DESIGN AND ANALYSIS OF AN UNMANNED SMALL-SCALE AIR-LAND-WATER VEHICLE

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ABSTRACT

The designs of small-scale unmanned aerial, land and water vehicles are currently being researched in both civilian and military applications. However, these unmanned vehicles are limited to only one and two mode of operation. The problems arise when a mission is required for two and three-mode of operation, it take two or three units of vehicles to support the mission. This thesis presents the design and analysis of an Unmanned Small-scale Air-Land-Water Vehicle (USALWaV). The vehicle named as a "three-mode vehicle", is aimed to be an innovative vehicle that could fly, move on the land and traversing the water surface for search and rescue, and surveillance missions. The design process starts with an analysis of requirements to translate the customer needs using a Quality Function Deployment (QFD) matrix. A design concept was generated by developing an optimal configuration for the platform using QFD with a non-exhaustive comparison method. A detailed analysis of the concept followed by designing, analyzing and developing main components of the drive train, main frame, main rotor, rotor blades, control system, transmission system, pontoon mechanism and propeller system. Further, the analysis was done to determine the vehicle weight, aerodynamics, and stability using several software; SolidWorks, XFLR5, and Matlab. Then, the model of USALWaV has been fabricated, tested and successfully operates using remote control system. The final USALWaV configuration is main coaxial rotor 460 mm in diameter, propeller diameter 85 mm, weighing 550 grams; it is capable of hovering and flying with forward speed between 0 and 0.7 m/s, move forward and backward speed between 0 and 0.11 m/s, and operation speed between 0 and 0.47 m/s on the water surface. It is powered by an Xtreme Lithium Polymer battery, and has an endurance of 10 minutes. The main contribution of this design results is provide a new concept of an unmanned vehicle system in three-mode of operation i.e. in air, land and water surface.

ABSTRAK

Rekaan kenderaan udara, darat dan air berskala kecil tanpa pemandu sedang dikaji dalam kedua-dua aplikasi awam dan tentera. Walau bagaimanapun, kenderaan tanpa pemandu itu adalah terhad kepada hanya satu dan dua mode operasi. Masalah timbul apabila misi diperlukan untuk dua dan tiga mode operasi, ia memerlukan dua atau tiga unit kenderaan untuk menyokong misi tersebut. Tesis ini membentangkan rekabentuk dan analisis satu kenderaan udara-darat-air bersekala kecil tanpa pemandu (USALWaV). Kenderaan ini dinamakan sebagai "kenderaan tiga-mode", bertujuan menjadi kenderaan inovatif yang boleh terbang, bergerak di atas tanah dan merentasi di permukaan air untuk mencari dan menyelamat, dan misi pengawasan. Proses rekabentuk bermula dengan analisis keperluan untuk menterjemahkan keperluan pelanggan menggunakan matriks *Quality Function Deployment* (QFD). Konsep rekabentuk telah dijana dengan membina konfigurasi yang optimum untuk *platform* menggunakan *QFD* dengan kaedah *non-exhaustive comparison*. Analisis konsep terperinci diikuti dengan merekabentuk, menganalisis dan membina komponen utama seperti pemandu kenderaan, kerangka kenderaan, bilah pemutar utama, sistem kawalan, sistem transmisi, mekanisme pontoon dan sistem kipas. Seterusnya, analisis telah dijalankan untuk menentukan berat optimum, aerodinamik, dan kestabilan kenderaan menggunakan beberapa perisian: SolidWorks, XFLR5 dan Matlab. Kemudian, model USALWaV telah direka, diuji dan berjaya beroperasi menggunakan sistem kawalan jauh. Konfigurasi USALWaV akhir adalah pemutar sepaksi utama diameter 460 mm, kipas diameter 85 mm, dan berat kenderaan 550 gram, ia mampu berlegar dan terbang dengan kelajuan di antara 0 dan 0.7 m/s, kelajuan di darat antara 0 dan 0.11 m/s, dan beroperasi antara 0 dan 0.47 m/s di permukaan air. Ia dikuasakan oleh bateri *Xtreme Lithium Polimer*, dan mempunyai daya tahan 10 minit. Sumbangan utama daripada keputusan rekabentuk ini ialah menyediakan satu konsep baru sistem kenderaan tanpa pemandu dalam tiga mode operasi iaitu di udara, darat dan permukaan air.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

$N_{C_{airmodel}}$	- Number of component for air mode
$N_{C_{joint}}$	- Number of component for joint purposes
$N_{C_{landmode}}$	- Number of component for land mode
$N_{C_{Total}}$	- The total of component
$N_{C_{watermodel}}$	- Number of component for water mode
W_{avi}	- Weight of avionics
W_{bat}	- Weight of battery
W_e	- Estimate of weight
W_{prop}	- Weight of propulsion system
W_{str}	- Weight of structure
W_v	- Weight of the vehicle
α	- Angle of Attack
$\dot{v}_u$	- Mass flow rate over the upper rotor
η	- Efficiency
κ_ϕ	- Stiffness of the suspension
μ	- Fluid dynamic viscosity
Ω	- Rotor speed
ϕ	- Roll angle
ρ	- Air density
τ_s	- Servo torque
$\triangle h$	- Vertical displacement
A	- Rotor disk area
a_{ylim}	- Lateral acceleration limit
B	- Buoyancy
b	- Vehicle track width
BM	- Meta-centric radius
c	- Chord length
C_D	- Drag Coefficient
C_L	- Lift Coefficient

D	- Drag force
F_v	- Vertical force
F_y	- Vehicle force in lateral direction
F_{zi}	- Normal force on the inside tires
F_{zo}	- Normal force on the outside tires
G	- Center of gravity for water mode analysis
g	- gravity
GM	- Length of center of gravity to meta-centric
GZ	- Stability curve
h_o	- Height of vehicle C.G above ground
i	- Gear ratio
K	- Keel
KB	- Vertical center of buoyancy
KG	- Vertical center of gravity
KM	- Reference point from keel to meta-centric
L	- Lift force
l_a	- Lever arm length of pontoon
LK	- Values for cross curve
M	- Metacenter
m_b	- Mass of blade
Mac	- Mach Number
N_a	- Actual speed of main motor
N_n	- Nominal speed of main motor
P_l	- Ideal power by the lower rotor
P_T	- Thrust power of propeller
P_u	- Ideal power by the upper rotor
R	- Rotor radius
Re	- Reynold's Number
S_f	- Free space between pontoon and propeller
$S_{pontoon}$	- Pontoon workspace
S_{prop}	- Propeller workspace
SS_F	- Static stability factor
t	- Airfoil thickness percentage
T_l	- Thrust of lower rotor
T_u	- Thrust of upper rotor
V_{cc}	- Positive voltage
v_i	- Induce velocity
v_l	- Induce velocity of lower rotor
v_m	- Mean velocity on the airfoil

v_u - Induce velocity of upper rotor
W_b - Weight of blade
w_l - Induce velocity at the wake
$W_{p1,2}$ - Weight of pontoon (right and left)
z_1 - The number of pinion teeth
z_2 - The number of gear teeth

Abbreviations

2D - Two Dimensional
3D - Three-Dimensional
AAV - Autonomous Amphibious Vehicle
ACAT - Autonomous Cargo Amphibious Transport
ALV - Autonomous Land Vehicle
ATRV - All Terrain Robot Vehicle
CAD - Computer-Aided Design
D.L - Disk loading
DARPA - Defense Advanced Research Projects Agency
ESC - Electronic Speed Controller
FBD - Free Body Diagram
FFD - Function Flow Diagram
FM - Figure of Merit
HALE - High Altitude Long Endurance
LTOL - Long Take-off and Landing
MAVs - Micro Air Vehicles
MDARS - Mobile Detection Assessment Response System
MRHA - Multiple Resource Host Architecture
MVs - Micro Vehicles
NASA - National Aeronautics and Space Administration
PWM - Pulse-width modulation
QFD - Quality Function Deployment
RF - Radio Frequency
ROA - Remotely Operated Aircraft
RPV - Remotely Piloted Vehicle
SDST - Shipboard Deployed Surface Target
UAGV - Unmanned Air Ground Vehicle
UAVs - Unmanned Aerial Vehicles
UGV - Unmanned Ground Vehicle
UMV - Unmanned Marine Vehicle

USVs	- Unmanned Surface Vehicles
UVS	- Unmanned Vehicle System
UVs	- Unmanned Vehicles
VTOL	- Vertical Take-off and Landing

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The name of Unmanned Vehicles (UVs) or Unmanned Systems (USs) covers all vehicles operating in air, ground, water and combination of them with no person on board the system with a capability controlling the vehicle. Research idea in UVs, especially their small-version as well as Micro Vehicles (MVs) has been proliferating in both civil and military applications.

The design of an Unmanned Aerial Vehicles (UAVs) for the past few decades and recent are being used in a broad number of dangerous, dirty and dull missions. For example, possible UAV uses for civilian sectors application such as search and rescue, surveying, covert imaging, bridge inspection, emergency response, scientific data collection, and detection of hazardous material. The advantages of a helicopter UAV are clear with the feasibility of vertical take-off and landing (VTOL), hover, and low-speed flight capabilities while retaining cruising abilities. This maneuverability and versatility comes at the expense of complicated system dynamics and mechanisms.

The development of the small-scale unmanned for aerial, ground and water vehicle are also ongoing and have challenges in many disciplines and common purposes. Some example development in the UVs are, however, mature enough to be integrated to some real-life applications in both the military and civilian domains.

Currently, military UAVs perform reconnaissance as well as attack missions, environmental observation, maritime surveillance, force protection and mine removal activities. While many successful drone attacks on militants have been reported, they are also prone to collateral damage and/or erroneous targeting, as with many other weapon types. UAVs are also used in a small but growing number of non-military applications, such as firefighting security work, such as surveillance of pipelines, a rice paddy remote sensing and spraying as well as infrastructure maintenance (Anon, 2002).

On the battlefield, the unmanned rotorcraft systems are mostly utilized for combat gunfire support, and surveillance and reconnaissance. The case reported in *Flightglobal* is a famous battlefield application of a *Honeywell* duct fan find out by Miami-Dade Police Department. In the agricultural development, the UAV RC helicopter carries the multi-spectral cameras and the pesticide sprayer. The most representative examples are the *R50* and *Rmax* helicopters developed by Yamaha (Shim *et al.*, 2009).

In addition, for the ground used, some researchers have been design of an Unmanned Ground Vehicle (UGV), named *Bearcat III*, describes from theory to practice. The purpose of this research is to describe the design and implementation of an unmanned ground vehicle. The *Bearcat III* is an electric powered, three-wheeled vehicle that was designed and test for the Intelligent Ground Vehicle Competition (Ghaffari *et al.*, 2004).

Issues on the watercraft, an Unmanned Surface Vehicle (USV) with the Navigation, Guidance and Control (NGC) system through extended at sea trials has carried out the prototype autonomous catamaran by *Charlie* (Caccia *et al.*, 2008). However, the *Charlie* USV model design is used to accomplish the design possibility on the water-mode.

The other approach design has developed a small-scale Autonomous Amphibious Vehicle (AAV). According to the research efforts, the vehicle has capable of traversing across aquatic and terrestrial environments (Michael & Nokleby, 2008). The most other version is named as an Unmanned Air Ground Vehicle (UAGV) (Janetka *et al.*, 2001), which is exploring the system in level concepts that can provide the capability using a combined unmanned air and ground vehicle. Furthermore, the development of autonomous cargo transport is also done for an unmanned aerial vehicle using visual servoing (Kuntz & Oh, 2008). The classifications and state of the art of the unmanned vehicle are described further in Chapter 2 in more detail.

1.2 Problem Statement

All UVs are of particular interest to many researchers, because of low cost relatively, yet offer the ability to address a multitude of semi or autonomous operation applications, high maneuverability and high size-to-payload ratio.

The interest in developing vehicle design has spanned several decades. Many UVs have been built up and capabilities to maneuver in any single and dual-mode operations (i.e. in air, land, water, amphibious vehicle, and air-land), including the works of Shim *et al.* (2000); Bedkowski *et al.* (2008); Caccia *et al.* (2008); Michael & Nokleby (2008); Dudek *et al.* (2007) and Kossett *et al.* (2010). These research discussed the possible roles these vehicles may have in search and rescue, surveillance, traffic monitoring, fire detection, pipelines inspection, and the agricultural application only a few.

In reviewing the design and development of unmanned-base vehicle model, several research points out their limitation as follows:

1. Development of an unmanned vehicle requires expertise in many areas including design tools, electronic device, mechanical design, software and hardware integration, controller design, and safety piloting. Many labs and institutions do not have all these areas of expertise available and thus must seek outside help for development.

2. Development of the systems are typically designed for single-mode of operation and in-house or indoor use are typically tightly integrated. Some small vehicle remain limited in their locomotion capabilities, often prevented from accessing areas restricted by tall obstacles or rough terrain.

3. Current published works especially for dual-mode operation are typically explore system in level concepts and sometime used for design competition.

Furthermore, there are many previous researches that discuss about an unmanned vehicle design indoor flight and do not account for environmental uncertainties. Trends in UVs which controlled by remotely piloted or self-piloted is the ability to carry cameras, sensors, communications equipment and other payloads at one mode of operation. However, literature becomes less available when it comes to small vehicles which have two function. Few relevant articles discussing the design process of small unmanned vehicles were found which start from design to the implementation. Moreover, the specific topic about unmanned vehicle that could be operated on three-mode such as in air, land and water is absence investigated in any research.

1.3 Motivation

The successful development of small fixed-wing UAVs requires a strong lightweight vehicle platform, a low-power, lightweight autopilot, intuitive, as well as increased autonomy including path planning, trajectory generation and tracking algorithms. However, long takeoff and landing of the UAVs with fixed-wing is required and not efficient for the narrow location. Furthermore, they require some space to turn because they cannot hover, so navigating them in close quarters is very difficult.

The Unmanned Aerial Vehicle (UAV), especially the unmanned rotary-wing systems are mostly utilized. Maybe the biggest advantage of a rotary-wing aircraft is the ability to hover for extended periods of time. This particular capability enables the use of rotary-wing for applications like convert imaging, surveillance and reconnaissance, and many more. Rotary-wing aircraft has been designed in several different shapes and sizes over the period of several decades. This aircraft is only reliable for the operation from the air, but worthless when operating on land and water.

For operations on land, some researchers have been designed and implemented the Unmanned Ground Vehicle (UGV) as a mobile robot for command and control system. The movement of these vehicles is limited only on land, but is not feasible to operate when it finds an area that is watery and precipitous environments.

Issues on the watercraft, the Unmanned Surface Vehicle (USV) with the navigation, guidance and control (NGC) system through extended at sea trials has carried out the prototype. However, the USV model is used to accomplish the design possibility on the water-mode.

The other design has developed the dual-mode vehicle such as a small-scale autonomous amphibious vehicle. According to the research efforts, the vehicle has capable of traversing across aquatic and terrestrial environments. The most other version is named as an unmanned air ground vehicle which is exploring the system in level concepts. Furthermore, the development of autonomous cargo transport is also done for an unmanned aerial vehicle using visual servoing. However, these unmanned vehicles are limited to only one and two mode of operation. The problems arise when a mission is required for two and three-mode of operation, it is need two or three units of vehicles to support the mission. This becomes important when it operates as an attack by air, land and water. Similarly, for security measures, the vehicle can switch to another operations when the enemy attacked. For instance, when the vehicle was attacked on the ground, the vehicle can fly immediately.

Based on these problem of the unmanned vehicle with has limitation in their operation, a new class of UV needs to be developed to perform locomotion in air, land and water operation, further named as "the three-mode unmanned vehicle". An effort is made in this research to use the commercial software for USALWaV design by following the steps in the design process.

1.4 Research Objectives

The research embark the following objectives:

1. To develop a technique for optimizing the USALWaV mission and design requirements using Quality Function Deployment (QFD) matrix.
2. To determine the USALWaV requirements and configurations that could enable to operate in air, land and water surface.
3. To design and analyze the mechanisms that support the functions of the USALWaV at flight, on land travel and water traversing.
4. To test the USALWaV reliability by making the prototype.

In order to accomplish these objective, it will stipulated the design technique of the USALWaV through the design process that involves mission requirements, conceptual, preliminaries, detail design, test and evaluation.

1.5 Scopes

This research deals with the flow design process and implementation of an Unmanned Small-scale Air-Land-Water Vehicle, completed with dimension and detail model in three-dimensional (3D). A large part of this thesis thus concerns the development of the vehicle mechanism design, electronic equipments selection and their interconnections for acquiring on design. Fabricating and testing will be done on prototype of the vehicle that could be operated in air, land and water surface. The rest of the work is completely in software implementation to analyze the vehicle performance, stability and control. The issues above are resolved using several software includes SolidWorks, XFLR5 and Matlab.

1.6 Organization of the Thesis

This thesis has 6 chapters organized as follows:

After this brief introduction, Chapter 2 describes the literature review. It is related to vehicle classification based on location where the vehicle operated. In this chapter also reviews the literature related to the existing technology and operation modes of unmanned vehicle systems.

Chapter 3 provides the research methodology. This chapter describes the proposed technique for design requirements analysis, referred as the Quality Function Deployment (QFD) technique. Based on the problem statement, detail justifications of the research is obtained here. Types of the design software and hardware utilized on the USALWaV design is mentioned in the last of this chapter.

Chapter 4 contains the process of current work. In this chapter discusses the methods to decide the best configuration of several unmanned vehicles that used to build the USALWaV. The description of the design process which follows requirements through conceptual design, preliminary and finally detailed design before manufacture begins.

Chapter 5 contains the results and discussion. In this chapter, the design results will be presented in detail. Discussion and analysis of the results of the proposed method will be in detail here. The chapter also discusses the prototype utilized for initial reliability testing and evaluation.

Finally, Chapter 6 describes conclusions and recommendations. In this chapter, the progress made so far and identifies the direction of the future research with some recommendations have been presented.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a comprehensive study of previously published work relevant to the vehicle design classification and the current project. The review of current existing technology UVs in different mode of operation is discussed. It also includes the benefits and drawbacks of recent works that have been done in this field.

In order to emphasize the simplicity of the UVs design concept and to familiarize the reader with vehicle principles in general, an introduction to operation modes and vehicle classification will be presented first.

2.1 Modes and Unmanned Vehicle Principles

Modes of operation of an Unmanned Vehicle (UV) in this study is the location where the vehicle operated. The location of the operation such as land, air and water environment. Single-mode vehicle means the vehicle that operated just at one location. Similarly, a vehicle named as dual-mode means the vehicle that can operated at two locations, namely, land-water (amphibious), land-air, and water-air vehicle. Thus, the three-mode vehicle in this case means the vehicle that can operated in three locations: on land, air and water. This vehicle is the core of the design in this study. Furthermore, review related to current researches will be discussed in detail. The overall UVs classification is summarized in Figure 2.1.

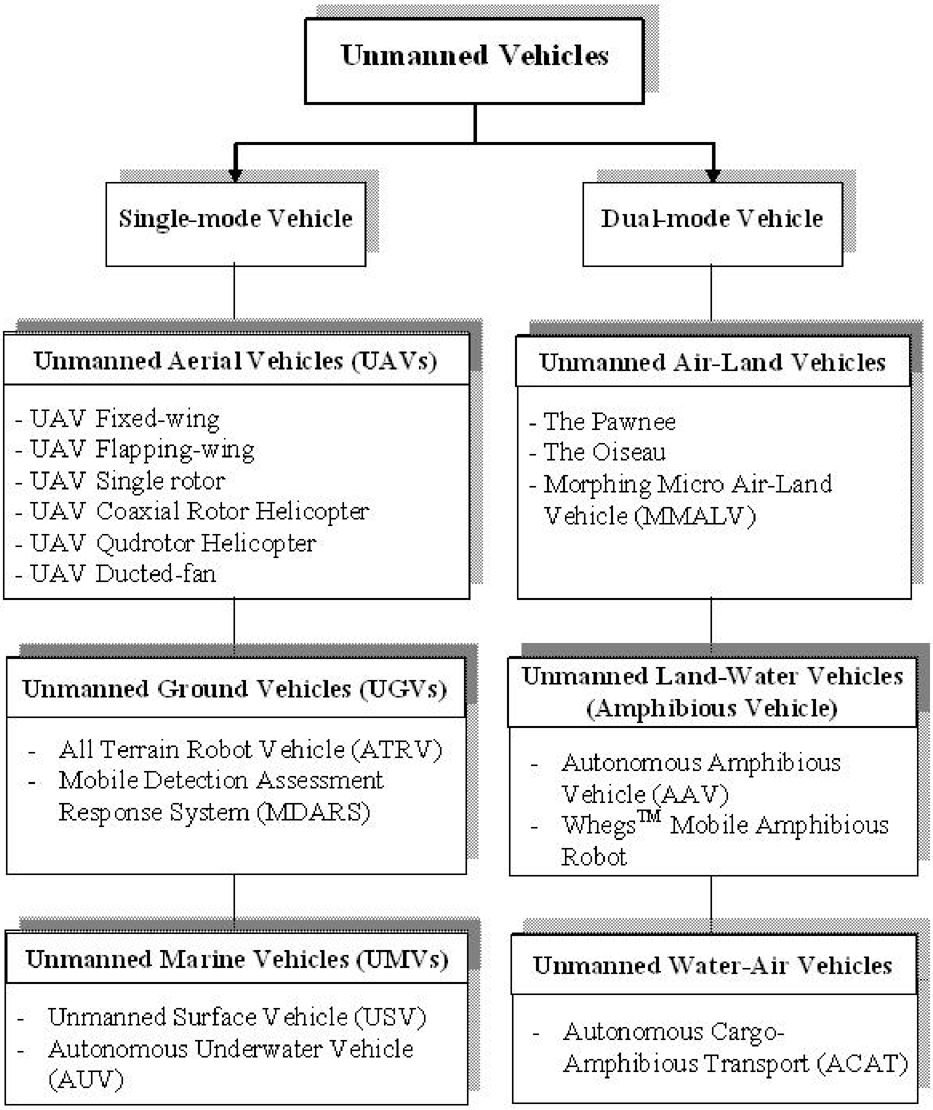


Figure 2.1: Unmanned vehicles classification and examples

Based on the above terms, UVs are classified in two categories. Firstly is the single-mode unmanned vehicle. These vehicles subdivided in three types: Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicle (UGV), and the Unmanned Marine Vehicle (UMV), includes Unmanned Surface Vehicles (USVs) and Unmanned Underwater Vehicles (UUVs). Secondly is the dual-mode unmanned vehicle. This vehicle is developed by the combination of two types of the single-mode. Vehicle which operates in this mode consists of three types: Unmanned Air-Ground Vehicle (UAGV), Unmanned Ground-Water Vehicle (Amphibious) and Unmanned Water-Air Vehicle (Flying Boat). The unmanned dual-mode vehicle class are relatively few implemented in civilian, but become important prior to the development for robotics and military mission. An important step from the full scale vehicles (manned) to small-scale vehicles (unmanned) are being used in a broad number of dangerous, dirty and dull environment application.

2.2 Single-mode Vehicle

Unmanned vehicle with single-mode of operation in this section presents the three categories: Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), and Unmanned Surface Vehicles (USVs).

2.2.1 Unmanned Aerial Vehicles (UAVs)

The UAV research as an application of single-mode vehicle is used commonly in the computer science and artificial intelligence community or robotics field. The terms like Remotely Piloted Vehicle (RPV), Remotely Operated Aircraft (ROA), Remote-Controlled Helicopter (RC-Helicopter), Unmanned Vehicle Systems (UVS) and model helicopter are often used too (Eisenbeiss, 2004).

Figure 2.2 based on a figure in Mueller & DeLaurier (2003) illustrates the scale groups of the aircraft proposed for the project, as well as the scales of existing and previously proposed UAVs. Furthermore, the definition of the UVS community, in which the helicopters fit, are listed in Table 2.1. All other class of unmanned aircraft are generalized also in the "High Altitude Long Endurance" (HALE) group (Eisenbeiss, 2004).

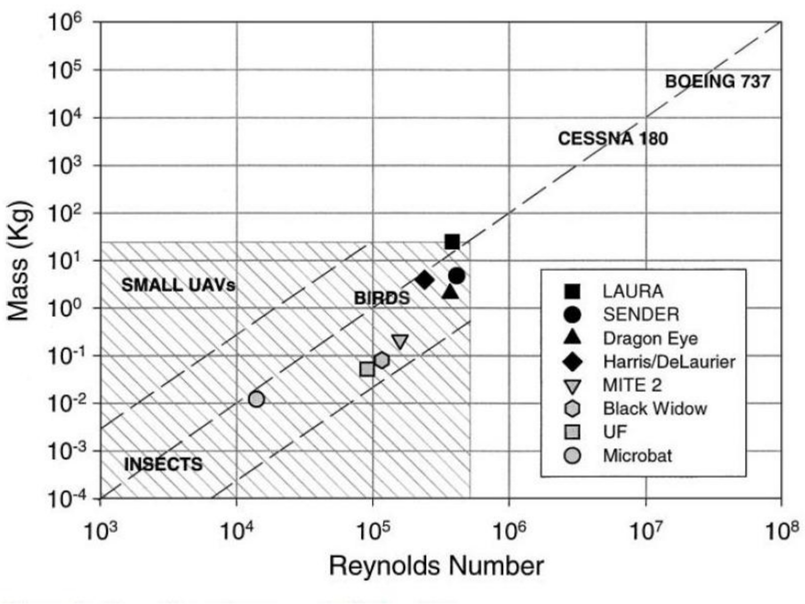


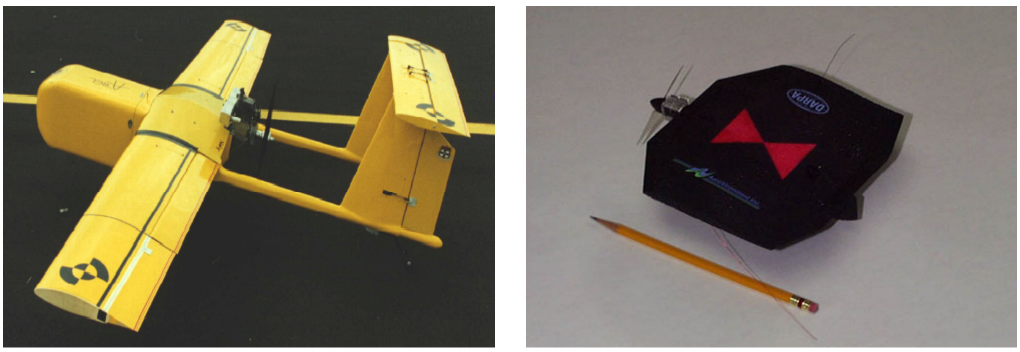
Figure 2.2: Scale groups of the existing UAV based on Reynolds Number vs Mass (Mueller & DeLaurier, 2003)

Based on controlled method, UAVs consists of two versions: some are controlled from a remote location, and others fly autonomously based on pre-programmed way-points selected by the operator using more complex dynamic automation systems (William R. Davis *et al.*, 1996). Both of the controller model depending on control range and duration of vehicle operation. The remote controlled and model helicopters are clearly defined as mini, short, light and medium-range of the UAVs depending on their size or weight, payload, endurance, range and flying altitude. Furthermore, the small-scale unmanned-based vehicle which might also be called robotic service vehicles.

Table 2.1: UAV categories defined by UVS International (Eisenbeiss, 2004)

Category name	**Mass** [kg]	**Range** [km]	**Flight altitude** [m]	**Endurance** [hours]
Micro	< 5	< 10	250	1
Mini	< 25 / 30 / 150	< 10	150 / 250 / 300	< 2
Close range	25 - 150	10 - 30	3000	2 - 4
Medium range	50 - 250	30 - 70	3000	3 - 6
High altitude long - endurance	> 250	> 70	> 3000	> 6

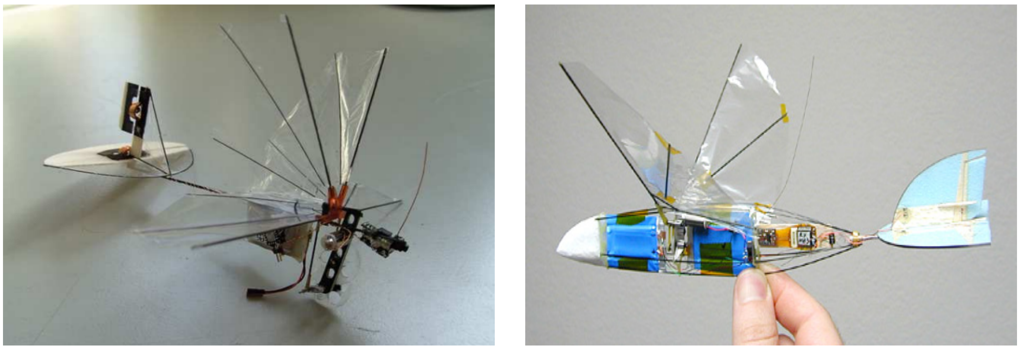
Based on wing types, UAVs are subdivided into three general categories: fixed-wing UAVs, rotary-wing UAVs, and flapping-wing UAVs. Fixed-wing system are used due to the higher energy efficiency and higher forward velocity. An example is UAV designed by Wong (1993) and Grasmeyer & Keennon (2001), as kind of fixed-wing aircraft as shown in Figure 2.3 (a) and Figure 2.3 (b) meet size and weight constraints, but fixed-wing models can not hovering.



(a) (b)

Figure 2.3: UAV fixed-wing model: (a) Ariel UAV and (b) Blackwidow (Wong, 1993; Grasmeyer & Keennon, 2001)

The other principle of UAV is the flapping-wing type. Flapping-wing aircrafts are still in the state of research mainly for Micro Aerial Vehicle (MAV). Researchers draw inspiration from natural systems and have develop mechanisms to realize the flapping motion and use these mechanisms in MAVs to demonstrate a flapping wing flight. For example birds, insects and bats on the other hand flap their wings are the variety of animals to be applied in design the flapping-wing MAV. The representative works in this area are *DelFly I* and *DelFly II* designed and developed at the Aerospace Faculty at Delft University of Technology. Some model of flapping-wing aircraft from DelFly (2012) and *MicroBat* prototype by Pornsin-Sirirak *et al.* (2001) can be seen in Figure 2.4 (a) and Figure 2.4 (b). Although some researchers represent the flapping-wing are good in maneuverability and low power but are lacking in performance, complex mechanics and control.



(a) (b)

Figure 2.4: Flapping-wing MAV model: (a) DelFly, and (b) MicroBat (DelFly, 2012; Pornsin-Sirirak *et al.*, 2001)

For rotary-wing vehicles, even with larger and heavier designs, endurance times are shorter than for the fixed-wing configurations. Rotary-wing aircraft are superior to their fixed-wing counterparts in terms of achieving higher degree of freedom, low speed flying, can move vertically, stationary flights (hovering), turn in place, and for indoor application. Many different rotor configurations for the single-mode RC rotorcraft. It based on the number and mounted position of the rotor. From the practical point of view, the rotor configuration can be further categorized in three types: single-rotor, double-rotor, and quad rotor helicopter. A description of prior rotor configuration on the UVs is provided in the next section.

The design and development of a small-scale UAV not only has been strongly proposed often in recent years as a military project but also rarely with civilian applications in mind. For reasons of hiding, these military studies have focused primarily on the design of MAVs, with wingspans on the order of a few inches and mass less than 5 kg. At present, the technology required to construct a UAV of this size has not been fully realized.

As part of the conceptualization, a specific effort was made to asses all approaches to UAVs, UGVs and USVs. It was important to start the design from the ground up considering every possibility. Some small-scale vehicle shows the performance, in terms of weight and endurance, of a series of rotary-wing MAVs along with selected fixed-wing as shown in Table 2.2. It can be clearly seen that the objective set by Defense Advanced Research Projects Agency (DARPA, 1958) is far from being reached, in which to determine how the feasibility and practicality of UAVs is affected by size.

Table 2.2: Relative performances of MAVs

MAVs Name	**Wing Type**	**Weight [g]**	**Endurance [min]**
muFly	Rotary-wing	80.31	5 - 10
Micor UMD	Rotary-wing	150	15
Commercial Electric Heli	Rotary-wing	350	15
CoaX	Rotary-wing	200	20
CoaX-2	Rotary-wing	230	18
Kolibri Lutronix	Rotary-wing	440	< 10
Honeywell iSTAR	Rotary-wing	1800	15
Aerovironment Black Widow	Fixed-wing	80	25
Lockhead-Sanders Microstar	Fixed-wing	110	25

2.2.2 Unmanned Ground Vehicles (UGVs)

An Unmanned Ground Vehicle (UGV) is defined as any vehicle that moves across the surface of the ground or land and serves as a means of carrying or transporting something without a person to be controller on board the system. In the robotic community, the UGV is usually considered as an automated motion platform or just a mobile robot. It can be classified as tele-operated or autonomous based on programmable system depending on whether it requires human intervention or not. The UGV is sometimes called an Autonomous Land Vehicle (ALV).

For the ground-based vehicles as shown in Figure 2.5 (a), there exist various designs such as the development mobile robot “All Terrain Robot Vehicle” (ATRV) for fire fighter services and dedicated to the risky intervention tasks (Bedkowski *et al.*, 2008). The other mode is the Mobile Detection Assessment Response System (MDARS) program as shown in Figure 2.5 (b). This vehicle executed by PM-FPS out of Fort Belvoir, VA. Space and Naval Warfare Systems Center (SSC) Pacific have been involved in MDARS since the late 1980’s as both the developer of the command and control system (the Multiple Resource Host Architecture or MRHA) and as the Chief Engineer for technical development and integration (Shoop *et al.*, 2006).

(a) (b)

Figure 2.5: Single-mode UGVs on the ground locomotion: (a) ATRV, and (b) MDARS (DelFly, 2012; Pornsin-Sirirak *et al.*, 2001)

2.2.3 Unmanned Surface Vehicles (USVs)

The other kind of single-mode vehicle is the Unmanned Surface Vehicles (USVs). The USVs is defined as a remotely controlled or autonomous vehicle that operates on the surface of the water without a crew on board the system.

Recent successes of the USVs in the *Afghan War* may pave the way for a new wave of USVs. However, insufficient attention has been paid to USVs. In fact, the US Navy did not release its first USV Master Plan until July 2007, where a USV is defined as a vehicle which displaces water at rest. Operates with near continuous contact with the water surface, capable of unmanned operations and has been varying degrees of autonomy: manual, semi-autonomous and fully autonomous (Thomsen *et al.*, 2007).

USVs have been tested since World War II for purposes such as mine-sweeping and battle damage assessment (BDA). For example, as shown in Figure 2.6 (a) approved by Thomsen *et al.* (2007), is the Shipboard Deployed Surface Target (SDST) or *X-Class* renamed later "*Roboski*". This vehicle has a jet-ski chassis initially used as target drone and the reconnaissance vehicle test-bed. Its applications include military, research and civilian purpose, surveillance of territorial waters, exploration and exploitation of hydrocarbon, environmental monitoring, research of ocean scientific, and so on (Manley, 2008; Veers & Bertram, 2006). The other USVs prototype version in the world are: Spartan (America), Charlie (Italy), Springer (Britain), and Delfim (Portugal).

In Caccia *et al.* (2008) discusses, the basic motion estimation, guidance and control system of the *Charlie* prototype USV, an autonomous catamaran prototype equipped with a navigation package constituted only by global positioning system (GPS) and compass as shown in Figure 2.6 (b). In this context, the design and implementation of an accurate and reliable navigation, guidance and control system, able to operate with only linear and angular position measurements, is fundamental to the development of relatively cheap remotely controlled vehicles for civil applications.

(a) (b)

Figure 2.6: Single-mode USVs on the water surface operation: (a) X-Class USV, and (b) Charlie USV (Thomsen *et al.*, 2007; Caccia *et al.*, 2008)

2.3 Dual-mode Vehicle

More generally, there are a number of small-scale unmanned vehicles and robots capable of dual-mode of locomotion in different environments. There are three distinct area of unmanned dual-mode vehicle: Unmanned Air-Ground Vehicle, Unmanned Land-Water Vehicle (Amphibious) and Unmanned Water-Air Vehicle.

2.3.1 Air-Ground Vehicle

The vision of the U.S. Advanced Systems Directorate or Aviation and Missile Command (AMCOM) are merging technologies to develop one vehicle that incorporates both air and ground capabilities that will be the dominant reconnoitering unit on the future battlefield. Since the specification does not require that the vehicle actually moved on the ground, wheels, legs, tracks, and other methods of ground mobility can be dropped from consideration. A simple solution is to utilize a system that is similar to most retractable landing gear systems used today. A landing strut will be housed within the skin of the vehicle and a push-pull pneumatic cylinder used to extend and retract the strut.

Some example, the "*Pawnee*," illustrates in Figure 2.7 (a) was chosen as a baseline concept design for air-ground vehicle based on a typical rotorcraft configuration. Janetka *et al.* (2001) states, the vehicle had some limitation, i.e.

difficulty meeting the requirements of near-quiet acoustic signature and could not meet the requirements for autonomous operation.

(a) (b)

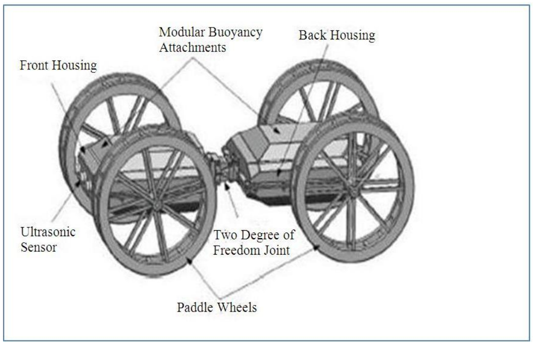
Figure 2.7: An unmanned-based air ground vehicle: (a) The Pawnee, and (b) The Oiseau (Janetka *et al.*, 2001)

Different with the "*Oiseau*," Figure 2.7 (b) a French word meaning bird, is a UAGV capable of meeting the future needs of US military forces. Utilizing an efficient design and mating together both technology and simplicity, the *Oiseau* meets the need of providing direct intelligence support during dirty, dangerous, and dull missions.

The other example of dual-mode operation included the Morphing Micro Air-Land Vehicle (MMALV) (Boria *et al.*, 2005), which utilizes flexible-wing flight and wheel-legs, and the *Entomopter* which uses flapping-wing flight and legs (Michelson, 1998). They are primarily UAVs and UGVs, with the ability to traveling once they land and water. Whereas the vehicle discussed in this thesis is intended primarily as an aerial vehicle with a flight, landing, and traversing on the water surface mode for intermittent use.

2.3.2 Land-Water Vehicle (Amphibious)

The design of an amphibious vehicle has been significant interest in the development of the vehicle that capable of amphibious operation. Such potential operations of an amphibious vehicle for a variety of reasons traversing to such places includes: terrain mapping, collecting and analyzing water samples in possible contaminated environments, search and rescue, delivering items or tools from one location to another, security surveillance, and filming animals in their natural environments.



(a)

(b)

Figure 2.8: Unmanned autonomous amphibious vehicle: (a) Autonomous amphibious vehicle, and (b) ARGO (Michael & Nokleby, 2008; Tran *et al.*, 2004)

The Computer-Aided Design (CAD) model of the Autonomous Amphibious Vehicle (AAV) is shown in Figure 2.8 (a). As shown, the AAV consists of two segment body connected by a unique two degree-of-freedom joint. This two degree-of-freedom joint allows the two segments to pitch as well as roll with respect to one another while traveling. Four paddle wheels propel the AAV across land and over water. Buoyancy attachments increase the buoyancy of the vehicle and are modular, which means they can be used as needed. Ultrasonic sensors are located in front, and they ensure the AAV can detect any obstacles along the way (Michael & Nokleby, 2008).

The other technology serving as an outdoor demonstrator for the research programmed is the *ARGO*, an autonomous amphibious vehicle as shown in Figure 2.8 (b). All parts of the vehicle's driveline from the engine, Continuously Variable Transmission (CVT), gearbox to wheels are analyzed and modeled. Tran *et al.* (2004) presents, the modeling of the AAV was developed at the Australian Center for Field Robotics, Sydney.

2.3.3 Air-Water Vehicle (Flying Boat)

In the air-water mode, National Aeronautics and Space Administration (NASA) had conducted experiments with a seaplane by Pisanich & Morris (2002), intended for use as the small, unmanned, amphibious cargo carrier. The aircraft named as Autonomous Cargo Amphibious Transport (ACAT) is intended to be a large cargo carrying unmanned aircraft that operates from water to avoid airspace and airfield conflict issues between manned and unmanned aircraft.

A completely autonomous flight that featured a water takeoff and landing was completed on October 4, 2001. The vehicle operated successfully but only in very calm conditions. Figure 2.9 shows the ACAT model.

Figure 2.9: Autonomous Cargo Amphibious Transport (ACAT) (Pisanich & Morris, 2002)

Several existing vehicle design have been a significant amount research and development done on small-scale unmanned vehicles. A couple of existing designs and technology are presented in this section. The research and development for all of these small-scale unmanned multiple-mode vehicles is ongoing, so concrete design and testing results are inherently limited. The design discussed here uses the development of combination single-mode and dual-mode vehicle to achieve capability end, eliminating this restriction.

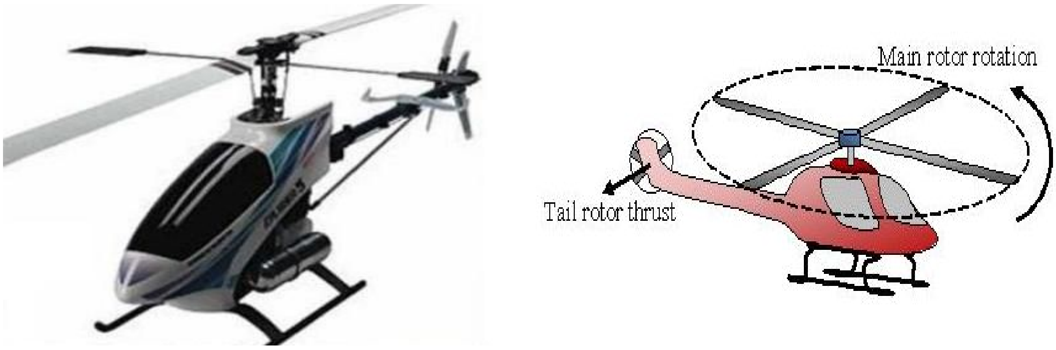
Prototypes design decisions made to reduce the weight of the vehicle enable in air, land and water, it is means the design here largely focused on air-mode. This research use of a commercially-available radio-controlled (RC) helicopter as a basis for the design. Furthermore, principles of the helicopter is described in the next section.

2.4 UAV Helicopter Principles

Although there is currently several principles of UAV helicopter, the work discussed here focuses on miniature UAV coaxial helicopter rotors to lift a vehicle from the ground. In order to emphasize the simplicity of the coaxial rotor concept and to familiarize the reader with helicopter typically in general, an introduction to a conventional single rotor helicopter will be presented first.

2.4.1 UAV Single-rotor Helicopter

This configuration have been commonly used for UAVs and MAVs. It is specially designed for the RC-hobby and Lab scale, an example currently available in the market named *Raptor 90 V2* of Thunder Tiger as viewed in Figure 2.10 (a). The lifting thrust of the single rotor helicopter is produced by the main rotor. When the main rotor is rotating it has to overcome the air resistance (drag) of the rotor blades.



(a) (b)

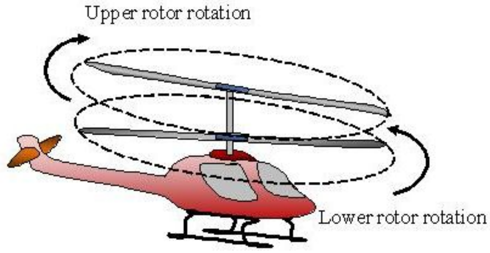
Figure 2.10: Single-rotor helicopter: (a) Conventional helicopter Raptor 90 v2, and (b) Single-rotor helicopter principle

The torque that is applied to the rotor shaft in order to overcome the drag and directly transmitted to the helicopter body to which the rotor is attached. The other characteristic features of the single rotor helicopter is the tail rotor. The tail rotor's thrust as shown in Figure 2.10 (b) generates an anti-torque effect which counter out the torque deriving from the main rotor as result of the blade drag.

2.4.2 UAV Double-rotor Helicopter

Three double-rotor configurations were considered in UAV: coaxials, tandems and ducted fan configurations. Coaxial principles has been widely used for UAV design. Figure 2.11 (a) is the vehicle with a counter-rotating coaxial main rotor with no tail rotor. The tail boom on this figure is neither functional nor required. The main rotor located upper and lower with equal dimension and concentric shafts.

(a)



(b)

Figure 2.11: Double-rotor helicopter: (a) μFR by Chiba University and Epson, and (b) Coaxial helicopter principles

The coaxial configuration is favored by most of the key design advantages: compactness of folding, no tail rotor needed so that making simplicity of structure and ease of packaging. There are also some disadvantages of coaxial rotors such as increase in mechanical complexity due to difficulty in assembling linkage and swash plates system around the rotor shaft. The research on double-rotor features as shown in Figure 2.11 (a) and Figure 2.11 (b). For example, design mechanism which are developed for μFR by Bermes *et al.* (2011), *CoaX* in Bouabdallah *et al.* (2006), and *LinkMAV* in Duranti *et al.* (2007) was originally conceived as an add-on to the *RMAX* where it could be flown to a location and deployed by the *RMAX* to fly around and inside building structures.

The tandem configuration which have fore and aft rotors shown in Figure 2.12 (a). Their hover efficiency is higher than that of the coaxial configuration due to the smaller adverse wake interference between the rotors. However, the construction of the control system is much more complicated, compared to a helicopter with a tailrotor.

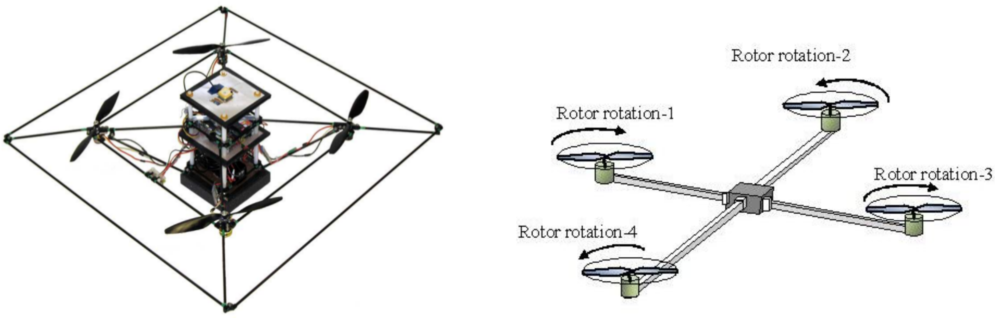
Furthermore Avanzini *et al.* (2005) had constructed another configuration of double rotor helicopter. This model is design and development of ducted fan UAV. The vehicle is characterized by a couple of counter-rotating coaxial blades to deliver the thrust and use the tilt of the fuselage to produce forward flight thrust. As shown in Figure 2.12 (b), the three blades set were surrounded by a shroud, eliminating the hazardous collision of blades and lowering the tip loss.

(a) (b)

Figure 2.12: Tandem and ducted twin-rotor helicopter: (a) Tandem, and (b) Ducted twin-rotor UAV (Tech-Model-Product, 2010; Avanzini *et al.*, 2005)

2.4.3 UAV Four-rotor Helicopter

The UAV with have four rotor named as quadrotor helicopter. The four rotor helicopter is built as a square, where rotors are mounted on each corner.



(a) (b)

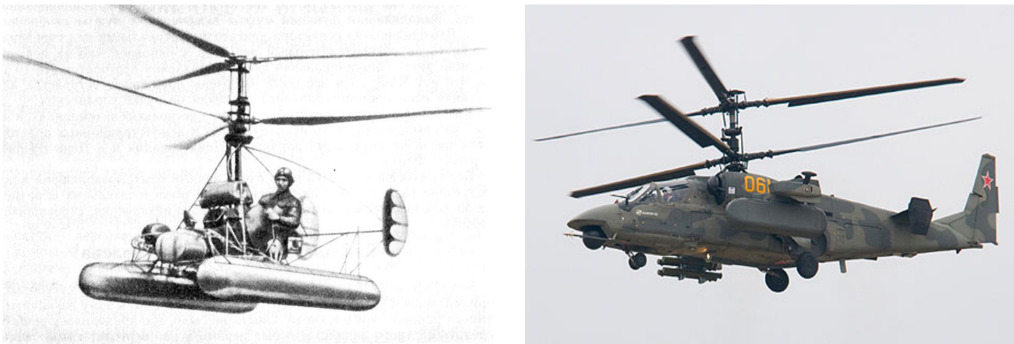
Figure 2.13: Quadrotor helicopter: (a) Quadrotor helicopter example, and (b) Quadrotor helicopter principles

Many research groups are working on four rotor helicopters as UAV testbeds. Some similar development to four rotor helicopter, a quadrotor presented by Azzam & Wang (2010) and Hoffmann *et al.* (2007), mainly in aerial robot dynamic modeling and configuration stabilization. The quadrotor example and its principle are shown in Figure 2.13 (a) and 2.13 (b).

2.5 Coaxial Rotor Helicopter

In this section the main principles of the helicopters with coaxial rotor configuration are illustrated. It is important to understand the mechanisms for the modeling and control of the helicopter as a basic concept on the USALWaV design for flight-mode.

A coaxial helicopter has a double main rotor helicopter configuration that uses two counter-rotating rotors of equal dimension, loading and with concentric shafts. This configuration is a feature of the helicopters and successful produced by Russian Kamov helicopter design bireau. The later main developer of coaxial helicopters *Nikolai I.* Kamov built autogyros in the 1930s and 1940s, named the Ka-6 and Ka-8. At present, Russian Kamov Company was built the Ka-52 with better flight and reliability. Figure 2.14 shows the Ka-8 and Ka-52 of coaxial rotor helicopter development.



(a) (b)

Figure 2.14: An early and the new one of the coaxial helicopter by Russian Kamov: (a) Ka-10, and (b) Ka-52 (Naval-Technology., 2010)

As remotely controlled (RC), an investigation step from the full scale helicopters to UAVs and MAVs is the development of the "Kamov Ka-37" and other UAVs. *Gyrodyne* went on to develop the *XRON* and *YRON* series, followed by the QH-50 series, which weapon-carrying drone used for antisubmarine warfare. The first successful RC helicopters were built in the 1970s. At present, there is a broad assortment of RC coaxial rotor helicopters in the toy market as well as in academic and industrial applications.

In the robotics field there are several models of coaxial rotor helicopter structures being explored and used by many companies and universities for research and developmental work. The interest in unmanned aerial helicopter especially for coaxial rotor configurations is rapidly growing thanks to the latest technological achievements which open the new various conceptual design and improvements.

The work examples includes coaxial helicopter *Lama X.R.B* from Hirobo Model Enterprise Company is used by Chen & McKerrow (2007), and Bouabdallah *et al.* (2006) in dynamic modeling and design control of indoor coaxial rotor helicopter. Furthermore, Dzul *et al.* (2002) make a simplified model and a nonlinear control algorithm for a coaxial helicopter, and Schafroth *et al.* (2010) analyze the nonlinear model based on the rigid body motion where all external forces and moments as well as the dynamics of the different hardware elements are derived.

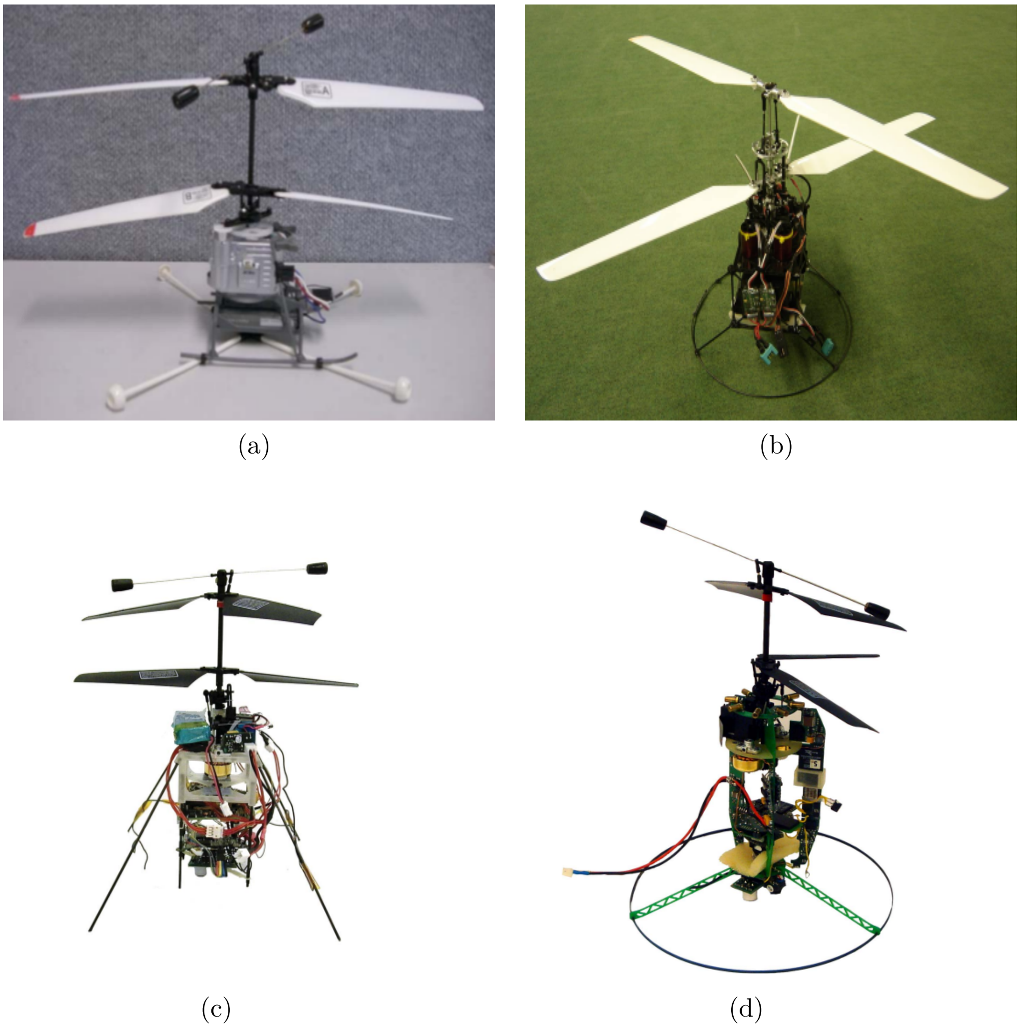


Figure 2.15: Small-scale coaxial helicopter model: (a) Lama X.R.B, (b) LinkMAV, (c) muFly V1.1, and (d) muFly V2 (Chen & McKerrow, 2007; Duranti *et al.*, 2007; Schafroth, 2010)

Another interesting development is *CoaX2* developed at ETHZ (Swiss Federal Institute of Technology Zurich), prototype design of the *LinkMAV* is the first MAV developed by UAVTech (Duranti *et al.*, 2007), and development of the *muFly* project by Schafroth (2010). In these project, design and preliminary control, problems related to aerodynamics and propulsion, stabilization and control system are presented. Figure 2.15 shows the prototype of micro-scale coaxial helicopter.

There are also some idea for coaxial rotor helicopter in effort to reduce the complexity of the rotor head (Eugene F, 2002; Arthur E *et al.*, 2002; Zimet &

Divon, 2007). In Rock's patent, the concept of a coaxial helicopter is simplified by using only one cyclic pitch control. Its mean pitch and roll control being provided by cyclic blade pitch control. In the patent, different possibilities for collective pitch are given. Collective pitch is possible on both, on one or on none of the two rotors. The two counter-rotating rotors are mounted on two shafts which are powered by one actuator. Figure 2.16 shows a sketch of this invention.

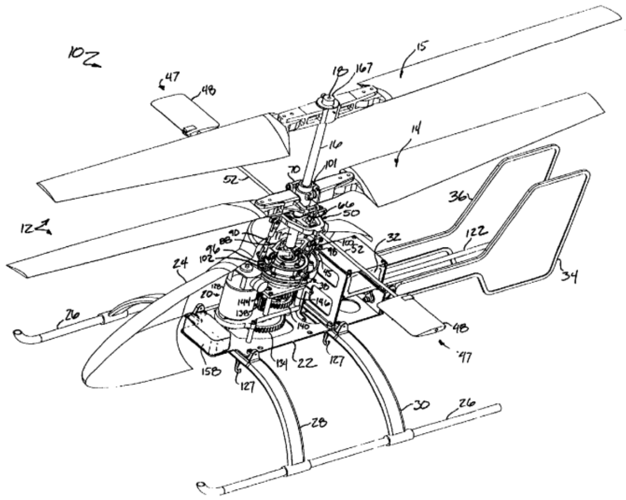


Figure 2.16: Coaxial rotor concept of Rock's patent (Eugene F, 2002)

In 2002 Arthur E *et al.*, from United State, also patented an ultralight coaxial rotor aircraft having a substantially L shaped frame. The helicopter is use the cranks actuators to provide tilts its rotor axis in order to control pitch and roll the craft. The rotor heads are simple compared to the rotor heads used for the Kamov concept. Since there is no collective pitch and swash plate. A motor actuates the two rotors over a belt drive. Since it is only intended to fly near ground, the altitude control has not to be very fast. The control of the altitude is done by varying the rotor angular velocity. In order to control yaw, a tiltable airfoil is placed in the rotor downwash. Since more power is necessary to control pitch and roll with a tilt rotor instead of a swash plate, this concept is only applicable in relatively small helicopters. Figure 2.17 shows a sketch of this coaxial concept (Arthur E *et al.*, 2002).

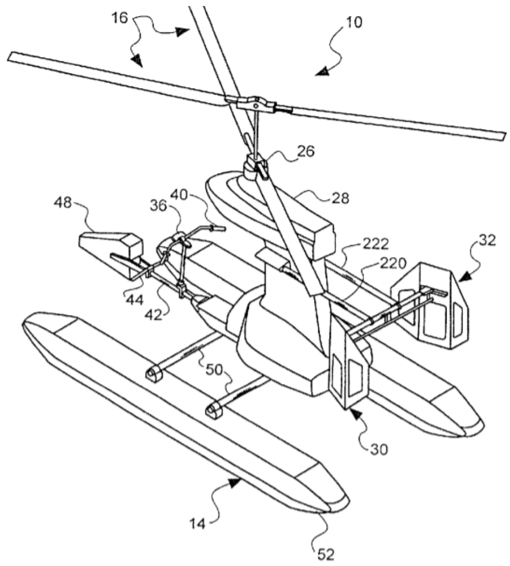


Figure 2.17: Ultralight coaxial helicopter (Arthur E *et al.*, 2002)

Another approach for a coaxial rotor helicopter concept is described in the European WO Patent of Nachman Zimet and Avner Divon in 2007. The invention of these two inventors is the development of pitch and roll stable and low cost object for the toy market.

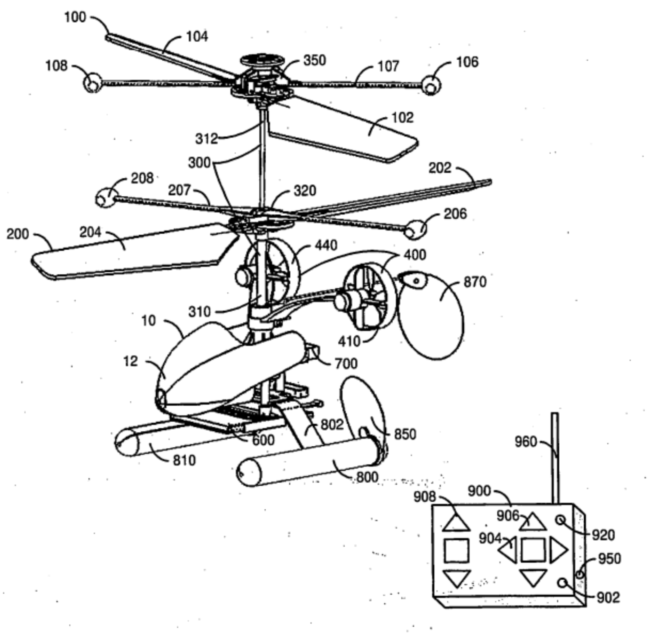


Figure 2.18: Rotary-wing vehicle system (Zimet & Divon, 2007)

Their rotary-wing vehicle system consists of two counter-rotating rotors (Figure 2.18). The rotors are not controlled by a swash plate. They are connected with stabilizer bars, which secure aeronautical stability. Since the main rotors are not controllable, additional two propeller are added in order to move the vehicle and use tail fin to provide improved directional stability.

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