited or become unfeasible depending on the mission range and the limitations in available energy. The techniques proposed in this thesis refer to constructive aspects that may open new possibilities on the improvement of lifetime of aerial robots. We are interested in understanding how morphological adaptations may impact in experimental field applications.

3.1.1 The Initial Deployment Problem Fundamentals

Well designed and fine tuned MAVs (specially those whose flight is omni directional) are extremely stable and may precisely remain in a given point to accomplish a given goal. Yet, in most of cases the region of interest may be distant to the base launching. In that case, most of energetic resources may be completely wasted during round trip flight. Hence, it is important to firstly look at the deployment problem, which has been first addressed for AGVs (Autonomous Ground Vehicles) utilization (BARILI et al. (1995)) (MEI et al. (2005)). Figure 3.1 depicts the initial deployment problem, where all possible situation are illustrated. Ideally, a MAV should be able to achieve goals from 1 to 5, that is, leave the base (1), fly to the target point (2), accomplishing a given task (3), head back (4) and get to base in safe (5) (yellow lines). Withal, MAVs actual energetic capabilities would probably allow only tasks 1 to 3 to be fulfilled.

The initial deployment problem may be partially solved *1)*by considering the in-flight launching possibility. Whether it is a fixed-wing or a rotary wing aircraft, scope of application could be drastically extended if, somehow, one could settle the MAV as near as possible to the target point. This possibility opens to two different missions, one that fits perfectly to rotary-wing and the other that matches fixed-wing MAVs. Both will be addressed shortly thereafter.

The slung-payload load carriage and the in-flight launching has been widely employed specially in military. However, as far as we know, the in-flight launching of MAVs has never been done before. It is well-know that it carries out big challenges to be successfully accomplished. Nevertheless, it does not represent an impossible perspective whatsoever, as it was presented in Chapter 2.

Figure 3.1: The initial deployment problem depicted in one image. Ideally, the MAV is expected to carry out stages 1 to 5. That does not represent practice whatsoever.

Another possibility regarding the initial deployment problem is 2) to minimize waste of energy for water applications. For example, a MAV may offer special hybrid features to navigate on the water environment and still be able to take off and land anytime even on the ground. That could extend the mission range since, a priori, the MAV may spend much less energy in water than while it is airborne. Besides, this possibility may bring up novel perspectives to aquatic application (e.g., water quality monitoring). A clear demand to automatize water analysis for a huge variety of reasons has raised lately, from biological/ecologic to human supply purposes (FORSBERG et al. (1995)) (ONU (2014)).

3.2 Novel Ways on Deployment, Launching & Operation

3.2.1 In-flight Launching of Quadrotors

As an illustration, a given electric flying robot (MAV) is sent from the base camp to a non-structured inaccessible remote area for a given task. A second aircraft could act as a carrier/mother-ship to which the quadrotor may be properly attached or even be released as a slung-payload. The MAV may be then in-flight launched as near as possible over a point of interest (Fig. 3.2). Passive aerodynamic breaking devices may decelerate the MAV to a proper terminal speed and pose the MAV in a appropriate attitude so that minimum effort from motors

are requested at descent phase. Moreover, a parachute may be designed to decrease speed and to be released shortly after descent. Energetic resources from batteries may be effectively used at the very moment when the MAV reaches the target point. That may bring sounding and considerable battery saving, which may directly impact on the rise of mission time, range and usage of embedded equipment.

Figure 3.2: Conceptual simulation of in-flight deployment of a specially shaped quadrotor.

Design and shape are crucial issues regarding efficient aerodynamic performance. One point however deserves to be investigated. The CoG position of the MAV may notable influence the overall stability of the aircraft in the in-flight launching. This will be extensively outlined in the further sections.

Before any further discussion, it is important to get it clear that any discussion on the ways, means and operational details of achievements that surround the in-flight launching, as for the interaction between MAV and mother ship and the nature of launching, are completely out of the scope of this thesis. We are straightly looking at the MAV point of view, not to the carrier aircraft nor to the phenomena that surround its accomplishment.

Deceleration Devices: Fixed Air Brake

A fixed speed brake is designed so that we may better understand the behavior of a MAV during descent. In Chapter 5 we run both CFD (Computer Fluid Dynamics) and wind tunnel experiments on that. The idea is that more that offering high drag forces during descent, it may have a small influence over stability. The MAV should keep its integrity in hovering also. Furthermore, considering the quadrotor attachment in a pylon or any deployable fixing structure, a convex surface may offer less drag than concave one.

3.2.2 In-Flight Launching of Hybrid MAVs

As it was outlined in Chapter 2, *a priori*, rotary-wing aircraft are the only possible configuration that allows that VTOL launching to be performed. Besides, omni directional flight is highly desirable quality offered by such machines. In the other hand, fixed-wing aircrafts present some other interesting aerodynamic features such as the gliding ratio ability.

Hence, what if a MAV may feature both characteristics? A MAV could take off in the VTOL configuration, as any regular helicopter but still perform the transition to the fixed-wing-like flight stunt (Fig. 3.3-(a)). Yet, the MAV could perform the transition back to quadrotor (Fig. 3.3-(b)). Hence, hybridization may bring outstanding qualities to MAVs where it could dispose of the best of each one in a single frame.

In that case, considering the circumstances of the in-flight launching and the possibilities previously discussed, a MAV may glide after being released, making exclusive use of the potential energy to navigate. The aircraft may head to the desired point saving precious energetic resources. Shortly before getting to point it may be realigned to the helicopter set up.

Figure 3.3: Conceptual simulation of a transition flight between VTOL and fixed-wing aircraft and *vice versa*.

3.2.3 Water Navigation of MAVs

One very attractive possibility is to provide a MAV with the ability to fully and stably perform maneuvers in water, in order to offer aquatic environment navigation capabilities. A MAV may be designed to water navigate with less energy than in airborne missions. Obviously,

the MAV may also land on the ground. Resulting platform may be a multi environment aircraft that may operate in any of the three scenarios (ground, air and water) (Fig. 3.4). Hybridization results in several project requirements. Furthermore, final flight mechanics leads to interesting problems, which are outlined in Chapter 6.

Figure 3.4: Conceptual simulation of a hybrid quadrotor/vessel MAV in water landing and navigation.

3.3 Morphological Adaptations: Sharky, SquidCop & H₂Omni Platforms

In this section we address the morphological adaptation problem driving our analysis to the feasibility point of view. We provide initial information around the three platforms described in this thesis with a straight look in the optimal design, followed by a robust methodology on the design of MAVs. We initially present analytical results to aid on the refinement and strengthening of final aircrafts described in Chapters 4, 5 and 6, which will lead to the results presented in Chapters 8 and 9.

3.3.1 SquidCop: Morphological Adaptations on Quadrotors

First attempts to reach hybridization led us to design a morphologically adapted quadrotor whose levers, (differently from conventional ones could act as airfoils. That would be feasible either to incorporate a given foil section to the surfaces or even let them flat (Fig. 3.5-(a)). A flat surface parallel to the air flow is highly indicated as stabilizer for longitudinal stability (the same principle of an arrow).

A second sketch is meant to incorporate passive breaking devices (a fixed parachute) in order

to increase drag during descent (Fig. 3.5-(b)). A concave hemisphere shape device presents elevate drag coefficients ($C_D \approx 1.5$) (MISES (1959)). Then a third sketch was finally proposed (Fig. 3.5-(c)), considering a quadruple hemisphere concave shape fixed breaking structure in order to add even more drag to the MAV during a possible in-flight launching vertical free fall.

In this thesis, we split SquidCop problem in two distinct parts. Firstly, we watch the helicopter from the breaking device angle. We deal with the full characterization of the breaking system both with CFD and experimental wind tunnel evaluation. Secondly, we take care of the stability problem, which has leaded to a fourth layout (Fig. 3.5-(d)), which presents a CoG shifting and was restructured in order to be lighter and offer less drag than conventional helicopters during conventional flight.

Figure 3.5: Evolution of SquidCop quadrotor to meet project requirements.

Throwing a body in the air is characterized by a typical stochastic problem where is not possible to determine the states of the falling object. For a well succeeded mission, in the best of the cases, controllers would have to dispose of considerable effort which represents huge amounts of energy wasted from batteries. Furthermore (and most important), the stabilization may never be accomplished. From the energetic perspective, any attempt to stabilize the MAV from torque control ultimately does not represent the best solution. To summarize, under such unprovable conditions, the MAV may hit the ground dead. From this perspective, whether the MAV is endowed with breaking devices or not, it is highly desirable that the wholly structure presets minimum stability. Considering the MAV attitude during descent, one useful trick is to shift CoG as low as possible so that the MAV may present a conventional pendulum features. The idea is favor the MAV correct positioning after launching.

Preliminary Results

Conventional quadrotors definitely do not offer passive stability. For a matter of comparison, we performed the open loop characterization of both conventional quadrotor (©AscTec Pelican) and SquidCop (Fig. 3.5-(d)). The conventional aircraft is unstable. In the other hand, SquidCop offers sounding passive stability characteristics whose meets stability requirements for a possible in-flight launching mission ($\omega_n \approx 6.2903\text{rad/s}$ and $\xi \approx 0.0476$). Thus, It is expected that the MAV pose may converge to the correct position during free-fall (Fig. 3.6). We present a full analysis in Appendix A.

Figure 3.6: Simulation of in-flight deployment of a conventional MAV and SquidCop.

3.3.2 Sharky: A Hybrid Fixed-Wing/Quadrotor Aircraft

From the concept inherent to SquidCop that was previously build up, a second MAV started to be figured out. Now, the qualities of an airplane and a quadrotor MAV started to be put together. Resulting platform should be efficient during airplane configuration while offering the desired characteristics of a quadrotor. Both features, *a priori*, should be performed in two distinct phases of flight.

Main goal is to produce a rigid aircraft, with no interchangeable parts (except control sur-

faces) whose same motor group that propels the quadrotor must also provide thrust to the MAV when it flies as an airplane. For the sake of simplifying the problem, all four motors are radially equidistant. Otherwise, that could lead to a asymmetric control problem, which could turn the problem more complex that it really is.

First essays were carried out with XPS (extruded polistirene) small scale models (Fig. 3.7-(a)) and later a real scale started to be modeled in CAD (Fig. 3.7-(b)). Final model is a fixed wing airplane provided with two mirrored vertical stabilizers comprehending a cross shaped structure. Such constructive features may allow the MAV to perform coordinate longitudinal flight and also perform 6-DoF omnidirectional maneuvers (Fig. 3.7-(c)).

Figure 3.7: First adaptations on Sharky hybrid MAV: from a simple low-scale depron model (a), going through a first sketch (b) to the final design (c).

As the biggest challenge on the design of an aircraft with such characteristics lies in achieving stability in the fixed-wing set up, first task is to try the above layout for static stability achievement. We must extract some characteristics from the new architecture so that they may ensure minimum stability to fly properly.

As long as we attest minimum stability for the fixed-wing set up, as for determining proper mass distribution, CoG and neutral point position, remaining problem refers to the quadrotor configuration. Figure 3.8 illustrates the CoG position for the stable and balanced fixed-wing set up. In the other hand, since CoG position remains unaltered, we have a 3D Inverted Pendulum Mode (3D-IPM) problem in the quadrotor configuration.

The 3D-IPM is a classic problem and may be easily solved. However, chronologically speaking, the first problem that must be solved reaching minimum stability in the fixed-wing set.

Figure 3.8: Two different problems related to Sharky CoG position: the stable and balanced fixed-wing aircraft (left) and the quadrotor as a 3D-IPM (right).

Preliminary Results

Aiming to evaluate static stability for Sharky fixed-wing MAV, preliminary numerical analysis was run employing the Panel and VLM (Vortex Lattice Method) methods (ETKIN (1996)). The goal is to attest if such structure, with proper mass distribution and CoG correct positioning leads to a stable aircraft that may fly with minimum static stability (Fig. 3.9). It is expected to extract qualitative information about lateral and longitudinal stability of the MAV so that we may proceed the full aircraft design. A full theoretic background is addressed in Chapter 4.

Figure 3.9: Sharky VLM/Panel analysis. The MAV described in panels (a) and running numerical aerodynamics simulation (b).

Tables 3.1 and 3.2 summarizes VLM/Panel preliminary analysis results for both lateral and longitudinal stability for the first sketch of Sharky MAV.

Table 3.1: Eigenvalues for Longitudinal Modes

Longitudinal Modes		
<i>Mode</i>	<i>Eigenvalue</i>	<i>Status</i>
Short Period	$-0.5417 \pm 2.325i$	stable
Phugoid Mode	5.525 ± 0	unstable

Table 3.2: Eigenvalues for Lateral Modes

Lateral Modes		
<i>Mode</i>	<i>Eigenvalue</i>	<i>Status</i>
Roll	$-5.132 \pm 0i$	stable
Dutch Roll	$-2.419 \pm 10.98i$	stable
Spiral	$1.624 \pm 0i$	unstable

First numbers reveal that the proposed architecture is feasible since eigenvalues are negative, which is related to static stability. Once we met static stability for the fixed-wing configuration, resulting quadrotor configures a 3D-IPM (3D Inverted Pendulum Mode) problem, which is a standard issue with realizable solution. Those subjects are widely explained in Chapter 4.

The MAV presents minimum stability requirements. As one may note, regarding to longitudinal modes, Sharky presents the following stability frequency characteristics:

- a pair of stable complex eigenvalues for the short period mode;
- one real unstable eigenvalue for phugoid mode;

As for lateral modes, we have:

- one real stable eigenvalue for the roll mode;
- one pair of stable complex eigenvalue for Dutch roll mode;
- one real unstable eigenvalue for spiral mode;

The fact that phugoid and spiral modes present unstable characteristics does not represent full instability whatsoever. Several military and civil airplanes present the same features. However, the real pole may be easily dislocated to stable quadrant by the active control surfaces (ETKIN (1996)).

3.3.3 H₂Omni: A Hybrid Air-Water-Ground Quadrotor

Main difficulty in designing a MAV that may be able to navigate both in the air and in the water lies in shaping the whole structure so that it may be efficient in both environments. One third variable must be introduced which is the static stability meanwhile it remains on the ground (landing gear).

One of the first shapes to be considered (Fig. 3.10-(a)) to the structure is the streamlined body (drop-like) due to the low drag coefficient ($C_D \approx 0.05$). That fits very well to fixed-wing aircrafts or any other craft whose movement is essentially longitudinal (in the same line of the fuselage). However, considering that the MAV kinematics should occur in all directions, this set up presents some disadvantages. For example, due to the asymmetry in the yz and xy planes, the smallest flow stream may cause undesirable pitching and yawing moments. In both cases, that may lead to difficulties on controlling and CoG balancing and may favor the MAV instability at a minimum disturbance. This problem, nonetheless, must be better investigated.

Figure 3.10: Three of initial shapes for H₂Omni MAV.

Secondly, the sphere shape structure (Fig. 3.10-(b)) would certainly bring relevant improvements when it comes to symmetry although the overall aero/hydrodynamically raising ($C_D \approx 1.4$). However, main drawback lies in the inefficient hydrodynamic thrust (Archimedes buoyancy effect). Water experiments have shown that such configuration is not sufficient to sustain the embedded equipment in terms of total hydrodynamic thrust (please refer to Chapter 6 for theoretical background). Enlarging central semi sphere could partially solve the issue. Besides of increasing drag, minor spheres would have to be displaced downwards in order to touch the water level. Otherwise, the helicopter would remain unlevelled/uneven, which is still a problem for landing in the ground also (Fig. 3.11). That would bring fixation problems and structural weakness. The second solution would be enlarging the spheres beneath each motors. However, one may instinctively note that, besides of increasing overall drag. That would result

in considerable loss of propellers efficiency and consequently detract thrust capabilities, which is not a option whatsoever (Fig. 3.12). Furthermore, that may turn the MAV susceptible to instability (due to the arm provided by the levers).

Figure 3.11: Asymmetric shape of “Layout a” brings uneven/unleveled landing gear. That may raise issues when calibrating inertial unit at the start up.

Figure 3.12: Limitations on the “layout b” due to the small volume of buoyant material. Desired small aerodynamic drag is followed by inefficiency on hydrodynamic (left) and propellers thrust (right).

When it comes to overall flight efficiency, the torus shape (Fig. 3.10-(c)) is interesting since the smooth round form at the central part, symmetry and the complete absence of corners and uneven structures considerably favors movement along the xy plane both in water and in the air besides of offering static stability on the water and ground (Chapter 6). The H₂Omniv MAV is crafted from expanding low density polyurethane and polyethylene foam. Resulting combination leads to a low density and an extremely low weight floating structure. More detailed information concerning technical data may be find in Appendix D.

Preliminary Results

Table 3.3 shows a summary of main pros and cons of each layout. The comparison is based on numeric analysis run through CFD (Appendix D) and also on the requirements for an optimal overall performance, considering all aspects described in this section. Figure 3.13 shows the graphical results of CFD analysis bringing the stream lines pattern and the dynamic pressure gradient as well for each one.

Table 3.3: Qualitative analysis between the three candidates to H₂Omni layout.

<i>Layout</i>	<i>Parameter</i>			
	Maneuverability	Landing Gear	Overall Stability	Buoyancy/ Payload
(A)	- Efficient along x - Inefficient along y and z - Undesirable moment about z and y	Unleveled	Inefficient	Good
(B)	- Full efficiency	Unleveled	Inefficient	Inefficient
(C)	- Medium efficiency along z - Efficient along x and y - Full efficiency on rollings	Good	Excellent	Excellent

3.4 Conclusions

In this Chapter we presented the initial deployment problem, which is the main inspiration to construct our novel MAVs. We have shown that energetic constraints may severely detract the utilization of the outstanding benefits offered by MAVs. In the other hand, we have shown that, under such limitations, other possibilities may raise.

We have presented the hybridization and morphological adaptations for MAVs aiming novel possibilities: the in-flight launching may be a solution to improve MAVs deployment. From this side, MAVs may be adapted to be compliant with the challenges that surround that kind of mission. We presented two novel aircrafts that may present the desired characteristics to match the in-flight launching. We also presented a hybrid MAV that may possibly operate in the three environments. Hybridization of a vessel (with a hull) and a quadrotor may lead to an efficient aircraft that may navigate in water with minimum energetic demands and still be able to fly. We carried out an introductory and preliminary analysis of possible shapes and morphological aspects for the three MAVs aiming optimality. First results were extremely optimistic and grounds the refinement, optimization and characterization of Sharky, SquidCop and H₂Omni in Chapters 4, 5 and 6.

(a)

(b)

(c)

Figure 3.13: CFD stream line flow analysis results and dynamic pressure gradients ($[Pa]$) of layouts a, b and c.

Part II: Novel MAVs for Novel Missions

Next, we present three novel morphologies, which are the main subject of this thesis. One may find a full analysis from concept to design with a strong aim in the field application.

Chapter 4

Sharky Hybrid MAV

Main contribution of this chapter is to present the design and the evaluation of a novel hybrid quadrotor/fixed-wing aircraft that may potentially be employed to the missions described in Chapter 3. After an exhaustive study, final aircraft combines quadrotor to fixed-wing motor-glider airplane features. Resulting peculiar morphology is a versatile and stable low weight MAV platform named Sharky (Fig. 4.1).

Figure 4.1: Sharky first flight, in a *quasi*-transition from quadrotor to fixed-wing stunt.

“The shuttle doesn’t fly like anything else. The control surfaces are huge. When you move them, you reduce your wing area, so, at first, pulling up makes you sink. Pushing over makes you sink faster. Pulsing the stick gets you into serious trouble. Below a certain altitude, every input you make is going to be wrong.”

Ralph Gibson, American former pilot/astronaut about the space shuttle.

4.1 Problem Statement & Project Requirements

From the preliminary problem statement addressed in Section 3.3.2, the following project requirements must be fulfilled:

- Except for usual moving parts (propellers, flaps, ailerons and rudders) the whole structure must be rigid, fixed and non interchangeable;
- The MAV foil must produce lift as a regular airplane;
- Foil must present considerable gliding ratio coefficient;
- The MAV must naturally present low moment coefficient with no active control;
- The same motor group must work both for the motor-glider and for the quadrotor configuration as well;
- All four motors must necessarily be symmetrically distant from each other around Sharky airplane configuration;
- Altogether, motor-gliding and quadrotor operation must be stable;

Brushless electric motors are strategically positioned at the end of each one of the four foils. Thus, as long as Sharky flies as a regular airplane, the electric motor group provides longitudinal thrust to the UAV. Sharky is also provided with elevons that may be used to increase lift during take-off and landing/approaching, still acting as flaps, elevators and differential ailerons. Besides, the MAV is endowed with two mirrored vertical stabilizers, each one containing one rudder that may be differentially operated. Thus, it may perform coordinate maneuvers as any other airplane.

4.1.1 Sharky Features

Figure 4.2 shows Sharky in the motor-glider configuration. Thrust forces $F_{1..4}$ are independently achieved through the motor group denoted by four motors $M_{1..4}$. An interesting characteristic intrinsic to Sharky longitudinal dynamics lies in the fact that both the motor group and the surface commands (elevons and rudders) δ_1 , δ_2 , δ_3 and δ_4 may produce the correct moments so that the MAV may perform all maneuvers. In example, meanwhile Sharky flies in the motor-glider configuration, coordinate turns, pitching and yawing moments may be achieved from the correct combinations between motor angular speeds Ω_1 , Ω_2 , Ω_3 and Ω_4 . In the other hand, suppose that Sharky is flying in the gliding configuration (motor group not operating), the same maneuvers may be achieved from the correct surface command deflections

δ_1 , δ_2 , δ_3 and δ_4 . Hence, Sharky active control module may configure a redundant active system. A fault tolerant system may be achieved from the appropriate and well-tuned control architecture and configuration. One may resort to a great variety of combinations between motor group and surface controllers in order to improve the MAV maneuverability and controllability, even allowing aggressive maneuvers to be performed. However, this is out of the scope of this thesis and will be further implemented and investigated.

Figure 4.2: Sharky propulsion and control surfaces in the fixed-wing set up.

Regarding Sharky flight as a quadrotor (Fig. 4.3), omnidirectional coordinate flight (6 DoF) may be obtained from the correct combinations between motors angular speeds Ω_1 , Ω_2 , Ω_3 and Ω_4 . Although it is expected that Sharky performs low speed hovering flight in that configuration, the combination between correct surface command deflections δ_1 , δ_2 , δ_3 and δ_4 and motor group torques may improve maneuverability. That may be useful to expedite turns and translations, leading to a fast-maneuverable and more agile MAV. Nevertheless, this is also out of the scope of this thesis and will be implemented and investigated in the future.

As one may note, the main impact of the resulting platform is the fact that due to CoG balancing in Sharky fixed-wing configuration, quadrotor set up configures an 3D-IPM (3D-Inverted Pendulum Mode). The 3D-IPM problem is well-known and many solutions have been extensively proposed to it.

Generally, Sharky is designed to meet the following five essential and critical phases (SAM-PAIO et al. (2014c)):

- ***In-flight stable launching*** - The MAV may possibly be in-flight deployed from a carrier aircraft at a specific point;

Figure 4.3: Sharky propulsion and kinematics in the quadrotor set up.

- **Gliding Ability** - Sharky may glide as soon as it is launched from the carrier aircraft.
 - **Powered Flight** - The MAV may also fly assisted by the motor group;
 - **Airplane/Quadrotor Transition** - The MAV may switch between motor-glider and quadrotor at any flight time;
 - **Base Launching** - Sharky may perform vertical take-off/landing from/to any base level.
- Furthermore, Sharky may be hand launched by a human operator.

It is important to highlight, however, that the evaluation of flight phases above are out of the scope of this thesis. Only base launching followed by a *quasi*-transition state will be approached in experimental evaluation (Chapter 9).

4.2 Stability Analysis

Stability analysis of the wholly Sharky MAV shall be now broken in two parts. As the reader must have noticed, two stability criteria must be achieved. One is inwardly related to the fixed-wing problem of a regular airplane and the other for the inverted pendulum-like quadrotor.

As for the fixed-wing MAV, we focus this analysis in the wing itself and in the propulsion group influence in longitudinal stability (pitching moments). We establish an analysis of the influence of Sharky motor group in the longitudinal stability of the aircraft. The quadrotor stability analysis is addressed with a focus on the 3D-IPM.

4.2.1 Requirements for Static Stability in Fixed-Wing Aircrafts

An aircraft may be characterized essentially from the study of static stability itself, considering only its equilibrium states leaving (*a priori*) dynamics apart for a while. For a reliable and concise study of any fixed-wing aircraft, we must first address the static stability problem (ETKIN (1996))(NELSON (1998)). Later, dynamics will be incorporated. so that this analysis may end in the control of the wholly aircraft.

It is possible to separate stability of aircrafts in two distinct modes:

- *Longitudinal/Symmetric* - where the aircraft CoG moves in a vertical plane, with wings leveled;
- *Lateral/Asymmetric* - observation of rolling, yawing and side slipping movements considering angle of attack, speed and angle of elevation constant.

However, longitudinal analysis plays the most important role in static stability study since it is directly related to the pitching moment that drives an aircraft to be stable or not. In a simply way (not considering dynamics) this is named pitch stiffness.

Basically, pitch stiffness may be defined as the relationship between moment coefficient C_m and angle of attack α ($\frac{\partial C_m}{\partial \alpha}$), which may give important information about longitudinal stability. For the equilibrium state of an aircraft, the sum of external forces must be null. Thus, it is desirable that moments is also zero at a given angle of attack.

Figure 4.4 shows the typical pitch stiffness curve for both stable and unstable aircrafts. Observing curve (a), one may note that, as the angle of attack raises from the the equilibrium (trimmed aircraft) condition, C_m becomes negative. In the other hand, as α decreases, C_m turns positive. That characterizes the stable aircraft whose reaction will always be a restoring pitching moment, named positive pitch stiffness. In this case, the slope of the curve is negative ($\frac{\partial C_m}{\partial \alpha} < 0$).

Curve (b) shows a typical balanced negative pitch stiffness curve, whose slope is positive ($\frac{\partial C_m}{\partial \alpha} > 0$). In practical terms, when the angle of attack decreases from the equilibrium point, C_m is negative and when the angle of attack raises, pitching the aircraft up, C_m is positive. The practical effect of this phenomena is that wherever the aircraft nose is shifted up or down, aircraft will tend to rotate far from the equilibrium point. Altogether, those features characterizes an unstable aircraft.

Figure 4.4: Pitch stiffness characteristics for both stable and unstable behavior.

Solutions for Meeting Stability in Negative Pitch Stiffness Aircrafts

Several solutions may be available to make ($\frac{\partial C_m}{\partial \alpha} < 0$). Thus, the fact that a given airplane presents positive pitch stiffness by itself is not ultimately enough reason to make it unfeasible. Flying tailless wings in particular, as it is the case of Sharky, generally present unstable behavior (balanced negative stiffness) which is intrinsically related to the absence of the tail itself. However, some solutions to improve flying wings stability may be applied (ETKIN (1996))(NELSON (1998)):

- *Proper choice of CoG position* - usually, the farther forward the CoG is located, more stable the aircraft becomes;
- *Wing camber* - negative wing camber allows stable flight for $\alpha > 0$;
- *Flap* - when a flap is incorporated upwards to the trailing edge of a symmetric foil that may lead to positive pitch stiffness;

However, negative camber wings are not commonly used because they generally does not present satisfactory characteristics, limited CoG displacement and because C_d and C_L are poor. In the case of low Reynolds and low speed flight, flying wings may perform stable flight by the combination of a positive cambered foil and the far forward position of the CoG. As for the use of positive cambered wings, it turns necessary to incorporate an auxiliary device, such as a canard for example. Another solution for flying wings is the swept-back configuration. Resulting is that, the front part of the wing will present positive lift and the rear portion will present negative lift. The binary will impose a positive momentum to the wing.

The most common solution in strictly wing tailless aircrafts, which has become a wing variation, is the delta wing. When appropriately constructed, positive C_m can be achieved by

either twisting the tips or incorporating an upturned tailing edge flap (ETKIN (1996))(NELSON (1998)). In the case of Sharky, the following devices were incorporated:

- MH-60 wing profile with suitable aerodynamics features, due to reflexed trailing edge;
- control surfaces in order to correct pitch stiffness;
- CoG balance;

The choice for the MH-60 airfoil for Sharky took some sound characteristics into consideration, such as:

- Low drag coefficient (C_D);
- Low moment coefficient (C_m);
- Relatively high lift coefficient (C_l);
- Good performance at low Reynolds numbers;
- Had been successfully used in tailless airplanes;

The MH-60 airfoil (see foil cross section in Fig. 4.5) is widely used in flying wings and in well-know high performance aircrafts (e.g., Boeing F3-B) and presents some of the above characteristics (HEPPERLE (1999)).

Figure 4.5: Typical MH-60 cross section.

As we present in Section 4.4.1, the incorporation of control surfaces (as flaps) may successfully correct the pitch stiffness for Sharky MAV. Besides, the appropriate position of CoG leads to a better result.

Lift & Pitching Moment of an Aircraft

Total pitch and lift are direct functions of many parameters such as angle of attack (α), deflection of control surfaces (δ), Mach number, Reynolds, thrust coefficient and dynamic pressure. Dynamic pressure is directly related to aeroelastic effects. In this thesis, since we consider the operation of the Sharky aircraft in low Reynolds number and in low speeds, the MAV is considered rigid and aeroelasticity is then neglected.

In general, total lift and pitching moments are determined by estimating individual contributions of many parts: wing, body, nacelles, propulsion group, tail and their mutual interaction.

Obviously, all data concerning pitch and lift may be directly obtained by experimental tests in wind tunnel, as it will be presented in Section 4.4.1. However, in this section, parametric equations of longitudinal dynamics will be sketched.

Wing Lift & Pitching Moments

Aerodynamic forces are given by lift and drag in a lifting surface. Result is a pitching moment about CoG, which may be given by:

$$M_w = M_{ac_w} + (L_w \cos \alpha_w + D_w \sin \alpha_w)(h - h_{n_w})\bar{c} + (L_w \sin \alpha_w - D_w \cos \alpha_w)z \quad (4.1)$$

Assuming $\cos \alpha \approx 1$ and $\sin \alpha \approx 1$ and substituting dividing 4.1 by $1/2\rho V^2 S\bar{c}$, yields:

$$C_{m_w} = C_{m_{ac_w}} + (C_{L_w} + C_{D_w\alpha})(h - h_{n_w}) + (C_{L_w}\alpha_w - C_{D_w})z/\bar{c} \quad (4.2)$$

Experience has shown that the last term may be neglected and that $C_{D_w}\alpha$ is too small compared to C_{L_w} , which yields (ETKIN (1996))(NELSON (1998)):

$$C_{m_w} = C_{m_{ac_w}} + \alpha_w a_w (h - h_{n_w}) \quad (4.3)$$

Where $a_w = C_{L_{\alpha_w}}$ is the lift-curve slope of the wing.

Overall Pitching Moment: Neutral Point Analysis

Neutral point is the location of the aircraft where no pitching moment is observed. Total moment of the tailless aircraft may be expressed by:

$$C_m = C_{m_w} + C_{m_p} = C_{m_w} + C_L(h - h_{n_w}) + C_{m_p} \quad (4.4)$$

Considering mean aerodynamic center of the flying wing as a fixed point, yields:

$$C_{m_\alpha} = \frac{\partial C_{ac_w}}{\partial \alpha} + C_{L_\alpha}(h - h_{n_w}) + \frac{\partial C_{m_p}}{\partial \alpha} \quad (4.5)$$

Recalling that $\frac{\partial C_{ac_w}}{\partial \alpha}$ must be zero for a true mean aerodynamic center, we obtain:

$$C_{m_\alpha} = C_{L_\alpha}(h - h_{n_w}) + \frac{\partial C_{m_p}}{\partial \alpha} \quad (4.6)$$

The position of CoG h linearly influences C_{M_α} , as it may be noted from Eq. (4.6), whose value will be determinant to the signal of C_{m_α} . Hence, this is the ground for the statement that we may achieve a suitable $C_{m_\alpha} < 0$ so that the aircraft may achieve static stability. To summarize, h may be calculated in order to lead aircraft to be stable.

Position of CoG to which C_{M_α} is zero is hereafter represented by h_n . This particular position is named neutral point (NP). In the case of the flying wing, it has the same connotation of the mean aerodynamic center, and may be known by vehicle aerodynamic center. Thus, NP may be calculate from Eq. (4.5), assuming the left hand side as zero, yields:

$$h_n = h_{n_w} - \frac{1}{C_{L_\alpha}} \left(\frac{\partial C_{m_{acw}}}{\partial \alpha} - \frac{\partial C_{m_p}}{\partial \alpha} \right) \quad (4.7)$$

Substituting Eq. (4.7) into Eq. (4.5), we achieve the following simplification:

$$C_{m_\alpha} = C_{L_\alpha}(h - h_{n_w}) \quad (4.8)$$

Equation (4.8) is valid for any $\frac{\partial C_{m_{ac}}}{\partial \alpha}$ and $\frac{\partial C_{m_p}}{\partial \alpha}$, even for null values. Years of wind tunnel experimentation and in-flight measurements proved that it may safely be used to determine h_n .

The difference between NP and CoG is named static margin K_n , and is given by:

$$K_n = (h_n - h) \quad (4.9)$$

Recalling to the fact that an aircraft must ideally present $C_{m_\alpha} < 0$ in order to achieve positive pitch stiffness, it is reasonable to say that $h - h_n$, which leads to $K_n > 0$. In practical terms, CoG position must be forward of NP. To summarize, the farther CoG is ahead from NP, more stable is the aircraft ($K_n \gg 0$).

Pitching Moment Due to Propulsion

The simple presence of a propulsion system directly interfere in the pitching moment of an aircraft. Forces produced by engines/propellers acts around the pitching axis and contributes to

the raising or decreasing of pitching moment. This problem is essentially divided in two parts, First deals with the reaction forces due to the motor unity itself and the second that deals with the interaction between the aerodynamic slipstream of propulsion system with the aircraft. In this thesis we look only to the first one. In the case of Sharky, This is an extremely important consideration since its motors have an influence in the pitch moment of the MAV.

Longitudinal & Lateral Modes

Aircrafts stability may be determined essentially by the eigenvalues and eigenvectors which are related to its ability to suppress disturbances in some specific directions.

As for the longitudinal modes, a typical aircraft presents the following eigenvalues:

- one stable complex pair, which is related to the short period mode;
- one marginally stable or unstable complex pair, which is related to the phugoid mode;

Short period mode is related to disturbances in α and q and generally presents good damping abilities (ξ) while Phugoid mode is mostly related to disturbances in θ and u and presents long time oscillatory characteristics (Fig. 4.6).

Figure 4.6: Longitudinal modes of an aircraft: phugoid (above) and short period (bellow) modes.

Lateral modes are typically characterized by the following eigenvalues:

- one stable real eigenvalue, which is related to roll mode;
- one stable complex pair, which is related to Dutch roll mode;

- one marginally stable or unstable real eigenvalue, which is related to spiral mode;

State space representation of longitudinal dynamics of any aircraft is given by the following:

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = A_{long} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + B_{long} F_{long}(t) \quad (4.10)$$

Where $F_{long}(t)$ is the control input vector, A_{long} and B_{long} are the aircraft longitudinal dynamic matrices. Control vector $F_{long}(t)$ is given by:

$$F_{long}(t) = \begin{bmatrix} \delta_e & \delta_T \end{bmatrix}^T \quad (4.11)$$

State matrices A_{long} and B_{long} are obtained through:

$$A_{long} = \begin{bmatrix} X_u & X_w & 0 & -g \cos \Theta_0 \\ \frac{Z_u}{1-Z_{\dot{w}}} & \frac{Z_w}{1-Z_{\dot{w}}} & \frac{u_0+Z_q}{1-Z_{\dot{w}}} & \frac{-g \sin \Theta_0}{1-Z_{\dot{w}}} \\ M_u + \frac{M_{\dot{w}} Z_u}{1-Z_{\dot{w}}} & M_w + \frac{M_{\dot{w}} Z_w}{1-Z_{\dot{w}}} & M_q + \frac{(u_0+Z_q) M_{\dot{w}}}{1-Z_{\dot{w}}} & \frac{-M_{\dot{w}} g \sin \Theta_0}{1-Z_{\dot{w}}} \\ 0 & 1 & 1 & 0 \end{bmatrix} \quad (4.12)$$

$$B_{long} = \begin{bmatrix} X_{\delta_e} & X_{\delta_T} \\ \frac{Z_{\delta_e}}{1-Z_{\dot{w}}} & \frac{Z_{\delta_T}}{1-Z_{\dot{w}}} \\ M_{\delta_e} + \frac{M_{\dot{w}} Z_{\delta_e}}{1-Z_{\dot{w}}} & \\ M_{\delta_T} + \frac{M_{\dot{w}} Z_{\delta_T}}{1-Z_{\dot{w}}} & 0 \end{bmatrix} \quad (4.13)$$

State space representation of lateral dynamics of any aircraft is given by the following:

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{\phi} \\ \dot{r} \end{bmatrix} = A_{lat} \begin{bmatrix} v \\ p \\ \phi \\ r \end{bmatrix} + B_{lat} \eta \quad (4.14)$$

Where η is equivalent to $F_{lat}(t)$ and represents the control input vector:

$$F_{lat}(t) = \begin{bmatrix} \delta_r & \delta_a \end{bmatrix}^T \quad (4.15)$$

State matrices A_{lat} and B_{lat} are obtained through:

$$A_{lat} = \begin{bmatrix} Y_v & Y_p & -g_0 \cos \Theta_0 & Y_r - u_0 \\ \frac{L_v + i_x N_v}{1 - i_x i_z} & \frac{L_p + i_x N_p}{1 - i_x i_z} & 0 & \frac{L_r + i_x N_r}{1 - i_x i_z} \\ 0 & 1 & 0 & 0 \\ \frac{N_v + i_z L_v}{1 - i_x i_z} & \frac{N_p + i_z L_p}{1 - i_x i_z} & 0 & \frac{N_r + i_z L_r}{1 - i_x i_z} \end{bmatrix} \quad (4.16)$$

$$B_{lat} = \begin{bmatrix} Y_{\delta_r} & 0 \\ \frac{L_{\delta_r} + i_x N_{\delta_r}}{1 - i_x i_z} & \frac{L_{\delta_a} + i_x N_{\delta_a}}{1 - i_x i_z} \\ 0 & 0 \\ \frac{N_{\delta_r} + i_z L_{\delta_r}}{1 - i_x i_z} & \frac{N_{\delta_a} + i_z L_{\delta_a}}{1 - i_x i_z} \end{bmatrix} \quad (4.17)$$

4.2.2 The 3D Inverted Pendulum Problem in a Quadrotor

The unbalanced mass characteristic of Sharky in the quadrotor configuration reveals a classic problem which is the 3D Inverted Pendulum Mode (3D-IPM). Sharky equations of motion, of forces and moments are presented in Section 4.3, through the pendulum-like behavior may be attested. Generally, the 3D-IPM configures a rod attached to a xy plane, moving along it and also performing rotations θ_p and ϕ_p . Regardless of the non-linearities intrinsic to the 3D-IPM, control inputs f_1 and f_2 shall be in control in order to cancel moments around the pendulum. Figure 4.7 illustrates the classic problem. The 3D-IPM is ruled by the following ODEs:

$$\ddot{y} = \frac{g}{z}y - \frac{k_1}{z}(x\ddot{y} - y\ddot{x}) - \frac{1}{mz}u_r \quad (4.18)$$

and

$$\ddot{x} = \frac{g}{z}x - \frac{k_2}{z}(x - y\ddot{x}) + \frac{1}{mz}u_p \quad (4.19)$$

Where movement constraints are limited by the vector $[k_x, k_y, -1]$. For the sake of simplifying the analysis, suppose that the MAV moves along the plane xy , with no movement along z , yields:

$$\ddot{y} = \frac{g}{z}y - \frac{1}{mz}u_r \quad (4.20)$$

and

$$\ddot{x} = \frac{g}{z}x + \frac{1}{mz}u_p \quad (4.21)$$

Figure 4.7: The 3D-IPM problem inherent to Sharky quadrotor dynamics.

Main difference to the classic problem lies in the fact that, considering Sharky a rigid body, the rod and the plane xy present the same angular rates $\dot{\theta}_p$ and $\dot{\phi}_p$ (roll and pitch rates p and q).

Succinctly speaking, in the case of the Sharky quadrotor, the angular rotations caused by the unbalanced mass may be treated as a rolling disturbance. Compensation is achieved by a counter torque generated by the thrust of motors. That is, θ_p and ϕ_p may be compensated in the form of control inputs $U_{1..4}$, which promotes the counter torque as it is next discussed from the mathematical model.

Figure 4.8 shows a preliminary simulation from Eqs. 4.23 to 4.24 with a simple classic controller. In fact, the 3D-IPM is a standard problem and does not represent any problem into Sharky context.

Figure 4.8: Model-based simulation of Sharky in the inverted pendulum control problem.

4.3 Sharky Mathematical Model

Sharky modeling, as for the airplane or for the quadrotor configuration as well, leads to a full parametric model. In other words, the equations of motion may represent any MAV with the same features than Sharky (SAMPAIO et al. (2014c)). A parametric model is very useful for a wide variety of reasons such as simulation since one may resort to a single set of equations while only parameters change.

It is, indeed, an extensive work to model such aircraft and all equations are quite large. Hence, for the sake of objectivity, we present here only movement and force equations. All development is full accessible in Appendix B.

Main consideration prior to go through the final models is that we have worked with two distinct coordinate systems. One refers to the inertial coordinate system I and the other regards to the body-fixed coordinate system B . In the name of simplicity, we consider the same body-fixed frame for both configurations. One may have noted that, indeed, we start from the quadrotor frame. B fits well the usually coordinate systems for quadrotors. However, when we rotate the MAV about y axis, B differs from the conventional frames usually employed for aircrafts (NED - North, East, Down). Nevertheless, final equations are exactly the same as those originated if we used the NED system. Actually, one single modeling leads to a set of six equation that perfectly represents both sets.

Inertial coordinate system I is given by x axis backwards in the longitudinal direction, y is pointed to east and z is pointed upwards, while B depends on the configuration (Fig. 4.9).

Figure 4.9: Sharky coordinate frames for the fixed-wing (a) and quadrotor (b) configurations.

The equations of movement that describes the wholly aircraft are given by Eq. 4.22, as follows. Such equations depend on forces and moments, which are described as Eq. 4.23 and yields:

$$\left\{ \begin{array}{l}
 \dot{u} = \frac{1}{m_T} [-C_L(\alpha)_{Bcg} V_{cg}^2 + m_T g \sin(\theta) - c_{w1} u^2 \text{sign}(u) + F_{xs2} + F_{xs4}] \\
 \dot{v} = \frac{1}{m_T} [-F_{ys1} - F_{ys3} - c_{w2} v^2 \text{sign}(v) - m_T g \cos(\theta) \sin(\phi)] \\
 \dot{w} = \frac{1}{m_T} [-C_d(\alpha)_{Bcg} V_{cg}^2 - m_T g \cos(\theta) \cos(\phi) - c_{w3} w^2 \text{sign}(w) \dots \\
 \quad \dots + \sum_{i=1}^4 (b\omega_i - F_{zsi})] \\
 \dot{p} = \frac{1}{I_{xx}} [-z_g (F_{ys1} + F_{ys3}) - y_s (F_{zs2} - F_{zs4}) + bl(\omega_2^2 - \omega_4^2) \dots \\
 \quad \dots - 4Jqr - Jq(\omega_1 + \omega_3 - \omega_2 - \omega_4) + (I_{yy} - I_{zz})qr + I_{xz}(pq + \dot{r}) - c_{w4} p^2 \text{sign}(p)] \\
 \dot{q} = \frac{1}{I_{yy}} [-z_g (F_{xs2} + F_{xs4}) + x_g (F_{zs1} + F_{zs3}) + x_s (F_{zs1} - F_{zs3}) \dots \\
 \quad \dots + bl(\omega_3^2 - \omega_1^2) - bx_g(\omega_1^2 + \omega_3^2) + 4Jpr + C_{mBcg} V_{cg}^2 \dots \\
 \quad \dots + Jp(\omega_1 + \omega_3 - \omega_2 - \omega_4) + (I_{zz} - I_{xx})pr + I_{xz}(\dot{p} - qr) - c_{w5} q^2 \text{sign}(q)] \\
 \dot{r} = \frac{1}{I_{zz} + 4J} [-x_g (F_{ys1} + F_{ys3}) - x_s (F_{ys1} - F_{ys3}) - y_s (F_{xs2} - F_{xs4}) \dots \\
 \quad \dots - d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2) + I_{xz}(\dot{p} - qr) + (I_{xx} - I_{yy})pq]
 \end{array} \right. \quad (4.22)$$

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} R_{zyx} & 0 \\ 0 & Id \end{bmatrix} \begin{bmatrix} U_1 - c_{W1}u^2 + F_{s2x}(\delta_{s2}) + F_{s4x}(\delta_{s4}) \\ U_1 - c_{W2}v^2 + F_{s1y}(\delta_{s1}) + F_{s3y}(\delta_{s3}) \\ U_1 - c_{W3}w^2 - \sum_{i=1}^4 F_{siz}(\delta_{si}) \\ l(U_2 - c_{W4}p^2) + r_{s1z}F_{s1y}(\delta_{s1}) + r_{s2y}F_{s2z}(\delta_{s2}) + \dots \\ r_{s3z}F_{s3y}(\delta_{s3}) - r_{s4y}F_{s4z}(\delta_{s4}) \\ l(U_3 - c_{W5}q^2) - r_{s1x}F_{s1z}(\delta_{s1}) - r_{s2z}F_{s2x}(\delta_{s2}) + \dots \\ r_{s3x}F_{s3z}(\delta_{s3}) - r_{s4z}F_{s4x}(\delta_{s4}) \\ Kl(U_4 - c_{W6}r^2) - r_{s1x}F_{s1y}(\delta_{s1}) + r_{s2y}F_{s2x}(\delta_{s2}) + \dots \\ r_{s3x}F_{s3y}(\delta_{s3}) - r_{s4y}F_{s4x}(\delta_{s4}) \end{bmatrix} + \dots \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} \quad (4.23)$$

Control action vector $U_{1..4}$ are related to rotation of the motors, and is given by:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & -b & 0 & b \\ b & 0 & -b & 0 \\ d & -d & d & -d \end{bmatrix} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} \quad (4.24)$$

Naturally, it is notable from Eq. 4.23 that the equations of movement are dependent of both the influence of propellers rotations and the control surfaces deflection, as we have introduced in Section 4.1. That is true for both configurations.

4.4 Design Results

4.4.1 Wind Tunnel Characterization

All experimental aerodynamic tests were run at USP/EESC/LAE wind tunnel (Fig. 4.10). Please refer to Appendix F for detailed technical information about LAE wind tunnel. Wind tunnel tests were run at the real speed at which is expected that Sharky flies. Reynolds number and the MAV real scale were extremely favorable to exactly reproduce real flight conditions. Wind speed at the test section was around 85 Km/h. Test data corrections follow ESDU (ESDU (2015)) norms for closed-circuit/closed-wall wind tunnels.

Figure 4.10: Sharky mounting inside the test section of LAE wind tunnel.

Figure 4.11 shows C_L plot at the baseline (elevation angles to 0°). Maximum lift achieved is $C_L \approx 0.6$. Still, stall occurs at an angle of attack $\alpha \approx 14^\circ$. Zero lift coefficient happens at $\alpha \approx -3^\circ$.

Figure 4.11: Sharky lift coefficient curve.

Figure 4.12 shows that minimum drag occurs at $\alpha \approx 0^\circ$. As it was expected, C_D raises as the angle of attack is increased. An important aspect that must be taken into account is that glide ratio can not be ensured just by raising angle off attack.

Figure 4.12: Sharky drag coefficient curve.

Figure 4.13 shows both previous plots together. One important analysis is to be done from the stall angle. At that point, it is noted that C_D raises faster as α is increased.

Figure 4.13: Lift & drag coefficients curves in the same plot.

Figure 4.14 shows lift curves to different angles of attack and different elevon angles. It is noted that C_L considerably increases as elevon angle also increases. Furthermore, stall angle decreases. In such circumstances, the wing produces more lift but stalls earlier than at the baseline with flat elevons. As it can be noted from the plot, the distance between curves is proportional to the difference between elevon angles. In other words, the elevon works appropriately and is in compliance to which it was designed to. Figure 4.15 shows Sharky drag polar.

Figure 4.14: Lift coefficients to different elevon angles.

Figure 4.15: Sharky drag polar (lift-drag relation).

Figure 4.16 shows gliding ratio at different angles of attack. Maximum gliding ratio is observed at $\alpha \approx 6^\circ$. Figure 4.17 shows distinct gliding ratios to different elevon angles. It is noted that an elevon deflection $\delta \approx 10^\circ$ produces the best gliding ratio (10 : 1) at the lower angle of attack ($\alpha \approx 2^\circ$).

Figure 4.16: Sharky gliding ratio.

Figure 4.17: Sharky gliding ration to variable α and elevon deflection.

Besides, a raising elevon angle does not necessarily implies gliding ratio increasing since drag raises as lift grows. Figure 4.18 shows C_L vs. C_D plot at the baseline.

Figure 4.18: Sharky C_L Vs. C_D relations.

Moment coefficient C_m linearly changes due to changes in lift coefficient C_L . That is, as angle of attack raises (and, consequently C_L raises), aerodynamic moment also raises (Figure 4.19). Longitudinal pitching tendency raises as well, as C_m also increases (Figure 4.20).

Figure 4.19: Sharky moment coefficient to variable α .

Figure 4.20: Sharky moment coefficient to variable C_L .

4.4.2 Sharky Qualitative Optimization Based in Wind Tunnel

An important qualitative result obtained in wind tunnel characterization is the observation of vorticity in determined points in the wing under certain circumstances. Sharky delta wing presented a considerable level of tip stall as the angle of attack began to be increased. This is a well-known phenomena in delta wing airplanes. Figure 4.21 shows the vortex formation along Sharky left foil. It may be noted that streamlines begin to twist as the angle of attack raises.

The vortex starts right at the wing tip. We may clearly see tip stall propagation towards root chord. Typically, tip stall may be prevented by endowing the wing with a small tip twist. The effect that is produced by the wing twist aims to rectify lift distribution so that the lift line approximates to the elliptical fashion.

However, it is expected that, due to the fact that Sharky propellers are positioned right at the tips, the air stream produced by it may favor the streamline to present a considerable level of laminarity at the tips.

Figure 4.21: Tip stall raising as the result of angle of attack increasing.

With a look in Sharky fuselage optimization, as well as in the improvement in the wing characteristics, a second layout was built. Figure 4.22 shows the new MAV. We replaced the delta wing by a swept-back one with the engines mounting in such position that may improve

flow streamline (Section 4.2.1).

The new design was first evaluated with panel/VLM method once again, in order to check the new layout characteristics, which is outlined in the next section.

Figure 4.22: The optimized new Sharky MAV prototype.

4.4.3 Longitudinal & Lateral Modes

Based on the optimistic preliminary evaluations presented in Chapter 3, and in the optimization of Sharky body based on wind tunnel evaluation, numerical panel/VLM method was run one more time. We used XFLR5 software which is an open source platform for longitudinal and lateral stability analysis of foils, wings and aircrafts subject to low Reynolds numbers operations. Software algorithm solves the aircraft equations of motion and follow theoretical background proposed in (ETKIN (1996))(NELSON (1998)).

Firstly, the aircraft was defined as a series of panels, which are defined by length (l), root (c_i) and tip chords (c_{i+1}), leading edge offset at root and tip chords (h_i and h_{i+1} , respectively), dihedral angle and the object mesh itself for the VLM (Vortex Lattice Method) analysis. Secondly, XFLR5 then performs CoG and inertia tensor calculation from the aircraft geometry. All points of concentrated mass is also included, which is necessary to guarantee reliability of the simulation and preserve Sharky mechanical characteristics.

Figure 4.23 shows the new Sharky layout panels in XFLR5 GUI. Tables 4.1 and 4.2 summarize VLM/Panel analysis results for both lateral and longitudinal stability, respectively. The complete data, as all stability plots, stability derivatives and matrices may be found in Appendix B.

Figure 4.23: Optimized model of Sharky MAV with VLM/Panel analysis. We may see the new layout described in panels (a) and running numerical aerodynamics simulation (b).

Table 4.1: Eigenvalues for longitudinal modes.

Longitudinal Modes				
<i>Mode</i>	<i>Eigenvalue</i>	ω_n [Hz]	ξ	<i>Status</i>
Short Period	$-21.83 \pm 22.68i$	3.61	0.693	stable
Phugoid Mode	$0.002145 \pm 0.639i$	0.102	0.003	unstable

In order to show that it is possible to turn phugoid and spiral mode stable, we have inserted a small gain control over longitudinal and lateral DoF. A positive result was achieved on making phugoid and spiral mode to respond stably. Figures 4.24 to 4.26 shows angular rates response to an impulse disturbance over the two modes. As one may see, active control may turn phugoid and spiral mode stable.

Figure 4.24: Rolling rate p lateral stability evaluation.

Table 4.2: Eigenvalues for lateral modes.

Lateral Modes				
<i>Mode</i>	<i>Eigenvalue</i>	ω_n [Hz]	ξ	<i>Status</i>
Roll	$-30.23 + 0i$	0	0	stable
Dutch Roll	$-0.508 \pm 4.284i$	0.682	0.118	stable
Spiral	$+0.02164 + 0i$	0	0	unstable

Figure 4.25: Rolling rate q around in lateral stability evaluation. Figure 4.26: Yawing rate r in lateral stability evaluation.

4.4.4 Influence of Sharky Motor Group to Moment Coefficient

Perhaps the most important evaluation (related to the previous stability analysis) lies in Sharky longitudinal stability control since the greater the C_m eventually reaches, more active control it will be necessary to drive the MAV to the in-flight equilibrium point. As it was discussed in Section 4.1, Sharky motor group configuration is strategically installed so that it may produce the all DoF of a motor-glider airplane. Thus, motors $M_1 - M_4$ torques could also be employed to control pitching oscillations and moments that might possible be intrinsic to Sharky constructive parameters.

Sharky pitching characteristics previously estimated from wind-tunnel experiments mixed to Eqs. 4.1 and 4.2 may lead to a new plot with the C_m vs. C_l considering the active longitudinal control from elevators. Figure 4.27 shows wind-tunnel results concerning the pitching moments for all possible attitude angles and elevon/flapping sets. For all situations, it may be noted that maximum reached pitching moment is $C_m \approx \pm 0.015$. That may be concluded that, due to the small C_m values, a little control effort from both elevons and motor groups will be requested. From the energetic perspective, less effort from battery charge would be wasted in Sharky stabilization.

Figure 4.27: Sharky moment analysis in wind tunnel to variable C_L and elevon deflection.

4.5 Conclusions

In this chapter we presented detailed information about a novel hybrid MAV named Sharky that combines fixed-wing airplane and quadrotor features in the same frame. We provided important and relevant information regarding to the Sharky MAV stability, looking at the two possible configurations.

We presented a full mathematical model of the wholly MAV, firstly aiming to reach fixed-wing both longitudinal and lateral stability. At the same time, after reaching a trimmed and minimally stable airplane, the quadrotor 3D-IPM stability problem was outlined. A preliminary result on the 3D-IPM was presented, showing that stability for the quadrotor set up is feasible.

Results were taken from the full characterization of Sharky aerodynamics, which gave us sounding information regarding the MAVs longitudinal controllability. Characterization of the wing pitching moment and its reflects on the active control were related and analyzed. We could see that, from the features extracted in wind tunnel tests and based on Sharky propulsion

features, longitudinal stability may be efficiently achieved.

Still from wind tunnel characterization, we proposed an optimization of the MAV design, aiming to improve its aerodynamic qualities. The new design was tested using VLM/Panel method through which longitudinal and lateral modes could be estimated. All stability eigenvalues shows the the MAV presents good dynamic tendencies in open loop control. Furthermore, we have simulated the aircraft under minimum longitudinal control gain. Results show that reaching global stability is perfectly feasible.

All above results are part of a complex process o validation of Sharky MAV, both for the fixed-wing and the quadrotor set up as well. Results are optimistic, so that it contributes to following flight simulations in Chapter 8, vision motion capture tests in Chapter 9 and on-the-field evaluation presented in Chapter 10.

Chapter 5

SquidCop MAV

The contribution of this chapter is the design of SquidCop (Fig. 5.1), a rotary-wing aircraft in the quadrotor configuration whose center of gravity is shifted downwards in order to improve passive stability looking at the in-flight launching possibilities. Moreover, the MAV final performance offers interesting filtering characteristics. We split the analysis in two distinct parts. Firstly, we focus our attention to the design looking at the MAV CoG shifting. Secondly, we perform a full analysis and characterization of the MAV under the influence of one fixed air break to the whole structure. That is the prelude to a better understanding about the new concept.

Figure 5.1: SquidCop during a very well succeeded maiden flight in a windy afternoon.

5.1 Problem Statement & Project Requirements

As it was previously presented in Chapter 3, for simplicity matters, conventional quadrotors are regularly crafted considering the mobile coordinate system and the MAV center of gravity to be coincident, which allows many modeling simplifications (BOUABDALLAH et al. (2004)). However, considering the circumstances of the in-flight deployment, regular MAV controllability turns difficult as the pose of the MAV may not be determined whatsoever (Appendice A).

Thus, SquidCop must be designed considering the following and sound criteria:

- speed break must offer considerable drag forces along the the longitudinal axis only in the counter direction of the flow stream;
- the aircraft must present low drag coefficient direction of the flow stream;
- still, drag must be minimum when the MAV is translating in hovering flight;
- the MAV must be stable during free-fall and while navigating in nominal operations;
- battery usage must be none or minimum at descent;

Differently than Sharky in the quadrotor set up, SquidCop presents its CoG shifted down along z axis by structurally stretching the body along z axis. Whereas battery (which represents $\approx 40\%$ of total weight) is positioned at the landing gear, CoG is naturally displaced downwards. Figure 5.2 illustrates SquidCop coordinate system scheme and the CoG position as well.

5.2 SquidCop Mathematical Model

The mathematical representation of SquidCop MAV exactly follows the equations of motion of Sharky in the quadrotor configuration. Hence, for the sake of non-redundancy, SquidCop dynamic and kinematic equations will be omitted. One may refer to Sections 4.3 to resort to such equations. For a more detailed developing please refer to Appendix B. Nonetheless, all analysis that are carried out from now on are based on such equations.

5.2.1 Considerations on the 3D Conventional Pendulum Problem

SquidCop presents conventional pendulum behavior. Main difference between SquidCop characteristics to the classic problem lies in the fact that, considering SquidCop a rigid body, the rod and the plane xy present the same angular rates $\dot{\theta}_p$ and $\dot{\phi}_p$ (roll and pitch rates p and q). Figure 5.3 depicts the problem. Nonetheless, such as in the classic problem, disturbances

Figure 5.2: SquidCop frames for the configuration with no speed break attached.

over ϕ and θ are suppressed by imposing a counter torque couple about x and y axis which have a linear component $[f_{px} f_{py}]$ along the same axis.

In truth, in the case of the SquidCop quadrotor, angular rotations caused by external forces and moments may be considered as angular disturbances. Compensation is achieved by a counter torque generated by the thrust of motors. That is, θ_p and ϕ_p may be compensated in the form of control inputs $U_{1..4}$. As result, linear components $[f_{px} f_{py}]$ also occur.

Figure 5.3: Conventional pendulum problem depicted for SquidCop dynamics. Angular displacements are considered as roll and pitch disturbances for the rigid body model.

Figure 5.4 refers to a simulation, where Squid is initially around angular equilibrium. This simulation represents a typical field situation, where windshear wind gusts constantly hit the aircraft. Impulse disturbances are inserted in order to shift roll and pitch angles. As one may see, disturbances are suppressed without any difficulties.

Figure 5.4: Simulation of stability control in the SquidCop conventional pendulum problem.

5.2.2 SquidCop with a Fixed Breaking Device

A fixed speed brake is initially designed to work as a passive deceleration device to SquidCop. Geometry follows project requirements to impose high drag forces on descent (stream in z direction) and still preserve hovering integrity while the aircraft translates in low speed over the ground. Furthermore, considering the quadrotor attachment in a pylon or in any deployable fixing structure, a convex surface may offer less drag than concave one (stream in z counter direction). In order to meet previous and sound requirements, the speed break device follows the shape that may be seen in Figure 5.5.

Figure 5.5: SquidCop frames for the configuration with speed break attached.

5.2.3 Conservation of Momentum in SquidCop Kinematics

An interesting SquidCop feature that was theoretically expected, but that was attested and found in practical field experiments is the conservation of momentum after rolling and pitching maneuvers. It is well-known that this is a physical phenomena that constantly occurs along the flight. Regarding SquidCop pendulum-like features, the conservative force is more visible. Since SquidCop is only provided with altitude and angular control (not endowed with hold mode in the xy plane) the MAV presents two non controlled DoF along x and y . Thus, supposing that we intentionally perform a pitching displacement about y axis, the MAV is expected to translate along x axis as a mean of recover part of the energy of the shifted pendulum mass (Fig. 5.6).

Figure 5.6: Illustration of momentum conservation in SquidCop model.

In practice, high pose angles are easily achieved ($\theta, \phi \approx 50^\circ$). Figure 5.7 depicts the conservation of momentum occurring right after a rolling suppression in an aggressive maneuver. As one may see, SquidCop is taken to an extreme shifting (60°). Next, controller precisely shifts the MAV back to angular equilibrium. However, since controller does not act over position hold control, we can clearly see a linear lateral draft through which SquidCop translates above the ground.

Figure 5.7: Experimental certification of the momentum conservation after rolling suppression. The MAV translates along lateral axis as the result of its capability to recover energy.

Hence, we may define linear acceleration along x as:

$$\dot{u} = g \sin \theta \quad (5.1)$$

Linear Velocity may be obtained by the time integration of Eq. 5.1, which yields:

$$|u| = g \int \sin \theta + c_0 \quad (5.2)$$

Thus, considering initial conditions null, we have:

$$|u| = g - g \cos(\theta) \quad (5.3)$$

Hence, for a pitching angle $\theta \approx 60^\circ$, yields a linear speed $|u| \approx 4.9m/s$ when the MAV starts to translate. Figure 5.8 shows that, in a experiment, SquidCop may reach linear accelerations of $\frac{g}{2}$. That means translations superior than 10 meters in 3 seconds, which is a considerable distance. Spent thrust energy ($\approx 50\%$) is used strictly to overcome gravitational forces. However, due to aerodynamic drag, velocity decreases, which is explained by the acceleration decay.

Figure 5.8: SquidCop inertial measurements after a high pitching angle. As one may see, conservation of moment may may easily drive the MAV to $|u| \approx 4m/s$.

5.3 Design Results

From the preliminary analysis sketched in Section 3.3.1, SquidCop design results comprehends computational analysis by solving its mathematical model in MATLAB/SIMULINK where the in-flight launching is simulated. The other one is an aerodynamic complete characterization through experimental aerodynamic tests in wind tunnel. Firstly, however, we take a look at the final design, which has led to interesting

5.3.1 SquidCop Free Fall Simulation

Free fall of SquidCop MAV was simulation through a ©MATLAB algorithm inspired in its equations of the motion. The simulation considers SquidCop without the fixed break device. We want to observe and attest SquidCop ability to fall steadily and in the correct pose angles, that is, as near as possible from zero.

Simulation is performed under the following conditions:

- Reynolds number $Re \approx 10^5$;
- inviscid incompressible flow;
- total load over the body is uniform;
- products of inertia are not considered since they are 100 times smaller than moments of inertia;
- launching happens in x direction at a speed of $u \approx 14m/s$ at a height of 65 ft (20m);
- initial Tait-Bryan attitude angles are initially zero ($\phi = \theta = \psi = 0$);
- propellers drag are neglected;
- perturbation is present during the entire simulation ($f = 100Hz$);

Simulation shows that, indeed, SquidCop tends to present small angle displacement. This is an important analysis that is in accordance to first assumptions and the initial frequency response preliminary experiment carried out in Chapter 3.

Figures 5.9, 5.10 and 5.11 refers to angular variation along the simulation while Figs. 5.12, 5.13 and 5.14 refers to angular rates. One may see that, theoretically, angular displacements are small.

Although in practice atmospheric components play an important role in flight dynamics, from the frequency response characterization carried out in Chapter 3, we see that SquidCop

behaves as a low pass filter ($\omega_n \approx 1Hz$). The two results, characterization and simulation, strengthen the assumptions about SquidCop stability, which are attested on-the-field (Chapter 10).

Figure 5.9: Pitch angle behavior during model simulation in ©MATLAB algorithm.

Figure 5.10: Roll angle behavior during model simulation in ©MATLAB algorithm..

Figure 5.11: Yaw angle behavior during model simulation in ©MATLAB algorithm.

Figure 5.12: Roll rate behavior during model simulation in ©MATLAB algorithm.

Figure 5.13: Pitch rate behavior during model simulation in MATLAB algorithm.

Figure 5.14: Yaw rate behavior during model simulation in MATLAB algorithm.

5.3.2 CFD Stability Analysis

During SquidCop design evaluation, CFD (Computer Fluid Dynamics) analysis results work as support information to experimental wind tunnel data. Computational analysis is an attempt to reproduce experimental conditions, providing preliminary quantitative information. It considered the MAV behavior to two distinct and fixed poses.

First CFD analysis considers air stream in the counter direction of x axis, that is, air hits the air break over the convex plane (Fig. 5.15-(left)) at a constant speed of $\approx 20m/s$. This simulation attempts to reproduce the MAV while its is possibly attached the a pylon in a mother ship. Second CFD analysis considers air stream in the direction to x axis over the concave plane at a maximum speed of $\approx 14 m/s$ (Fig. 5.15-(right)). Now, simulation attempts to reproduce air stream influence during the MAV descent. Both analysis were carried out at constant speeds, exactly at the same speeds applied in wind tunnel experiments.

Main goal is to give us a very preliminary estimation of the global drag forces acting on the MAV to those different pose angles in order to qualify the quadrotor to the two different situations.

Firstly, considering air stream evaluation in the counter direction of x axis, a mean drag force $F_d \approx 14.2N$ was observed. Secondly, air stream in the counter direction of x axis produced drag

Figure 5.15: SquidCop CFD evaluation, where the MAV speed break was evaluated for small (left) and elevate drag (right) features.

forces $F_d \approx 27.1N$. That may be noted that the quadrotor offers approximately the double of the drag force when inflow hits the fixed air break. That is essentially induced by the geometric convex shape of the structure as a parachute.

5.3.3 Wind Tunnel Evaluation

One more time, experimental aerodynamics evaluation was run at USP/EESC/LAE wind tunnel (Fig. 5.16). Please refer to Appendix F for detailed technical information about LAE wind tunnel. Likewise CFD evaluation, SquidCop wind tunnel experiments considered air stream in two opposite directions along x axis, at the same speeds. However, for both cases, aerodynamic data is scanned considering variable angle of attack in a range $\alpha \pm 25^\circ$. The MAV was attached to a symmetric NACA foil shaped rod over the balance. Variation in α is intended to cover eventual angle variations that might happen in the real situation (SANTANA et al. (2010)).

Figure 5.16: Wind tunnel evaluation with SquidCop to small (a) and high (b) drag forces.

Flow Stream in x Axis Counter Direction

First wind tunnel test considers inflow air stream in counter direction of x axis at a speed of $\approx 20m/s$ at an angle of attack (Fig. 5.16-(a)). The goal is to measure overall drag and moments as a possible way to simulate the MAV attached to the mother-aircraft.

Figure 5.17 shows C_d curve. It may be noted a mean value of $C_d \approx 0.81$. No significant variations are observed and the MAV drag keeps practically constant for all different angles.

Figure 5.18 shows overall resulting drag force D acting over SquidCop. A mean value of $D \approx 13.65N$ is observed. It is also noted that no significant variations are measured. Comparatively, experimental and CFD estimated drag force present percent error of $\approx 4\%$.

Figure 5.19 presents SquidCop C_m values. It is noted that the quadrotor presents low C_m even with variations in the streamline incidence angle. That characteristics directly impacts over the MAV static stability when it is attached to the mother-aircraft at the eminence of launching. Furthermore, the moment curve reveals that the prototype model is symmetric indeed.

Figure 5.20 shows resulting drag moment M acting over the MAV. It may be seen that, at such conditions, a restoring tendency occurs, which may return the MAV to the equilibrium angle, as the angle of attack absolute value raises. In other other words, the quadrotor presents stable behavior in such conditions. It is also perceived that no significant variations in moment are measured as α varies.

During the above experiments, the MAV did not present unexpected behavior nor considerable and oscillatory resonant vibrations, which ratifies the above results and grounds important project requirements.

Flow Stream in x Axis Direction

Second test considered inflow air stream in the same direction along x axis (Fig. 5.16-(b)). Constant speed of $\approx 14m/s$ was performed. In other words, this experimental evaluation particularly aims to simulate probable real conditions when the MAV is under the influence of the streamline impact over the speed break concavity during descent.

Figure 5.21 shows that the speed break introduces an overall drag of about $C_d \approx 0.84$, which is maintained practically constant for all angles tested in this experiment. Once again, no variations are observed and the MAV drag keeps constant for $\alpha \approx \pm 10^\circ$.

Figure 5.22 shows overall mean resulting drag force $D \approx 24.47N$ acting over SquidCop. No significant variations are measured. Comparatively to CFD estimated evaluation, experimental drag force present percent error of $\approx 10\%$.

Figure 5.23 shows that C_m absolute value considerably increased as angle of attack raises. Plot reveals the MAV symmetry. However, C_m is positive to negative angles of attack. Moreover, C_m is negative to positive angles of attack. That is also directly related to a natural moment tendency that restores SquidCop back to stability point when attitude is displaced from baseline angle $\alpha = 0$. Thus, a preliminary conclusion may be that the quadrotor is stable during descent.

Figure 5.24 shows that resulting drag moment M presents low values. However, quadrotor natural tendency to restore the MAV to the stability angle is noted, as the angle of attack absolute value raises. The counter torque apparently attempts to drive the MAV back to $\alpha = 0^\circ$. One more time, no significant variations in moment are measured.

An oscillatory mode was observed after 30 seconds after the experiment starts due to the fact that streamline was kept at a constant speed of 20 m/s . Although constant speed does not represent SquidCop terminal speed, this stress test is useful to indicate the conditions that may cause it to behave unexpectedly. In practice, it is expected that the quadrotor will not present resonant behavior after launching as falling speed will decrease to a lower descent rate.

Figure 5.17: Drag coefficient C_d to variations in α at 20 m/s (x counter direction).

Figure 5.18: Drag force D to variations in α at 20 m/s (x counter direction).

Figure 5.19: Moment coefficient C_m to variations in α at 20 m/s (x counter direction).

Figure 5.20: Moment M to variations in α at 20 m/s (x counter direction).

Figure 5.21: Drag coefficient C_d to variations in α at 20 m/s (x direction).

Figure 5.22: Drag force D to variations in α at 20 m/s (x direction).

Figure 5.23: Moment coefficient C_m to variations in α at 20 m/s (x direction).

Figure 5.24: Moment M to variations in α at 20 m/s (x direction).

5.4 Conclusions

The contribution of this chapter is to present a novel morphology for a quadrotor MAV, with a clear aim in improving the overall stability for a possible in-flight launching.

The novelty of first part is to address a novel concept where the CoG down shifting is proposed on the raising of static stability. Although it sounds like a very simple concept (indeed it is), some interesting features may be theoretically and experimentally attested, such as its ability to recover kinetic rolling energy to drive the MAV in linear translations. Besides, we have shown that stable and controlled free fall is a possibility.

The novelty of second part is to present simulation and experimental results on the project of a fixed air break device to decelerate the MAV during the in-flight mission. The fixed air break designed in this chapter exclusively aims to aid on gathering information about how the MAV may behave in free fall. Besides, it was also useful to a better understand on how to design a device that may work well both as a parachute and also offer small drag forces in a possible attachment in pylon on the carrier aircraft.

Both simulation and experimental data have pointed to very optimistic results. It is important to highlight that it does not represent the final solution yet. Nevertheless, this chapter is intended to provide valuable data concerning the novel concepts inherent to this proposal. Finally, contributions of this chapter will endorse flight simulations in Chapter 8, vision motion capture tests in Chapter 9 and on-the-field evaluation presented in Chapter 10.

Chapter 6

H₂Omni MAV

In this chapter we introduce a novel hybrid MAV fully capable to navigate in water environment (Fig. 6.1). Main contribution of this chapter is to present a thorough analysis on the torus shape structure, from the hydrodynamics perspective, which will lead to a more efficient morphology for air and water applications. As far as we know this is the very first time that hybridization of a vessel and a MAV is taken as straight as it deserves to be studied, with a strong concern in the stability analysis as for the hull design and the water and aerial robot as well.

Figure 6.1: H₂Omni in a successful first water launching (left) and after its maiden on-the-field flight (right).

6.1 Problem Statement & Project Requirements

After a careful preliminary analysis addressed in Section 3.3.3, morphological aspects of the H₂Omni MAV are grounded in the following project requirements:

- The structure must fit water and air operations, that is, the MAV must navigate in that two different environments;
- the structure must present minimum drag for low Reynolds for omnidirectional navigation;
- no interchangeable parts nor moving mechanisms are optional whatsoever;
- overall weight must be MAV compliant;
- the structure (hull) must offer sufficient buoyancy to meet payload mass;
- the aircraft must be statically stable both in air and in the water;

H₂Omni is a VTOL flying robot in the quadrotor configuration that may be launched both from land and water environment. Main contribution, however, lies in its ability to successfully navigate on water making use of the same kinematics of any quadrotor does while airborne. Since there is a considerable minimization of weight force due to hydrostatic thrust produced by the floating structure, it is expected that much less energy must be used to pull the MAV in water navigation. In the next sections, we state a detailed study around the mechanical main aspects that surrounds the MAV.

6.2 H₂Omni Equations of Movement

H₂Omni kinematics as well as its dynamics follow the same equations that govern any regular quadrotor (Fig. 6.2). From the mechanical point of view, Sharky (quadrotor) and SquidCop equations of motion may safely represent H₂Omni. Hence, for the sake of non-redundancy, H₂Omni dynamic and kinematic equations will be omitted. One may refer to Section 4.3 to resort to such equations. For a more detailed developing please refer to Appendix B. Nonetheless, all analysis that are carried out from now on are based on such equations.

In the other hand, due to its peculiar shape which composes the wholly structure, friction effects produced by drag caused by the hull differ the MAV from the others. Drag may be considered as the external force acting over the wholly torus structure due to its translations and rotations. Thus, a full analysis on drag effects over H₂Omni is depicted in Section 6.4.

Figure 6.2: H₂Omni frames.

6.3 Applied Hydrostatic on a Torus Hull

6.3.1 Hydrostatic Thrust Computation

Hydrostatic forces produced by any floating structure are important to be computed for payload, dimensional and morphological purposes. Hydrostatic computations are based on Archimedes (212 B.C) Principles that relates thrust force of wholly or partially submerged object to its density and the volume of fluid that is displaced by it. Firstly, when a given object is completely submerged in static equilibrium, the whole body is under the influence of hydrostatic pressure. Secondly, when the same object is partially subject to the atmospheric pressure and the other part is under the influence of hydrostatic pressure, the buoyancy phenomena raises, which is desirable in the case of floating structures.

Buoyancy is the effect that occurs due to lifting resulting force of hydrostatic force over the body (Fig. 6.3). Considering a rigid object fully submerged into a homogeneous fluid, vertical component of resulting lift of a submerged may be expressed as follows:

$$dF_1 = (p_{atm} + p_1)dA_z = (p_{atm} + \rho r z_1)dA_z \quad (6.1)$$

and

$$dF_2 = (p_{atm} + p_2)dA_z = (p_{atm} + \rho r z_2)dA_z \quad (6.2)$$

The buoyancy force F_B may then be stated as:

$$dF_B = dF_2 - dF_1 = \rho g(z_2 - z_1)dA_z = \rho g d\forall \quad (6.3)$$

Where $\forall$ is the volume of the submerged mass. Thus, total buoyancy force F_B is:

$$F_B = \int \int \int dF_B = \int \int \int \rho g d\forall = \rho g \forall \quad (6.4)$$

Hence, considering an asymmetric object, the line of acting force may be obtained by determining the moment of F_B relating to z axis, by multiplying it times the displacement of the buoyancy force to the centroid position x_B as follows:

$$x_B F_B = \int x dF_B \quad (6.5)$$

Making use of Eqs. 6.3 and 6.4 in 6.5 yields:

$$x_B F_B = \int \int \int x d\forall \quad (6.6)$$

Which is Archimedes Principle in the formal shape. In a simpler way, Archimedes Principle states that the buoyancy force (or hydrostatic thrust) is equivalent to the weight of the liquid that is displaced by it:

$$F_B = \rho g \forall \quad (6.7)$$

In a symmetric floating body at static equilibrium, $F_B = mg$ and both act exactly in the same vertical line that contains CoG and the centroid of the submersed part (Fig. 6.3). As the shape of the displaced volume is equivalent to the volume that causes the shifting, it is reasonable to state that B coincides to the centroid of the submersed part.

Another important relation, regarding the capacity of a body to effectively present buoyancy properties may be taken from Archimedes Principles. More precisely from Eq. 6.7. If $F_B = W$

Figure 6.3: Acting forces in a balanced floating body.

and since the buoyancy force F_B is equivalent to the displaced volume, yields:

$$\frac{\rho_b}{\rho_f} = \frac{\forall_i}{\forall_b} \quad (6.8)$$

Where ρ_b and ρ_f are the density of the body and the fluid, respectively, and $\forall_i$ and $\forall_b$ are, respectively, volumes of immersed body and volume of the wholly body. That is a fundamental relation through which we may chose the proper material that meets the buoyancy requirements of any hull. As H₂O₂ hull is mostly built from polyethylene foam which presents a density of about $\rho \approx 5kg/m^3$ and considering the torus hull dimensions (more about in Section 6.5), we compute total immersed volume of $\forall_i \approx 0.0156m^3$, which corresponds to a draft (height of the submerged portion) of $d_b \approx 0.01m$.

6.3.2 Static Stability of Floating Bodies

The principle of stability for buoyant objects directly lies in four entities, represented by physical positions related to the floating body (Fig. 6.4). Such locations are related to hydrostatic theorems, which together compose the cornerstone of stability achievement of any floating structure (YOUNG (2001))(BERTRAM (2000)):

- *Center of Buoyancy (B)* - point in an immersed object over which thrust due to buoyancy force acts;
- *Center of Gravity (CoG)* - point in the wholly structure over which weight force acts and is directly related to payload distribution;
- *Keel (K)* - the extreme lower point of the hull;

- *Metacentre* (M) - point of intersection of buoyancy forces;

Distances between each point are important for stability computation, such as:

- KB - distance between K and B;
- KM - distance between K and M;
- GM - distance between G and M;
- KG - distance between K and G;

Figure 6.4: Position of B, K, G and M in a given floating structure in hydrostatic equilibrium.

Suppose that the symmetric floating structure from Fig. 6.4 lies completely steady positioned with no disturbances. From the above parameters, the following relation may be safely stated:

$$KM = KG + GM \quad (6.9)$$

Say that an external impulse disturbance force acts over the floating object B is shifted towards to the new centroid B' of the new submersed portion. That produces a moment M_B that acts as a restoring counter force about CoG (Fig. 6.5), which shifts the body back to the equilibrium point. Note that metacentre is the point in which vertical lines of B and B' intersects each other (Fig. 6.5).

Figure 6.5: Buoyancy force point shifting due to an external disturbance moment in a floating body.

An external disturbance force does not necessarily implies in a restoring stable counter moment. Depending on the relations between all four points and on their relative positions, the body may configure neutral stability, unstable or stable conditions. The necessary precondition for a floating body to be stable may be summarized as follows (YOUNG (2001))(BERTRAM (2000)):

- displacement of the watercraft must equal the upthrust due to buoyancy;
- force of gravity and buoyancy must be on the same vertical line;
- CoG must be below the metacentre.

Nonetheless, equilibrium state in a floating structure is conditioned to be neutral, stable or unstable. Figure 6.6 depicts each one of them.

Figure 6.6: Equilibrium conditions in a floating structure (adapted from (YOUNG (2001))).

Static Stability of a Floating Torus

The torus shape floating structure has an interesting behavior due to radial symmetry. For steady position W and B are over the same axis. Naturally, CoG is located at the center of the body while B is slightly below. Figure 6.7 shows the torus shaped shifted due to an external force while M arises. For small angles, whenever the body is displaced, regardless of what point over the torus, stability conditions may be ensured. A new B' produces a restoring counter torque. And after all, metacentre is above CoG.

Figure 6.7: Static stability in a torus shape floating vessel. Under normal envelope, static stability is achieved regardless of what point is disturbed over the vessel.

Metacentric Diagram (MD)

An important analytical resource widely employed in the ship industry is the Metacentric Diagram (MD). The MD is a chart related to stability diagram through which the metacentric height may be determined from draft (d_f) distance. Basically, it uses some relations between KB , BM and KM to determine a floating body stability:

$$BM = \frac{L^2}{12d} \quad (6.10)$$

$$KB = \frac{d}{2} \quad (6.11)$$

$$KM = BM + KB \quad (6.12)$$

Figure 6.8 shows the MD for the torus shape hull based on H₂Omni nominal parameters. For detailed information please refer to Appendix D.

Considering nominal operations, H₂Omni torus hull (with no payload) presents $KG \approx 0.035m$ for a draft of about $d_b = 0.01m$. From MD we note that $KM \gg 1$. From Eq. 6.9, we may see that $GM > 0$, which reveals a stable condition. One may note from the MD that BM decreases as we increase draft. That is, distance between buoyancy point and metacentre are directly related to the ship stability.

Figure 6.8: Metacentric diagram for H₂Omni torus shape hull.

In the case of H₂Omni hull, as we presented in Chapter 3, CoG is located slightly below engines levers, to provide the MAV with more static stability during flight (please refer to Appendix A).

6.4 Aero/Hydrodynamics of a Torus Shaped Structure

As it was detailed in Chapter 3, torus shape has proven to be the optimal form considering less drag coefficient (overall drag forces consequently) and load capacity due to the buoyancy effect, when we compare all layouts (Tab. 3.3). Computer Fluid Dynamics (CFD) analysis have shown that torus shaped structures are best shape between three. For detailed calculation please refer to Appendix D.

According to (JOHNSON (1979)) and (JOHNSON (1977)), the motion of a torus shaped object in a Newtonian fluid (e.g., water and air) satisfies the Stokes equations (Fig. 6.9).

$$\nabla p = \mu \nabla^2 u, \nabla u = 0 \quad (6.13)$$

For incompressible fluids (which is the case in all platforms in this thesis), the linearity of the Stokes equations favors the separation of the movement of the torus in five different problems, such as:

- lateral translations along x and y axes;
- rotation about x and y axes;
- rotation about the z axis;
- translation along z axis;
- expanding torus from z axis;

With a straight focus on field applicability, the last one is the only movement that does not match H₂Omi features. Considering the torus structure as a perfect rigid body, we will take all movements above, except the last one since the MAV is an non interchangeable with no morphing frame.

Figure 6.9: Main constructive parameters of a torus shape body for fluid computation based on Stokes equations.

6.4.1 Translations in the xy Plane

Based on the evident and clear symmetry of the torus geometry about z axis (thus, xy plane), only the x translation will be taken into calculation. This assumption extends, obviously, to y axis or any other orientation on xy plane.

According to (JOHNSON (1979)) and (JOHNSON (1977)), forces per unit length in radial and tangential directions axis may be safely computed as 6.14 and 6.15, respectively:

$$f_r = \frac{4\pi\mu[\ln L - 3]u\sin\theta}{[\ln L - \frac{1}{2}][\ln L - 2] - 2} + O(\epsilon^2) \quad (6.14)$$

and

$$f_\theta = \frac{2\pi\mu[\ln L - \frac{5}{2}]u\cos\theta}{[\ln L - \frac{1}{2}][\ln L - 2] - 2} + O(\epsilon^2) \quad (6.15)$$

Based on 6.14 and 6.15, total force F_{Dxy} may be written as:

$$F_{Dx} = 2\pi a\mu C_{Dx}u \quad (6.16)$$

Still according to (JOHNSON (1979)) and (JOHNSON (1977)), a slender torus translating perpendicularly to z axis presents drag coefficient C_D :

$$C_{Dx} = \frac{3\pi}{L + \frac{1}{3}} + O(\frac{1}{\epsilon})^3 \quad (6.17)$$

Where L is given by:

$$L = \ln \frac{8}{\epsilon} \quad (6.18)$$

The coefficient ϵ represents the relation between the centerline radius a and the cross-sectional radius b , as one may see from Fig. 6.9 and is denoted by:

$$\epsilon = \frac{b}{a} \quad (6.19)$$

Hence, neglecting term $O(\frac{1}{\epsilon})^3$, the drag coefficient C_{Dxy} may be rewritten as:

$$C_{Dx} = \frac{3\pi}{\ln \frac{8}{\frac{b}{a}} + \frac{1}{3}} \quad (6.20)$$

6.4.2 On-Edge Rotation (About x and y Axes)

This movement characterizes roll and pitch rotations while rotation about z axis is null. Although it is well-know that quadrotors perform rolling and pitching rates in order to walk

through xy plane, that happens only for a brief instant of time so that angular speeds quickly vanishes. However, we feel the need to put it into the formalism, although it is may be latter simplified.

We take the example to rotation about x axis since it may be extended to y axis. Thus, according to (JOHNSON (1979)) and (JOHNSON (1977)), resulting radial, tangential and axial moment per unit length may be respectively computed as:

$$M_r = -4\pi\mu K_z b\epsilon \cos\theta \quad (6.21)$$

$$M_\theta = 4\pi\mu K_z b\epsilon(3L - \frac{11}{2})\sin\theta \quad (6.22)$$

$$M_z = 0 \quad (6.23)$$

Where the constant K_z , which satisfies the boundary conditions, may be defined as:

$$K_z = \frac{pa}{2[\ln\frac{8}{\epsilon} - \frac{3}{2}]} \quad (6.24)$$

The body does not sense any radial friction force. The friction force sensed by z axis, however, may be defined as:

$$f_z = -8\pi\mu a \sin\theta \quad (6.25)$$

6.4.3 Spinning About z Axis

Yaw maneuver essentially consists of spinning about z axis. According to (JOHNSON (1979)) and (JOHNSON (1977)), tangential force f_θ and moment M_z per unit length in toroidal shaped objects spinning about z axis may be calculated as follows:

$$f_\theta = -8\pi\mu a = -\mu C_S w \quad (6.26)$$

and

$$M_z = -2\pi\mu\epsilon b(6L - 13)K_\theta \quad (6.27)$$

Where K_θ is a constant related to the boundary conditions, and may be given by:

$$K_\theta = \frac{\psi a}{\frac{4}{L-2}} \quad (6.28)$$

The body does not sense any radial friction force nor any force along z axis.

6.4.4 Translation Along z Axis

As for translations along z axis, we may approximate the structure to a flat round plate. Thus, drag force D_z may be safely computed as:

$$D_z = \frac{1}{2}C_d\rho Au^2 \quad (6.29)$$

6.5 Hull Design

6.5.1 Preliminary Hull Computation

Considering the functional aspects and dimensional proportions of the prototype, such as engines/propellers efficiency and consequent payload capacity, the torus shaped hull presents outer and inner diameter of $\mathcal{O}_o \approx 370mm$ and $\mathcal{O}_i \approx 300mm$, respectively. Cross sectional diameter is $\mathcal{O}_c \approx 70mm$. Field experiments with the structure have shown that, for a good equilibrium condition, so that the inner part would be less susceptible to water income, is reached to a draft of $d_b \approx \frac{\mathcal{O}_c}{2} \approx 35mm$. Under those conditions, we compute a submerged volume of $\forall \approx 1.56L$. Recalling to Section 6.3.1, that should be the total amount of water displaced by the structure. Hence, from Eq. 6.7, the buoyancy upthrust force shall be $F_B \approx 15.31N$.

Considering the total weight force of the torus $W \approx 2,05N$, we may safely compute the effective payload for this case:

$$W_P = B - W = 15.31 - 2.05 = 13.25N \quad (6.30)$$

Which is approximately 11% larger than total weight of the MAV. Figure 6.10 shows a field essay in water where the torus hull was submitted to a payload of exactly 13.25N (1.35L of water) in a bottle. We observed that a half of the structure was indeed submerged.

Figure 6.10: Initial payload evaluation of the torus hull with 13.25N (1.35L of water) in a bottle.

6.5.2 Hull Optimization

Considering the bases and theoretical background from Sections 6.3 and 6.4 and with a strong look at H₂Omni from the field application perspective from the last section, a hull optimization is now proposed. The goal is to make use of a little percent of engines thrust force during water navigation. Besides, in this operation, reducing drag is a desirable and welcome option. Hence, reducing hull drag means reducing torus diameter. However, we need to ensure minimum buoyancy. After all, we need to keep attention to the project requirements described in Section 6.1.

The solution for the hull design is the incorporation of a smaller torus downwards to the horizon plane so that symmetry axes of the larger torus is coincident to it. An empty volume (corresponding to the big torus inner space) is intentionally left hollowed. Batteries weight are expected to ensure CoG to be downwards shifted in order to improve stability by keeping GM as high as possible (Section 6.3.2). Figure 6.11 shows a sketch of the new hull in two scenarios. First considers engines off (no thrust from motor group so), where the structure normally sustains the whole craft. Second regards to the use of a small part of total engines thrust when minor torus provides hydrostatic thrust enough to assist on the MAV buoyancy.

Considering dimensions of inner space of big torus, into which the small one shall be installed, we may compute small torus B force. For the mounting from Fig. 6.11, we computed $B \approx 4.4N$. Total weight is estimated in $W \approx 14N$ (1.420Kg). Thus, effective thrust force necessary to sustain the MAV is:

Figure 6.11: Optimization of H₂Omni hull. Main goal is to decrease drag and battery usage during water navigation.

$$T = W - B = 14 - 4.4 = 9.6N \quad (6.31)$$

Since motor group offers an average thrust of $T \approx 45N$, this represents about 21% of total energy spent during navigation. For detailed computing please refer to Appendix D.

6.6 Design Results

We have discussed our choice for the torus shaped structure in Section 3.3.3, where we grounded the fundamentals of the H₂Omni ultimate design. In truth, the optimality of the torus shape lies in the theoretical background presented in Section 6.4. Next we show some results from CDF analysis, considering the four possible movements.

6.6.1 Water Evaluation of First Design

Hydrostatic Thrust

Figure 6.12 shows an hydrostatic thrust test where the torus shaped hull was submitted to a total weight (hull and payload) of approximately $W \approx 3Kg$ with two milk boxes fulfilled with sand ($\rho \approx 1,5Kg/L$). Total draft was about $d_f \approx 0.03m$.

Considering that H₂Omni is expected to carry out a payload of approximately $1.5Kg$, the design of the torus hull is intentionally over dimensioned to ensure safe and stable field operations.

Figure 6.12: Payload field evaluation for the optimized H₂Omni hull.

Finally, from the design data we may now trace H₂Omni ultimate Metacentric Diagram for the MAV. Figure 6.13 shows the MD chart from where we may see, for $d = 0.03m$, $KM \approx 0.3953m$ is achieved. In this case, $KG \approx 0.05m$. From Eq. 6.9, we get to $GM \approx$ which yields $GM \approx +0.3453$. Hence, this is the proof that H₂Omni is stable.

Figure 6.13: H₂Omni metacentric diagram after optimization, for nominal operation.

Still following (YOUNG (2001))(BERTRAM (2000)), a vessel presents rolling movement as a pendulum does. The rolling period of a ship may be determine pretty similarly to the pendulum. Hence, for a squared shape vessel, the rolling period T_r may be determined as follows:

$$T_R = 2\pi \sqrt{\frac{k^2}{g \cdot GM}} \quad (6.32)$$

Where $k \approx 35\%$ of hull width (YOUNG (2001))(BERTRAM (2000)). Hence, we compute

H₂Omni rolling period as $T_R \approx 0.4421s$ our a natural frequency $W_{nw} \approx 2.262Hz$.

6.6.2 Computer Fluid Dynamics Analysis

The theory behind H₂Omni stream flow may be better observed from CFD analysis simulation. We shall register that this is a very simple analysis that aims to give us a very basic outlook specially regarding stream flow qualities through dynamic pressure distribution along the body. As dynamic pressure is directly related to the the ways fluid impacts over body, kinetic energy is implicit to this analysis which is a good indicative of how easy the MAV flows. All CFD tests consider air as the fluid.

Translation in the xy Plane

Translation considers flow speed along y axis at $u = 15m/s$, which is the mean maximum cruise speed that a MAV such as H₂Omni may reach. That is, this is the speed at which maximum drag forces may act over the aircraft.

Figure 6.14 shows flow streamlines along the body as well as dynamic pressure distribution. As it is expected, the same pattern for circular bodies in low Reynolds may be seen. Also, no vorticity nor prominent gradient from outer to inner regions is visible, which indicates flow laminarity. Indeed, one may observe that dynamic pressure is equivalent to mean atmospheric pressure (92.085 KPa at 856m from sea level).

Figure 6.14: Flow stream during lateral translations with dynamic pressure gradient [Pa]).

On-Edge Rotation

As we already stated in Section 6.6.2, on-edge rotation comprehends roll and pitch rotations. Although full rotations are more related to acrobatic aircrafts (which is completely out of the scope of this work) a good understanding on the behavior of the structure to full spins about x and y axes may give us a wide impression specially to flow stream behavior.

We simulated a full rotation about x axis at a rate of 6.28 rad/s , which is the nominal rolling/pitching rates found in experimentations. As one may note, we may extend the very same analysis to y axis. As we may see from Fig. 6.15, stream is characterized by straight lines that spin around in laminar pattern.

Actually, this is a very systematic and thorough analysis. In practice, non acrobatic MAVs perform maneuvers at small angles which vary at low angular rates so that the aircraft will experience the drag on-edge effect very briefly.

Figure 6.15: Flow stream during on-edge rotation with dynamic pressure gradient $[Pa]$.

Translation Along Z Axis

This represents climbing movements when the MAV increases altitude. This simulation is important because it reveals much about the overall drag and consequently the impact of the friction acting forces during fast climbs. Main reflex lies on the overall stability and fast maneuvers capability.

In this simulations the MAV climbs at a rate of $15m/s$. This is the average maximum climb speed for a MAV such as H₂Omni, which means that this is the worst situations in terms of dragging forces in such direction.

As one may see from Fig. 6.16, stream lines behave laminar. There is a raise of 30% in dynamic pressure from atmospheric pressure for this altitude. That was expected since the structure behaves similarly to a flat plate ($C_D \approx 1.28$) in that circumstances. A low relative pressure is observed underneath the body which may suggest vorticity. That deerves to be better investigated, however.

Figure 6.16: Flow stream during translations along z axis with dynamic pressure gradient $[Pa]$.

Spinning About Z Axis

This evaluation is important since it reveals much about how tangential drag forces affects yawing maneuvers. Stable yawing is an important DoF through which the MAV may be reoriented. Less tangential drag impacts in more agility.

Spinning evaluation considers the MAV at a rotating speed $6.28rad/s$ ($360^\circ/s$) about z axis. Due to dynamic limitations, in practice the MAV yawing rate is much bellow this speed. Figure 6.17 shows that, even at a rate much nigger than the nominal rate, stream lines present laminarity and low dynamic pressure, which means that yawing movement is expected to be relatively easy moving.

Figure 6.17: Flow stream during spinning about z axis with dynamic pressure gradient $[Pa]$.

6.7 Conclusions

In this chapter we have presented a novel analysis about the full hybridization of a MAV and an aquatic vehicle that presents water navigation capabilities with no critical adaptations nor any interchangeable parts. We also have presented the theoretical background of the fluid dynamics behind the torus shape of its structure as well as

All above results are part of a complex process of validation of Sharky MAV, both for the fixed-wing and the quadrotor set up as well. Results are optimistic, so that it contributes to following flight simulations in Chapter 8, vision motion capture tests in Chapter 9 and on-the-field evaluation presented in Chapter 10.

Part III: Control Fundamentals & Flight Simulation

Third part of this thesis aims to begin bringing our MAVs into life.

Chapter 7

Control Fundamentals

In this chapter we address a solid background and a concise overview on the robust control theory to be implemented in the control of our three MAVs. Main contribution of this chapter is to provide readers with an easy understanding on the step-by-step of the synthesis and the implementation of an optimal H_∞ robust controller (Fig. 7.1). At the end, after a well-succeeded control synthesis, we depict the practical implementation of the H_∞ in a flight simulation model of a quadrotor MAV, which is another novelty of this chapter. It offers a new angle on how to reach stability, specially for the novel MAVs described in this thesis and which were presented in Chapters 4, 5 and 6. Main goal is to exploit the H_∞ controller ability to get robust to external disturbances, parametric variations and model uncertainties, desired characteristics for the stability control of our MAVs in Chapters 9 and 10.

Figure 7.1: Robust control closed loop general architecture.

7.1 Control of MAVs

In this section we discuss the synthesis of optimal H_∞ robust controllers and all theoretical background for the achievement of a wide band final state space compensator that stabilizes MAVs in the quadrotor configuration. From the quadrotor state space model described in Chapters 4, 5 and 6, the possibility to determine a state space realization of a robust controller is real.

It is important to highlight that, however, autonomous navigation is completely out of the scope of this thesis. Instead, we focus our attention in a assisted flight control through which pilot requests new set points via a radio link. At idle position, all attitude angles are set to zero by the controller as long as a new set point is manually inserted. Nonetheless, without loss of generality, the assisted flight control with the use of the H_∞ proposed in this thesis may perfectly work with other control layers (e.g., navigation) which may autonomously control the MAV trajectory.

7.1.1 Classic Approach *vs.* Modern Theory

The stability control of MAVs have been widely addressed and several approaches have been presented, discussed and implemented. Classic theory, into which P, PI, PD and PID compensators are included, has proven its worth due to accessible and well rounded and defined methods for fine tuning (e.g., *Ziegler-Nichols*). It is a fact that, contrary to what classic theory announces, many of aerial applications (both for industry and/or academic as well) have gotten excellent results since it is well designed. However, although classic methods apparently sounds easy going, things turn extremely difficult when it comes to find a set of gains that may ensure field operations minimally safe to different situations in the same application.

In the other hand, modern control theory brings relevant improvements when it comes to quality of control ZHOU (1998) K. ZHOU. (1995). Aerial applications are subject to external agents that directly affect the aircraft and may detract the quality of the flight, such as atmospheric components. Windshear conditions, for instance, brutally affects aircrafts stability. Table 7.1 lists main pros and cons of each approach.

Main difficulty to synthesize H_∞ controllers is that it considers the mathematical model of the plant. However, it is fairly easy to be determined with MBD/CAD software, such as ©ADAMS and/or ©SolidWorks. The fact H_∞ considers the plant model assigns final compensator with

filtering properties, which considerably contributes to a high quality stability system.

Finally, since synthesis not rarely leads to superior rank matrices, the controller demands considerable computational resources so that it may solve a system of equations.

Table 7.1: Comparison between classic and modern control approach.

<i>Approach</i>	<i>Pros</i>	<i>Cons</i>
PID	<ul style="list-style-type: none"> - Relative easiness to fine tuning - Mathematical model not required - Easy implementation - Low computational cost 	<ul style="list-style-type: none"> - Not robust to external disturbances - Demands expertise to fine tune
H_∞	<ul style="list-style-type: none"> - Fine tuning requires solid background in control theory - Filtering capabilities - Robust to external disturbances - Robust to parametric variations - Robust to model uncertainties 	<ul style="list-style-type: none"> - Demands mathematical model of the plant - Not so intelligible for beginners - Implementation implies in high computational cost - Demands high performance hardware

The optimal H_∞ controller synthesized to control the MAV in hovering mode is a 6-input/4-output system, which considers the adjustment of the quadrotor pose angles (ϕ, θ, ψ) and translations (x, y, z) as well.

7.2 Optimal H_∞ Controller Design & Implementation

Controller synthesis considered the stabilizability and detectability of the plant according to SAMPAIO et al. (2011) ZHOU (1998) K. ZHOU. (1995) STEFANI (1993), which results in the augmented plant G_{ap} (Fig. 7.2).

Figure 7.2: Linear fractional transformation of augmented plant G_{ap} matrix.

Where W_e and W_u are, respectively, the error e and the control u weighting functions. Sensitivity function is given by S while R is the transfer function between the control action and the reference input. Obviously, $G(s)$ represents our plant in frequency domain. However, we

may transport the Laplace representation to time domain without any loss of fidelity whatsoever. Indeed, we use the MAV dynamic matrices A , B , C and D in the synthesis procedures. In the other hand, control gain matrices A_k , B_k , C_k and D_k are obtained at the end.

In order to guarantee stability and robustness relative to disturbances/noises/uncertainties, it is necessary that the gains of S are low at low frequencies so that noises/disturbances rejection can be assured, that is, $|W_e S| \leq 1$. On the other hand, R gains must be low at high frequencies to achieve the same noise rejection level, that is, $|W_u R| \leq 1$. Aiming to achieve the above robustness criteria, mixed sensitivity problem was considered, which states that:

$$S = (I + L)^{-1} \quad (7.1)$$

And

$$R = (I + L)^{-1} \quad (7.2)$$

The previous two robustness criteria are directly related to:

- stability against model parametric variations;
- stationary error $\rightarrow 0$;
- robustness even with open-loop uncertainties and variations;
- robustness against noises which are inserted into the plant.

Actually, the sensitivity function must ideally satisfy the peak sensitivity M_s and also the bandwidth ω_b , so that the following relation must be respected:

$$|S(s)| \leq \left| \frac{s}{\frac{s}{M_s} + \omega_b} \right| \quad (7.3)$$

The closed-loop bandwidth value is such that $\omega_b \approx \omega_n$. A good control design depends on M_s with lower values. Both bandwidth and peak sensitivity were chosen by observing the frequency responses and the natural frequency of the plant

Goal is to minimize the norm of transfer function T_{zw} between G_{ap} input and output. The γ -iteration algorithm is programmed in order to find an optimal controller K such that G_{ap} closed-loop transfer function matrix norm T_{zw} satisfies the following:

$$T_{zw} = \left\| \begin{array}{c} W_e S \\ W_u K S \end{array} \right\|_{\infty} = \left\| \begin{array}{c} W_e S \\ W_u R \end{array} \right\|_{\infty} < \gamma \quad (7.4)$$

The optimality condition stands for the following:

$$\gamma > \gamma_{opt} = \min^{KStability} \|T_{zw}\|_{\infty} \quad (7.5)$$

For $\gamma < 1$. Therefore, γ -iteration algorithm stop condition occurs when γ is as small as possible in an iteration limit. Thus, when γ achieved is less than 1, the controller is said to be optimal (ZHOU (1998)) (K. ZHOU. (1995)).

7.2.1 Optimal H_{∞} Controller Synthesis

The γ -iteration algorithm designed (Appendix E for detailed information) reached $\gamma_{opt} = 0.1915$, which is in accordance with the optimal H_{∞} definition. Weighting functions W_e and W_u obtained from are given, respectively, by (7.6) and (7.7)

$$W_e(s) = \frac{0.1s + 30}{s + 0.03} \quad (7.6)$$

$$W_u(s) = \frac{s + 0.06667}{330s + 10} \quad (7.7)$$

The frequency responses of S and R can be seen in Figs. 7.3 and 7.4. As it is notable, the gains of S are lower at lower frequencies. On the other hand, the gains of R are lower at higher frequencies, limited by the controller bandwidth.

Figure 7.3: Frequency response for the S function.

Hence, K controller composed by a set of four gain matrices A_k , B, C_k and D_k , was success-

Figure 7.4: Frequency response for the R function.

fully determined.

Finally, the implementation of a state space controller such as the one proposed here may be easily implemented in the shape of Algorithm 7.1. Thus, as long as a closed loop interconnection is established, control may act over the MAV. For hardware information, please refer to Appendix E.

Algorithm 7.1 SiL Optimal H_∞ Control Algorithm

input : State vector X , Setpoints X_d

output: Individual control signals to motors $u_{1..4}$

```

1 if Connected_to_the_MAV then
2   | Closed_Loop_is_Active  $\leftarrow$  true
3 end
4 while Control Module is Active do
5   | while Control Module is Active do
6     | for All State Variables do
7       |  $[X] = \text{Read}(\text{states})$ 
8     | end
9     |  $e \leftarrow [X_d - X]$ 
10    |  $x_k \leftarrow A_k \cdot x_k + B_k \cdot e$ 
11    |  $U \leftarrow C_k \cdot x_k + D_k \cdot e$ 
12    |  $\text{Write}(U(1))$ 
12    |  $\text{Write}(U(2))$ 
12    |  $\text{Write}(U(3))$ 
12    |  $\text{Write}(U(4))$ 
13  | end
14 end

```

7.3 Assisted Flight Control of MAVs

As it was mentioned in Section 7.1, we focus our effort in the design of a stability control system, which does not comprehend an autonomous navigation system. Instead, we designed an assisted flight control system, which may autonomously take control of the stability pose angles in order to guarantee that the MAVs might not present unexpected and unstable behavior. An operator, human or a robot, may change set point vector X_d (thrust, roll, pitch and yaw) based on the MAV observed states X_o . In parallel, a perception layer (embedded sensors) measures inertial states X_m which are feedback so that error $e(t)$ may feed control K_{H_∞} . Figure 7.5 refers to the assisted flight control architecture in which the optimal H_∞ controller is employed.

Figure 7.5: Closed-loop control architecture for a typical assisted flight control, where an operator (human or not) may compute new set point values at anytime during the flight.

The above architecture aims to be current regulations compliant since a human operator shall be in charge of controlling all phases of flight of any ROV.

7.4 Results

After a meticulous and careful process of synthesis of our H_∞ controller to the point to find a set of optimal gain matrices A_k , B_k , C_k and D_k , we tested it firstly in flight simulation. As it will be outlined in the next chapter (Chapter 8), we have successfully developed a custom computing framework, named Flight Variables Management System (FVMS), based on flight simulation that has proven to be an outstanding platform for validating a great variety of algorithms, control is included.

In order to show the controller realizability in practical applications, two possible implementation types were considered. Firstly, we have implemented the H_∞ using the Software-in-the-Loop (SiL) technique, which basically consists in a closed loop control in the same computer scope. Secondly, we have fully embedded the controller in an external hardware, which configures a Hardware-in-the-Loop (HiL) implementation. In this case, closed loop is achieved through serial communication bus.

We use the ©AscTec Pelican MAV model in flight simulation for both experiments. In this case, inputs are MAV states X and its respective set point vector X_d . Output is the control vector u , that contains the corrective actions to motors the virtual MAV ($M_{1..4}$), through changing the angular rotations of their propellers ($\Omega_{1..4}$).

7.4.1 Optimal H_∞ Controller Experimental Results in SiL Simulation

First control evaluation considers SiL simulation (7.6) with the H_∞ controller. The MAV was submitted to a well-defined hovering task, which consists in maintaining the robot at a certain altitude at its equilibrium point. In other words, the MAV must start from ground, climb up until it reaches the altitude set point, keeping the attitude angles near from zero ($\phi \approx \theta \approx \psi \approx 0$) and remain still.

Figure 7.6: Optimal H_∞ controller experiment with a SiL set up.

To make the analysis more realistic and, thus, allow the observation of noise rejection that is intrinsic to optimal robust controllers, Gaussian noise of around 4 rad/sec and standard deviation of 2% was inserted into the closed loop control (BOUABDALLAH et al. (2004)). Additionally, to reinforce noise rejection ability, windy conditions (5-7 knots) were present during the essay.

The MAV climbs to 33ft. and then remains in hovering mode, as it can be seen in Fig. 7.8-(a). The MAV gently reached the set point in approximately 7 seconds. No overshoot was

noted, neither steady state error.

Figure 7.7: Pelican MAV during HiL experiments.

Figure 7.8: Altitude hold mode (a), angular stability (b) and linear displacement (c) with an optimal H_∞ controller in SiL flight simulation.

Another important point to be highlighted in this essay lies in the states of roll, pitch and yaw angles. Figure 7.8-(b) illustrates the attitude angles of the Pelican MAV during climb. It is noted that not only the MAV translated straightly up to the desired altitude with minimum angular shifting but also presented low influence of the wind and external disturbances. As for the MAV position in XY plane, Fig. 7.8-(c) shows that the position dispersion always occurred around the initial position. A standard deviation of $\sigma \approx 0.3974m$ and mean error $\bar{e} \approx -0.0457m$ are observed.

An in-depth quantitative analysis of the SiL architecture proposed in this work shows that Algorithm 7.1 performs the closed loop control of the 6 DoF with the optimal H_∞ controller at 125Hz approximately (AMD Turion 64 X2 1.6 GHz processor).

7.4.2 Optimal H_∞ Controller Experimental Results in HiL Simulation

Secondly, the H_∞ controller was embedded in a ©Microchip 16 bits DSC dsPIC33FJ128MC706. Again, we interface our hardware with FVMS flight simulation framework via serial bus. Figure 7.9 shows the experiment set up.

Figure 7.9: Optimal H_∞ controller experiment with a HiL set up.

Despite its complexity on the synthesis process, H_∞ controllers have a simple implementation on hardware, which will lead to a faster response of the controller. The embedded H_∞ control uses the same shape as Algorithm 7.1.

The test consist in starting the autopilot to control the aircraft pitch and roll during a human-controlled take-off, done to ensure a safe distance from the ground, and during its hovering maneuver in the presence of MiL (Man-in-the-Loop) disturbances. Such disturbances were introduced in the MSFS via USB joystick. The disturbances introduced were wide and steady movements, first positively on pitch, then negatively. Then, positively on roll, and again negative. Finally two joint movements were performed. One may see the H_∞ response in the take-off phase and to those disturbances on Fig. 7.10-(a), 7.10-(b) and 7.10-(c), respectively. Aircraft behavior is stable in the three plots.

7.5 Conclusions

In this chapter we presented a complete description on the synthesis of the optimal H_∞ robust controller, which is suitable to be implemented in MAVs such as those presented in this thesis. We also presented detailed information on how to get the controller that was implemented. Furthermore, we offered important results from flight simulation, using a virtual graphic and dynamic representation of the ©Pelican MAV.

Figure 7.10: Roll and pitch stability control with an optimal H_∞ controller in HiL flight simulation.

Flight simulation results have attested that the H_∞ controller synthesized in this chapter fulfills MAVs applications and grounds the next step, which is the application both in flight simulation models and in the real ones.

Chapter 8

Flight Simulation Evaluation

After a careful watch on the design of all three MAVs with a well defined project goal, we have developed a novel flight simulation framework through which we start to bring the new platforms to life (Fig. 8.1). The main contribution and novelty of this chapter is to successfully achieve the layout of virtual models of each of our aircrafts in a realistic fashion which is visually and analytically attractive. Indeed, our framework has proven to be extremely useful and versatile for testing and validating several classes of algorithms, such as those for control, guidance, navigation, perception, etc. This is the overture to maiden flight come true.

Figure 8.1: Sharky, SquidCop and H₂Omni dynamic and visual feedback during flight simulation experiments with the H_∞ controller in FVMS framework.

8.1 Relevance of Flight Simulation Assisted Evaluation

Generally, experimental tests represent a major concern regarding the evaluation of aerospace systems. In fact, some relevant drawbacks may often turn experimental realization unfeasible due to:

- high cost of construction and uncertainties around the success of maiden flight;
- difficulties on reaching parts (e.g., electronics, mechanical devices, software);
- algorithms may misbehave, damaging the robot and being dangerous to people nearby as well;
- considering electric systems, battery limits demand a considerable number of spare kits and frequent replacements;
- constant code updating, control gains improvements and fine tuning, wiring/re-wiring communication cabling takes time;
- even teleoperated aircrafts demand the expertise and the ability of an experienced human pilot. Consequences of unexperienced operators may be hazardous;
- limitations in airspace due to the airfield restrictions or even the full absence of segregated airspace for tests may derail experimental tests or even make it impractical;

The possibility to interact to a reliable virtual representation of a flying system is an outstanding possibility. A huge number of previous works have brought up relevant works restricted to ©MATLAB based aircraft models, which has undoubtedly proven its worth and effectiveness. However, differently of strictly granting numerical information, this work offers a new framework that may provide a more tangible way to evaluate and analyze aerospace systems. The Flight Variables Management System framework (FVMS) is a complete software solution that interfaces Microsoft Flight Simulator (MSFS) and makes use of Man/Software/Hardware-in-the-Loop techniques to get to the aircraft model, which will be further outlined in this chapter.

8.2 FVMS: A Novel Tool in Flight Simulation Assisted Design of UAS

We have designed a full computation framework named Flight Variables Management System (FVMS) which may fully interact to Microsoft Flight Simulator (MSFS) (SAMPAIO et al. (2013b)). We have also published important works related to a wide variety of applications

involving guidance, control and navigation of aircrafts (SAMPAIO et al. (2014))(SAMPAIO et al. (2011))(SAMPAIO E BECKER (2010)).

None of commercial and/or open source flight simulators are FAA certified to be used as a ready-to-use training station. However, FAA recognizes the potentialities of non certified aerospace commercial software. In an official document from the year of 1997, FAA establishes a series of recommendations (AC61126), through which the value of computer-based simulations is recognized. The advisory circular lays out the requirements for an approved training device where MSFS is included.

Regarding MSFS, the flight simulator was chosen for some sound reasons:

- MSFS is a robust commercial flight simulator provided with an well-rounded background in both quality graphical development and also in aerospace engineering. For that reason, the simulator has continuously been improved, even after 25 years;
- Although Microsoft has already released a newer version (FSX), it demands more processing resources than the previous one. In fact, FS2004 presents very satisfactory graphical response using less computing resources. Yet, it preserves the analytical integrity of the SiL simulation with fast response;
- The works of SAMPAIO E BECKER (2009) FELDSTEIN (2004) attest that FS2004 features real-time simulation capabilities. Additionally, the work of LOUALL (2004) technically confirms that FS2004 presents real-time simulation characteristics, presenting a sampling rate of 75 Hz with a 100ns deviation;
- FS2004 is MDL extension compatible, which facilitates the incorporation of custom 3D models;
- Aircraft parametric information is easily set up, which may be done directly through a CFG file;
- FS2004 natively offers the option of changing simulation weather conditions. It makes the simulation more realistic, allowing the user to analyze how atmospheric disturbances affect the stability of the virtual aircraft.

FVMS offers easy integration to ©MATLAB engines, which allows the exchange of information for a variety of tasks - e.g., plot displaying, online use of native toolboxes, among others. For example, one may run algorithms from ©MATLAB to interact to the aircraft in full-duplex communication.

8.2.1 Software/Hardware/Man-in-the-Loop Architectures

Basically, FVMS allows read/write operations from/to MSFS, which means that one may interact directly to every variable that is generated while the simulation is running. Figure 8.2 shows FVMS user interface through which one may interact to the simulation.

Figure 8.2: FVMS interface. Users may interact to more than 2000 variables related to the flight (aircraft, atmosphere, etc.).

Man-in-the-Loop simulation is a resource through which a human pilot may interfere with the flight simulation by imposing manual commands with a joystick. The MiL configuration makes use of the same SiL architecture (see Fig. 8.3). Furthermore, the pilot may also interact even in the HiL since the Joystick connection is recognized by MSFS. Basically, FVMS SiL/HiL/MiL is achieved from steps 1-9 where all read/write operations are performed.

Figure 8.3: FVMS SiL/HiL/MiL general architecture.

8.3 FVMS Reliability

8.3.1 Emulation of Aircraft Sensors

Regarding the control of stability of an aircraft, it is essential to consider the availability of the aircraft state vector, so that the 6-DoF dynamic equations may be solved:

$$X = [x \ \dot{x} \ y \ \dot{y} \ z \ \dot{z} \ \phi \ \dot{\phi} \ \theta \ \dot{\theta} \ \psi \ \dot{\psi}]^T \quad (8.1)$$

State vector is composed by linear translations (x, y, z) , angular rotations (ϕ, θ, ψ) , as well as their time derivatives $(\dot{x}, \dot{y}, \dot{z}, \dot{\phi}, \dot{\theta}, \dot{\psi})$. Thanks to FVMS SiL configuration discussed in the previous section, each variable of the above mentioned state vector is available. Thus, FVMS framework is able to emulate the following sensors, but not limited to:

- *IMU (Inertial Measurement Unit);*
- *Radio altimeter*
- *GPS*
- *Gyroscopes*
- *Pitot tube*

A critical feature in FVMS, which guarantees the reliability of experiments, is the fact that sensors may also reproduce the noisy measured information (raw data). In real life most of measurements are severely affected by the disturbing influence of environmental conditions. Figure 8.4-(a) shows an example of noisy data captured by a virtual quadrotor through FVMS. Comparing to the real model of the same aircraft (Fig. 8.4)-(b), similarity is notable.

8.3.2 Dynamic Atmosphere Conditions

MSFS is able to generate a great variety of controlled and/or random atmospheric conditions such as pressure variations, visibility changes due to fog and/or rainy scenarios, windshear situations and many others. Most of that may be manipulated and online changed through FVMS GUI program. Considering the analysis and observation of the aircraft stability, windshear conditions are very attractive. It is possible to insert different wind patterns and change direction and magnitude.

Figure 8.4: Noisy inertial data captured during FVMS experiment (a) and inertial data measured from a real IMU. That is only a small sample about FVMS reliability on the sensors emulation.

8.3.3 Aircraft Graphic & Dynamic Models

The new aircraft model comes to life from a two steps procedure, achieved from 3D designing and dynamic modeling separately. In example, Fig. 8.5 shows our ©AscTec Pelican all the way through the design process.

Figure 8.5: From left to right the graphic modeling process of the ©Ascending Technologies Pelican MAV in 3D Studio Max suite starts to be formed, with Hokuyo URG-04LX and ©Kinect attached to the MAV body.

As MSFS solves the complete set of 6 dynamic equation of the aircraft, one must properly set a CFG (configuration) file with the aircraft main parameters. Resulting graphic/dynamic

behavior of the virtual representation is quite similar to the real one. The feeling of flying both is positively verified for an experience pilot.

8.4 Capabilities and Versatility

It is important to highlight that our framework capabilities go further than basic features. One of the most original FVMS possibilities is its integrability to computing vision algorithms. A set of many camera viewpoints may be previously configured from the MAV perspective. In example, one may configure a downwards camera, pointing to the floor. Hence, FVMS can run Optical Flow (OF) algorithms on the estimation of the aircraft speed (Fig 8.6-(a)). MAV ground speed measured by the IMU sensor and the speed which was estimated by the OF algorithm are very similar and may aid on the refinement of trajectory control algorithms or a wide number of other possibilities (Fig. 8.6-(b)).

(a)

(b)

Figure 8.6: Real time OpenCV optical flow algorithm in running mode (a) during the MAV flight capturing downward images (right). When compared to estimated speed from inertial measurement (b), one may see that optical flow is successfully achieved through FVMS algorithms.

More complex navigation algorithms may also be implemented with high reliability. Figure 8.7 shows FVMS capabilities on GNC (Guidance, Navigation & Control) algorithms. In that

case, nonlinear *Lyapunov* based path following control algorithms are run in order to guarantee a given trajectory (SAMPAIO et al. (2014b)).

Figure 8.7: Lyapunov non-linear GNC algorithm on the path following (a), bank (b) and pitch (c) control shows a snapshot of Sharky in the quadrotor mission with FVMS.

8.5 Results

Up to this date, Sharky, SquidCop and H₂Omni graphics and dynamics have been successfully modeled. All three MAVs have been satisfyingly replicated after an systematic design process. First experimental flight simulation results are presented next.

All experiments involving the quadrotor configurations consider hovering control and comprehends take off, climb and hold position at about 30ft. from ground level. Moderate wind conditions are set up at a speed of around 12knots. However, due to the random windshear pattern, we may not guarantee the exact reproducibility.

Regarding experiments with Sharky in the fixed-wing configuration the aircraft we have simulated descent maneuvers, mixing powered flight and gliding from about 5500ft. Once again, moderate random wind was introduced to the essay (around 16knots). The nature of releasing and its effects are out of the scope of this thesis as well as landing procedures.

Another important point regards to water experiments with H₂Omni. As far as we know, MSFS is not able to reproduce the mechanics of navigating in water environment. Thus, only air operation is taken into consideration.

Software-in-the-Loop simulation was selected for all experiments, where the optimal H_∞ controller synthesized in Section 7.2 acts on the stabilization of the MAVs. Algorithm 7.1 was implemented. More detailed information may be found in Appendix E. As for Sharky in fixed-

wing configuration, the MAV was fully Man-in-the-Loop teleoperated with a joystick.

8.5.1 Sharky in FVMS

Sharky Quadrotor

Figure 8.8 shows the virtual MAV taking off from ground to a given hovering position. Figure 8.9 shows inertial measurement and thrust level. One may note that roll and pitch angles are sustained around less than $\pm 10^\circ$. That is an excellent result considering that stability during climb must take into account the 3D-IPM depicted in Chapter 4.

Figure 8.8: Virtual model of the Sharky MAV in the quadrotor configuration airborne in MSFS.

Figure 8.9: Sharky quadrotor inertial sensors measurement during the experiment.

Sharky Airplane

Figure 8.10-(a) shows a snapshot of Sharky in the quadrotor configurations during descent in a windy scenario while Fig. 8.10-(b) shows a plot of the MAV trajectory. Spiraling trajectory was intentionally produced in order to check the aircraft maneuverability. Figure 8.11 refers to inertial response during the experiment. According to gathered data, the aircraft presented normal behavior both for lateral and longitudinal stability during all maneuvers.

(a)

(b)

Figure 8.10: Virtual model of the Sharky MAV in fixed-wing configuration airborne in MSFS (a) and Sharky path lines during descent (b).

Figure 8.11: Sharky sensors response during descent flight maneuvers.

8.5.2 SquidCop in FVMS

Figure 8.12 presents the sequence of snapshots taken during SquidCop climb. As it is notable from inertial data (Fig. 8.13), the MAV climbs normally without any loss in the stable attitude integrity. Furthermore, one may note the very small angle shifting (an average of $\pm 2^{\circ}$). That is actually an outstanding response considering that the MAV is designed to present low levels of oscillations in roll and pitch modes.

Figure 8.12: Virtual model of the SquidCop MAV airborne in MSFS.

Figure 8.13: SquidCop inertial sensors measurement during the experiment.

8.5.3 H₂Omni in FVMS

Finally, H₂Omni was submitted to the same experiment. Figure 8.14 shows the MAV in climb mode till it reaches the hovering state. Figure 8.15 refers to inertial data. Since H₂Omni dynamic features presents faster response (much more agile than previous MAV), it is expected that roll and pitch angles are quite larger. However, one may see that both angles remained between $\pm 10^\circ$ and at an average of 5° . This is also an excellent behavior, pretty much similar to the real one, which will be presented in Chapter 10.

We have also evaluated the MAV during an aggressive maneuver, which consists in accelerating the MAV forward and then pitching it up to an abrupt and fast breaking. Figure 8.16 refers to inertial information during the experiment. We may observe that the MAV reaches critical angles (around $\pm 50^\circ$), which is compliant to aggressive flight for quadrotors. We may also note that the MAV completely recovers stability after breaking, a likely effect that also happens to the real MAV.

Figure 8.14: Virtual model of the H₂Omni airborne in MSFS.

Figure 8.15: H₂Omni inertial sensors measurement during the experiment.

Figure 8.16: H₂Omni during aggressive maneuvers. Note that attitude angle (roll) travels from approximately 50° to -50° in about 2 sec.

8.6 Conclusions

All results taken from FVMS flight simulation were very favorable, so that we may now go through the process of experimental validation of our controller in the real platforms in Chapters 9 and 10. Prior to head to the so-expected maiden flight, we shall establish two considerations, which are outlined next.

8.6.1 Considerations on the FVMS/MSFS Evaluation

When it comes to evaluating hardware-based controllers for MAVs, Hardware-in-the-Loop (HiL) simulation may bring outstanding facilities. A HiL may perfectly be integrated to a flight model of any aerial robot as it was really acting over the real plant. As long as the HiL is set up, it becomes easy to achieve real time experiments and, furthermore, perform quick adaptations in the control algorithms, e.g. redefine gains, fine tuning or even switch from an specific aircraft to another in a blink of an eye SAMPAIO et al. (2013b) SAMPAIO et al. (2013). From this perspective, FVMS has attested its versatility, expediting several tasks related to the validation of aircrafts.

Another important contribution of this chapter is to build the virtual representations of the

three MAVs proposed in this thesis with high reliability. From the three designed models, it was possible to get an outstanding representation of both graphic and dynamic response. Final visual feedback is a very attractive and reliable stunt of the real one.

8.6.2 FVMS Didactics Qualities

Yet, one aspect that raises optimistic points is that simulation tools are extremely attractive and useful in teaching aerospace sciences. In example, when it comes to undergraduate students, handling a virtual MAV does not demand the usual ability to deal with the real one. Therefore, a reliable computing set up, composed by a realistic flight simulator and software interface may be a very useful tool to improve such process. Besides, as FVMS allows user to interact to about 2000 flight variables, the process of learning gets more attractive and still reliable, once one may directly handle the aircrafts variables in full duplex communication.

Part IV: Preflight

Fourth part aims to validate stability and controllability criteria. This is the briefing room and the prelude to the field application.

Chapter 9

Vision Motion Capture Analysis on the Stability of MAVs

This chapter presents after-design first experimental results for Sharky, SquidCop and H₂Omni platforms. Main contribution is to offer a robust and concise validation of the stability control of the three novel platforms using vision motion capture analysis (MOCAP) with ©VICON system. When it comes to the stability quality of the MAVs, ©VICON tracking system allows the precise observation of the inertial states of the three aircrafts. We simultaneously capture all flight data from the MAVs embedded IMU for the sake of redundancy and to ensure validation robustness. Final analysis leads to well-grounded stability double check results.

Figure 9.1: Successful vision motion capture evaluation of Sharky(a), SquidCop(b) and H₂Omni(c) MAVs with ©VICON System.

9.1 Important Notice on ©VICON System Evaluation

All experiments described in this Chapter were run in an enclosed room, limited by walls, with no humans in the vicinity. Flights were conducted by an experienced pilot. All tests are in observance to CAVE (Certificado de Autorização de Voo Experimental para Veículos Aéreos Não Tripulados), section 21.191 e 21.193 of Brazilian Civil Aviation Authority n° 21 - RBAC 21, and Portaria DAC N°. 646/DGAC, from December the 15th, 1998.

The embedded control is endowed with a failsafe back up system for security.

9.2 Important Notice on ©VICON System Capture Data

Due to limitations in our ©VICON system license, we were not able to plot our curves from cloud of points generated by the software. Actually, the ©VICON Tracker 2.1 software does not allow us to export curve points (to a **.txt* file, in example) so that it is not possible to customize our plots in ©MATLAB. We had to take snapshots, which resulted in low quality graphic images. Nevertheless, the low quality image does not have any relation to the experiment quality at all. In the other hand, inertial data from embedded sensors are in high quality.

Thus, we apologize for the low resolution and poor quality of our ©VICON plots.

9.3 MOCAP Analysis: ©VICON System

Vision motion capture is a technique based on visual motion capture (MOCAP) of objects in the 3D space aided by cameras and artificial vision computer systems. In this analysis the ©VICON System is used. Four cameras are assembled in each corners of an enclosed room aiming the center point of the floor. Cameras range covers almost the wholly space. Workspace is a $8m^3$ (3mx3mx2m) room at USP/EESC/SEL/LASI and any object may be tracked inside that volume. The ©VICON system is a high resolution device through which one me track the smallest linear and angular variations (Fig. 9.2).

The MOCAP technique is based on tracking small shiny markers that are attached along the body (Fig. 9.2-(a)). A minimum of three cameras are mandatory so that the marker can be detected and reconstructed. When cameras detect three markers, the body is then triangulated. In that point, after calibration, a fixed coordinate system is established and the body pose may

Figure 9.2: Sharky markers position for MOCAP @VICON system evaluation (a) and tracker software triangulation coordinate system (b).

be determined (Fig. 9.2-(b)).

We expect that @VICON may provide us with precise information regarding our MAVs behavior during stabilization. At the same time, for redundancy, we collect information from embedded IMU. We intend to have a double check evaluation to strengthening our analysis.

9.3.1 Sharky Visual Motion Capture/Tracking

Sharky quadrotor was submitted to a simple stability evaluation while flying inside the @VICON chamber. Figure 9.3 presents data from roll and pitch angles during the experiment. It may be noted that, as expected from the mathematic model simulated in Section 4.2.2, the 3D-IPM like quadrotor may be successfully and easily controlled around the stability pose. Figure 9.4 shows IMU data captured during the experiment. One may resort specially to the bottom left plot to confirm that there is a clear correlation between stability data from embedded sensors and the visual tracking estimation.

Figure 9.3: Sharky stability response capture by ©VICON System.

Figure 9.4: Sharky IMU data capture during ©VICON visual tracking.

9.3.2 SquidCop Visual Motion Capture/Tracking

Figure 9.5 refers to inertial measurements estimated by ©VICON during hover flight in the chamber. Tracing a comparison to the embedded IMU inertial data from Fig. 9.6, we may note that both estimations converge and we may attest the MAV stability.

Furthermore, one may see a very small angle shifting during the experiment. As it was addressed in Chapter 5, the conventional pendulum works as passive stabilizer and contributes to the overall stability improvement.

Figure 9.5: SquidCop stability response capture by ©VICON System.

Figure 9.6: SquidCop IMU data capture during ©VICON visual tracking. Note that the bottom left plot, composed by roll and pitch angles colincides with visual tracking estimation.

Forced Disturbances/Perturbation Experiment

SquidCop was subject to a series of man-made manual high impact disturbances in order to destabilize roll pitch and angles. We want to take a close look at the robustness and at the capability to suppress such perturbations. Figure 9.7 shows a graphical sketch of the MAV kinematic during disturbance input captured by ©VICON cameras and Fig. 9.8 shows inertial data estimated by its software. Figure 9.9 shows inertial data from embedded IMU while consecutive attempts to destabilize roll and pitch happens. We may see from SquidCop response

that the controller guarantees stability at a good robustness level. Perturbations are promptly suppressed and the MAV keeps stable around the equilibrium roll and pitch angles.

Figure 9.7: SquidCOP triangulation during ©VICON visual tracking where the MAV was submitted to forced disturbance with engines off. Stability is recovered as soon as controller assumes attitude control.

Figure 9.8: SquidCOP ©VICON inertial data estimation at forced disturbance situation.

Figure 9.9: SquidCop IMU data captured during ©VICON visual tracking at forced disturbance situation. Stability is recovered as soon as controller acts over the MAV.

Figure 9.10: Detail of SquidCop IMU data capture during ©VICON visual tracking at forced disturbance situation.

9.3.3 H₂Omni Visual Motion Capture/Tracking

Figure 9.11 refers to H₂Omni ©VICON system data during hovering inside the chamber. It is noted an average maximum angle shifting of $\approx \pm 5^\circ$. As one may note from Fig. 9.12, both estimations are coherent and converge to same measurement. As for H₂Omni stability, we may see that our controller successfully keeps the MAV about the equilibrium point.

Figure 9.11: H₂Omni stability response capture by ©VICON System.

Figure 9.12: H₂Omni IMU data capture during ©VICON visual tracking.

9.4 Conclusions

All three platforms were basically subject to the same set of experiments. One common technical aspect is that a high level of turbulence was present in all experiments. The ©VICON system is enclosed within a small room constrained by walls and a roof. The propellers together displace a large volume of air which randomly circulates and then hits the three helicopters. However, that does not represent the experiment detracting whatsoever since it works as a good way to check the controllability robustness and the stability as well when air blow in gusts.

Results from MOCAP evaluation were extremely favorable. All experiments show that a robust control is able to successfully handle the stability control of our MAVs. They head our MAVs to the maiden on-the-field flight in Chapter 10.

Part V: Maiden Flight: On-the-Field Evaluation

Last part of this thesis, this is the grand finale, where all three MAVs are put into real flight conditions.

Chapter 10

On-the-Field Evaluation

Main contribution of this chapter is to bring experimental on-the-field results with the three novel MAVs designed in this thesis. We also offer an in loco in-depth evaluation of the performance of the three proposed vehicles always looking to each one from the perspective to which they were designed to. All experiments were performed outdoor subject to the atmosphere dynamics, such as windshear disturbances. That is, all tests attempts to meet real conditions of real field applications, where our MAVs are taken to the most of their flight envelopes.

Figure 10.1: Sharky(a), SquidCop(b) and H₂Omni(c) MAVs on the field.

10.1 Important Notice on Field Evaluation

All experiments described in this Chapter were carried out in a remote area with no humans nor wildlife presence in the vicinity. Flights were conducted by an experienced pilot. All tests are in observance to CAVE (Certificado de Autorização de Voo Experimental para Veículos Aéreos Não Tripulados), section 21.191 e 21.193 of Brazilian Civil Aviation Authority n° 21 - RBAC 21, and Portaria DAC N° 646/DGAC, from December the 15th, 1998.

The embedded control is endowed with a failsafe back up system for security reasons.

10.2 Technical Considerations About On-the-Field Experiments

All experiments described in this Chapter considers outdoor flight into which all MAVs are subject to atmospheric conditions in a vast open field. Table 10.1 shows atmospheric information of the city of São Carlos/SP, Brazil, under which tests were carried out.

Table 10.1: Atmosphere information - São Carlos-SP, Brazil during tests.

Localization	W47°30' / S21°30'
Average Temperature	20°C (68F)
Altitude	856m (2808ft)
Relative Humidity	76%
Average Atm. Pressure	690,7mmHg
Wind Direction	NNE
Wind Speed	7knots (13km/h)
Wind Gust	11knots (20 km/h)

(*)Source: INPE - Instituto Nacional de Pesquisas Espaciais

10.3 Sharky Quadrotor Field Evaluation

The Sharky quadrotor configuration is evaluated for the following situations:

- hovering mode;
- fast climb;
- double batteries;

The flight essays above are sufficient to cover all flight envelopes that might happen in nominal operations.

10.3.1 Hovering Mode

Hovering mode was performed in a windy day, with moderate winds, where the MAV was constantly hit by wing gusts (Fig 10.2). Figure 10.3 shows inertial data measured during the experiment. We may note that the MAV response is extremely favorable considering atmosphere conditions, spite of the influence of dragging forces over the airfoils.

Figure 10.2: Sharky airborne in hovering flight moderate under windy conditions.

Figure 10.3: Sharky inertial response to hover flight subject to wind.

10.3.2 Fast Climb

Sharky was submitted to a fast climb test through which we submit the aircraft to an abnormal vertical acceleration profile. That does not mean, however, full throttle. More than a quantitative evaluation, this test is just a part of many situation in which we may observe the MAV qualitative response.

Figure 10.4 shows a sequence of snapshots of Sharky on take off maneuver to a ceiling altitude of around 100ft.. Figure 10.5 refers to inertial measurement during the test. As we may note, the aircraft presented an outstanding angular behavior. Average angular displacement bot for roll and pitch is less than $\pm 10^\circ$.

Figure 10.4: Sharky during fast climb test.

Figure 10.5: Sharky inertial response to fast climb subject to wind.

10.3.3 Double Batteries Hovering

The double battery test refers to adding an extra battery package (0.250 Kg) in the same position as the first one (Fig. 10.6). The idea is to attest the controller capabilities when inertia is added to the 3D-IPM problem. Figure 10.7 refers to inertial information during take off and hover. Once again Sharky response is extremely stable. Regardless off the extra mass in the 3D-IPM, a very good level of maneuverability was preserved, which allowed a safe flight and landing as well. Average angular shifting is no larger than $\approx \pm 10^\circ$.

Figure 10.6: Sharky take-off and hover subject to wind and double batteries.

Figure 10.7: Sharky inertial response to hover flight subject to wind and double batteries.

10.4 Sharky Fixed-Wing Field Evaluation

After the analysis and the design of a minimum stable fixed-wing Sharky airplane we carried out very conservative experiments due to infrastructural limitations. As it was addressed in Chapter 4, Sharky presents special characteristics which allows several flight phases to be performed. One critical phase is the transition between quadrotor and airplane.

The transition is a maneuver that demands time and more investigation in order to be successfully achieved. Thus, in this thesis, we limit our analysis about the transition to a more conservative one, which we name the *quasi*-transition phase.

10.4.1 *Quasi*-Transition State

The *quasi*-transition state consist in flying Sharky quadrotor in high attitude angles. Considering that the 3D-IPM problem must be simultaneously solved in flight, putting the MAV at a high angle represents a risky task. However, it may be achieved and we may observe and learn much about the stability control and the behavior of the wholly fuselage and wings when the MAV is airborne.

Figure 10.8 refers to inertial data during the *quasi*-transition maneuver. One may see that

a maximum angle of 40° was reached for 5 seconds (Fig. 10.9). That was a huge achievement, specially if we look at the stability control quality during the experiment. An average thrust of 50% was observed. After the pitching maneuver, the controller smoothly brings the MAV to a complete state of equilibrium again.

Figure 10.8: Sharky during the *quasi*-transition maneuver.

Figure 10.9: Sharky inertial response during the *quasi*-transition maneuver.

10.5 SquidCop Field Evaluation

Evaluation of SquidCop considers the following situations:

- hover maneuvers at small angles;
- stability in vertical over accelerated take off and landing (elevate climbing rate);
- aggressive maneuvers at high angles, fast low pass flight;
- free fall, with assisted but reduced thrust;

All three sceneries together absolutely cover all possible flight envelopes that the platform may face during any mission.

10.5.1 Hovering Mode

Hover flight experiment considers the MAV coming from 100 ft in descending rate to approximately 30 ft as one may see from Fig. 10.10. One may note from Fig. 10.11 that the MAV keeps attitude angles between $\pm 5^\circ$. This is a remarkable achievement considering the windy conditions into which the experiment was conducted. This is an outstanding indication about SquidCop stability.

Figure 10.10: SquidCop at hover during outdoor on-the-field evaluation in a windy situation.

Figure 10.11: SquidCop inertial response to hover flight subject to wind.

10.5.2 Fast Climb

SquidCop was submitted to a fast climb test where the MAV experiences an abrupt upwards acceleration (Fig. 10.12).

One may see from the inertial data from Fig. 10.13 that, even under the influence of windy gusts, the MAV minimum climbing angular displacement (between $\pm 5^\circ$), which confirms the aircraft stability.

Figure 10.12: SquidCop during fast climb take off subject to wind conditions.

Figure 10.13: SquidCop inertial response to fast climb subject to wind.

10.5.3 Aggressive Maneuvers

SquidCop was submitted to extreme maneuvers, which consist in take the attitude angles of the MAV to $\pm 50^\circ$. Figure 10.14 shows a sequence of snapshots taken during the aggressive maneuvers stunt. Figure 10.15 refers to inertial data from sensors. As one may note, the aircraft reaches elevate attitude angles. Figure 10.16 shows IMU data when the MAV is initially steadily hovering. The pilot intentionally inputs a given impulsive disturbance shifting the MAV to a pitching $\theta \approx 60^\circ$ and rolling $\phi \approx 40^\circ$. This situation indeed is extreme for any flying robot. However, we may see that the MAV quickly restores its equilibrium position.

Figure 10.14: SquidCop performing high angles in aggressive maneuvers at high altitude (100ft.) outdoor in a windy day (left-to-right reading direction).

Figure 10.15: SquidCop inertial response during aggressive maneuvers.

Figure 10.16 shows an extreme angular shifting impulse. Sharky control promptly brings the MAV again to the equilibrium point very smoothly.

Figure 10.16: SquidCop damping response to high angle disturbances.

10.5.4 Free-Fall

In this field experiment we are interested in observing the MAV behavior when thrust is considerably reduced and passive stability is put into test to keep the attitude angle stable during descend. Figure 10.17 shows the MAV in high descending rate. Figure 10.18 shows inertial sensors measurement during the experiment. We may note that roll and pitch angles keep stable (less than $\pm 20^\circ$), which is acceptable considering the circumstances and the nature of the experiment.

Figure 10.17: SquidCop during a free-fall maneuver.

Figure 10.18: SquidCop inertial measurement during a free-fall maneuver.

10.6 H₂Omni Airborne Field Evaluation

Evaluation of H₂Omni in aerial performances considers the following situations:

- hover maneuvers at small angles;
- stability in vertical over accelerated take off and landing (elevate climbing rate);
- aggressive maneuvers at high angles, fast low pass flight;

All three sceneries together absolutely cover all possible flight envelopes that the platform may face during any mission.

10.6.1 Hovering Mode

Figure 10.20 refers to inertial measurement during hover flight. As one may see, the MAV attitude is normal, even in the presence of wind gusts. Average angle shifting is $\approx \pm 5^\circ$, which is an outstanding response.

Figure 10.19: H₂Omni during take off and hovering flight subject to wind gusts.

Figure 10.20: H₂Omni inertial measurement during hover mode subject to wind gusts.

10.6.2 Fast Climb

Fast climb is an important stunt through which we may observe stability, that is, how roll and pitch behavior (Fig. 10.21). Further, that is an important qualitative essay which may tell much about overall drag. The MAV was firstly submitted to maximum acceleration by manually imposing maximum thrust.

Figure 10.21: H₂Omni snapshot sequence during fast climb maneuver subject to wind conditions.

Figure 10.22 shows that roll and pitch angles remain small (under 10°) which is a very good indication about aircraft symmetry and thus stability.

Figure 10.22: H₂Omni inertial measurement during fast climb maneuver subject to wind conditions.

10.6.3 Aggressive Maneuvers

The H₂Omni MAV was submitted to a stressing sort of evaluation named aggressive maneuvers where the aircraft may experience elevate angles and to be under extreme acceleration envelopes (Fig. 10.23). Figure 10.24 shows incidence angles of about 45° .

The MAV presented excellent maneuverability as well as extremely fast response. Figure 10.25 shows the angle travel of approximately 90° (-45° to $+45^\circ$) in less than 2 seconds in a breaking maneuver.

Figure 10.23: H₂Omni during high angles in aggressive maneuvers outdoor in a windy day (left-to-right reading direction.)

Figure 10.24: H₂Omni inertial measurement during aggressive and extreme attitude maneuvers.

Figure 10.25: H₂Omni high pitching angles ($\pm 50^\circ$) are achieved in 2 seconds.

10.7 H₂Omni Water Navigation Evaluation

Evaluation of H₂Omni in water performances considers the following situations:

- navigation at small angles;
- disturbances suppression to water perturbation;
- take off / landing;
- minimum water touch navigation;

10.7.1 Navigation at Small Angles

This experiment aims to see H₂Omni navigation qualities (Fig. 10.26). Besides, we want to observe its stability, the angular shifting during maneuvers and specially to measure the amount of energy wasted in the process. Figure 10.27 refers to inertial measurements while the MAV navigates on water at a speed of approximately 1m/s . One may note that, at this average speed, angles are small ($\pm 10^\circ$) and thrust is about 10% of maximum power.

Figure 10.26: Water navigation. Note the small angle and small low energy cost (10% thrust).

Figure 10.27: H₂Omni inertial measurement during water navigation at small angles.

10.7.2 Robustness to Water Disturbances

This experiment aims to observe how robust H₂Omni is in water disturbances situations (Fig. 10.28). In this case, we provoke wave disturbances at $f \approx 1Hz$ in order to destabilize the MAV. Fig. 10.29 shows the exact point when waves hit the helicopter ($t=40s$). Still, one may note the the angular disturbances are suppressed ($t=42s$). When engines are turned off ($t=45s$), the MAV responds to the disturbances again. One may note that about 21% of total thrust is expended, as it was predicted in Section 6.5.2

Figure 10.28: Water evaluation to $1Hz$ perturbation. Note that disturbances are suppressed with low energy cost (21% thrust).

Figure 10.29: H₂Omni inertial measurement during perturbation suppression.

10.7.3 Hard Landing

H₂Omni was released from about $500mm$ from water level, when thrust was completely put to idle (Fig. 10.30). This is an interesting stability test since it may reflect a situation when the MAV may face trouble during descent on the water. Figure 10.31 shows inertial information during the stunt. As one may note, a relative metacentre position ensures full stability even face to a hard landing.

Figure 10.30: H₂Omni hard water landing evaluation.

Figure 10.31: H₂Omni inertial measurement during hard water landing. One may note that, In spite of the critical situation in terms of stability, controller is able to stabilize the MAV without any loss in quality.

Minimum Water Touch Navigation

As we discussed in Section 6.3.2, H₂Omni is designed to make the best use of the buoyancy effect at the most. This experiment shows how the the hydrodynamic thrust plus a well designed hull may considerably favor navigation will minimum energy. Figure 10.32 shows H₂Omni during a minimum water touch navigation. One may note that the MAV floats using only a small volume

of the hull.

Figure 10.33 refers to inertial data captured during the experiment. As it was predicted in 6.5.2 we may see that the MAV needs an average of only 21% of total thrust available. That is a desired characteristics which has a positive impact on the energetic perspective since that directly impacts on the MAV efficiency.

Figure 10.32: H₂Omni in water navigation (left) and airborne (right).

Figure 10.33: H₂Omni inertial measurement during water navigation with the minimum drag mode thanks to the hull optimization. One may see that $\approx 21\%$ of total thrust is spent, as it was predicted.

10.8 Conclusions

In this chapter we presented important qualitative and quantitative results of the wholly process of design of our three platforms addressed in Chapters 4, 5 and 6. Sharky, SquidCop and H₂Omni MAVs were put into rigorous on-the-field experimentation, through which we could validate our MAVs in the real operational conditions, subject to external disturbances offered by the atmospheric components. The on-the-field validation of our platforms under such conditions is the epilogue of a straight process of conceiving and developing novel morphologies for stable MAVs.

Firstly, the rigorous design criteria of Sharky MAV has driven to a novel morphology that offers interesting stability characteristics. As for the quadrotor set up, the 3D-IPM problem was successfully overcome even in the presence of moderate wind gusts on-the-field. Inertial data attests the well-succeeded design procedures for the stability control system. As for the fixed-wing configuration, although it is still embryonic, the *quasi*-transition state has revealed very optimistic results that encourages the further full-transition maneuver.

Secondly, the CoG displacement in SquidCop MAV has led to a full stable aircraft, endowed with a high level of passive stability, which still offers excellent maneuverability features. SquidCop overall stability has been put into extreme tests, under real windy conditions, through which it was possible to confirm the initial design predictions, followed by straight requirements. Thus, all the observation of SquidCop behavior on-the-field brings positive perspectives to a future possible in-flight test.

Finally, the H₂Omni complete validation (water and air operations) has proven that a well rounded design process, grounded by a straight theoretical fundamental driven us to achieve an extremely efficient hybrid MAV in both environments. Results has shown that H₂Omni shape is the optimal design for a MAV that respects the peculiarities of each one of the two environments.

Chapter 11

Conclusions & Future Works

This chapter aims to point to the contributions of this thesis and propose sound perspectives for further works.

11.1 Summary

Looking at the outstanding advantages from the utilization of MAVs on-the-field applications, we have outlined the initial deployment problem with a strong will to propose novel layouts for aerial robots. Our aim is to offer a new outlook and a new panorama for a well rounded and grounded methodology for the design of hybrid MAVs. This thesis addressed the following issues regarding to the novel design of morphologically adapted MAVs:

- novel means to deploy MAVs under the perspective of the practical detracting low energetic resources imposed by low efficient batteries;
- new potential fields of application for MAVs, which actually inspired the design of the three MAVs in this thesis;
- possibilities of different layouts from different solutions aiming the optimality in the final design of MAVs;
- design refinement grounded in a strong theoretical background and still looking to a feasible, applicable and realizable way to achieve optimal and robust experimental on-the-field results;
- novel possibilities in meeting global static stability in novel MAVs considering the distinct nature of different aircrafts merged together in the same frame, respecting the individual

requirements of each one;

- a concise process of validation of the stability control for three novel MAVs, from analytical, flight simulation, visual inertial tracking and on-the-field real flight conditions experiments.

This thesis starts from presenting the initial deployment problem, a real issue that detracts many of outstanding possibilities that could be effectively accomplished or even improved by using MAV in the daily basis. More than that (as readers may have noticed) we intentionally focus our analysis in a strictly outdoor application. In this context, the utilization of MAVs are even more critical. Thus, in Chapter 3 we presented the possibilities of the in-flight-launching of MAVs during low speed/altitude in order to plant the robot as near as possible from the interest point. Under such circumstances, a morphologically adapted quadrotor could fit a mission like that, being planted at any region with low energy cost. Moreover, in the case of a higher altitude in-flight launching, the flight qualities of a fixed-wing moto-glider could be more interesting if it also presents the omnidirectional qualities of a quadrotor helicopter. We also presented novel possibilities on the optimal utilization of a MAV in aquatic environments.

in Chapter 4 we presented a novel hybrid MAV that combines fixed-wing and quadrotor features, looking at the possibility of a higher altitude in-flight launching possibility. Sharky is specially designed under firm project requirements, with the less active moving parts as possible, to be functionally simple operationally morphologically speaking. Resulting concept raised two distinct subjects. First refers to the design of the airplane stage and demanded a strong theoretical background on meeting longitudinal static stability. The second, which is a consequence of the fixed-wing set up design, regards to the 3D-IPM, which occurs when the transition airplane-quadrotor happens. We also sketched a complete aircraft parametric model, which fits the other two aircrafts designed in Chapters 5 and 6. We have found that it is possible to design hybrid aircrafts such Sharky so that global static stability may be guaranteed. As far as we know, a tilt-body hybrid MAV with Sharky characteristics has never been addressed looking at the in-flight launching problem nor using the well-rounded theoretical background that we have employed in its design.

In Chapter 5 we designed a novel morphology for a quadrotor MAV, with a strong look at the low speed/altitude in-flight launching. We addressed the problem by splitting it in two different sub problems. Firstly, we analyzed the overall stability by downwards displacing the MAV CoG aiming to improve static passive stability. Secondly, we carried out a complete characterization of the same MAV in wind tunnel with a fixed air break device, in order to better know what

would be the effects of a parachute structure in the MAV fuselage. We discovered that a fixed breaking device attached to a statically stable MAV may possibly lead to a potential in-flight deployable MAV. Furthermore, we also found that a MAV with a stable down shifted CoG may present interesting energy conservative characteristics. We have found (theoretically and experimentally) that SquidCop may make use of rolling energy to keep translating. As far as we could go through our researches, this is the first time that a MAV with SquidCop peculiarities is thought and designed to be employed in the in-flight launching mission.

We presented the full design of a hybrid MAV that combines boat stable buoyancy effect capabilities with a quadrotor that may fly regularly (Chapter 6). As far as we know, before this work, no other has addressed the subject with a strong theoretical background, merging naval and aerospace engineering concepts to reach the optimal design of a “flying hull”.

Chapter 7 addressed the standard problem on the synthesis of a robust H_∞ optimal controller, which presents the desired characteristics for field applications, subject to external disturbances. Furthermore, a robust controller offers high stability even under parametric variations and model uncertainties. The last two issues specially are important considering the fact that the same stability controller was embedded in the three MAVs.

In Chapter 8 we presented a novel method for the analysis of MAVs using a novel flight simulation framework developed during this thesis, named FVMS. FVMS is able to interact to commercial Microsoft Flight Simulator via Software/Hardware-in-the-Loop simulation. We have also designed the virtual representation of Sharky, SquidCop and H₂Omni MAVS, which resulted in a reliable representation of the real MAV, as for graphic and dynamics as well. Resulting virtual aircrafts allow user to “feel-the-real-flight” during simulations. This is a good approach that may expedite the refinement of a great variety of algorithms, including vision based, GNC and control modules. We have shown FVMS reliability and how real sensors may be emulated with high fidelity. As far as we have gone in our researches, this is the first time that a flight simulation framework like this is employed on the emulation of quadrotors and also of novel morphologies for MAVs. FVMS has also proven its worth on teaching flight control and dynamics. The friendly user interface is favorable to a better understanding of aircrafts behavior. Besides, the framework has successfully been used for training new pilots. In that sense, a flight simulation of our platforms may be safer to be flew prior to going directly to the real MAV.

Chapter 9 presents a very conservative analysis of the ready-to-fly MAVs endowed with the stability control, as the prelude to the maiden on-the-field flight. A flying system shall be firstly evaluated in a safe and controlled space under strong criteria. We have used the ©VICON high accuracy/precision vision motion system to observe the behavior of each one in-flight. To ensure that the three MAVs were ready to go airborne, we have doubled checked the evaluation. At the same time we gathered inertial data from the MAVs embedded IMU. At the end, we could have a double confirmation about the robustness of the embedded control system on the stabilization of Sharky, SquidCop and H₂Omni.

Finally, Chapter 10 presents experimental results, where the three of our MAVS were put into real atmospheric conditions. He have presented a vast experimental flight evaluation of Sharky (in the quadrotor set up), SquidCop and H₂Omni. The MAVs have passed through an exhaustive series of tests in order to ensure stability. All have presented outstanding features and behavior. We have been more conservative with Sharky in the fixed-wing configuration specially due to the fact that Sharky demands very specific hardware and software architectures to work properly perform the transition phase. However, we have tested the MAV for the *quasi*-transition state, through which we have put it into an extreme angular pose (for a aircraft such as Sharky this is a high angle). Indeed, the MAV behavior was satisfactory in the *quasi*-transition state. Stability control was effective in holding Sharky in the position and then in bringing it back to the quadrotor configuration. Finally, we have performed a wide number of tests in H₂Omni in water. We have confirmed that, as we expected, it is possible to design a MAV that that present low energy water quadrotor-like navigation features. In other words, a floating MAV does not need any other propulsion system (underwater or not) to translate on an aquatic environment. The non-interchangeable body, that perfectly works as a boat hull also works as an efficient helicopter fuselage. To summarize, the wholly design procedures utilized since Chapter 3 leaded to important contributions for many problems found in the aerial robotics daily basis.

11.2 Outlook

Even with promising experimental results, some particular problems that have raised as the result of this works may be improved, as follows:

- Sharky transition problem may certainly be achieved in the near future. A more specific study on the design of a software based controller to manage the different flight stages is necessary to ensure the correct accomplishment of each one;
- SquidCop real in-flight launching is also a feasible. Improvements, such as optimal design involving mixing a new sketch for the parachute must be addressed;
- an interesting possibility could be using solar panels in H₂Omni, while the MAV remains in the low energy consumption mode in water at a given mission. The long time Sun exposure could ease the utilization of solar transducers to recover electric energy back to batteries;
- regarding the three MAVs proposed in this thesis, the autonomous flight is now feasible for on-the-field applications;
- after the exhaustive validation of the three platforms, other control architectures may be addressed for each one, respecting the flight mechanics peculiarities of each MAV;
- the three MAVs plus on-the-field application new possibilities may open new perspectives for perception layers for reactive, deliberative and hybrid control.

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Appendix A

Preliminary Frequency Response & Stability Analysis

A.1 Stability Analysis

Figures A.2, A.4 and A.6 present time response of oscillation for Pelican (Fig. A.1), H₂Omni (Fig. A.3) and SquidCop (Fig. A.5) MAVs, all relative to y axis (pitching axis). This is a preliminary experiment that aims to offer an overview around the stability characteristics of the three helicopters.

Figure A.1: Stability check in ©AscTec Pelican about pitching axis.

Figure A.2: IMU data captured during stability experiment in ©AscTec Pelican MAV.

Figure A.3: Stability check in H₂Omni MAV about pitching axis.

Figure A.4: IMU data captured during stability experiment in H₂Omni MAV.

Figure A.5: Stability check in SquidCop MAV about pitching axis.

Figure A.6: IMU data captured during stability experiment in SquidCop MAV.

Thus, from time response parameters one may swap to frequency domain, through which a more concise and accessible stability analysis may be developed. From the dynamics of vibrations, it is well-know that natural frequency ω_n and damping ξ may be determined as follows:

$$\omega_n = \frac{\sqrt{4\pi^2 + \delta^2}}{T} \quad (\text{A.1})$$

and

$$\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \quad (\text{A.2})$$

Where δ is the logarithmic decrement, given by:

$$\delta = \frac{1}{n} \log \left(\frac{x_0}{x_n} \right) \quad (\text{A.3})$$

Where x_0 is the the displacement at the first peak and x_n is the displacement at the n th peak.

Table A.1 show a summary of main frequency characteristics of the two MAVs. Both transfer functions may safely be represented as a 2nd order polynomial.

Table A.1: Frequency characterization for pitching oscillations of the MAVs.

MAV	ω_n [rad/s]	ξ	Poles	T.F.
©Asctec Pelican	15.1692	-0.9102	$+13.8068 \pm 6.2832i$	$G(s) = \frac{230.1}{s^2 - 27.61s + 230.1}$
H ₂ Omni	6.2835	0.0099	$-0.0623 \pm 6.2832i$	$G(s) = \frac{39.84}{s^2 + 0.1245s + 39.48}$
SquidCop	6.2903	0.0476	$-0.2996 \pm 6.2832i$	$G(s) = \frac{39.57}{s^2 + 0.5991s + 39.57}$

Figure A.7: Bode diagram for pitching stability in ©Pelican MAV.

Figure A.8: Bode diagram for pitching stability in H₂Omni MAV.

Figure A.9: Bode diagram for pitching stability in SquidCop MAV.

Appendix B

Sharky Additional Data & Information

B.1 Sharky Technical Data

Table B.1: Sharky MAV technical specifications.

Component	Weight
Battery	456g
4xMotors	257g
4xESC	177g
Cabling	87g
Control Board	35g
Sensors	25g
Fuselage + Wings	373g
Engine Supports	76g
<i>Payload</i>	<i>1486</i>

B.2 Handcrafting Characteristics

Sharky is essentially handcrafted from expanded polyurethane foam and polystyrene reinforced with balsa wood and glass fiber stringers along the fuselage and wings. Engines mounting are 3D-printed with biodegradable PLA (polylactide) thermoplastic aliphatic polyester in a honeycomb pattern, which ensures mechanical resistance and still low weight.

B.3 Sharky Complete Mathematical Model

Sharky mathematical model involves the full development of equations of movement and forces and moments as well for both fixed-wing and quadrotor. Equations are parametrized so that it fits aircraft with Sharky features.

As for the quadrotor set up, besides of working for Sharky, it is perfectly suitable for both SquidCop and H2Omni.

B.3.1 Definitions

We firstly define coordinate systems. Inertial reference system is indicated by I while CoG coordinate system will be indicated by B_{cg} and each engine i coordinate system will be indicated by B_{mi} , where i indicates the motor number from 1 (positioned in B_1x positive) and ending with 4 (positioned in B_1y negative).

Base B_{cg} was defined with axis $B_{cg}x$ oriented to downwards while in fixed-wing aircraft configuration. Axis $B_{cg}y$ was oriented to left. Axis $B_{cg}z$ was oriented forward. Bases B_{mi} , with $i = 1..4$, that is, axis Ix were similarly oriented. Finally, inertial base is EAST-NORTH-UP, that is, Ix is pointed to East, Iy to North and Iz is pointed upwards.

Following, we define rotation matrices between coordinate systems. From B_{cg} base to the others (B_{mi} with $i = 1..4$), transform matrices is identity. Transformation from B_{cg} to I is the same as if we performed Euler rotations X-Y-Z over the body regarding a fixed inertial frame. Resulting matrix is expressed by Eq. B.1a:

$$\begin{aligned}
 R_{zyx} &= \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi) & \cos(\phi) \end{bmatrix} \\
 &= \begin{bmatrix} c\psi c\theta & c\psi s\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{B.1a}
 \end{aligned}$$

Where *cângulo* is an abbreviation for $\cos(\hat{ângulo})$ and *sângulo* an abbreviation to $\sin(\hat{ângulo})$ and angles (ϕ, θ, ψ) are roll, pitch and yaw angles, respectively.

We also define distances between CoG and motors:

$$\begin{aligned} Bcg r_{m1/cg} &= \begin{bmatrix} (l + x_g) \\ y_g \\ -z_g \end{bmatrix}, Bcg r_{m2/cg} = \begin{bmatrix} x_g \\ (l + y_g) \\ -z_g \end{bmatrix}, \\ Bcg r_{m3/cg} &= \begin{bmatrix} (-l + x_g) \\ y_g \\ -z_g \end{bmatrix}, Bcg r_{m4/cg} = \begin{bmatrix} x_g \\ (-l + y_g) \\ -z_g \end{bmatrix} \end{aligned} \quad (B.2)$$

Where $2l$ Sharky wingspan and x_g, y_g e z_g distances from CG to the crossing point between motor lines.

B.3.2 Simplifying Assumptions

Another step to be taken in order to obtain dynamic equations is to establish the following simplifying assumptions:

1. Dynamic equations will be derived from Newton-Euler formalism;
2. Sharky is a rigid body, so aeroelasticity and vibrations are neglected;
3. Aerodynamics forces and moments are proportional to Sharky squared airspeed and are limited to the domain previously tested in wind tunnel;
4. Forces produced from control surfaces are taken in the aerodynamic medium point of each one and they are known;
5. Inertial measurements are considered over CoG, although they may not necessarily be positioned in the CoG;
6. We consider control action to be quickly acting so that propellers angular accelerations considered null;
7. We include aerodynamic losses proportional to the aircraft squared speed;
8. Forces produced by propellers/engines are proportional their squared rotation;
9. Motors inertia is only considered along do rotation axis;
10. Motors mass is neglected;
11. xz is considered plane of symmetry;
12. y distance from CoG to symmetry axis is considered null;

13. Inertia variations due to surface control deflections are neglected.

B.3.3 Free Body Diagram

From 1 assumption, equations of motion and relations between Sharky bodies may be determined from the Free Body Diagram (FBD) of all them separately. We have fuselage and control surfaces attached to it and motors as well. Each body is responsible for the 6 equations of motion. Thus, we have 30 equations: 24 for the internal efforts a 6 to the general Sharky movement. Figures x.1 to x.5 show the

B.3.4 Linear Momentum Derivatives

We now describe linear portion of Sharky movement. We have $\sum_{Bcg} F = m_{Bcg} \vec{a}_{cg}$ for fuselage and $\sum_{Bcg} F = m_{Bcg} \vec{a}_{mi}$ for motors, where $i = 1..4$ and $_{Bcg} \vec{a}_{mi}$ is total acceleration vector which is defined as:

$$\begin{aligned} _{Bcg} \vec{a}_{mi} = & _{Bcg} \vec{a}_{cg} + _{Bcg} \dot{\Omega}_{mi} \times _{Bcg} \vec{r}_{mi/cg} + _{Bcg} \Omega_{mi} \times _{Bcg} \Omega_{mi} \times _{Bcg} \vec{r}_{mi/cg} \\ & + 2_{Bcg} \Omega_{mi} \times _{Bcg} \vec{v}_{mi/cg} + _{Bcg} \vec{a}_{mi/cg} \end{aligned} \quad (B.3)$$

From 5 assumption, vector $_{Bcg} \vec{a}_{cg}$ is known and defined by $_{Bcg} \vec{a}_{cg} = [\dot{u}, \dot{v}, \dot{w}]^T$. Vector $_{Bcg} \Omega_{cg}$ is known and defined by $_{Bcg} \Omega_{cg} = [p, q, r]^T$ in which the transformation matrix from base Bcg to Bmi is the identity matrix.

Expanding Eq. B.3 and replacing values for $i = 1$, yields:

$$\begin{aligned}
{}_{Bcg}\vec{a}_{m1} &= {}_{Bcg}\vec{a}_{cg} + {}_{Bcg}\dot{\Omega}_{m1} \times {}_{Bcg}\vec{r}_{m1/cg} + {}_{Bcg}\Omega_{m1} \times {}_{Bcg}\Omega_{m1} \times {}_{Bcg}\vec{r}_{m1/cg} \\
&\quad + 2{}_{Bcg}\Omega_{m1} \times {}_{Bcg}\vec{v}_{m1/cg} + {}_{Bcg}\vec{a}_{m1/cg} \\
&= \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} + \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \times \begin{bmatrix} l + x_g \\ y_g \\ -z_g \end{bmatrix} + \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} l + x_g \\ y_g \\ -z_g \end{bmatrix} \\
&= \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} + \begin{bmatrix} -\dot{r}y_g - \dot{q}z_g \\ \dot{p}z_g + \dot{r}(l + x_g) \\ -\dot{q}(l + x_g) + \dot{p}y_g \end{bmatrix} + \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} -ry_g - qz_g \\ pz_g + r(l + x_g) \\ -q(l + x_g) + py_g \end{bmatrix} \\
&= \begin{bmatrix} \dot{u} - (q^2 + r^2)(l + x_g) + (pq - \dot{r})y_g - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)(l + x_g) - (p^2 + r^2)y_g + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})(l + x_g) + (\dot{p} + qr)y_g + (p^2 + q^2)z_g \end{bmatrix} \tag{B.4a}
\end{aligned}$$

Analogously, using distance values from Eq. B.2, yields:

$$\begin{aligned}
{}_{Bcg}a_{m2} &= \begin{bmatrix} \dot{u} - (q^2 + r^2)x_g + (pq - \dot{r})(l + y_g) - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)x_g - (p^2 + r^2)(l + y_g) + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})x_g + (\dot{p} + qr)(l + y_g) + (p^2 + q^2)z_g \end{bmatrix}, \\
{}_{Bcg}a_{m3} &= \begin{bmatrix} \dot{u} - (q^2 + r^2)(-l + x_g) + (pq - \dot{r})y_g - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)(-l + x_g) - (p^2 + r^2)y_g + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})(-l + x_g) + (\dot{p} + qr)y_g + (p^2 + q^2)z_g \end{bmatrix}, \tag{B.5} \\
{}_{Bcg}a_{m4} &= \begin{bmatrix} \dot{u} - (q^2 + r^2)x_g + (pq - \dot{r})(-l + y_g) - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)x_g - (p^2 + r^2)(-l + y_g) + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})x_g + (\dot{p} + qr)(-l + y_g) + (p^2 + q^2)z_g \end{bmatrix}
\end{aligned}$$

Hence, linear momentum derivatives are presented in Eq. B.6:

$$\begin{aligned}
m_{fBcg}a_{cg} &= m_f \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix}, \\
m_{mBcg}a_{m1} &= m_m \begin{bmatrix} \dot{u} - (q^2 + r^2)(l + x_g) + (pq - \dot{r})y_g - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)(l + x_g) - (p^2 + r^2)y_g + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})(l + x_g) + (\dot{p} + qr)y_g + (p^2 + q^2)z_g \end{bmatrix}, \\
m_{mBcg}a_{m2} &= m_m \begin{bmatrix} \dot{u} - (q^2 + r^2)x_g + (pq - \dot{r})(l + y_g) - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)x_g - (p^2 + r^2)(l + y_g) + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})x_g + (\dot{p} + qr)(l + y_g) + (p^2 + q^2)z_g \end{bmatrix}, \\
m_{mBcg}a_{m3} &= m_m \begin{bmatrix} \dot{u} - (q^2 + r^2)(-l + x_g) + (pq - \dot{r})y_g - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)(-l + x_g) - (p^2 + r^2)y_g + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})(-l + x_g) + (\dot{p} + qr)y_g + (p^2 + q^2)z_g \end{bmatrix}, \\
m_{mBcg}a_{m4} &= m_m \begin{bmatrix} \dot{u} - (q^2 + r^2)x_g + (pq - \dot{r})(-l + y_g) - (\dot{q} + pr)z_g \\ \dot{v} + (\dot{r} + pq)x_g - (p^2 + r^2)(-l + y_g) + (\dot{p} - qr)z_g \\ \dot{w} + (pr - \dot{q})x_g + (\dot{p} + qr)(-l + y_g) + (p^2 + q^2)z_g \end{bmatrix},
\end{aligned} \tag{B.6}$$

B.3.5 Angular Momentum Derivative

Another analogous calculation may be performed for angular momentum movement from assumption 1. We have $\sum_{Bcg} M = \frac{d_{Bcg}H_{cg}}{dt} + Bcg\Omega_{cg} \times BcgH_{cg}$, where $BcgH_{cg} = \tilde{I}_{cg}Bcg\omega_{cg} + m_{Bcg}r_{cg/cg} \times Bcg\vec{v}_{cg}$, $\tilde{I}_{cg}$ is the inertia tensor evaluated in the origin of coordinate system Bcg , $Bcg\omega_{cg}$ the angular speed in Bcg and $Bcg\vec{v}_{cg}$ is the absolute speed of origin of the system Bcg .

Since $r_{cg/cg} = 0$, we may simplify angular momentum equation to $BcgH_{cg} = \tilde{I}_{cg}Bcg\omega_{cg}$, which must be analyzed for fuselage and motors. From Assumption 5, vector $Bcg\Omega_{cg}$ is known and is defines as $Bcg\Omega_{cg} = [p, q, r]^T$. Hence, applying Assumption 9 angular momentum for the fuselage and motor may be defined as:

$$\begin{aligned}
{}_{Bcg}H_{cg} &= \tilde{I}_{cg}{}_{Bcg}\omega_{cg} \\
&= \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}, \tag{B.7a}
\end{aligned}$$

$$\begin{aligned}
{}_{Bcg}H_{m1} &= \tilde{I}_{m1}{}_{Bcg}\omega_{m1} \\
&= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} p \\ q \\ r + \omega_1 \end{bmatrix}, \tag{B.7b}
\end{aligned}$$

$$\begin{aligned}
{}_{Bcg}H_{m2} &= \tilde{I}_{m2}{}_{Bcg}\omega_{m2} \\
&= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} p \\ q \\ r - \omega_2 \end{bmatrix}, \tag{B.7c}
\end{aligned}$$

$$\begin{aligned}
{}_{Bcg}H_{m3} &= \tilde{I}_{m3}{}_{Bcg}\omega_{m3} \\
&= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} p \\ q \\ r + \omega_3 \end{bmatrix}, \tag{B.7d}
\end{aligned}$$

$$\begin{aligned}
{}_{Bcg}H_{m4} &= \tilde{I}_{m4}{}_{Bcg}\omega_{m4} \\
&= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} p \\ q \\ r - \omega_4 \end{bmatrix} \tag{B.7e}
\end{aligned}$$

Where J is the propellers inertia and ω_i is their angular speed for $i = 1..4$. Applying Assumption 13, for the fuselage, $\tilde{I}_{cg}$ is constant. Thus, angular momentum derivative is define by:

$$\begin{aligned}
\frac{d_{Bcg}H_{cg}}{dt} + {}_{Bcg}\Omega_{cg} \times {}_{Bcg}H_{cg} &= \\
&= \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \\
&+ \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \\
&= \begin{bmatrix} I_{xx}\dot{p} + I_{xy}(pr - \dot{q}) - I_{xz}(\dot{r} + pq) \dots \\ \dots + I_{yz}(r^2 - q^2) + (I_{zz} - I_{yy})qr \\ I_{yy}\dot{q} - I_{xy}(\dot{p} + qr) + I_{xz}(p^2 - r^2) \dots \\ \dots + I_{yz}(pq - \dot{r}) + (I_{xx} - I_{yy})pr \\ I_{zz}\dot{r} + I_{xy}(q^2 - p^2) + I_{xz}(qr - \dot{p}) \dots \\ \dots - I_{yz}(pr + \dot{q}) + (I_{yy} - I_{xx})pq \end{bmatrix} \quad (B.8a)
\end{aligned}$$

Applying Assumption 6, motor 1 angular momentum derivative is:

$$\begin{aligned}
\frac{d_{Bcg}H_{m1}}{dt} + {}_{Bcg}\Omega_{m1} \times {}_{Bcg}H_{m1} &= \\
&= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \\
&+ \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} p \\ q \\ r + \omega_1 \end{bmatrix} \\
&= \begin{bmatrix} Jq(\omega_1 + r) \\ -Jp(\omega_1 + r) \\ J\dot{r} \end{bmatrix} \quad (B.9a)
\end{aligned}$$

Analogously, related derivatives for motors 2,3 e 4 are given by:

$$\begin{aligned}
\frac{d_{Bcg}H_{m2}}{dt} + {}_{Bcg}\Omega_{m2} \times {}_{Bcg}H_{m2} &= \begin{bmatrix} Jq(-\omega_2 + r) \\ -Jp(-\omega_2 + r) \\ J\dot{r} \end{bmatrix}, \\
\frac{d_{Bcg}H_{m3}}{dt} + {}_{Bcg}\Omega_{m3} \times {}_{Bcg}H_{m3} &= \begin{bmatrix} Jq(\omega_3 + r) \\ -Jp(\omega_3 + r) \\ J\dot{r} \end{bmatrix}, \\
\frac{d_{Bcg}H_{m4}}{dt} + {}_{Bcg}\Omega_{m4} \times {}_{Bcg}H_{m4} &= \begin{bmatrix} Jq(-\omega_4 + r) \\ -Jp(-\omega_4 + r) \\ J\dot{r} \end{bmatrix}
\end{aligned} \tag{B.10}$$

B.3.6 Acting Forces

Only one side of equations were evaluated so far: derivatives of linear and angular moments. We shall look at external forces and moments in order to determine Sharky dynamic equations. Firstly, we estimate acting forces over fuselaged and motors. For each motor i we have a reacting force applied over the motor CoG as well as a lifting force generated by the propeller rotation. Taking that into consideration, we apply Assumption 8, which yields:

$$\begin{aligned}
\sum {}_{Bcg}\vec{F}_{m1} &= \begin{bmatrix} -T_{x1} \\ -T_{y1} \\ -T_{z1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ b\omega_1^2 \end{bmatrix}, \\
\sum {}_{Bcg}\vec{F}_{m2} &= \begin{bmatrix} -T_{x2} \\ -T_{y2} \\ -T_{z2} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ b\omega_2^2 \end{bmatrix}, \\
\sum {}_{Bcg}\vec{F}_{m3} &= \begin{bmatrix} -T_{x3} \\ -T_{y3} \\ -T_{z3} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ b\omega_3^2 \end{bmatrix}, \\
\sum {}_{Bcg}\vec{F}_{m4} &= \begin{bmatrix} -T_{x4} \\ -T_{y4} \\ -T_{z4} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ b\omega_4^2 \end{bmatrix}
\end{aligned} \tag{B.11}$$

Likewise, all reacting forces over fuselage have the same intensity. However, they present opposite directions. Besides, due to the airfoil profile aerodynamic forces will raise. Also, weight force, which is better defined in the inertial base, must be rotated to be inserted into the equations. Hence, we may list all forces acting over the fuselage as:

$$\begin{aligned}
 {}_{Bcg}\vec{F}_{s1} &= \begin{bmatrix} 0 \\ -F_{ys1} \\ -F_{zs1} \end{bmatrix}, {}_{Bcg}\vec{F}_{s2} = \begin{bmatrix} F_{xs2} \\ 0 \\ -F_{zs2} \end{bmatrix}, {}_{Bcg}\vec{F}_{s3} = \begin{bmatrix} 0 \\ -F_{ys3} \\ -F_{zs3} \end{bmatrix}, {}_{Bcg}\vec{F}_{s4} = \begin{bmatrix} F_{xs4} \\ 0 \\ -F_{zs4} \end{bmatrix} \\
 {}_{Bcg}\vec{F}_L &= \begin{bmatrix} -C_l(\alpha)_{Bcg}V_{cg}^2 \\ 0 \\ -C_d(\alpha)_{Bcg}V_{cg}^2 \end{bmatrix}, {}_{Bcg}\vec{F}_{Arrasto} = \begin{bmatrix} -c_{w1}u^2\text{sign}(u) \\ -c_{w2}v^2\text{sign}(v) \\ -c_{w3}w^2\text{sign}(w) \end{bmatrix} \\
 {}_{Bcg}\vec{P} &= R_{zyx}^{-1}I\vec{P} = \begin{bmatrix} m_T g \text{sen}(\theta) \\ -m_T g \cos(\theta) \text{sen}(\phi) \\ -m_T g \cos(\theta) \cos(\phi) \end{bmatrix}
 \end{aligned} \tag{B.12}$$

Using reaction obtained in Eq. B.11 and forces describe by Eq. B.12, yields:

$$\sum {}_{Bcg}\vec{F}_{cg} = \begin{bmatrix} F_{xs2} + F_{xs4} + \sum_{i=1}^4 T_{xi} + m_T g \text{sen}(\theta) - c_{w1}u^2\text{sign}(u) - C_l(\alpha)_{Bcg}V_{cg}^2 \\ -F_{ys1} - F_{ys3} - c_{w2}v^2\text{sign}(v) - m_T g \cos(\theta) \text{sen}(\phi) + \sum_{i=1}^4 T_{yi} \\ -C_d(\alpha)_{Bcg}V_{cg}^2 - m_T g \cos(\theta) \cos(\phi) - c_{w3}w^2\text{sign}(w) + \sum_{i=1}^4 T_{zi} - F_{si} \end{bmatrix} \tag{B.13}$$

B.3.7 Acting Moments

Now we shall analyze external moments acting over fuselage and motors as well. For each motorwe i we have a reacting moment and moment generated by the propellers dragging force. Thus, we apply Assumption 8, which yields:

$$\begin{aligned}
\sum_{Bcg} \vec{M}_{m1} &= \begin{bmatrix} -M_{x1} \\ -M_{y1} \\ -M_{z1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -d\omega_1^2 \end{bmatrix}, \\
\sum_{Bcg} \vec{M}_{m2} &= \begin{bmatrix} -M_{x2} \\ -M_{y2} \\ -M_{z2} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ d\omega_2^2 \end{bmatrix}, \\
\sum_{Bcg} \vec{M}_{m3} &= \begin{bmatrix} -M_{x3} \\ -M_{y3} \\ -M_{z3} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -d\omega_3^2 \end{bmatrix}, \\
\sum_{Bcg} \vec{M}_{m4} &= \begin{bmatrix} -M_{x4} \\ -M_{y4} \\ -M_{z4} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ d\omega_4^2 \end{bmatrix}
\end{aligned} \tag{B.14}$$

Likewise, we have external moments acting over fuselage. Moment of the force acting over the control surface 1 may be described as:

$$\begin{aligned}
{}_{Bcg} \vec{M}_{s1} &= \vec{r}_{s1/cg} \times \vec{F}_{s1} \\
&= \begin{bmatrix} x_s + x_g \\ 0 \\ -z_g \end{bmatrix} \times \begin{bmatrix} 0 \\ -F_{ys1} \\ -F_{zs1} \end{bmatrix} \\
&= \begin{bmatrix} -F_{ys1}z_g \\ F_{zs1}(x_s + x_g) \\ -(x_s + x_g)F_{ys1} \end{bmatrix}
\end{aligned} \tag{B.15a}$$

Analogously, control surfaces 2, 3 and 4 external moments may be computed as:

$$\begin{aligned}
{}_{Bcg}\vec{M}_{s2} &= \begin{bmatrix} -F_{zs2}(y_g + y_s) \\ -F_{xs2}z_g \\ -F_{xs2}(y_g + y_s) \end{bmatrix}, \\
{}_{Bcg}\vec{M}_{s3} &= \begin{bmatrix} -F_{ys3}z_g \\ F_{zs3}(-x_s + x_g) \\ -(-x_s + x_g)F_{ys3} \end{bmatrix}, \\
{}_{Bcg}\vec{M}_{s4} &= \begin{bmatrix} -F_{zs4}(y_g - y_s) \\ -F_{xs4}z_g \\ -F_{xs4}(y_g - y_s) \end{bmatrix}
\end{aligned} \tag{B.16}$$

Moment of reacting force ${}_{Bcg}\vec{T}_{m1}$ in fuselage is:

$$\begin{aligned}
{}_{Bcg}\vec{M}_{T1} &= \vec{r}_{m1/cg} \times {}_{Bcg}\vec{T}_{m1} \\
&= \begin{bmatrix} l + x_g \\ 0 \\ -z_g \end{bmatrix} \times \begin{bmatrix} T_{x1} \\ T_{y1} \\ T_{z1} \end{bmatrix} \\
&= \begin{bmatrix} l + x_g \\ 0 \\ -z_g \end{bmatrix} \times \begin{bmatrix} -m_m(\dot{u} - (q^2 + r^2)(l + x_g) + (pq - \dot{r})y_g - (\dot{q} + pr)z_g) \\ -m_m(\dot{v} + (\dot{r} + pq)(l + x_g) - (p^2 + r^2)y_g + (\dot{p} - qr)z_g) \\ b\omega_1^2 - m_m(\dot{w} + (pr - \dot{q})(l + x_g) + (\dot{p} + qr)y_g + (p^2 + q^2)z_g) \end{bmatrix}
\end{aligned} \tag{B.17a}$$

Analogously, moments of reacting forces are given by:

$$\begin{aligned}
{}_{Bcg}\vec{M}_{T2} &= \begin{bmatrix} 0 \\ l + y_g \\ -z_g \end{bmatrix} \times \\
&\begin{bmatrix} -m_m(\dot{u} - (q^2 + r^2)x_g + (pq - \dot{r})(l + y_g) - (\dot{q} + pr)z_g) \\ -m_m(\dot{v} + (\dot{r} + pq)x_g - (p^2 + r^2)(l + y_g) + (\dot{p} - qr)z_g) \\ b\omega_2^2 - m_m(\dot{w} + (pr - \dot{q})x_g + (\dot{p} + qr)(l + y_g) + (p^2 + q^2)z_g) \end{bmatrix}, \\
{}_{Bcg}\vec{M}_{T3} &= \begin{bmatrix} -l + x_g \\ 0 \\ -z_g \end{bmatrix} \times \\
&\begin{bmatrix} -m_m(\dot{u} - (q^2 + r^2)(-l + x_g) + (pq - \dot{r})y_g - (\dot{q} + pr)z_g) \\ -m_m(\dot{v} + (\dot{r} + pq)(-l + x_g) - (p^2 + r^2)y_g + (\dot{p} - qr)z_g) \\ b\omega_3^2 - m_m(\dot{w} + (pr - \dot{q})(-l + x_g) + (\dot{p} + qr)y_g + (p^2 + q^2)z_g) \end{bmatrix}, \\
{}_{Bcg}\vec{M}_{T4} &= \begin{bmatrix} 0 \\ -l + y_g \\ -z_g \end{bmatrix} \times \\
&\begin{bmatrix} -m_m(\dot{u} - (q^2 + r^2)x_g + (pq - \dot{r})(-l + y_g) - (\dot{q} + pr)z_g) \\ -m_m(\dot{v} + (\dot{r} + pq)x_g - (p^2 + r^2)(-l + y_g) + (\dot{p} - qr)z_g) \\ b\omega_4^2 - m_m(\dot{w} + (pr - \dot{q})x_g + (\dot{p} + qr)(-l + y_g) + (p^2 + q^2)z_g) \end{bmatrix}
\end{aligned}$$

Reacting moments over fuselage present same intensity. However, the present opposite directions related to those over motors. Hence, sum if reacting moments are given by:

$${}_{Bcg}\vec{M}_{rm} = \begin{bmatrix} -Jq(\omega_1 + \omega_3 - \omega_2 - \omega_4 + 4r) \\ Jp(\omega_1 + \omega_3 - \omega_2 - \omega_4 + 4r) \\ -d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2) - 4J\dot{r} \end{bmatrix} \quad (B.18)$$

Finally, aerodynamic forces caused by the airfoil produce a given moment, which may be described as:

$${}_{Bcg}\vec{M}_L = \begin{bmatrix} 0 \\ C_m(\alpha)_{Bcg}V_{cg}^2 \\ 0 \end{bmatrix} \quad (B.19)$$

Fuselage drag moments may be described as:

$${}_{Bcg}\vec{M}_{arrasto} = \begin{bmatrix} -c_{w4}p^2 \text{sign}(p) \\ -c_{w5}q^2 \text{sign}(q) \\ -c_{w6}r^2 \text{sign}(r) \end{bmatrix} \quad (B.20)$$

B.3.8 Equations of Movement

The last part is to present the equations of moment using the equations described in Section B.3.1 to Section B.3.7. Furthermore, Assumptions 10, 11 e 12 were taken into account in the equations. Hence, we have:

$$\left\{ \begin{array}{l} \dot{u} = \frac{1}{m_T} [-C_l(\alpha)_{Bcg}V_{cg}^2 + m_T g \sin(\theta) - c_{w1}u^2 \text{sign}(u) + F_{xs2} + F_{xs4}] \\ \dot{v} = \frac{1}{m_T} [-F_{ys1} - F_{ys3} - c_{w2}v^2 \text{sign}(v) - m_T g \cos(\theta) \sin(\phi)] \\ \dot{w} = \frac{1}{m_T} [-C_d(\alpha)_{Bcg}V_{cg}^2 - m_T g \cos(\theta) \cos(\phi) - c_{w3}w^2 \text{sign}(w) \dots \\ \dots + \sum_{i=1}^4 (b\omega_i - F_{zsi})] \\ \dot{p} = \frac{1}{I_{xx}} [-z_g(F_{ys1} + F_{ys3}) - y_s(F_{zs2} - F_{zs4}) + bl(\omega_2^2 - \omega_4^2) \dots \\ \dots - 4Jqr - Jq(\omega_1 + \omega_3 - \omega_2 - \omega_4) + (I_{yy} - I_{zz})qr + I_{xz}(pq + \dot{r}) - c_{w4}p^2 \text{sign}(p)] \\ \dot{q} = \frac{1}{I_{yy}} [-z_g(F_{xs2} + F_{xs4}) + x_g(F_{zs1} + F_{zs3}) + x_s(F_{zs1} - F_{zs3}) \dots \\ \dots + bl(\omega_3^2 - \omega_1^2) - bx_g(\omega_1^2 + \omega_3^2) + 4Jpr + C_{mBcg}V_{cg}^2 \dots \\ \dots + Jp(\omega_1 + \omega_3 - \omega_2 - \omega_4) + (I_{zz} - I_{xx})pr + I_{xz}(\dot{p} - qr) - c_{w5}q^2 \text{sign}(q)] \\ \dot{r} = \frac{1}{I_{zz} + 4J} [-x_g(F_{ys1} + F_{ys3}) - x_s(F_{ys1} - F_{ys3}) - y_s(F_{xs2} - F_{xs4}) \dots \\ \dots - d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2) + I_{xz}(\dot{p} - qr) + (I_{xx} - I_{yy})pq] \end{array} \right. \quad (B.21)$$

B.4 Numerical Method Additional Information

Bellow one may find a series of plots regarding the overall stability of Sharky aircraft using VLM/Panels method. We introduced a small input control gain in order to turn phugoid and spiral mode stable. As one may see from Figs. (B.1)-(B.5), Sharky is stable in every one of the 6-DoF.

Figure B.1: Linear velocity v in lateral stability evaluation.

Figure B.2: Euler rolling rate ϕ in lateral stability evaluation.

Figure B.3: Linear velocity u in lateral stability evaluation.

Figure B.4: Linear velocity w in lateral stability evaluation.

Figure B.5: Euler pitching rate θ in lateral stability evaluation.

B.5 Sharky Stability Derivatives and Modes

Tables B.2, B.3 and B.4 presents Sharky stability derivatives for aircraft trimmed at $u \approx 10 \text{ m/s}^2$. That is the cruise speed at which weight is balanced ($\alpha \approx 22^\circ$).

Table B.2: Longitudinal stability derivatives.

Stability Derivatives	
$X_u = -0.0034725$	$C_{xu} = -0.00074098$
$X_w = 0.38927$	$C_{xa} = 0.083064$
$Z_u = -1.0389$	$C_{zu} = -6.4464\text{e-}05$
$Z_w = -21.47$	$CL_a = 4.5814$
$Z_q = -2.6158$	$CL_q = 5.1731$
$M_u = -4.6578\text{e-}10$	$C_{mu} = -4.6058\text{e-}10$
$M_w = -0.63725$	$C_{ma} = -0.63014$
$M_q = -0.35379$	$C_{mq} = -3.2424$

Table B.3: Lateral stability derivatives.

Stability Derivatives	
Yv= -0.53053	CYb= -0.11321
Yp= -0.29148	CYp= -0.055041
Yr= 0.24064	CYr= 0.045441
Lv= -0.28594	Clb= -0.026998
Lp= -4.8871	Clp= -0.40834
Lr= 0.31196	Clr= 0.026066
Nv= 0.18931	Cnb= 0.017874
Np= 0.018802	Cnp= 0.001571
Nr= -0.08049	Cnr= -0.0067254

Table B.4: Control derivatives.

Control derivatives	
Xde= -1.5285	CXde= -0.018974
Yde= -7.9689e-14	CYde= -9.8919e-16
Zde= -365.55	CZde= -4.5376
Lde= -2.8193e-12	CLde= -1.5485e-14
Mde= -27.108	CMde= -1.5593
Nde= 2.7158e-14	CNde= 1.4917e-16

$$A_{long} = \begin{bmatrix} -0.00381597 & 0.42777 & 0 & -9.81 \\ -1.14169 & -23.5935 & 14.3156 & 0 \\ -2.64139e-08 & -36.1382 & -20.0634 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (\text{B.22})$$

$$B_{long} = \begin{bmatrix} -1.679712 \\ -401.7028 \\ -1537.255 \\ 0 \end{bmatrix} \quad (\text{B.23})$$

$$A_{lat} = \begin{bmatrix} -0.58299 & -0.320308 & -16.9256 & 9.81 \\ -1.77157 & -30.1818 & 1.929 & 0 \\ 1.06408 & 0.251256 & -0.458123 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (\text{B.24})$$

$$B_{lat} = \begin{bmatrix} -8.757018e-14 \\ -1.74122e-11 \\ 2.358916e-13 \\ 0 \end{bmatrix} \quad (\text{B.25})$$

Table B.5: Sharky Fixed-Wing Trimming Parameters.

<i>Parameter</i>	<i>Value</i>
Neutral Point Position ($\{h\}$)	334.87mm
Zero-Moment Angle	$\approx 1.84580^\circ$
Speed for Balancing Weight	$\approx 17.19m/s$

Appendix C

SquidCop Additional Data & Information

C.1 SquidCop Technical Data

Table C.1: SquidCop MAV technical specifications.

Component	Weight
Battery	456g
4xMotors	257g
4xESC	177g
Cabling	58g
Control Board	35g
Sensors	25g
Glass Fiber Frame	298g
Engine Supports	76g
<i>Payload</i>	<i>1382</i>

C.2 Handcrafting Characteristics

SquidCop is mostly crafted with low density glass fiber thin tubular structures. Resulting frame is a low weight resistant mounting which offers low drag and high mechanical resistance features. Engines mounting are 3D-printed with biodegradable PLA (polylactide) thermoplastic aliphatic polyester in a honeycomb pattern, which ensures mechanical resistance and still low weight.

Appendix D

H₂Omni Additional Data & Information

D.1 H₂Omni Technical Data

Table D.1: H₂Omni MAV technical specifications.

Component	Weight
Battery	456g
4xMotors	257g
4xESC	177g
Cabling	58g
Control Board	35g
Sensors	25g
Torus+Fixing Elements	279g
Glass Fiber Levers	107g
Engine Supports	76g
<i>Payload</i>	<i>1470</i>

D.2 Handcrafting Characteristics

H₂Omni is essentially handcrafted from expanded low density polyurethane foam and polyethylene, which ensures very low density, high buoyancy and very good mechanical resistance properties. Levers are made from tubular low density glass fiber structure, which ensures extremely low weigh high mechanical resistance structural properties. Engines mounting are 3D-printed with biodegradable PLA (polylactide) thermoplastic aliphatic polyester in a honeycomb pattern,

which ensures mechanical resistance and still low weight.

D.2.1 CFD Full Analytical Data - Layouts A, B and C

Table D.2: Table of forces and moments for Layout A on the design of H₂Omn.

Goal Name	Unit	Flow Direction		
		X	Y	Z
Normal Force (X)	[N]	16,44274	-3,67074	-6,29566
Normal Force (Y)	[N]	0,229192	22,97428	0,448758
Normal Force (Z)	[N]	-3,95201	-1,70989	42,19602
Force (X)	[N]	16,71657	-3,65319	-6,2807
Force (Y)	[N]	0,2274	23,18468	0,450334
Force (Z)	[N]	-3,96076	-1,70822	42,29249
Friction Force (X)	[N]	0,273835	0,01755	0,014958
Friction Force (Y)	[N]	-0,00179	0,210404	0,001576
Friction Force (Z)	[N]	-0,00875	0,001674	0,096468
Torque (X)	[Nm]	-0,30649	0,940387	4,078191
Torque (Y)	[Nm]	0,214161	0,620582	-8,64756
Torque (Z)	[Nm]	-1,51792	6,185366	0,741466

Table D.3: Table of forces and moments for Layout B on the design of H₂Omni.

Force	Unit	Flow Direction		
		X	Y	Z
Normal Force (X)	[N]	11,0682	0,520708	-0,08711
Normal Force (Y)	[N]	-0,47746	10,96715	0,687357
Normal Force (Z)	[N]	-2,90775	0,287496	14,39335
Force (X)	[N]	11,16811	0,52621	-0,08938
Force (Y)	[N]	-0,47028	11,10296	0,687953
Force (Z)	[N]	-2,91317	0,281265	14,43585
Friction Force (X)	[N]	0,099907	0,005502	-0,00227
Friction Force (Y)	[N]	0,007185	0,13581	0,000596
Friction Force (Z)	[N]	-0,00542	-0,00623	0,042506
Torque (X)	[Nm]	-0,31801	-0,01078	2,223752
Torque (Y)	[Nm]	0,422659	-0,03534	-2,51568
Torque (Z)	[Nm]	-1,68148	2,689035	0,173802

Table D.4: Table of forces and moments for Layout C on the design of H₂Omni.

Force	Unit	Flow Direction		
		X	Y	Z
Normal Force (X)	[N]	8,366	-0,27691	0,418342
Normal Force (Y)	[N]	0,117494	8,353441	-0,17392
Normal Force (Z)	[N]	0,385217	0,520451	47,53495
Force (X)	[N]	8,575028	-0,27772	0,431745
Force (Y)	[N]	0,116152	8,572822	-0,17722
Force (Z)	[N]	0,369541	0,50848	47,62453
Friction Force (X)	[N]	0,209028	-0,00081	0,013402
Friction Force (Y)	[N]	-0,00134	0,219381	-0,00331
Friction Force (Z)	[N]	-0,01568	-0,01197	0,089585
Torque (X)	[Nm]	0,0153	-0,06368	4,572685
Torque (Y)	[Nm]	0,10159	-0,1351	-11,0851
Torque (Z)	[Nm]	-0,78684	1,981513	-0,07889

D.3 H₂Omni Additional CFD Data

Figure D.1 shows the dynamic pressure distribution in H₂Omni MAV while translating along xy plane.

Figure D.1: Flow stream for translations Along xy Plane.

Figure D.2: Flow stream for On-Edge Rotations.

Figure D.3: Flow stream for translations Along z Axis.

Figure D.4: Flow stream for spinning About Z Axis.

D.4 Layouts A and B Additional CFD Data

D.4.1 Layout A - Lateral Translation

Figure D.5: Flow stream for lateral translation in Layout A.

D.4.2 Layout B - Lateral Translation

Figure D.6: Flow stream for lateral translation in Layout B.

Appendix E

Control Additional Data

E.1 Hardware Specifications

All three MAVs designed in this thesis are endowed with the same hardware specifications. Control board is a ARM7 based hardware in which the stability control is embedded. Control architecture follows the scheme described in Fig. 7.5 from Section 7.1. For patent pending protection and product registry purposes, we reserve the right to keep detailed information confidential.

E.2 γ -Iteration Algorithm

```
%=====
%===== H-INFINITY CONTROLLER =====
%=====
%
%Author: Rafael Coronel
%Date:    MAY/28/2013
%Info:    Optimal H-Infinity Controller for a
%          6DoF quadrotor.
%          4 inputs(U1 .. U4), 12 states ,
%          3 outputs (roll , pitch , yaw).
%=====
```

```
close all
```

```
clear all
```

```
clc
```

```
%Loads dynamic matrices for the augmented plant
```

```
Ag = load('A');
```

```
Bg = load('B');
```

```
Cg = load('C');
```

```
Dg = load('D');
```

```
%Packs the State-Space representation in the compact form
```

```
G=pck(Ag,Bg,Cg,Dg);
```

```
%Defining Weighting Functions
```

```
%We (for error)
```

```
Ms=1e10;
```

```
wb=1;
```

```
E=0.0001;
```

```
nwe=[1/Ms wb];
```

```
dwe=[1 wb*E]; % Eq. 6.6 Zhou pg. 92
```

```
M = 15;
```

```
w1 = 5;
```

```
w2 = 12;
```

```
nwe=(w1/w2)*[1 w2];
```

```
dwe=(10^(M/20))*[1 w1];
```

```
We=nd2sys(nwe,dwe);
```

```
We=daug(We,We,We,We);
```

```
%Defining Weighting Functions
```

```
%Wu (for control)
```

```
Mu=100;
```

```
wbc=1000;
E1=0.01/100;
nwu=[1 wbc/Mu];
dwu=[E1 wbc];           % Eq. 6.8 Zhou pg. 92
```

```
%Wu - Input u
w1 = 10000;
w2 = 100;
Mu = 10;
nwu = (w2/w1)*[1 w1];
dwu = (10^(Mu/20))*[1 w2];
Wu=nd2sys(nwu,dwu)
Wu=daug(Wu,Wu,Wu,Wu);
```

```
% Sets parameters up to augmented plant consolidation
systemnames='G Wu We';
inputvar='[r(4); dist(4); control(4)]';
outputvar='[Wu; We; r-G]';
input_to_G='[control+dist]';
input_to_Wu='[control]';
input_to_We='[r-G]';
sysoutname='P';
cleanupsysic='yes';
sysic
```

```
%Augmented Plant
systemnames='G';
inputvar='[r(3); dist(4); control(4)]';
outputvar='[control; r-G; r-G]';
input_to_G='[control+dist]';
sysoutname='P';
cleanupsysic='yes';
sysic
```

```
%H-INF Synthesis
```

```
gmin=0.1;
```

```
gmax=150;
```

```
[K1,CL,gama]=hinfsyn(P,4,4,gmin,gmax,0.05);
```

```
[Ak,Bk,Ck,Dk]=unpck(K1);
```

```
K=ss(Ak,Bk,Ck,Dk);
```

```
%Plots
```

```
[Agk,Bgk,Cgk,Dgk]=series(Ak,Bk,Ck,Dk,Ag,Bg,Cg,Dg);
```

```
Lo=ss(Agk,Bgk,Cgk,Dgk);
```

```
We=tf(nwe,dwe);
```

```
WE=eye(2)*We;
```

```
Wu=tf(nwu,dwu);
```

```
WU=eye(2)*Wu;
```

```
%Output Sensibility Funtion
```

```
So=inv(eye(size(Lo))+Lo);
```

```
figure
```

```
sigma(inv(WE),So,{1e-15,1e15}); % Plot 6.6 pag. 91 Zhou
```

```
SYS=series(So,K);
```

```
figure
```

```
sigma(inv(WU),SYS,{1e-15,1e15}); % Plot 6.8 pag. 93 Zhou
```

```
[Acl,Bcl,Ccl,Dcl]=unpck(CL);
```

```
sysCL = ss(Acl,Bcl,Ccl,Dcl);
```

```
figure;
```

```
step(sysCL)
```

Appendix F

Computational & Wind Tunnel Data

F.1 Wind Tunnel Additional Information

F.1.1 Closed Circuit Wind Tunnel Information

Wind tunnel evaluation was run in the LAE (USP/EESC) SANTANA et al. (2010) closed circuit wind-tunnel which was first designed as a 3/8 scale pilot wind-tunnel for automotive industry purposes. Construction started on 1998 and was finished in 2002. It is predominantly crafted with naval plywood. As automotive industry investment decreased and Brazilian aeronautic industry has considerably grew in the past years, LAE wind tunnel became a multi task wind tunnel whose instrumentation is specially focused on aeronautical tests both for industry and academic reasons.

Figure F.1 presents a plan view of the LAE-1 closed circuit wind tunnel. The wind-tunnel test section dimensions are 3.00 m long, 1.30 m high and 1.70 m wide. The maximum design flow speed is 50 m/s, with a turbulence level of 0.25%, nowadays due to safety and components long range issues, this velocity is limited to 45 m/s. Its electric motor, with 110 HP, drives an 8 blades fan with 7 straighteners localized downstream the fan. In the flow stabilization section there are two mesh screens of 54% porosity following by the 1:8 contraction cone designed using two 3rd order polynomials joined at 45° inflection point. The tunnel is endowed with low angle diffusers, low-drag corner-vanes and high-efficiency propeller blades designed with a combination of CFD and semi-empirical techniques. Besides, background noise is reduced in order to carried-out beam-form noise measurements SANTANA et al. (2010).

Figure F.1: USP/EESC/LAE Wind Tunnel Features.