UNSW SYDNEY Engineering

Thesis A (Group 22)

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Abstract

Water is the essence for all life and particularly for developing countries this has been a long unresolved problem. As such, three developing countries were reviewed and it was uniquely identified that the Yamuna River in India has one of the most toxic rivers in the world. To resolve this, water quality chemical analyses are required to understand the parameters that make waters unsafe. Several vehicle solutions were considered and a Unmanned Aerial Vehicle was decided to best fit the constraints of the problem. A quad-rotor configuration was chosen due to having high stability as well as providing modest payload capacity as the increase of more motors significantly increases the amount of power required to fly, in turn effecting the drones flight time. From this configuration, the Tarot 650 frame was suggested as it is sufficient for meeting performance requirements as well as the implementation of fold-able arms for portability. A flotation device on the legs of the drone was suggested to mitigate the likelihood of critical failure, allowing the drone able to rest on water as well as the suggestion of a custom waterproof casing to house board circuitry, battery and water sampling mechanisms. The sampling mechanism itself has not been chosen however, recommendations have been made for 3 rivers detailed in the report. These sampling mechanisms will have additional modifications to allows for in-situ measurements. A common issue with current UAVs is their maximal 30-minute time of flight, the incorporation of a hybrid system along with algorithms are utilised to maximise the amount of power available as well as predict amount of available flight time. The open-sourced Pixhawk controller was chosen as the desired controller for its cost-effectiveness and flexibility however, a control algorithm has not been chosen as of yet however will be further explored in Thesis B. Due to no singular system being the most optimal for multiple environmental conditions, different autonomy levels were analysed and compared where consideration of customer need and government regulations were accounted. Sensors, on board computers, frameworks and algorithms will also be further explored. In terms of communication with the UAV, there are a lack of cost-effective solutions thus a study of different off the shelf RF modules were studied that complied with Indian airspace regulations.

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Chapter 1

Introduction

1.1 Background

Author: Alexandar Nguyen

This section will address current water pollution issues in third-world countries. The contents of this section include current issues communities are facing due to polluted waters as well as common areas of pollution. Furthermore, it explores the common types of pollution within the water and their effects on the human body and the environment with 3 example countries.

1.1.1 Sources of Water & Water Quality

1.1.1.1 Third World Water Crisis

Water is the essence of all life and is pivotal for sustainable development and is critical for socio-economic development, food production, a healthy environment and economic growth [63]. Regardless of this, many communities in 3rd world countries do not have access to clean water resulting in horrible living conditions and mortality.

- 2.3 billion people do not have access to basic sanitation facilities [64].
- 1.8 billion people world-wide drink water from untreated rivers [64].
- 4.5 billion people lack safely managed sanitation services [64].
- 340,000 children under five die every year from diarrhoeal diseases [64].
- Water scarcity already affects four out of every 10 people [65]
- 90% of all natural disasters are water-related [66].
- 80% of wastewater flows back into the ecosystem without being treated or reused [67].

Water pollution can occur in notably two different ways, ground water pollution and surface water pollution.

1.1.1.1.1 Ground Water

Ground water refers to water that is underneath the earth's surface, such as waster in soil and water between rock formations [68]. For rural communities, pumping from these unconfined aquifers (essentially groundwater) is their main source for obtaining drinkable water. Groundwater is susceptible to pollution when contaminated with agents such as pesticides and fertilizers [63], storage tanks, septic system, landfills, chemical and rock salts etc. [69] causing the aquifers to be unsafe for human consumption leading to possible diseases such as hepatitis and dysentery.

Contamination Sources

Storage Tanks:

- Can be situated above or below the ground, containing gasoline, oil and or chemicals and due to weather conditions these can start to corrode or crack causing leaks and serious contamination [69]

Septic Systems:

- These are designed to slowly drain human waste underground at slow rate which can be found in homes, offices, buildings etc. any malfunction or corrosion can cause leakage of bacteria, viruses, household chemicals etc. [69]

Landfills:

- These are areas where our garbage is buried and are designed such that there exists a protective layer underneath that prevents contaminants from entering the water. If any malfunction occurs, contaminants such as car battery acid, paint, household cleaners will affect the waters. [69]

Chemical and Road Salts:

- Chemicals include products used on lawns and farm fields to kill weeds and insects and to fertilize plants, and other products used in homes and businesses.
- When it rains, these chemicals can seep into the ground and eventually into the water.
- Road salts are used during the wintertime on melted ice on roads to keep cars from sliding around. When the ice melts, the salt gets washed off the roads and eventually ends up in the water causing contamination [69]

1.1.1.1.2 Surface Water

As the name suggests this pollution occurs on the surface of the water due to, most notably, human waste and fertilizer in developing countries however, similar to ground water, storage tanks of oil, Landfills, Septic tanks and Chemicals are still large factors in surface water toxification.

1.1.1.2 Type of Pollution and the Effect on Population

As mentioned previously, certain types of pollution can have certain effects on the human body, this will be further explored:

1.1.1.2.1 Diseases

Micro-organisms, bio-toxins, toxic contaminants [70] can be passed through bodies of

water and consumed by individuals causing the development of diseases. Common diseases from water pollution are:
Cholera [70]

- An acute diarrhoeal disease that can be fatal within a couple of hours if untreated [71]
- Estimated 1.3-4.0 million cases every year [10]
- 21,000 - 143,000 deaths worldwide [72]

Schistosomiasis [70]

- Acute and chronic diseases caused by parasitic worms (tremtode worms)
- Can be infected through lack of hygiene and swimming, or fishing in waters with these worms. Infected by the penetration through the skin
- Results in abdominal pain, diarrhoea, and blood in the stool [73]

Giardia [63]

- Bowel infection cause by parasite Giardia duodenalis.
- The parasite must be ingested, through the mouth, in order to cause infection. (i.e. drinking the water)
- Results in, stomach cramps, diarrhoea, weight loss, fatigue [74]

Typhoid [63]

- Caused by bacteria Salmonella Typhi that is ingested through drinking contaminated water
- Results in, prolonged fever, severe headache, abdominal pain and Diarrhoea

1.1.1.3 Heavy Metal Pollution

Heavy metals are metallic elements such as, arsenic, cadmium, chromium, lead, mercury etc. that are of higher density compared to water [75]. These are "systematic toxicants" that can cause organ damage at low levels of exposure [76] and can even have effects "from cancer to hormone disruption to altered brain function" [63].

1.1.1.3.1 Arsenic

Arsenic water pollution can naturally occur through the erosion of soil and rocks as well as water situated in areas of volcanic activity [77]. However, pollution can occur through manufactured products used for agriculture, such as pesticides, insecticides, wood-preservatives etc. [76].

High level of arsenic exposure can cause many health concerns such as the increased risk of cancer and overall damage of multiple organs and tissues [77]. More specifically, when drinking arsenic contaminated waters reports had found issues regarding "cardiovascular and peripheral vascular disease", brain disorders, development of anomalies, hearing loss, cancer etc. [77] [78] [79].

1.1.1.3.2 Cadmium

Cadmium can pollute drinking water through the corrosion of galvanized plumbing, industrial waste and even fertilizers [80]. Certain Cadmium exposure can cause changes in pulmonary function, cause emphysema and decrease olfactory function [76],

1.1.1.3.3 Chromium

The degree of hazard for these is dependent on its oxidation state. If ingested it can cause irritation and ulcers in the stomach and small intestine, anaemia, sperm damage and male reproductive system damage [76].

1.1.1.3.4 Lead

Lead is a natural occurring metal which lays within the Earth's crust. However, the burning of man-made fossil fuels, mining and manufacturing can also release high concentrations of lead [76].

The amount of lead absorbed by the human body is dependent on age and size of the human body, thus a small child drinking contaminated water with high lead content will cause more harm than to that of an adult. Certain side effects of high lead consumption may include loss of memory, irritability, headaches, etc. [81].

1.1.1.3.5 Mercury

Mercury is a naturally occurring element found in nature: air, water and soil [82] and each having its own level of toxicity [76].
Severity of Contamination Depends on:

- Type of mercury consumed
- The dose
- Age of the person
- Duration of exposure
- Inhalation/Ingestion/Dermal Contact

Neurological and behavioral disorders can occur through the ingestion of mercury and other symptoms include tremors, insomnia, memory loss, motor dysfunctions [82] etc.

These are the most common metals that can harm humans in third world countries however, there are many other types of heavy metals that can affect the drinker neurologically and behaviorally.

1.1.2 The Effect of Water Quality on Environment & Society

In a natural environment, there exists a self-thriving ecosystem that rely on the relationships between flora, fauna, fungi, bacteria etc. This ecosystem could be broken and disrupt the flow of all living creatures if when one of the elements of the system is removed, creating a cascading effect. This would be the case when a body of water becomes contaminated with heavy metals and/or chemicals resulting in the intoxication of marine life causing their expected life span to be reduced as well as absorbing high levels of mercury, which become poisonous for humans and other animals to consume.

In addition, the ability for marine life to reproduce is also reduced, further damaging the ecosystem [83].

Other cases may include the body of water beginning to be enriched with nutrients and minerals as a result of fertilizer run-off entering the aquatic system [84]. Due to rapid growth of algae, causing the penetration of sunlight through the surface of water to be impossible [84], the level of oxygen will diminish and prevent fish and aquatic life from existing in these areas [85].

Aside from chemical and metal toxicity, physical debris are also a hazard to marine life as it can cause strangulation and suffocation if ingested. Large bodies of debris can also deter marine life from continuing to inhabit the area, thus causing a link in the ecosystem to disappear thus damaging the society and environment.

1.1.3 Affected Regions

1.1.3.1 India - Yamuna River

Yamuna, crossing 7 states extending from Delhei to Etwah, provides water to 57 million inhabitants for their daily use. This river is heavily contaminated with wastes and pollutants from households, industries and agriculture run-off which affects 3/4 of the population of Delhi causing:

- Toxicity
- Water-Bone Disease

Figure 1.1: Yamuna River

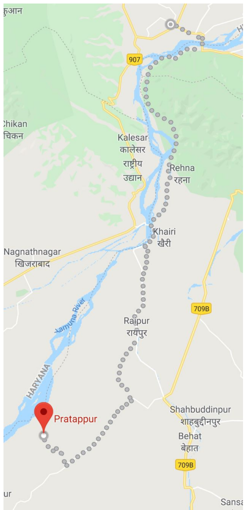


Figure 1.2: Poanata to Pratappur

"Scientists monitored the pollution at 12 points between **Poanta** in Himachal Pradesh to **Pratappur** in Uttar Pradesh and discovered that water from Delhi to Etawah is highly polluted. Water samples were collected in the middle of the river at these stations between 2014 and 2015. It was found that waters found in *Agura (Uttar Pradesh)* and *Etawah (Uttar Pradesh)* were unfit for drinking and bathing as they were heavily polluted with household and agriculture waste [86].

Culturally, Indians have religious ceremonies that take place in "holy water" which is a purifying process, however in this case it is highly toxic. Not only that, they also bathe and drink from this water which is highly toxic and dangerous.

1.1.3.1.1 Pollution

Toxic Foam on top of the river, this is caused by industrial waste, sewage from cities, chemical waste from manufacturing plants and pesticide run-off.

Figure 1.3: India Foam River

The coordinator of South Asian Networkon Dams, Rivers and people stated that "There are already 1.5 billion liters of untreated sewage entering the river each day and 500 litters of industrial waste." [87]

Metal Toxicity was examined in the fish species [88] and high concentrations of Calcium (Ca), Potassium (K), Magnesium (Mg), and Phosphorus (P) were found and were extremely high in comparison with other metals and were exceeding max permissible limits set by the World Health Organisation (WHO).

Similar to what was stated above, "industrial discharge, release of organic material into water, domestic waste etc." have caused a reduction of oxygen in the water and in conjunction the eutrophication of the water. This is when the body of water is excessively enriched with nutrients and minerals, it will spike the rapid growth of algae [1].

Further samples were taken from Delhi to Haryana on the affect of heavy metal water on soil and development of vegetables, the results found that to be unfit for propagation of wildlife and fisheries.

Heavy metals in water is stated to be one of the most prevalent and high impactful forms of pollution within the aquatic environment due to their high toxicity and accumulation by marine organisms [89].

- Speculated that multiple industrial outlets that dump their waste in the river are the cause of this high metal concentrations in the river.
- Due to this, when humans eat the fish from the river or the plants even, due to high metal contents, they become delirious.

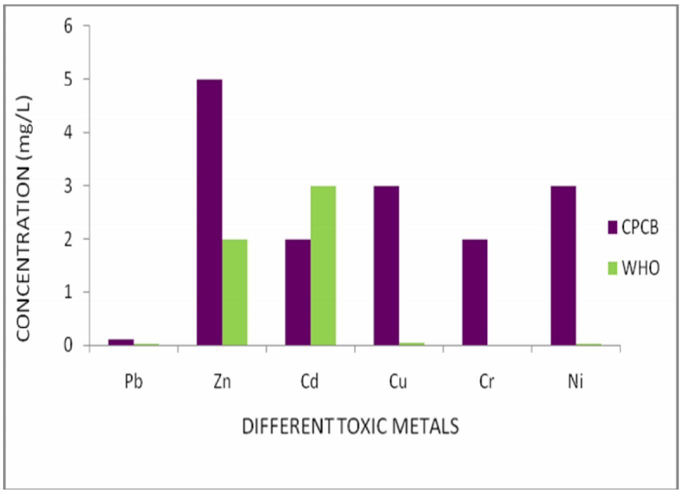


Figure 1.4: Comparison between the prescribed concentration of toxic metals from World Health Organisation and the reported CPCB (Central Pollution Control Board) [1]

Heavy Metal Effects on human Health

Table 1.1: Effect of Metals on Humans and Possible Sources

Metals	**Effects on Human Health**	**Possible Source**
Lead	• Cognitive Impairment in Children • Peripheral Neuropathy in Adults • Developmental Delay	• Paint • Batteries Pesticide
Copper	• Headaches • Nausea • Vomiting Diarrhea and Kidney Malfunction	• Mining • Pesticide Production • Electroplating
Zinc	• Vomiting • Diarrhea • Icterus (Yellowish Discoloration of Skin and mucous membranes) • Liver and Kidney Damage	• Sewage Discharge • Immersion of Painted Idols
Nickel	• Neurotoxic • Genotoxic	• Stainless Steel • Manufacturing Units
Cadmium	• Kidney and Liver Damage • Renal Dysfunction • Gastrointestinal Damage	• Electroplating • Batteries • Control Rods • Shields within Nuclear Reactors • Television Phosphors
Chromium	• Gastrointestinal • Hepatic • Renal • Neuronal Damage	• Mines • Electroplating

[90]

Health, Society and Environmental Impacts

- It is damaging the aquatic life as the water is heavily toxic due to industrial waste, metal toxicity etc.
- Damages the community and religion as drinkable water is toxic, and ceremonial rituals are performed in toxic, not 'purifying' water
- Vegetables in crops near the water are growing with high metal concentrations, which is affecting the quality of crop food. [1]
- Animals that feed of fish or plant seeds, such as observed flamingos. "There is an urgent requirement to restore the water quality for conservation of habitat of rare and endangered Flamingos at Okhla Barrage" [1]

1.1.3.2 Nepal - Bagmati River

Nepal is a country with an abundance of water however most rivers are facing contamination problems and communities are at a lack of sanitation facilities where 30% of population practice open defecation [31] making it one of the poorest nations with an estimated GDP capita of $470 USD [91].

- 42% of the population living below the poverty line and only 27% with improved access to sanitation [91]
- 87.4% of people have access to water, but out of the 41,205 rural water supply schemes are [92]:
  - Only 26% are fully functional [93]
  - 45% require repair [93]
  - 29% needs to be rehabilitated or require a new system [93]

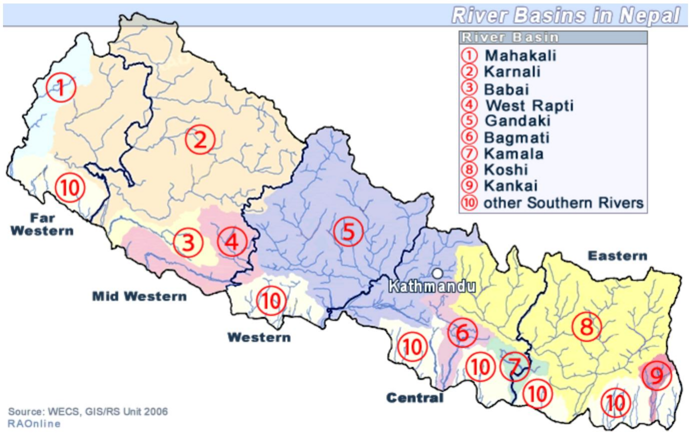


Figure 1.5: Bagmati River

A major reason contributing to the contamination of water is that the surface and ground water in the Kathmandu Valley is deteriorating by natural and anthropogenic contamination [91]. Industrial and domestic waste, and discharge from untreated sewerage are the main culprits to the contamination of this water. The capital city of Kathmandu is estimated to produce 150 tons of waste daily and almost half of this is dumped into rivers and 80% of the wastewater is generated by households [91].

The Bagmati River is located in Province 3, with a population of 5,529,452 [94], which is increasing every year however sanitary water solutions are not. Hypothetically if all river water was drinkable this would still not be enough to support the community [91] as the total demand of water is 320 litres per day in which they receive only 160 litres [92]. Since this water come once a week, or even every two weeks some result in obtaining waters from well which are contaminated resulting in deaths; 44,000 children die due to waterborne diseases [91].

Previously, Nepal had developed allowing for a 96% increase in access to basic sanitation however in 2015 an earthquake struck setting back an immense amount of development and caused "significant destruction of infrastructure, damaging water supply systems and toilets over 30 districts (over 500,000 houses)". Another natural disaster, the Teri Flood, occurred in 2017 and destroyed or damaged over 190,000 houses [93]. Further solutions included the infusing of chlorine in water to kill bacteria that caused water-borne diseases however, due to the pungent odour, locals preferred the waters in wells which were contaminated.

The quality and quantity of the Bagmati river water was at alarming levels, especially during the summer seasons where the river:

- Had low dissolved oxygen concentrations
- Bacterial Contamination
- Metal Toxicity [37]
  - Cd - Cadmium
  - Pb - Palladium
  - Cu - Copper
  - Zn - zinc

These are a bi-product of the rapid urban expansion, inadequate wastewater treatment facilities, low awareness, lack of regulation and little adherence to waste water laws.

1.1.3.3 Bangladesh - Buriganga River

The Buriganga river is located in the south-west skirts of the capital city of Bangladesh, Dhaka spanning a length of 17 km. The River is utilized for many social and economic purposes such as industries, warehouses, hospitals and even residential purposes [95] and previously was the city's primary water supply, drainage [96] and even for swimming, washing and bathing [95].

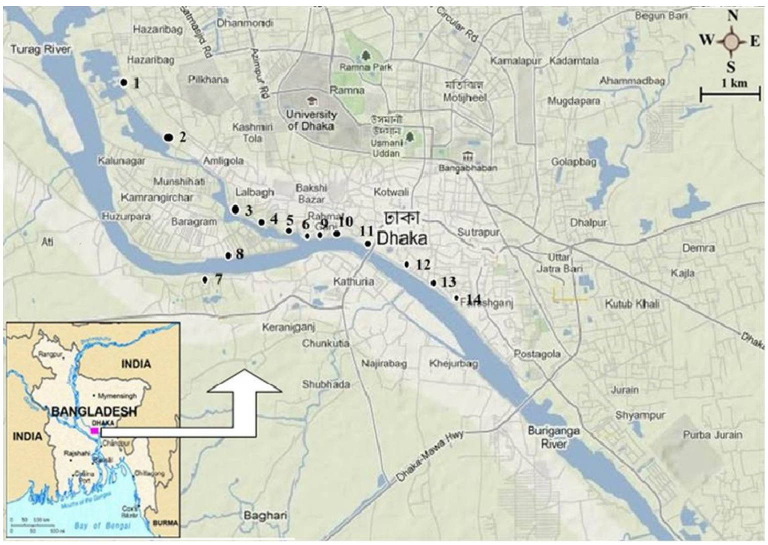


Figure 1.6: Buriganga River

Over the years, after the country's independence in 1971, the Buriganga river had become more and more heavily polluted [96] as the rise of industrialization caused for the increase of industrial discharge waste [97], household waste from residential areas, clinical waste from hospitals, oils as well as human excreta [95]. Overtime, the periphery of the river became a large bumping ground for all forms of waste.

1.1.3.3.1 Industrial Waste

The main industrial wastes that are contributing to the pollution of the Buriganga river are as follows:

- Pulp and paper
- Tanneries
- Metal Processing
- Fertelisers
- Pharmaceuticals
- Pesticides
- The Food Industry
- Textiles and painting

It is stated that 700 tanneries in the Capital City discharge 16,000m^3 of toxic waste in the river [97].

Table 1.2: Industrial Waste Emissions [46]

Industry	**Emission (tons/yr)**	**Pollution (%)**
Pulp and Paper	91,768.10	47.4
Pharmaceuticals	30,866.72	15.9
Metal	27,174.61	14
Food Industry	24,403.39	12.1
Fertilizers/Pesticides	12,715.00	6.6

1.1.3.3.2 Solid Waste and Sewage Disposal

Another major factor to Buriganga's pollution, as stated before, is hospital and domestic waste. Hospitals along the rivers of Dhaka, more than 500 of them, constantly discharge hazardous and toxic waste:

1.1.3.3.3 Effect of Pollution

One of the most dangerous aftermaths of pollution in the Buriganga river's water is the high arsenic content in the water and the ground in the periphery of the river. This can prove to be a serious environmental hazard as about 97% of Bangladesh people utilize ground water as their main source of drinking water, in which is contaminated with arsenic. Ingesting high amounts of arsenic does not cause any immediate health concerns however, it is cumulative hence causing melanosis, kurtosis and conjunctivitis [97]. Besides impacting health, pollution in the water has caused communities to migrate away from the river and away from possible family. It has impacted the agriculture around

Table 1.3: Hopsital Waste [47]

Name of Hospital/Clinic	Generated Waste (kg/bed/day)	Nonhazardous Waste		Hazardous Waste	
		Qty	**% of Total Waste**	**Qty**	**% of Total Waste**
DMCH	1.19	1.07	90	0.12	10
SSMCH	1.23	1.09	89	0.14	11
RIHD	1.2	0.91	76	0.29	24
HFRCH	1.59	1.29	81	0.3	19
DNMCH	0.8	0.7	88	0.1	12
SAHL	0.83	0.72	87	0.11	13

the river, as the soil in the land is continually increasing in arsenic, thus loosing fertility as well as the river water beside it, unable to be utilized for irrigation. Furthermore, the economy in the Dhaka area will be affected as all tourism based around the Buriganga river area will not flourish, as well as fishermen within the area loosing their jobs [98].

1.1.4 Background of Water Sampling

Author: Brandon Voon

In July 2010, water and sanitation has been officially considered to be a part of a human rights by the United Nation General Assembly [99]. Despite that, water crisis continues to be deemed as a growing global concern in many developing countries. Water scarcity is defined to be the lack of sufficient water (quantity) and or the lack of access to safe water (quality) [100]. For the purpose of this thesis, the concept of water scarcity will be applied into economic scarcity within the same context - which is, high cost and time incurred to find a reliable source of water and the lack of water within an area (physical scarcity) [100]. As such, the ability to monitor and analyse water samples are important aspects in terms of delivering safe, consumable water. Water scarcity is due to several reasons: geographical location, polluted water source and inaccessibility [101–104]. Water being the core of sustainable development causes a long-term chain effect in countries that are facing water scarcity: lack of clean water, diseases outbreak, food and energy shortage as well as economic slowdown [99, 105, 106].

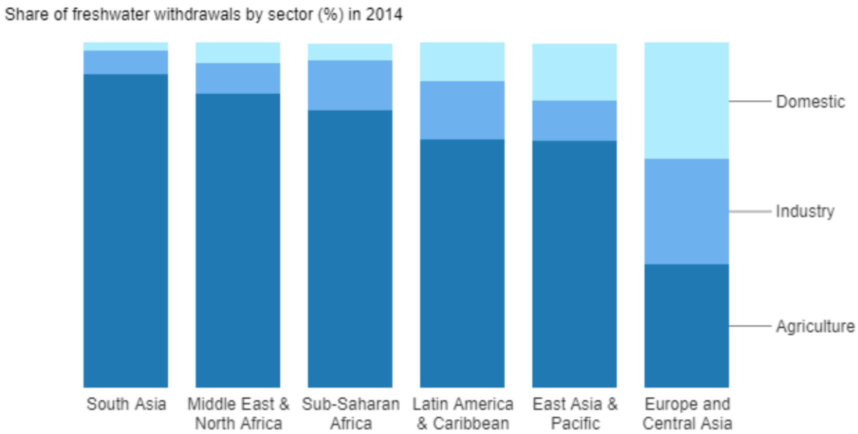


Figure 1.7: Water usage by categories [2]

Table 1.4: Causes and Effect of Water scarcity

Causes [101–104]	**Effect** [99, 105, 106]
Geographical location	Increased global conflict
Polluted water source	Lack of access to clean water
Inaccessibility	Disease outbreak
Climate change	Food shortage
Increase population	Energy shortage
Exploitation of water by selling them at high price	Economic slowdown
Agriculture	Sanitation issue
War and politics	Poverty
Poor government management and control	

1.2 Context

Author: Henry Gourley

1.2.1 Problem Statement

Design a remotely operable, amphibious device capable of autonomously retrieving water samples from various hard-to-access environments. Previous literature and field devices predominantly focus on unmanned vehicles sampling water in developed areas by trained operators. Such precedent will be analysed and adapted to ensure the appropriate amphibious vehicle is selected.

1.2.2 Vehicle Solutions to Water Sampling

The amphibious vehicle's primary objective is to provide an alternative water quality monitoring method to time consuming and expensive conventional techniques. Whilst the design detailed throughout this report is modelled according to the environmental conditions of Yamuna river in Nepal, a broader scope of terrain parameters is considered for multi-environment usage [?]. As with any design concept, optimization is dependent upon application. The chosen device will best satisfy the given functional requirements and ecological features detailed in Figure 1.8.

Functional Requirements	**Ecological features**
Suitable for use in developing countries (cost, easy to use,	wind
Compact and portable	Water toxicity
Robust	Water salinity
Reliable	Accessibility
Maintainable, repairable and sustainable	Rainfall
Cost	Water/Air Currents
Able to navigate on water away from line-of-sight	Topography
Amphibious	Water depth
	Optimal Sampling Depth

Figure 1.8: Functional Requirements and Ecological Features Amphibious vehicle will aim to optimize

The amphibious vehicle is selected prior to sub-component analysis, that is, the method of marine and terrestrial propulsion that will then determine required design parameters. The applicability of three amphibious technologies will be considered: Airborne, surface, and underwater vehicles. The author acknowledges most existing underwater vehicles are specialized for maritime use. The feasibility of modifications allowing terrestrial coverage is hence considered.

1.2.2.1 Conventional Methods

Water sampling for all three nodes of monitoring is commonly conducted through spot bottling, followed by extraction and analysis [107]. Regulatory authorities enforce this methodology under legislation. Surface and deep water layers are normally accessed via a manned flotation device such as a kayak or boat while shallow waters require wading for access. Such sampling methodology is undertaken by regulatory authorities in developing countries when access and equipment permits however improper sampling procedures are commonplace. Traditional methods have proven laborious, time consuming and costly with proposed improvements including: a higher sampling frequency, easier accessibility, autonomous procedures and drastically reduced cost. Such measures are particularly relevant in remote, hard-to-access communities and developing regions with high chemical and pollutant exposure to reduce human interference with hazardous substances.

1.2.2.2 AUV

Rapid developments and applications of AUV's for aquaculture and military use have instigated an affordable and reliable platform for performing a variety of underwater tasks. UAV's can traverse considerable water column coverage proving especially useful in scanning ocean bed terrain, monitoring and repairing submerged structures and collecting water samples at varying depths [108]. Whilst scanning and structure repair fall outside of this project's scope, depth water sampling variations are useful in providing comprehensive data and are particularly relevant to the objectives under consideration. It should be noted however that tenable water column extraction methods exist for other vehicular designs. By nature, AUV's are not susceptible to weather profiles of wind, rainfall, wind swell and humidity that increase failure possibilities, especially so in Yamuna river. However, exposure to underwater currents may offset these advantages over surface exposed vehicles.

A drawback for AUV's applicability lies in its inability to rely on GPS for positioning when underwater, with either advanced dead reckoning navigation or acoustic localisation required for positional accuracy. Such additional features substantially increase costings and limit on-site reparability. Additionally, the contaminated waters and AUV would traverse are characteristically littered with macro and micro pollutants that would restrict its linear trajectory and increase the risk of damage.

Beijing University recently developed a four thruster AUV, displayed in Figure 1.9, designed specifically to collect water samples. Whilst providing a significant framework for this project's design, it is noted that fieldwork testing has yet to be undertaken, providing no experimental verification of the structure's feasibility in contaminated waters [7]. Outfitting an AUV with terrestrial capabilities is a relatively unknown field because they are generally deployed and collected from other marine vessels.

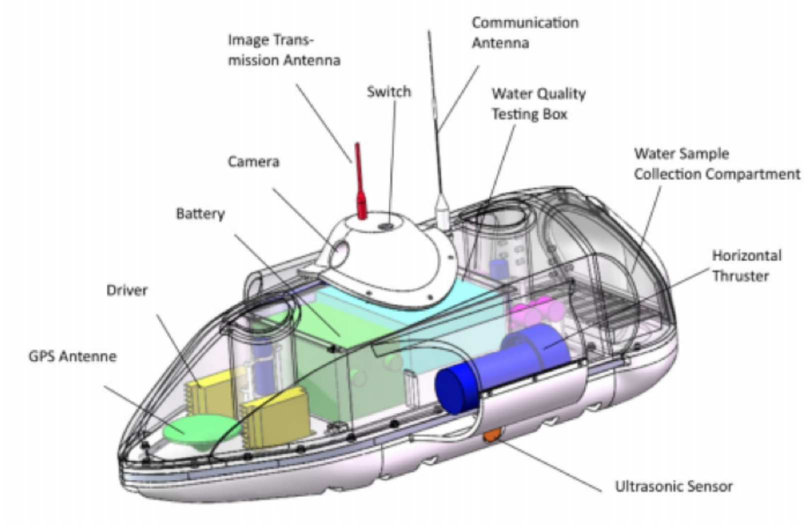


Figure 1.9: Four thruster water collecting AUV

1.2.2.3 ASV

ASV's capabilities of long-range missions and safe navigation in various real world scenarios characterise low cost assets for numerous research projects. The kayak SCOUT collects hydrographic data [109], the autonomous measuring dolphin catamaran [110] are used as a communication relay for a companion AUV (Delfin catamaran [111]), for collecting surface microlayers (Charlie catamaran) and for tracing and monitoring pollutants (Springer catamaran [112]). Whilst these represent aquatic vehicles; vast precedent exists for retrofitting terrestrial propulsion equipment onto ASV's, requiring extensive but manageable modifications. Whilst the Catamaran Series and SCOUT are designed for purposes outside of this project's scope, proven sub-component applications including autonomous navigation, seafaring design, positional awareness and water collecting mechanisms provide valuable insight into ASV's feasibility for water sampling.

Commercial solutions are also available, with Liquid Robotics 'Waveglider' offering long range, non-autonomous monitoring at low speed. Another commercially available ASV vehicle of relevance to this project is HydroNet's small-sized, autonomous catamaran displayed in Figure 1.10, designed and tested for real time monitoring of water quality in coastal environments [9]. Despite the agendas of private business ventures, this project is considered an accurate and valuable source of information for the successful implementation of water collecting surface vehicles.

With commercial solutions for small vehicle deep water sampling attachments lacking, Hydronet designed a winch system representing a water collection mechanism modifiable for any amphibious mode. Additionally, low draft and protective propellers allow the vehicle to move within shallow waters and regions of high obstacle presence including plastic bags. Land-based deployment of an amphibious device would encounter shallow waters at marine edges upon deployment as well as numerous plastics therefore increasing the vehicles versatility.

A trade-off between various factors were considered: length weight limitations, On-board payload capabilities, robust at-sea sampling and achievable navigational capabilities in terms of velocity and robustness to surface disturbances (suited to larger dimensions enabling superior wave/wind resistance and higher speed/endurance). The same trade-off is applicable to this project's scope, with modifications accommodating amphibious design and non-sea robustness required. Overall weight and dimensional limitations were employed for ease of transportability, use and deployment of only two persons. Similar limitations are required to meet the specified client demands of this project.

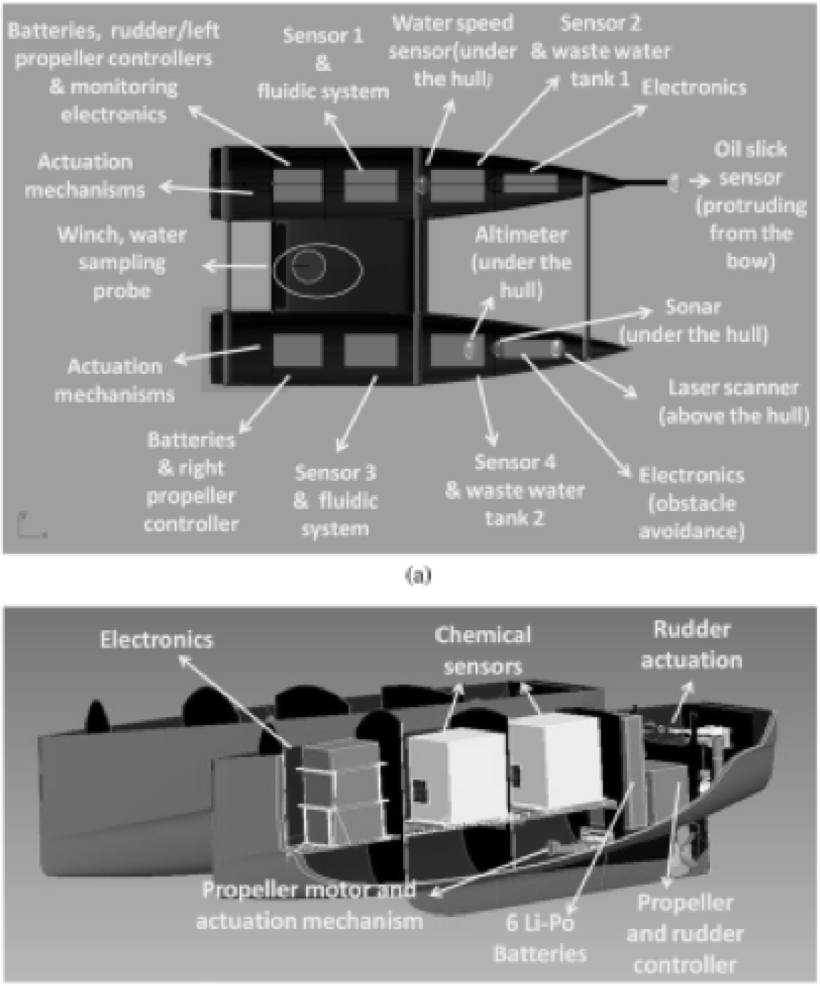


Figure 1.10: HydroNet's small-sized, autonomous catamaran

Modifying off-the shelf components opposed to customised, purpose-built devices can drastically reduce design parameters, cost and time. Customization does however allow optimization of design parameters including payload mass, arrangement of equipment, robustness and other functional requirements representing a trade-off that must be weighed accordingly.

1.2.2.4 UAV

Over the preceding decade Unmanned Aerial Vehicles (UAV), or drones, have proven an adaptable, versatile and flexible technology for high resolution assessment and monitoring of the natural environment [113]. Drones represent the meeting point between conventional field operations and airborne remote sensing of topographical features. Drones have been extensively used in evaluating species conservation biology [114], invasive species distribution [115] and flood plain monitoring [116] among a variety of other applications to improve access and safety to isolated and hazardous marine and terrestrial ecosystems.

Of the numerous impending drone opportunities, remote retrieval of physical, chemical and biological data from waterbodies presents the most promise [100]. Rapid technological advancements of drone platform capabilities (battery endurance, payload weight capacity, aerodynamics, navigation, flights time etc.) and attachable lightweight payload developments have increased the viability of their application within large scale sampling programs.

The research field of in-situ hydro-chemical data collection from drones is young, with the first related publishment occurring in 2013. Prior experimental tests have utilised modified off-the shelf drones (Six Rotor LAB645 and Ascending Technologies Firefly hexarotor) [117] and custom built platforms [118]. The preferred method of design depends upon a variety of factors including cost, scalability and application. Custom built chassis and water sampling payloads have improved the design's functionality. A University of Florida designed Drone, shown in Figure 1.11, achieved sampling payloads of 330ml, however this was deemed insufficient for reliable hydro-chemical analysis [119]. Therefore, to present a viable solution for this project larger samples and drone thrust capabilities are required. To accommodate additional payload capacity a larger and stronger chassis frame will be required. Also, experimental trials only yielded a 60-80 percent successful water capture rate with problems predominantly originating from environmental conditions and pumping [118]. Despite these issues, drones have exhibited a proof of concept to autonomously collect water samples from aquatic environments.

Figure 1.11: UOF water collecting drone

1.2.3 UAV Justification

The favoured amphibious mode should best optimise the given functional requirements and ecological features, with additional advantageous properties of the different modes also considered and weighed accordingly. ASV precedent for autonomous water sampling provides foundational groundwork for this project, while also enabling superior payload weight, running time and robustness to UAVs. AUV technology is a lesser researched and field tested field containing similar benefits to ASV, however retrofitting existing aquatic devices for amphibious usage and the additional navigational and vertical control equipment associated with AUVs would prove too difficult. Drone devices can navigate terrain without encountering the pollutants, currents and steep, muddy slopes that amphibious ASV and AUV devices would have to traverse. Yamuna River, amongst numerous others, fit this profile and as such UAV technology is deemed the most feasible to satisfy the given functional requirements.

1.2.3.1 Societal and Environmental Impacts

Unlike other amphibious vehicles, UAV's are not required to directly traverse aquatic terrain, therefore reducing potential for localised sea life disturbance. However, drone noise pollution is considerably more pronounced than ASV and AUV vehicles, and can interfere with terrestrial and airborne wildlife. Moreover, if not handled properly drone propellers can cause considerable damage to operators. Of equal concern is critical in-flight drone failure, that has the potential to pollute the surrounding environment should battery leakage occur.

1.2.3.2 Drone related legislation

Many countries impose legislation restricting UAV flights. Maintaining a constant line of sight between the operator and drone, designated no-fly zones, drone size limitations and compulsory licences present legal barriers to operation. Obtaining permits to overcome these obstacles is possible however they're often bureaucratic and time consuming. Dealing with authorities regarding matters of new implementation procedures is expected however, relieving or relaxing these policies for long term health benefits would satisfy all parties.

1.3 Thesis Outline

1.3.1 Outcomes

Table 1.5: Table of Outcomes

Index	**Outcome**
O1	Literature review of problem space and identifying typical water quality measures.
O2	Identification and description of Group portfolio ares of responsibility.
O3	Group report with individually authored portfolio chapters.
O4	Research, design and provide proof-of-concept of remotely-operable, portable device to retrieve water samples from the environment for chemical analysis.

1.3.2 Constraints

Table 1.6: Table of Constraints

Index	**Constraints**
C1	Suitable for use in developing countries
C2	Compact and portable
C3	Robust
C4	Reliable
C5	Maintainable, repairable and sustainable
C6	Amphibious
C7	Remotely-operable

1.3.3 Performance Objectives

Table 1.7: Table of Performance Metrics

Index	Performance Metrics
P1	Function successfully in real environment
P2	Societal impact
P3	Environmental impact
P4	Technologically transferable
P5	Meet in-country legislation requirements
P6	Ability to navigate on water away from line-of-sight
P7	Feasibility
P8	Ability to retrieve water samples from environment for chemical analysis from:
P8.1	- Lake
P8.2	- River
P8.3	- Creek
P8.4	- Catchments
P8.5	- Sheltered coastal salt-water areas

1.4 Summary of Literature Reviews

1.4.1 Anthony Leung

In the current state of available literature for power managing in UAV, it was found that the most common limitation was performance for long endurance missions. Study into two methods to improve on this were extracted from literature reviews, being Direct & Auxiliary power sources and Energy Management System methods. This report analysed the different power sources that have successfully extended application times for drones and ways to gather prognostics, applying power systems more efficiently and effectively.

Additionally, water detection devices have been included in this study. This is directly applying to Yamuna River, which is characterised by high foam, which is disrupting and misleading for the UAV to detect. A review of the technologies were briefed upon and how these can be implemented into the use of this project was considered.

Furthermore, research was conducted onto what flight controllers were best to use for UAV applications. It was found that flight controllers have been highly commercialised for some time, and a review of what was best to use for the application of water sampling UAV was considered. Tables were formulated for clear comparisons.

1.4.2 Aaron Su

The literature review of Autonomous System examines the state-of-the-art technologies in achieving autonomous UAV operations that are most relevant to water sampling problem. The most widely used GNC (Guidance, Navigation and Control) framework is adopted as the fundamental classification method. Within each category, technologies are further divided according to the level of autonomy they provide, namely, Sensing, State Estimation, Perception for Navigation System; Path Planning, Mission Planning for Guidance System.

For Guidance System, numerous methods in UAV path planning exist which can be categorized as Conventional, Cell-based, Model-based, Learning-based. Within these, algorithms such as D-star, Potential Field, Probabilistic Road Map and Rapidly Exploring Random Trees are most popular in 3D dynamic onboard path planning for small UAV. Hybrid algorithms that combine these algorithms into multiple planning layers are often necessary for real-world application. Few study focused on mission planning on small scale UAV, however, methods using finite-state machines, tree-based framework and fuzzy-logic control were employed in several MAV applications.

For Navigation System, most commonly used sensors in UAV are identified as conventional sensors, ranging sensor and cameras, where cameras are generally more versatile and cost effective than range sensors. State Estimation algorithms based on these sensors or their combination are reviewed. Literatures shows that conventional based system is vulnerable in low altitude operation and clustered environment. While ranging sensors-based system provide accuracy estimation in confided environment, they are less useful for outdoor application. In more complex mission, Perception for UAV is often needed, such as mapping, obstacle avoidance, target recognition and tracking. LiDAR-based approach provides more accurate measurement in indoor environment and require less computational power at a cost of energy and weight, while vision-based approach is more suited for light-weight outdoor operations and provides additional utilities such as object recognition, at a cost of computation burden.

1.4.3 Alexandar Nguyen

The literature review of Flight Control Algorithms details existing control algorithms and their applications. Control systems are categorised in 3 different categories, Learning-Based Flight Controllers, Linear Flight Control Systems and Model-Based Nonlinear Controllers each yielding their own advantages and disadvantages. A comparison between open-sourced and closed-sourced flight controllers ultimately concluded with the selection of open-sourced due to it being cost-effective and alterable. Most Open-Sourced controllers were found to have a base controller comprising of a PID system, known as the most simple yet effective to implement. The Ardupilot and Pixhawk were compared quantitatively and qualitatively by Cherub Dim et al to provide further evidence supporting which controller was better. More advanced systems incorporated 2 categories of controllers in unison, such as the incorporation of Artificial Intelligence and a PID system.

1.4.4 Alex Peterlin

The literature review of propulsion systems examined the most commonly used and applied drone configurations for commercial and research purposes. The drone types were only considered if they met the constraints outlined by the design brief. An essential condition was that the drone would need to have the ability to hover, preferably with a good level of stability and control, so as to facilitate the sampling of water. For this reason, only vertical rotary propeller configurations were considered, namely single-rotor and quad-rotor. The applications and benefits of each configuration was analysed with the intent of determining the most ideal design for this assignment. The hovering, stability, flight duration and potential risks involved with each drone were investigated and compared.

1.4.5 Brandon Voon

Water sampling comes in various form and complexity. Oftentimes, this involves personnel manually collecting samples from shorelines or from the side of the boat using bottles such as Niskin, Van Dorn or bailers. However, a more technological approach involves the use of pneumatic syringe or pump: suction lift or submersible pump.

Additionally, manual sampling poses several health and physical risks to the personnel. Therefore, in order to mitigate this issue, the use of unmanned vehicles that are capable of collecting water samples from water source that are inaccessible and dangerous has been heavily researched upon. This paper showcased a range of methods employed for the purpose of water sampling. No specific methods were chosen but comparisons of these methods were made constructively based off field reports, water sampling guidelines and product descriptions by companies.

One of the most important aspect of water sampling is the ability to conduct water analysis in the future in a laboratory environment rather than on-site. These water analysis, depends on the amount of water collected as different analysis requires different volume of samples. Such analysis falls under 3 main categories: physical, chemical and biological, which forms the general basis of clean consumable water. Sample volumes for different test are usually specified by the laboratory, governmental body and Non-Government Organisations such as United Nations (UN) and World Health Organisation (WHO).

1.4.6 Henry Gourley

The drone frame provides structural integrity for flight and connects all components together. The central hub houses the main boards, battery, avionic processors and sensors.

Booms or arms, radiate from the central hub to connect the motors and propellers that control flight trajectory. Most drone frames will also include leg components to mitigate the risk of critical failure during take-off and landing. Protective coverings can also be implemented to reduce contamination that may affect internal circuitry or structural design.

1.4.7 Dylan Dam

The literature review of the UAV telemetry section details the study of five different applications of UAV for remote data collection. Kopran and Ore both designed a UAV for water sampling and collection, whereas Srivastava designed a UAV for aerial photography in order to study crop growths via image processing. All three designs were cost effective and fulfilled their intended purpose, but failed to be operated beyond line of sight. Guenzi's UAV design was intended for geospatial study and therefore required the UAV to survey a large section of space. The UAV was capable of beyond line of sight operation, but the RF module used for the operation was expensive and not technologically transferable to a developing country. Zmarz's UAV was intended for Antarctic geospatial study, therefore the telemetry module used for this design was specifically designed to resist the frigid and harsh climate of Antarctica as well as being able to operate BVLOS. The RF module used was locally sourced and expensive and its capabilities far exceeded what was needed for our design. While cost effective solutions are able to perform tasks that are similar to our problem the UAVs used do not possess BVLOS capabilities. However, for UAVs that do have BVLOS capabilities, the expenses used to design the UAVs are not technologically transferable and cannot be maintained locally by the host country.

1.5 List of Responsibilities

The following is the list of responsibilities for this report and the respectively authored chapters.

- Alexandar Nguyen:
    - Background
    - Algorithm
    - Flight Control System Problem
    - Flight Control System Design
    - Flight Control System Design Progression
- Henry Gourley:
    - Context
    - Vehicle Solutions to Water Sampling
    - Structural Chassis Problem
    - Structural Chassis Design
    - Structural Chassis Design Progression
- Anthony Leung:

Thesis Outline
Outcomes
Constraints
Performance Objectives
Summary of Literature Reviews
List of Responsibilities
Controller
Water Detection
Energy Management System (EMS)
Power System Problem
Power System Design
Power System Design Progression

- Alex Peterlin:
  Mobility System
  Singlerotor (Helicopter)
  Aerodynamic Problem
  Aerodynamic Design
  Aerodynamic Design Progression
- Brandon Voon:
  Background of Water Sampling
  Water Sampling System
  Water Samplers
  Water Sampling System Problem
  Water Sampling System Design
  Water Sampling System Design Progression
- Dylan Dam:
  Communication System
  Current UAV Telemetry Solutions
  Literature Review
  Communication System Problem
  Communication System Design
  Communication System Design Progression
- Shanda (Aaron) Su:
  Navigation System
  Autonomous System Problem
  Autonomous System Design
  Autonomous System Design Progression

Chapter 2

Literature Review

2.1 Mechanical System

2.1.1 Mobility System

Author: Alex Peterlin

2.1.1.1 Propulsion System

Drones have become a popular device in the last decade as unmanned autonomous flying vehicles (UAVs). They're attractiveness stems from their friendly user interface and ease of operation. Depending on the activity, different rotor configurations are used to improve the drone's stability or payload capacity. Currently, there are three main categories of drone configurations; single-rotor (helicopter), quad-rotor and fixed wing drones. Due to the unstable and spontaneous nature of two or three rotor configurations, they are almost never used as they are difficult to control and operate. Furthermore, drones with more than four propellers are simply referred to as multi-rotor drones and are mainly employed to cater to higher payload capacities and longer flight time requirements.

In recent years, fixed wing drones have become a favourable option for mapping and surveillance purposes, due to their high speed and prolonged flight time. However, since these fixed wing drones are unable to hover, they are not suitable for missions where an object needs to be picked up or dropped off over a fixed short distance. To resolve this drawback whilst allowing controllers to benefit from the extended flight time of fixed wing drones, a modified version where two propellers are added to each wing has been designed to enable hovering for fixed wing drones, known as fixed-wing hybrid VTOL. However, this drones hovering abilities are still in development. To design a drone capable of sampling water from a water body, our drone will require a high level of stability whilst flying and hovering, a medium payload capacity and a moderate flight time. To determine the most appropriate rotor configuration to meet these constraints, the following two configurations will be considered; single-rotor and quad-rotor.

2.1.1.1.1 Quad-rotor

Drones have been extensively used in the last few years for transporting urgent medical supplies to locations with difficult access. These urgent medical supplies often include serum samples needed for blood transfusions for patients who have lost a lot of blood during surgery or from bodily injuries. Due to the fragile nature of these samples, they're transportation must be carried out with the utmost precaution as even small fluctuations in ambient temperature or leaks could compromise a sample. Timely delivery of vaccine and blood samples are often critical in healthcare for countries with poor infrastructure or in the aftermath of natural disasters. For this reason, drones have become a practical solution for transporting these medical vials to countries in disaster affected regions with limited transportation.

An example of a quad-rotor drone used in healthcare delivery is the Matternet's drone, which can carry approximately 1-2kg and travel up to 10km [120]. The Matternet's drone design is shown in fig. 2.1. To reach its location accurately, it uses GPS and other sensors to navigate terrain using automated ground stations as a guide. This allows it to deliver urgent medical supplies in remote locations that lack adequate road infrastructure. Travelling at an average speed of 40km/hr, the Matternet's flight time is just under 18 minutes, which includes taking off and landing procedures. This drone can be controlled using existing smartphone software and a travel path can be automatically made from a list of possible locations. The software uses available data on the population density, weather conditions and land terrain to automatically generate the most optimal route. As this drone is tasked with carrying critical medical supplies, it includes a built-in parachute which will deploy in case of an emergency such as power failure or propeller malfunction. Following its successful deliveries in the 2010 Haiti Earthquake, the company now works with UNICEF and Doctors without borders to further develop and refine its drone delivery system [121].

Figure 2.1: Matternet blood transportation drone [3]

Ensuring the delivery of clean and safe serum samples to disaster affected regions is of extreme importance. If mishandled, red blood cells can rupture and contaminate the sample, also known as hemolysis [122]. This can lead to a blood transfusion patient feeling fatigued and weak, as their body now has to work overtime to get oxygen to their cells. This can be extremely dangerous for patients who have already lost a lot of blood and need to rest and recover. To examine the risk of blood contamination when transporting samples, a study by Amukele et al. assessed the effect of fluctuations in ambient temperature recordings as a result of using a drone to transport blood samples [123]. Majority of laboratory specimens are tolerant to a wide range of storage temperatures, but blood products contain very fragile cells such as red blood cells (RBC) and platelets (PLT), which need to be stored and transported at specific temperatures to avoid being damaged [124]. Not only does the storage temperature of the samples need to be kept constant, but the storage duration must also be kept as short as possible. Even under ideal storage conditions, the quality of blood samples deteriorates over time which means to prevent a decline in quality of the samples, the storage duration must be kept to a minimum [124]. When being shipped or transported, serum samples are often stored in sealed vials, which are placed in sealable plastic bags containing absorbent materials such as cotton wool. This is done to soak up any leakage that may occur whilst in transit. The study by Amukele et al. found that there was no evidence of the vials being damaged, and no RBC hemolysis or significant changes in PLT count was observed. Moreover, the temperature of all units was maintained during loading and flight. The study concluded that as there were no observed contaminations of the serum samples, drone transportation systems are a viable option for the transportation of blood products.

Since some of these regions the drone is attempting to deliver to are prone to unfavourable weather conditions whilst carrying urgent medical samples, the stability and movement of the drone has always been a primary concern. To ensure our drone can carry out its task efficiently and reliably, its stability and control are essential to success. A study by Bristeau et al. into the versatility and effectiveness of the quad-rotor as a popular aerial platform has been conducted to determine an optimal design for this drone configuration [125]. The study found that this drone configuration had been proven to be able to perform successful automatic flights, whilst keeping a low cost and having agile dynamics. The mechanical structure of a quad-rotor simply involves four rotors with four propellers and a rigid frame. The study modelled its assumptions on widely available data from helicopters. The paper importantly noted that the location of the center of gravity plays a pivotal role in the overall stability of the quad-rotor. This would be further compounded by our design having a water sampling device underneath the main chassis, which could alter our drones stability. To avoid the translational velocity that is caused by wind gust, it would be ideal to have the center of gravity above the equatorial plane to generate a contra rotating torque. This would increase the stability of our drone by counteracting the effects of the wind gust. The paper concluded that to design an efficient layout, the flexibility of the propellers and the location of the center of gravity should be explicitly considered.

Limitations

While quad-copters can provide superior stability over short distances, they are severely range limited compared to wing-type drones and as such they are unable to transport samples over long distances. In addition, due to the four-rotor configuration, this drone type has a much higher energy consumption to comparable plane-type drones, which restricts its payload capacity and flight time. Unlike fixed-wing drones, rotary drones need rotors to provide vertical lift as well as forward movement, which consumes a lot more power from the batteries and makes them much less efficient over long distances.

The design of the propellers makes the drone susceptible to changes in wind speed and weather conditions. This could decrease the accuracy of our water sampling collection and increase the time needed per trip. Furthermore, a sudden fluctuation in wind pressure could reduce the controllability of the drone and potentially damage the samples as well as the drone itself. This would have extremely high maintenance costs as most of our drone would not be covered in water repellent material, meaning most of the on-board circuits and electrical components would be heavily damaged.

2.1.1.1.2 Singlerotor (Helicopter)

Helicopters or single-rotor unmanned aerial vehicles are another type of drone that have recently been developed for use in aerial mapping and surveillance. These single-rotor designs are have historically been used for efficient travel purposes which include emergency services, military applications and normal passenger travel. While helicopters and similar UAV's are powered by only a single rotor, they possess a remarkable range of movement and stability during flight, which makes them a viable option for various drone applications.

Single rotor drones are rarely used commercially or experimentally as they are simply outclassed by multi-rotor drones in many aspects such as stability, speed and controllability. As the most attractive quality of a single-rotor drone is its higher efficiency and increased payload capacity compared to other drones of similar size, it is often employed on a larger scale; hence the usage of helicopters. The main reason multi-rotor drones are kept on a small scale is because of their increased power consumption which is proportional to the number of rotors they have. Once a multi-rotor drone becomes too large, its higher energy needs outweighs its superior stability and increased payload capacity. Increased payloads do not impact a single-rotor drones' flight time as heavily as multi-rotor designs. This means that single-rotor drones are much more favourable for heavier payloads and longer flight times, as only one rotor is needed to be powered. For this reason, single-rotor drones are ideal for agricultural applications such as insect pest control. Due to their high efficiency and speed, these UAV's can be equipped with a regular sprayer and cover large areas of crop fields, significantly reducing the time and labour normally required. This is particularly advantageous for dispersing poisons such as pesticides which can be dangerous to humans if inhaled or exposed to for prolonged periods [126].

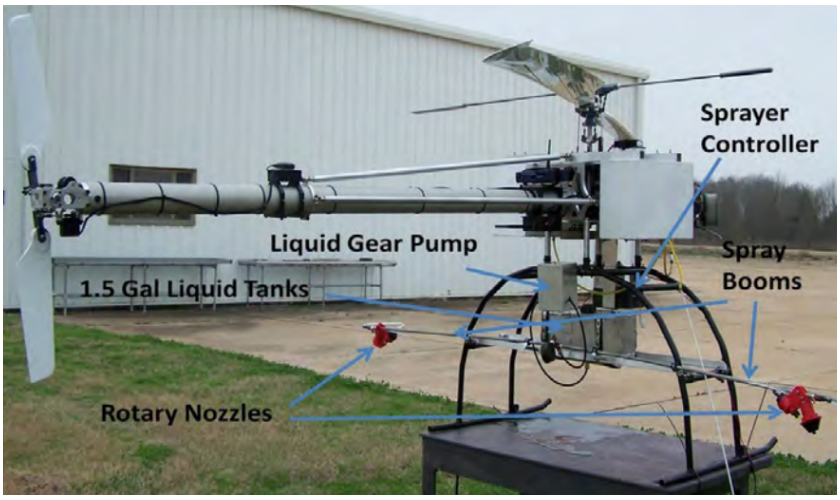


Figure 2.2: UAV helicopter spray system of Huang et al. [4]

To evaluate the effectiveness of the UAV to perform aerial pesticide delivery, a study was conducted by Huang et al. [4]. The helicopter prototype used had a main rotor diameter of 3m and a maximum payload of 22.7kg. A low-volume sprayer was designed to be retrofitted onto the undercarriage of the UAV helicopter, as shown in fig. 2.2. The sprayer was connected directly to the electrical control system on-board to ensure the trigger spray was precisely released on pre-programmed GPS spray locations. It is important to note that this prototype employed a nitro engine compared to a conventional battery, as single-rotor drones can be modified to use these higher efficiency engines and benefit greatly. When designing the sprayer, it was desired that an application rate of 0.3L/ha would be used to cover a minimum of 14 ha per spray mission. The team found that while the release height did not have any significant impact on the pesticide spray deposition, the spray coverage was sensitive to the power voltage. From the results, the study concluded that this prototype could be feasibly used in developing aerial applications such as crop production management due to its high precision delivery and low variance.

A highly desirable trait of single-rotor drones is their ability to hover with heavy payloads, which makes them ideal for corridor mapping applications. However, while single-rotor drones offer longer endurance and fast forward flight, the vibrations caused by its single propeller and gas engine can often lead to decreased stability and accuracy when using mapping technology such as LiDAR laser scanner [127]. Due to the explosive engine stroke of typical gas or nitro powered helicopter drone, large vibrations can be induced and lead to false measurements of on-board equipment and destabilising the drone. To investigate the effects of vibrations caused by the components of a single-rotor drone, a study was conducted by Cai et al. [5]. The group estimated the frequency of vibrations based on a governed motor speed of 1850 rpm, and found that the combined vibration had an amplitude of around 2g or 19.5 m/s-2. The main source of vibration was found to be the engine (260.5Hz).

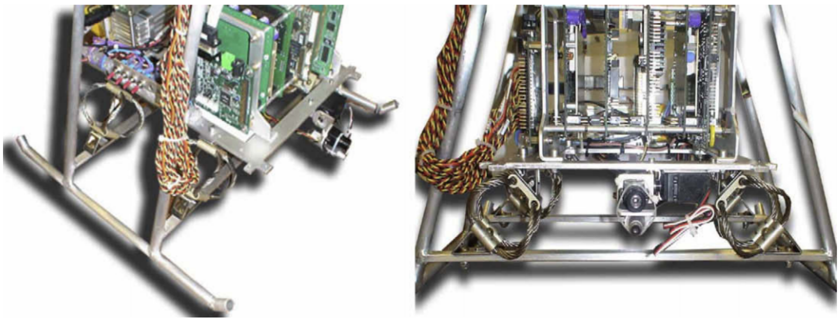


Figure 2.3: Anti-vibration design for the on-board computer system of Cai et al. (left, side view; right, front view) [5]

These vibrations had to be suppressed as they had the potential to introduce bias to sensitive UAV subsystems that measure and record data. For example, vibrations from drone components are known to interfere with the angular accuracy of the LiDAR's IMU, which can cause data error and increase the amount of data collection needed [127]. Furthermore, prolonged vibration can loosen mechanical components over time and ultimately cause them to fail. This would have catastrophic consequences on the drone as it could damage expensive components such as the flight controller during flight causing it to malfunction and potentially crash. The data collected using this drone was then used to design and implement an anti-vibration system with the purpose of reducing the effect on sensitive drone components, which can be seen in fig. 2.3. By using two small-size vibration detecting sensors, the results were able to demonstrate that their anti-vibration design had been successful in effectively reducing the harmful raw vibration and increasing the overall safety of the drone.

<u>Limitations</u>

The main drawback of single-rotor drones is that they are much harder to fly than multi-rotor drone types as well as more dangerous. With only one propeller, it can be challenging to manoeuvre the drone around with a high degree of accuracy. This is mainly because the drone is very sensitive to any tilt or change in direction. While the small rotor on the tail aims to increase stability by preventing the drone from tilting too heavily to one side, it does not compensate for the roughness incurred when performing a turn. As the drone is powered by one large motor, the spinning blade must have a large diameter to provide the necessary lift. Due to this heavy spinning blade, these drone types can be quite dangerous if mishandled. Furthermore, the propeller blades of multi-rotor drones are usually made of plastic, as the heavier metal weight is not compatible with this configuration. This means that while they may be spinning at a faster RPM than single-rotor drones, they are much smaller and flexible since they are made of plastic, and thus the risk of injury is very low.

Conclusion

It is clear that while quad-rotor drones encounter some difficulties in missions requiring prolonged flight time, they have proven to be a reliable and efficient way of safely transporting parcels such as urgently needed medications and blood samples without negatively affecting its contents. Given that our task will only require small sample collection within a short time frame, the benefits of the quad-rotor design; namely its high level of stability and ease of operation, will compensate for these drawbacks, making it an ideal design selection. While helicopter drones do provide higher efficiency and endurance, the vibrations caused by the engine makes it harder to manoeuvre and stabilise whilst hovering. This would prove to be a major obstacle as our drone would need to have maximum controllability whilst the sampling device is retrieving water. Furthermore, installing an anti-vibration design would be costly and inefficient.

2.1.2 Structural Material Design

Author: Henry Gourley

2.1.2.1 Amphibious UAV Types

2.1.2.1.1 Commercial Options

As discussed in Chapter 1, water sampling drones are not commercially available. Current literature and experimental studies have either modified market drones or constructed customised frames with similar results [128]. The recent rise of recreational and professional drone applications has increased drone market availability and affordability. Preliminary payload capacity estimations for the water sampling drone under consideration are 3kg. Such a high payload capacity constitutes a 'medium lift' drone usually designed to accommodate high detail sensors, munition or pesticides for agricultural use. Due to the high-end technological development involved and relatively niche applications, heavy and medium lift drones are significantly more expensive than typical recreational drones [129]. The purchase and required modifications of an off-the-shelf drone favour a small number of produced units due to high development costs associated with customised production. There exists a market gap between light and heavy lift drones, with only three drone payload capacities suitable for this project. The most appropriate market drones for this project are detailed in Table 2.4 below.

Drones	Price ($AUD)	Payload capacity (kg)	Visual	Additional Features
SteadyDrone Q4D-X Quadcopter [1]	15,000	8kg		-return to homes function
DJI Matrice 100	5700	3.6		-predefined missions -obstacle avoidance -storage kit
DJI Matric 600 [2]	7899	6		-predefined missions -obstacle avoidance -storage kit

Figure 2.4: Commercially available Drones suitable to project specifications

Cost and Design considerations suggest the DJI Matrice 100 represents the most feasible option among these [129]. However, these drone configurations would prove too costly for scalable projects requiring numerous units. Drone frames are considerably cheaper than assembled configurations and present a significantly more tenable option. Table 2.5 below details three off-the-shelf drone frames.

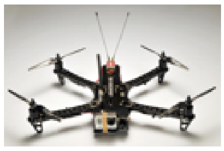
Frames	Price ($AUD)	Payload capacity (kg)	Visual	Additional Features
Tarot 650 Sport Quadcopter [3]	220	3.5-4		-Foldable arms -Adjustable battery mount -Inbuit PCB top frame
TBS Discovery FPV Frame [4]	$100	1.6		- Inbuit PCB top frame
Readytosky S500 Quadcopter Frame Stretch X FPV Drone Kit	$60	2.5		-PCB centre plate

Figure 2.5: Commercially available Drone Frames suitable to project specifications

2.1.2.1.2 Customised Frame

Short operational times represent the largest obstacle to drone technologies feasibility within this project [130]. Run times are directly influenced through a variety of factors including the battery, aerodynamics, velocity and drone and payload weights. A customisable drone would allow minimalistic design within a factor of safety to reduce overall weight and thus increase run time. A larger production volume of drones would support a customised design due to inherent cost reductions associated with scalability with current market designs incorporated into the customised Chassis [131]. Having undergone rigorous testing procedures and numerous optimisation iterations, integrating proven configurations would reduce design time, improve quality and ensure a superior product. Should a customised chassis prove feasible, initial geometry and dimensions would likely be modelled off the DJI Matrice 100, designed to carry a maximum 3.6kg payload that should be sufficient for the requirements under analysis [132]. The DJI Matric 100 is constructed of Carbon Fibre reinforced plastic (CFRP) with X-frame quadcopter configuration and 650mm diagonal wheel base as displayed in Figures 2.6 and 2.7 below. Drone arms are hollow to reduce weight and waterproof circuitry from body components to motors, a particularly useful feature when operating in proximity to aquatic environments.

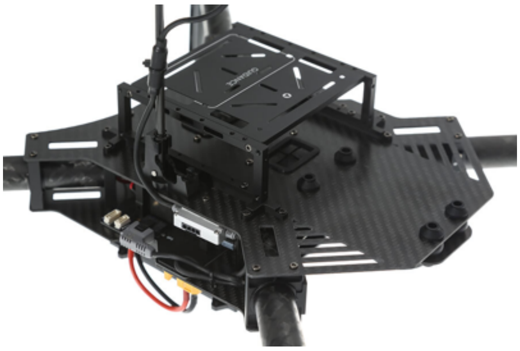


Figure 2.6: DJI Matrice 100 central body frame

Figure 2.7: DJI Matrice 100

Materials

Materials are influential factors in determining a drone's stability and efficiency. Drones are most frequently constructed of the following materials:

- Plastic: Cheaper material and construction however Inferior performance to composites. Used by low range drones including DJI phantom pro.
- Carbon fibre composite: Recent carbon fibre cost reductions have enabled widespread use within drone applications [133]. Carbon fiber can however interfere with radio signalling. Used by higher end drones such as DJI Inspire/Matrice 100 and MicroDrones.
- Aluminium: Heavier material requiring more powerful motors. Robust however susceptible to vibrations.

Method of Construction

3D Printing

Additive manufacturing (AM) enables manufacturers to design and test faster iterations of customized end-use components in a variety of carbon fiber, polymer, ceramic and metallic filaments [118]. Novel geometries, impossible to produce via conventional methods (CM) are manufacturable via AM, leading to performance and environmental benefits in the product's application. AM produces complex parts coincident with the functional requirements of conventional components with less material, whilst providing identical or better mechanical performances than the same products manufactured through CM. Inherent delamination weaknesses at overhangs, pinch points and thin members would require reinforcement. Research has this been found to be a particularly necessary feature at propeller to frame arm connections [134]. Further surface finish refinement is also required to improve aerodynamic properties and aesthetic appeal. Unlike traditional CM methods, AM technology is yet to reach the maturity required for large-volume output with slow production speeds and expensive feedstock inputs inhibiting scalability.

Molding

Non-sacrificial moulds of this nature are typically suited to large scale production due to high initial design and development costs [135]. Depending on the moulding method, connections between members may be require fixings and joinings i.e. skarf/double skarf joints, nut/bolt.

2.1.2.1.3 Failure Detection

Failure detection methods enhance reliability by providing early signs of damage, and prevent critical failure through provision of a structured resolution approach. The appropriate failure detection method is dependent upon the drone material. Carbon fibre composites and thermoplastics are the proposed materials for this design [133]. While both material choices are inherently layered, failure detection methods differ. Several recent carbon matric composite drone designs have detected damage via measuring electrical conductivity and resistance between adjacent composite layers using carbon nanotubes. These nanotubes relay measurements to the PCB board that alerts the user of potential damage. Nascent research into the viability of quadcopter to tri-copter conversion mid-flight is also being examined to prevent critical failure. The lack of experimental data, implementation procedure and commercial component availability will likely preclude the use of this technology for this design and is recommended for future works. Visual inspection after mission completion is a non-expensive and effective technique for examining macro fractures for both carbon fibre composites and thermoplastics. Washing contaminants with a soluble solution after missions will also help mitigate corrosion [133].

2.1.2.1.4 Component Integration

Additional components related to navigation, control and water sampling are to be incorporated and attached to the frame. Components will be positioned to ensure geometrical and mass centres are aligned, this promoting flight stability. Minimising exposure of components mitigates the risk of contamination via corrosive elements and alien particles [136].

Considering the drone will be operating near marine environments the risk of saturation is high if not certain, and such a protective covering must ensure all electrical components are completely watertight. The protective covering must also allow access to components for ease of repairability and maintenance [37]. This covering will act as a contingency to waterproof coatings applied to these components that are discussed in their respective chapters. Most commercially available waterproof drones waterproof the entire chassis in a plastic frame as shown in Figure 2.8, increasing weight and thus reducing overall run time.

Figure 2.8: Swellpro Spash Drone 3 Auto [6]

The main electrical components are housed in the drone's central body. The experimental water sampling drone shown in Figure 2.9 below, [118] doesn't incorporate a centrally sealed covering to protect against water intrusion, however prototypes are often lacking fundamental design parameters that are resolved after further iterations.

2.1.2.1.5 Flotation

Previous customised designs have attached flotation devices to the legs as shown in Figure 2.9 below [137]. This enables the drone to rest on the water's surface whilst collecting samples. It was proven to conserve battery life and hence allow sampling at more distant locations.

Figure 2.9: Flotation device attached to drone legs [7]

2.1.3 Water Sampling System

Author: Brandon Voon

The development of unmanned vehicles such as drones, boats and underwater vehicle that can be deployed to perform such activity overcomes several issues that humans face when conducting manual sampling. This includes drowning, landslides and slipping, falling from high elevation as well as the dangers posed by remoteness of water source [138, 139]. Drones are commonly used as they are versatile. They come in different flight range limit, size, payload capacity as well as number of rotors. Larger scale applications require the use of a hexacopter due to its high payload capacity as well as flight range. Additionally, custom designed attachments can also be made to support water sampling capabilities in these vehicles [140]. At present, several sampling devices has been designed and field tested on various occasions [141]. This includes the Niskin, Go-flo, Van-Dorn, bailers and pumps

2.1.3.1 Water Samplers

2.1.3.1.1 Thief Sampler

The thief sampler comes in various forms such as a Niskin bottle, Kemmerer bottle, Van Dorn bottle and bailers but all having very similar mechanism [142]. It can be classified as a non-isokinetic sampler and categorised into the Kemmerer bottle, Van Dorn bottle and Double check-valve bailer [143]. Although the Niskin bottle have very similar design compared to the Van Dorn bottle, both are considered acceptable and recognized as a suitable method for water sampling [144]. The use of Niskin bottle, Van Dorn bottle and Double check valve bailer will be further discussed below along with its deployment in real-life application.

Niskin bottle

Mechanical sampling devices have fairly similar design in terms of its sampling mechanism. A remarkable example of such is the Niskin Bottle.

The Niskin bottle works as a mechanical system that consists of a spring-loaded pushrod, lanyards and latex tubing. In an open position, the end stoppers will be forced open by the lanyard [145]. The lanyards are connected to the L-shaped pin that is part of the spring-loaded pushrod [146]. The end stoppers are also connected internally by a latex tubing that is stretched when in an open position [147]. The closing mechanism is triggered by a 800g messenger that will be released in which it will travel down the tether and come in contact with the pushrod. Upon contact, the pushrod spring compresses, releasing the lanyard [148]. The stretched latex tubing will then pull both the end stopper to the closed position containing the water inside. The bottle consists of an air vent screw at the top and a petcock at the bottom for convenient drainage of the content [8, 149].

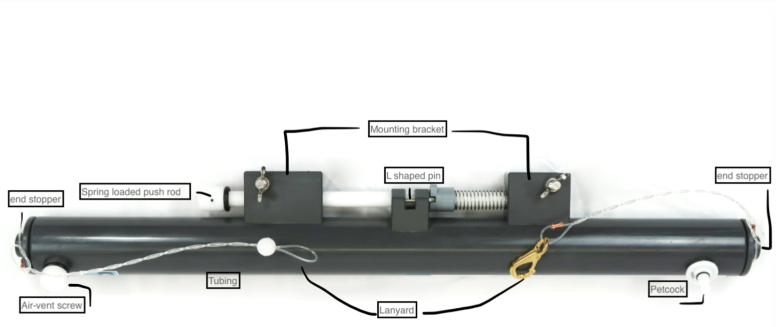


Figure 2.10: Labelled Niskin Bottle [8]

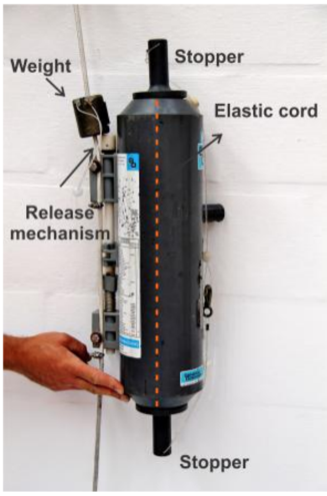


Figure 2.11: Niskin Bottle [9]

Figure 2.12: Niskin bottle in opened position [10]

An improved version of a niskin bottle is the go-flo bottle. It employs very similar closing mechanism as the niskin. However, the go-flo bottle uses a close-open-close operation [150]. This prevents the possibility of contamination when the bottle is lowered into the water [151]. The opening of the bottle is controlled by a stopper ball on the top and bottom of the bottle [152]. On land, the ball has to be rotated 90 degrees to put the stopper ball in a close position and the pressure release valve has to be pulled out [151]. At a depth of about 10m (2atm) the hydrostatic pressure against the bottle will push the pressure release valve in and the stopper ball will roll 90 degrees to allow for the water to enter the bottle [151, 152]. Like the niskin bottle, the closing of the bottle is done by a messenger. When triggered, it will travel down the tether and come into contact with the pressure release valve, triggering it to pop outwards and stopping the flow of water whilst containing the water inside [152]. The entire closing mechanism consist of the pressure release valve and a wheel that controls the tightness of the bungee cord that will be used to rotate the stopper ball during the closing of the bottle [152].

Figure 2.13: Go-Flo [11]

Results and Achievements
There have been several applications that relies on the use of Niskin bottle to collect water sample for further investigation of certain water and biological composition. Such uses include the study of total transparent exopolymer particles (TEP), Environmental DNA and water quality sampling [138, 153–155]. All three studies conducted by Suter et al., Yamahara et al. and Castendyk et al. has concluded that the use of Niskin bottle for water sampling is acceptable and has successfully provided the necessary data for further study and experimentation. Furthermore, the use of Niskin bottle is proven to be a reliable substitute to the traditional water sampling method [138, 154, 155].

An astonishing employment of the Niskin bottle is by Hatch Engineering. This company custom designed an attachment that is compatible with the DJI Matrice 600 drone [139]. The attachment will be connected to the chassis of the drone with the sampling bottle and a free weight attached to the other end by a tether or a line [138]. The purpose of the weight is to ensure that the bottle is fully submerged in the water body during sampling as well as to ensure its orientation. Additionally, a pressure transducer is independently attached to the outer surface of the bottle midway [155]. This allows the sample depth to be identified with a $\pm$ 5 -10cm accuracy depending on its flight height [138, 155]. The sampling bottle used is a 1.2L niskin bottle manufactured by General Oceanics that weighs 2kg when empty and 3.25kg when full. The drone used has a payload capacity of 6kg [156].

The attachment consists of 2 independent retractable pistons connected to independent motors [146]. The primary retractable piston acts as a safety mechanism to the drone that will be triggered automatically in the case of an entanglement or other emergencies [146]. Once triggered, the primary releasable connection frees the tether from the attachment ensuring that the drone is safe to leave. The second piston controls the collection of water sample [146]. When triggered, a messenger will be released allowing the sample to close.

Yamahara et al. and Castendyk et al. conducted a comparison between the use of Niskin bottle and other sampling method. The study of environmental DNA (eDNA): microbes, phytoplanktons, vertebretes and invertebretes by Yamahara et al. demonstrated no significant discrepancies between the three methods: Niskin bottle, benchtop Environmental Sampler Processor and the use of Environmental Sampler Processor (ESP) mounted onto a autonomous underwater vehicle (AUV) referred to as LRAUV-ESP. The on-board ESP processed and filtered 4 water samples by travelling in spirals between 10 and 40m depth while 8 x 10L of water samples were collected using the Niskin bottle with close proximity with the LRAUV-ESP with depth ranging from 10 to 40m [154]. A total of 10L were collected using the Niskin bottle to match the spiral diving samples collected from the AUV [154]. Similarly, the benchtop ESP filters and preserves water from the same source and the content for DNA extraction will be conducted later on for comparison with samples collected using Niskin bottles [154]. Upon comparison, no major discrepancies were observed between the benchtop ESP and Niskin bottle samples. However due to the limited samples collected by the LRAUV-ESP, a solid statistical inference could not be made but the comparison between the LRAUV-ESP and traditional Niskin bottle sampling, no major discrepancies were observed [154]. Castendyk et al. on the other hand conducted a comparison between two water sampling methods: Niskin bottle operated by drone using a custom-made attachment by Hatch Engineering and remote sampling using a custom-made drone boat by Montana Tech. It was concluded that both methods yielded similar results in terms of its ability to collect water samples as well as in-situ water data such as temperature and electrical conductivity [138, 155]. All in all, both studies has proven that the Niskin bottle is reliable and can perform the required task [138, 154, 155].

The study by Suter et al. differs from the other two such that Suter et al. used the Niskin bottle to collect water samples for the study of total transparent exopolymer particles (TEP), presence of microbial abundances and bacteria clades in and below the spout of the Niskin bottle over a certain period of time. It was mentioned that, micro particles as small as 4 micrometer can sink to the bottom of the niskin bottle as time passes in which if not being considered will causes an inaccurate result during analysis. This is because of the position of the spout being slightly higher above the bottom end of the bottle. Hence, any micro-particles that settles below it will not be drained and analysed. A total of 21 water samples from different depth were collected during the CARIACO Ocean Time Series Program. A handful of these samples were collected from depth of 250m and below [153]. From analysis conducted on water samples in and below the spout, there has been a consistent observation of higher concentration of particles and bacteria in the below spout samples. Suter et al. concluded that the use of Niskin bottle for such sampling is acceptable however, the analysis of samples from only the spout is insufficient to provide a complete representation of micro-particles found in the water and the samples.

Limitations
Although proven to be a reliable method for sampling water, the Niskin bottle has its limitation that can be improved upon by other methods. In regard to the study conducted by Castendyk et al., the group used a drone to carry the Niskin bottle. This proves to be a challenge in terms of sampling size of water as well as maximum depth of sampling because of the restricted airspace in the United States and Canada [138]. The Niskin bottle used has a tether cord length of 100m and hence sampling depth is limited [138]. Besides, the free hanging bottle below the drone increases the risk of entanglement with trees or power line [138]. Similar to what this paper aims to propose, weight plays a very a big role in terms of its payload capacity. However, sampling size is also another important factor because different amount of water is required for different type of analysis as reported by the Lam group from WHOI who used a pump to collect hundreds of thousands of litres of water for particulate analysis [157].

Additionally, Suter et al. observed the presence of gas on the top of the Niskin bottle. This gives room for collected water to slosh in the bottle creating a violent motion that could possibly break up particles and affect the results of the experiment [153]. Besides, it is important to note that the use of Niskin bottle for deeper depth sampling restricts further study on evolving gas in water [158]. This is because the deeper the sample depth, the higher the pressure experienced. Similarly, as it ascends, trapped gasses expands and will be forced out of the bottle. The escape of gas is possible because of the design of a Niskin bottle that uses a latex cord to hold the rubber end stopper in place. Finally, water samples collected using the Niskin bottle has to be filtered through a filtration apparatus and this entire process of collection and filtration allows for further contamination of the samples [159]. The possibility of contamination, however, will most likely occur when dealing with seawater of low organic carbon concentration [159].

Van Dorn bottle

The Van Dorn bottle having similar mechanism as the Niskin bottle is considered to be a more versatile version of it. It allows for sampling at shallow depth due to its orientation being parallel to the water surface (horizontal) as well as vertical sampling [13]. Like the Niskin bottle, the end stoppers are held together by a latex cord internally and a lanyard on the outside that will be attached to the release mechanism when in an open position [160]. Similarly, the Van Dorn bottle features a closing mechanism that is triggered by the use of a messenger that will be released on the other end of the tether [160]. Van Dorn bottle is usually classified into two categories: Alpha and Beta series bottles [131]. Both bottles have similar mechanism as well as appearance. The difference is in the material used in the end seals and the latex cord inside. As such, the Beta bottle is capable of collecting water samples for the purpose of trace metal sampling whereas the Alpha bottle is not suitable for the same purpose [131, 161]. This lies in the use of ASA plastic seals and amber latex that does not leach mercury and contaminants whereas the end seals and latex cord used by the Alpha bottle is made from polyurethane and latex [131]. Additionally, each sampler comes in two material that allows for immediate observation of water samples: Acrylic or PVC [131, 160].

Figure 2.14: BVan Dorn Bottle [12]

Figure 2.15: Van Dorn Closing Mechanism [13]

<u>Results and Achievements</u>
The Van Dorn bottle have been employed for the use of water sampling to allow for a more in-depth study of water quality and quantitative analysis of micro-zooplankton in water bodies as described by James. M. R., Hampton et al. and Koparan et al.

The use of Van Dorn bottle has been widely used for the quantitative enumeration of microzooplankton as it allows for water content as well as tiny organisms to be collected [162]. James M. R. And Hampton et al. conducted similar study. James M. R. conducted an experiment to investigate the different methods of water and organism sampling for the use of quantitative enumeration of microzooplankton: Van Dorn bottle with 10 and 20 micrometer filter, pump with 20 micrometer mesh and vertical nets of 20 micrometer mesh. A total of 10 x 3L water samples were collected from two different lakes with depths up to 10m [162]. Upon comparison of the results, there had been an observed discrepancy between the methods. However, it was justified that the results were not affected by the sampler itself but by the use of different screen mesh size for the nets and Van Dorn bottle filtration [162]. Hampton et al. on the other hand conducted a study based on a long term water analysis data collection conducted by a Siberian family since 1945. Consistent water sampling is conducted at intervals of 7 to 10 days using 10Litre Van-Dorn bottles. The enumeration of zooplanktons and phytoplankton are the main parameters being analysed [163]. Water samples are collected at specific depths with the deepest being 250m for the purpose of abiotic variables analyses. Additionally, a 37.5cm diameter, 100 micrometer mesh is also used for the collection of single zooplankton sample [163]. Based on all the data collected, there has been an increase in overall temperature of the lake [163]. The ability to obtain such result provides important information about the region. This is because the lake is considered to be one of the most climate resistance due to its huge volume.

The study of water quality on the other hand was conducted by Koparan et al. A Van Dorn bottle mounted to a UAV was used to collect water samples at a pond. Parameters such as dissolved oxygen, electrical conductivity, pH, temperature and chloride measurements were collected and compared to the results obtained by the traditional manual sampling: use of kayak and extendable wooden apparatus attached to a bottle [118]. Manual sampling follows after a UAV sampling with the same sampling depth. The sampling time between the manual and autonomous sampling is less than 60 seconds and the analysis of both water samples were conducted together within 3 hours [118]. The 130mL bottle closing mechanism is controlled by the servo motor mounted to the UAV [118]. A total of 73 flights were conducted at the pond [118]. The overall comparison between two methods for consistency were within acceptable range except for chloride level. The large discrepancy in chloride level from the two methods were due to the difference in temperature of the water level [118]. However, the use of Van Dorn for this application was proven to be successful.

In conclusion, the use of Van Dorn bottle has been proven to be reliable for the purpose of water sampling although the aim of the experiments conducted was not leaning towards the ability of the bottle to collect water samples but to perform analysis on the water itself. Additionally, several guidelines suggest that the use of Van Dorn bottle for quantitative analysis as well as water quality analysis is acceptable [164–166].

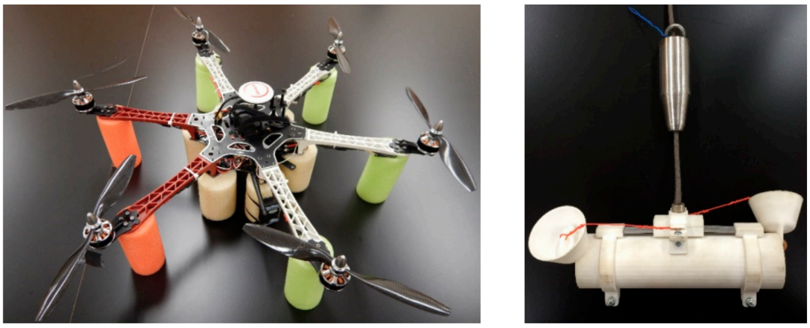


Figure 2.16: Design by Koparan et al.

<u>Limitations</u>

The limitations experienced includes of messenger malfunction as discussed by Koparan et al. but this issue was not experienced by other experimenters [118,162,163].However, the failure to deploy was due to an issue with the servo motor used to actuate the release of messenger [118]. Besides, velocity reduction of the messenger when it enters the water causes the release mechanism to stay put when in contact [118]. To improve the issue, the plastic servo was changed to a metal gear and no further issue were being observed [118].

Bailers

Bailers are a type of water sampler that consists of a hollow tubing and a one-way check valve [167]. It comes in various types, such as weighted and unweighted and single or double check-valve [167]. The check valve bailer is a simple mechanism that uses the principal of gravity and water pressure to collect and contain water samples at particular depth. When lowered into a water source, the bottom ball is pushed upwards and away from its opening, allowing for the flow of water to enter the bottle and similarly as the bottle is being retrieved, the weight of water pushes the ball against the opening, containing the water content inside [168]. The double check valve too operates using similar mechanism. However, presence of the second check valve above allows for water to be displaced as it descends and closes during retrieval so a specific water column can be sampled [167, 169, 170]. Bailers usually comes in two options: reusable, and biodegradable [167, 171]. Reusable bailers are usually made from Teflon, PVC or stainless steel and have a removable screw-on bottom check-valve for easy accessible decontamination for future use [167, 172]. Biodegradable bailers are made from PVC or High-Density Polyethylene (HDPE) with small amount of additive such as Ecopure to give it's biodegradable ability [171,173]. PVC bailers does not require additional weights as it is denser than water and will sink as it is lowered into a water source [174]. Additionally, its biodegradation capabilities has to be lab tested and verified by independent bodies [130].

Figure 2.17: Bio Bailer [14]

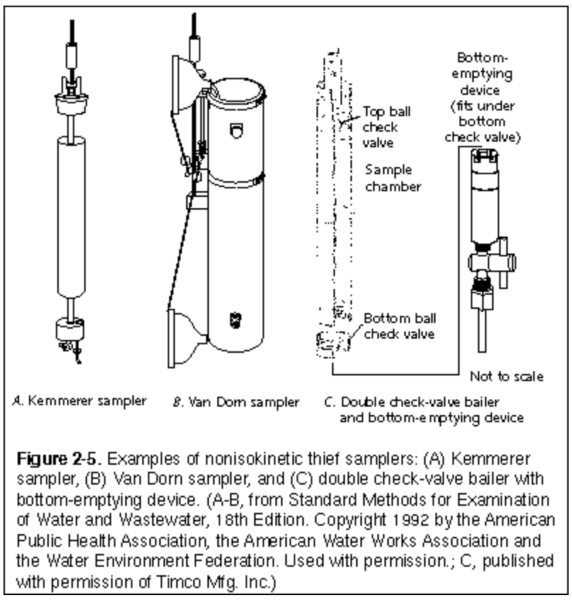


Figure 2.18: Bailer [15]

<u>Results and Achievements</u>

Bailers are often times used in bore sampling because of its cylindrical profile. However, the main purpose is to collect water samples and hence can be used in various application and location. Terada et al. conducted a study on water properties from water sampled in Yugama crater lake. A comparison between samples collected from bailers and by hand [119]. Water collected using the bailer was operated using a drone [119]. The sampling depth was 0.8m and the sample volume collected was 250mL [119]. Upon comparison, electrical conductivity, pH, chemical concentrations and stable isotope ratios were found to be very similar in both sampling methods. However, a discrepancy was observed for anion concentration, hence Terada et al. recommended the use of other sampling method to be coupled together with the bailer.

Dabrowska et al. and Korbel et al. conducted very similar study on the monitoring of groundwater quality using a bailer before and after purging and comparing water properties with other sampling and analysis methods. Dabrowska et al. collected two samples from different piezometers: before and after purging for the evaluation of vertical hydrogeochemical gradient [132]. Although the results reported an increase in Electrolytic Conductivity (EC) in water from samples collected using bailers, it was justified that the increase was due to several reasons related to the geological location of the piezometer in relation to pollution source and depth of sampling [132]. Considering this, the use of bailer for the purpose of water sampling for the further study of hydrogeochemical gradient has been successful. Similarly, a comparison of biota composition for water collected before and after purging of a well and traditional stygofauna sampling were conducted through the study of DNA community mainly the 16S rDNA and 18S rDNA [175]. Purged wells (aquifer) are usually dominated by bacteria associated with the nitrification and fermentation process whereas purged wells contained pathogenic bacteria derived from denitrification as mentioned by Korbel et al. Sampling and analysis were conducted from 4 catchment totaling to 25 sites between them. Physico-chemical analysis of water quality were similar for all 25 wells [175]. 2L of water sample was collected before purging the well and a pump was used to collect water after purging of well [175]. However, a significant difference was observed for Molecular prokaryotic (16S) and eukaryotic (18S) communities [175]. The results obtained by Dabrowska et al. and Korbel et al. however, are out of the scope of this paper.

Gomo et al. on the other hand conducted a study to examine the performance of bailer for groundwater sampling by analyzing inorganic chemistry and total coliform parameters compared to the conventional purge method. A total of 43 wells from 3 sites were being tested [176]. Bailer were used to collect sample of well before purging and compared to the results of water collected after purging [176]. Analysis of Variance (ANOVA) was used to statistically determine the difference between inorganic chemistry parameters [176]. Additional comparisons were conducted for samples collected from each individual well. It can be concluded that there were no statistical significance between both methods as outlined by Gomo et al. The observed results, however, does not mean that both sampling method gives the same result but is rather dependent on several factors related to the sampling site. This includes hydrogeology, hydrogeochemistry and depth of sample collection [176].

In conclusion, the use of bailers for different water sampling has been shown to be effective and reliable in certain conditions. It has been recommended by several guidelines for the use of this method for groundwater sampling [177, 178]. However, based on the above four articles in relation to the use of bailer as one of the methods to collect water samples, an observed difference was found within water sampling analysis mainly in the biological compositions: bacteria and viruses in the comparison of other sampling methods such as manual collection or by pump. Most of these discrepancies occur due to several external reasons such as the purging method and site location being close to a polluted source. Water parameters in an aquifer and wells are very different in terms of chemical and biological compositions. This is due to their independent characteristics as well as surrounding environments. The difference in biological compositions in wells and aquifers were also being researched by several other authors [175, 179, 180].

Table 2.1: Additional findings by author

Author	**Findings**
Korbel et al.	Significant difference in prokaryote community profile between wells and aquifers
Roudnew et al.	Higher number of virus like particle in wells than aquifer
Sorensen et al.	Higher number of bacteria cells in wells than in aquifer

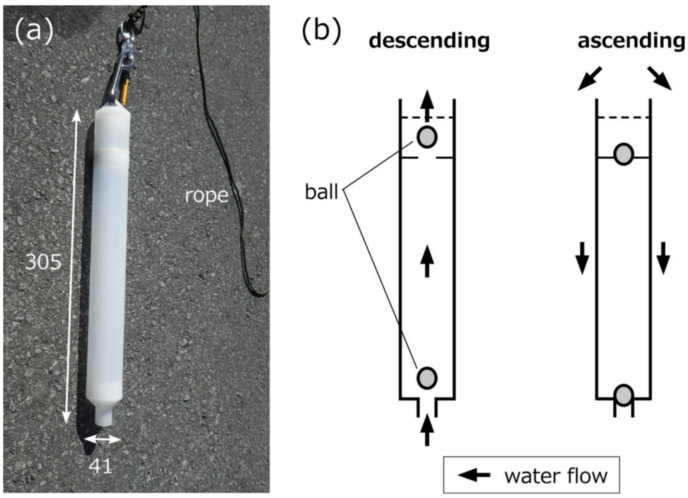


Figure 2.19: Bailer design by Terada et al.

<u>Limitations</u>

Terada et al. conducted the experiment with the help of a drone to perform the necessary tasks. It was mentioned that, the bottle was swinging freely below during the landing phase of the drone which require personnel to hold the sample [119]. Besides, the camera view of the drone was unable to provide sufficient information regarding the relative height of drone to the water surface [119]. Additionally, there has been several water sampling guidelines that states the limitation in the use of a bailer. This includes the limitation of the bottle to sample water containing volatile organics as it introduces a potential bias to the sample. Bailers have also been shown to increase turbidity while purging and sampling water in wells hence should be avoided when trace elements, PCB and pesticide are the parameters tested [178, 181]. Additionally, the use of bailers tend to aerate water samples during collection and the transfer of water from bailer to bottles [182]. Air sensitive chemicals also tends to be affected during prolonged deep-water sampling [182].

The use of bailer can be a very effective method of sampling however, as observed there is a consistent discrepancy between results collected from wells and aquifers. Therefore, it is recommended that the use of bailer is coupled with other sampling methods to ensure consistency and accuracy.

2.1.3.1.2 Pumps

A more advanced water sampling technique employs the use of a pump. There are two type of pumps available in the market that has been widely used by industries for water sampling: suction-lift pumps and submersible pump [15]. Suction-lift pumps are pumps that are stationed on land and usually comprises of peristaltic pump and jet pump whereas submersible pump are pumps that are usually placed under water. This includes helical rotor, gear, bladder, piston, inertial submersible, and centrifugal pumps [15]. The selection of pump is very important in regard to water sampling and analysis. Because of its operating mechanism, a pump can cause contamination to water source as well as alteration to analyte concentration which could affect the results of specific analysis [15]. A suction lift pump operates by creating a vacuum in its intake region causing a pressure gradient to exist between the pump and water [183]. The water region will then be of higher pressure than the intake line and hence water will be drawn up. Submersible pump works by being fully submerged into the water body. Its main operating components are the impellers that is rotated by the motor and the diffuser [184]. This rotation creates a centrifugal force that causes the water to move radially outwards into the diffuser [184–186]. Through the impeller, the fluid gains pressure and kinetic energy as it moves through the pump, creating a low-pressure region at the inlet which eventually draws more water inwards [184–186]. This cycle continues as long as the motor is in operation.

Both pumps come with their own pros and cons. The use of submersible pump is more ideal compared to suction lift pump because it is more efficient and water pressure drives water into the pump rather than that of being sucked into [187]. Besides, due to the nature of a submersible pump, it does not require priming [183]. Peristaltic pump, an example of a suction-lift pump is more versatile in terms of application and has fewer parts that are easily replaceable [15]. Additionally, the pressure gradient created by a suction lift pump means it produces a consistent flow rate [188]. The use of pumps is generally preferred over the thief sampler depending on certain scenarios such as site location, availability of power and types of study conducted later on [15].

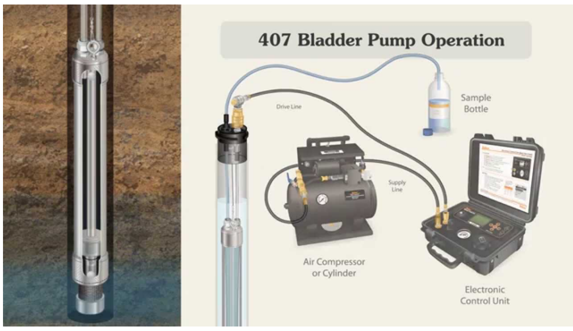


Figure 2.20: Bladder Pump [16]

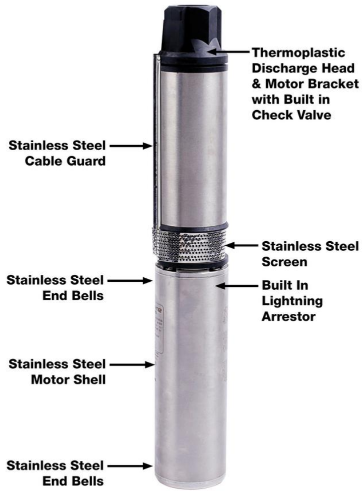


Figure 2.21: Submersible Pump [17]

Figure 2.22: Jet Pump [18]

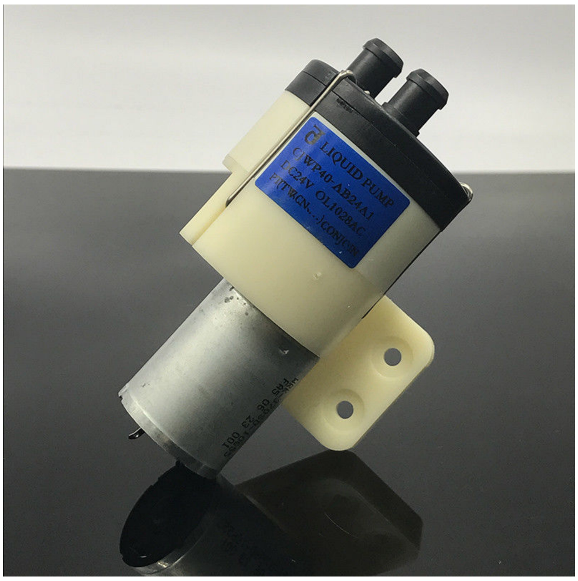


Figure 2.23: Micro-pump [19]

Results and Achievements

Documentation on the use of pumps for autonomous water sampling has been found to be very limited. Oftentimes, such pumps are used in borehole sampling and are considered to be of larger scale operations. Ore et al. and Schwarzbach et al. examined the use of an autonomous aerial vehicle (UAV) with a free hanging submersible pump for water sampling and a fixed container for storage. The idea of a free hanging pump and a fixed bottle increases its overall center of gravity for a more stable maneuver when the bottle is filled [189, 190]. For safety purposes, the pump and hose are connected to a release mechanism in which if a maximum tension force is achieved, both the pump and hose will be released from the UAV [189, 190]. Ore et al. used a 3 x 20mL sample size rotated by a servo motor after filling. The cover of the vials are spring activated [189]. The entire system is controlled by several water conductivity sensors to identify the position of pump relative to the water [189]. The on-board controller switches on the pump after being wet for 400ms. Additionally, as the UAV is capable of conducting multiple samples, a flushing system is available to clear the hose between samples [189]. A comparison of Dissolved Oxygen level (DO), sulfate and chloride ions and water temperature was made. Dissolved oxygen and water temperaure will be measured on site and at the shore when the UAV returns. Upon comparison between autonomous sampling and manual sampling, dissolved oxygen and water temperature obtained fairly similar results [189]. Chloride and Sulphate ions have slight difference in values but are still within the acceptable range of 10 to 60mg/L for sulphates and 10 to 100mg/L for chloride [189]. Schwarzbach et al. used current sensors to provide feedback of the condition of the pump. During the process of sampling, if the current reading depicts a free running pump, the UAV will be lowered until an increase in pump motor current is observed [190]. The fixed container used for water storage has a capacity of 500mL. Overall, Ore et al. reported that the use of pump for water sampling is successful. Alternatively, the design employed by Schwarzbach et al. is still in the testing phase with a positive outlook in general, several other modifications will also be made to the vehicle and the sampling system. Overall, both Ore et al. and Schwarzbach et al. concluded that there were no induced biasness for the use of UAV sampling mechanism.

Fitzgerald et al, Roman et al. and Yamahara et al. performed several studies on water samples collected using peristaltic pump. Fitzgerald et al. created a prototype for autonomous water sampler using a pump to collect water samples for pesticides analysis. The sampler has to be lowered down into the water using a rope [191]. A total of 14 units were tested over a four months period in diverse weather condition [191]. Samples collected will be sent to the National Water Quality Laboratory (NWQL) in Denver, Colorado for future analysis [191]. All in all, the design was a success with very positive feedback from the 7 USGS personnel that was involve in the testing and use of the sampling mechanism. However, several comments were made on the hardware and software that could be improved upon. Roman et al. designed a pump operated sampler attached to an autonomous underwater vehicle (AUV) that is capable of collecting 8 water samples. A multiport valve is used for the filling of samples and a piston is used for the purpose of re-sampling [192]. This allows for water samples to be ejected before re-sampling occur. Additionally, the use of a piston allows for high-pressured water samples to be extracted by means of a bench top high-pressure pump [192]. This allows lab personnel to conduct water analysis at bottom pressure [192]. The internal pump is capable of producing 360 to 540mL of water per revolution. The design by Roman et al. is still in the prototyping and testing phase therefore no solid conclusions were made on the ability to conduct water samples without inducing biasness. The experiment conducted by Yamahara et al. on the other hand involves the study of environmental DNA (eDNA). The result obtained through the use of pump for water sampling was compared to that of a Niskin bottle as mentioned above. All three experiments performed by the above-mentioned authors are successful in the sense that the use of pump was proven to be a reliable method that can be employed [154, 191, 192].

The use of pump is proven versatile and can be deployed by several methods including the use of UAV and a fully submersible autonomous vehicle that utilizes different size of pumps.

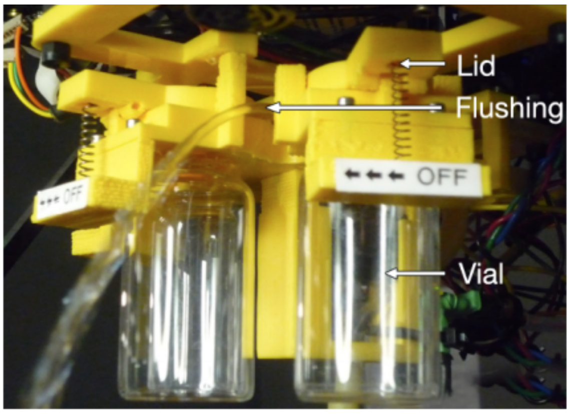


Figure 2.24: Flushing mechanism by Ore et al.

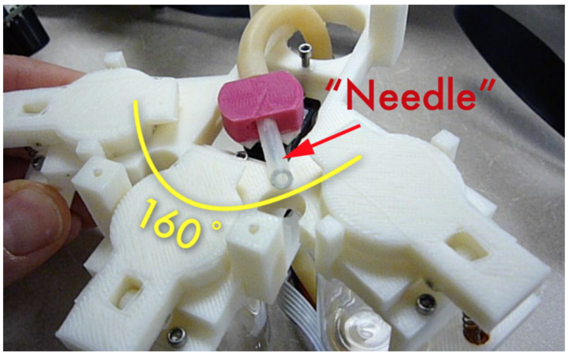


Figure 2.25: Lid mechanism by Ore et al.

Figure 2.26: Sampling mechanism by Fitzgerald et al.

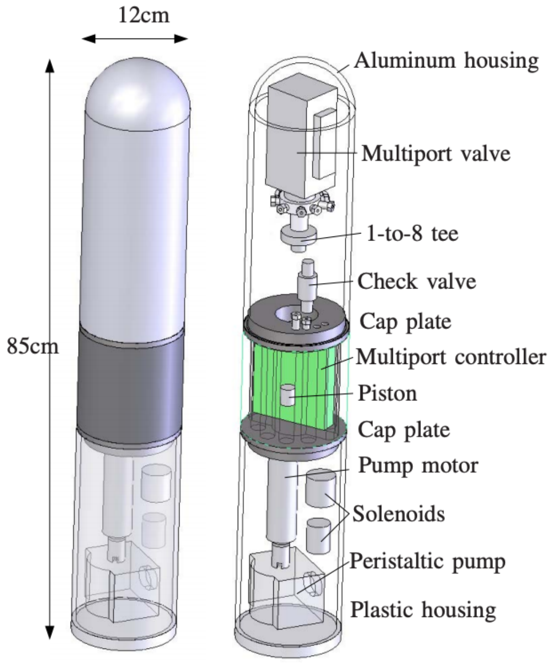


Figure 2.27: Sampling mechanism by Roman et al.

Figure 2.28: AUV with sampling mechanism by Yamahara et al.

Limitations

The use of pump, although oftentimes preferred over the use of thief sampler in some applications like borehole sampling, poses several disadvantages as well. Depending on the analysis conducted later on, the use of pump can sometimes induce water chemistry changes, affect analytes concentration and causes loss of dissolved gases and Volatile Organic Compound (VOC) that causes an unreliable analysis [189,193]. Besides that, the use of pump is expensive due to its complicated mechanism and use of power supply [194]. Due to the high-speed impellers and diffusers, samples collected may damage organisms that are of interest [194]. Besides, the suction force generated by pumps allows for other sediments solid particles to be collected hence requiring filtration in the later process [194]. These sediments, particles and abrasive material in water can also damage moving parts in the pump [195,196]. Moreover, deployment of pump for water sampling causes mixing and agitation of water column that might affect the accuracy of the results obtained [195,196].

Several other limitations were observed in the design by the above mentioned authors. Ore et al. identified several factor that could lead to a potential diffence between autonomous and manual sampling. This includes, the process of pumping, transit of water through the tubing into the sampling bottle, agitation of water sample in flight and changes of water properties such as Dissolved Oxygen during the collection of other samples and travelling time [189]. Changes in water property is possible due to photosynthesis that is happening in the sampled water. The prototype designed by Fitzgerald et al. although being tested by several USGS personnel still lacks additional testing and deployment. The use of the prototype was only deployed to a single sampling point within a water source hence lacking sample population. Besides, the prototype also lack deployment in a variety of water and weather condition, therefore it is not made clear how the prototype will perform under harsher weather condition. Roman et al. on the other hand realised several points of contamination that could potentially affect the accuracy of the analyses. As the sampling mechanism uses a pump, residual fluid that are not related to the current sample remaining in the tube that is connect to the sample bottle causes a mixture in samples. This causes cross contamination between sources of water samples that would lead to a false and inaccurate result.

2.1.3.1.3 Non-conventional Methods

A low cost method for water sampling was investigated by Banerjee et al. The main mechanism involves the use of a syringe, servo motor and a 2.5m teflon tubing [6]. The principal behind the ability to collect water samples is pressure difference. The servo motor will be connected to the plunger of the syringe, when activated, the servo motor rotates 90 degrees creating a 20mm lateral motion on the plunger [6]. This causes a lower pressure region in the syringe. Difference in pressure between syringe and surrounding atmosphere pushes water into the teflon tubing. With a lateral motion of 20mm, water will fill 1.27m of the tubing corresponding to 25mL [6]. Pressure gradient ensures that the water stays within the tube and not in the syringe. This prevents for any cross-contamination [6]. Banerjee et al. uses 6 syringes arranged in a hexagon shape for water sampling, where the power unit and trans-receiver unit will be placed within. This is to prevent spillage and minimise wire clutter. Additionally, a downward looking video-transmission system was attached to the side for monitoring purposes [6]. This simple design that weights 1.5kg allows it to be mounted to a commercial quadcopter.

A total of 7 water samples were being collected in two different locations for the test of pH, electrical conductivity and dissolved oxygen level [6]. Additionally, this design has been tested in the laboratory and in-field and has proven to successfully collect water samples. However, the collection of water samples from extremely shallow water body is found to be lower in volume [6]. This is because of the teflon tubing touching the bottom of the water body preventing the pneumatic suction mechanism from collecting more water [6].

All in all, this sampling mechanism designed by Banerjee et al. has been proven to work perfectly and is able to overcome several issues faced by manual grab sampling despite being low cost. However, the lack of additional testing and application may result in a bias report.

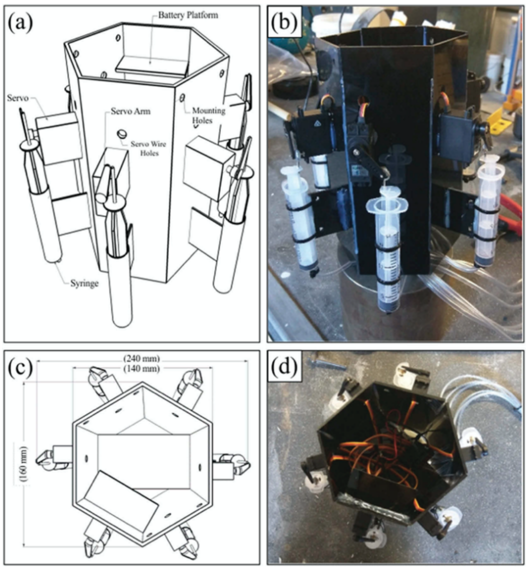


Figure 2.29: Electromechanical Pneumatic System by Banerjee et al.

2.2 Electrical Hardware and Firmware

2.2.1 Communication System

Author: Dylan Dam

The task of water sampling may require the robot to traverse through harsh terrain. As stated above, UAVs provide the required flexibility to acquire samples from hazardous/rugged terrain. Whilst UAVs appear to be a simple solution to the task, problems arise about the telemetry of the UAV. Telemetry refers to the process of establishing two way communication with the UAV to accurately and precisely control and operate it. This section of the thesis will study the telemetry solutions currently used by UAVs and using that information to formulate a problem space and design. The objective of this section of the report is to research about current UAV telemetry designs used for remote sampling and formulate a design strategy for the team's UAV in order to fit with our imposed constraints.

2.2.1.1 UAV Telemetry

2.2.1.1.1 Literature Review

All telecommunication relies on the transmission of information via electromagnetic radiation (EMR). The electromagnetic spectrum deals with a whole range of EMRs that vary in wavelength and energy. While different EMR waves exist, all telecommunication is limited to a select band of wavelengths as higher wavelengths have high ionizing potential [197]. Traditionally radio waves have been the most used form of EMR for telecommunications as radio waves are easily transmitted through the air and pose little threat to life [198]. Within the radio wave frequency band different standards have arose. The four most common standards for radio frequency band communication are Bluetooth(IEEE 802.15.1), ZigBee(IEEE 802.15.4), Ultra Wide Band/ UWB (IEEE 802.15.3a) and WiFi(802.11a/b/g).

Thomas Nolte et al [199] conducted a comparative study on the advantages and limitations of said wireless communication technologies. Nolte provides an adequate summary on the technical limitations and specification of each telecommunication standard (Figure 2.30).

Standard	Bluetooth IEEE 802.15.1	ZigBee IEEE 802.15.4	UWB IEEE 802.15.3a	Wi-Fi IEEE 802.11a/b/g
Freq. band	• 2.4 Ghz & 2.5 Ghz (ver 1.2)	• 2.4 Ghz	• 3.1-10.6 Ghz	• 2.4 Ghz (b/g) & 5 Ghz (a)
Network	• P2P	• Mesh	• P2P	• P2P
Modulation technique	• Frequency Hopping Spread Spectrum (FHSS)	• Direct Sequence Spread Spectrum (DSSS)	• Orthogonal Frequency Division Multiplexing (OFDM) or Direct-Sequence UWB (DS-UWB)	• OFDM or DSSS with Complementary Code Keying (CCK)
Maximum network speed	• 1 Mbps (ver 1.0) • 3 Mbps (ver 1.2) • 12 Mbps (ver 2.0)	• 250 Kbps	• 50-100 Mbps (480 Mbps within short ranges expected).	• 54 Mbps (802.11a) • 11 Mbps (802.11b) • 54 Mbps (802.11g)
Network range	• Up to 100 meters, depending on radio class (effective 10 meters).	• Up to 70 meters (effective 20 meters).	• Up to 20 meters (effective 10 meters).	• Up to 100 meters (effective 50 meters).
Main usage	• Voice applications. • Eliminating short-distance cabling.	• Sensors/control applications. • Grand-scale automation. • Remote control.	• Multimedia applications. • Healthcare applications.	• Office and home networks. • WLAN. • Replace Ethernet cables.
Strong points	• Dominating PAN tech. • In vehicles today. • Easy synchronization of mobile devices. • Frequency hopping tolerant to harsh environments.	• Static network. • Control/sensor. • Many devices/nodes. • Small data packets. • Low duty cycle. • Low power.	• Easy and cheap to build. • Consume very little power. • Provides high bandwidth. • Broad spectrum of frequencies (robustness).	• Dominating WLAN tech. • Know-how.
Weak points	• Interference with WiFi. • Consume medium power.	• Low bandwidth.	• Short range. • Interference.	• Traditionally consume high power.
Automotive usage (potential)	• Portable devices. • Diagnostics tools. • Real-time communications. • Device connectivity.	• In-vehicle communications. • Mobile/static sensor networks.	• Robust vehicle communications. • High bandwidth communications.	• Inter-vehicle communications. • Vehicle-to-vehicle. • Vehicle-to-roadside.

Figure 2.30: Summary of Radio Frequency Wireless Standards [199]

Nolte comments that each network standard is optimised for its particular use. Bluetooth was designed to address short distance cabling and therefore has limited range but high transmission speed to address for voice application sizes. ZigBee was designed for sensors and control that typically have short messages. As ZigBee was designed for larger network sizes where nodes that need to be linked could be spread apart, it has considerably higher range but lower transmission speed rates. UWB occupies a much larger bandwidth compared to all the other wireless standards and has high data transmission rates but has a short range and may be subjected to interference. WiFi has high transmission speeds and high range and was designed to replace wired Ethernet cables and therefore has the highest range and transmission speed out of all the wireless technology standards. [199] Typically UAV communication would use one of these standards, further study will be conducted to examine the telemetry used for contemporary UAV design.

Current UAV Telemetry Solutions

A water sampling UAV was built and tested at the Department of Agricultural Science of Clemson University [200]. Gengiz Kopran et al built a custom made UAV comprising of a list of parts. The custom made UAV was operated within line-of-sight which ultimately dictated the type of telemetry used. The telemetry module used for this project was a Turnigy 9X radio receiver which was used to receive commands from the Ground Control Station (GCS) and a 3DR radio which was used to send commands from the GCS. To evaluate the quality of the telemetry used, it is important to understand how the UAV was used. The UAV was able to be operated in two modes, a manual mode where flight commands were radioed to the UAVs micro controller and autonomous mode, where way points were selected and the UAV had to visit the way points and execute the water sampling (Figure 2.31).

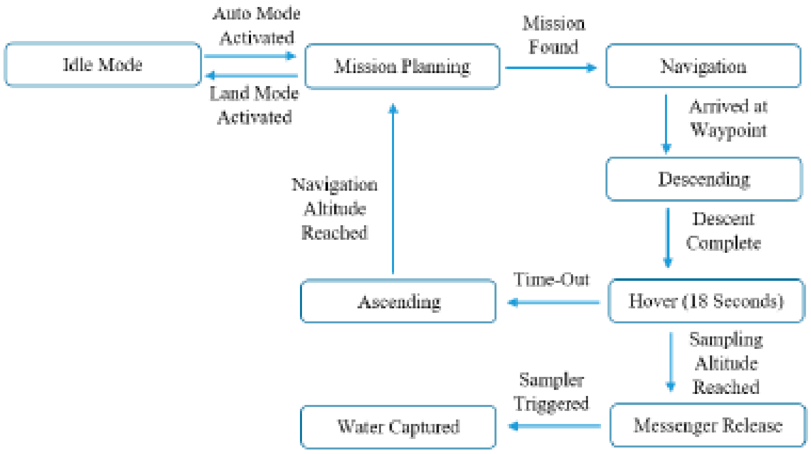


Figure 2.31: Kopran's UAV Logic Flow
[200]

For the first design an in depth analysis to the telemetry design will be conducted. The operating modes of the UAV uses two different types of telemetry. For manual mode, a Turnigy 9X controller was used (Figure 2.32). The Turnigy 9X is a 2.4 GHz radio that comes with a programmable receiver and eight channels. The transmission type is Frequency-Hopping Spread Spectrum (FHSS). FHSS requires the user to continually change frequencies during use. This is referred to as frequency hopping and prevents other users from hijacking control of the UAV [201]. As FHSS generally has a power/signal strength this mean that the UAV is able to be controlled at longer ranges and is generally less sensitive to interference.

Figure 2.32: Turnigy 9X Controller [20]

The receiver used for the controller is the RF9X-V2 (Figure 2.33) and when paired together have an effective tested range of 500m [20]. As the GCS was located at the base of the body of water, 500m was an adequate range for manual control of the UAV. For the autonomous mode of the UAV a 3DR Radio set was used (Figure 2.34). The 3DR Radio Set contains two radio modules with antennas that uses FHSS modulation which allows for 2 way full-duplex communication. Properties of this radio set are that it's extremely small and lightweight and has data transfer rates of 250kbps with an expected range of 500m.

Figure 2.33: RF9X-V2 Receiver [20]

Figure 2.34: 3DR Radio Set [20]

The success rate of this design is 60%, out of twenty test flights only eight flights failed to complete the entire mission. Kopran attributes these failed missions to the design of the water sampling device and grade of servos used. The design used was cost effective and exceptionally reliable. However, as the test was conducted within line of sight, there was no requirement for the transmission rate to be high as the size of the data packet that needed to be transmitted was not large. As one of the parameters requires the UAV to be able to be operated out of line of sight, a telemetry design that allows for higher data transmission may be required.

John Paul Ore et al from the University of Nebraska repurposed an AscTec Firefly hexrotor UAV (Figure 2.35) with a water sampling device. This design differed from Kopran's design in that water was sucked up onto an onboard testing platform that conducted the water sampling test. Sensors and modules that come equipped on the Firefly are a GPS, 3-axis accelerometers and gyroscopes, a compass and an altimeter. The telemetry used for the Firefly are two 802.15.4 (ZigBee) radios, where one is used for autonomous control and the other for sensor feedback [21]. One clear difference between the two designs is that Ore's approach lacks a manual mode, therefore the flight paths and navigation is all done autonomously.

Figure 2.35: AscTec Firefly [21]

Similar to Kopran's design, the AscTec Firefly uses two XBee (modelled after the 802.15.4 protocols) modules for telemetry. Ore states that due to U.S. Regulations on flying UAVs beyond line-of-sight, the onboard telemetry was sufficient for their intended use and no changes were made to the onboard telemetry. Our team's problem statement requires the UAV to be flown out of sight and therefore sufficient development would be needed to address the design specification.

Kshitiji Srivastava et al [202] also implemented a UAV for data gathering. The purpose of the experiment required the team to use a UAV to obtain area photos of crop fields for post image processing. The team built a custom made UAV to perform said task. The telemetry module that was used for Srivastava's UAV design was the FlySky FS-i6S radio transmitter controller. This module was mainly used for controlled flight of the UAV, but was capable of relaying information about the sensors that were connected on board through the FS-iA6B receiver (Figure 2.36). The transmitter and receiver pair are responsible for controlling and monitoring the state of the UAV during its mission. The FS-i6S/IA6B contains two internal dual omnidirectional high gain antennas that allow for dual way communication. The reported range of the FS-i6S is about 1km [22]. The data transmitted to the UAV include the throttle, yaw, roll and the flight mode. The data that was transmitted back would include information relevant to compute and monitor the flight path as no large data packets were needed for this experiment. The RC used is sufficient. The UAV used in this experiment was not designed to operate outside line of sight, therefore the telemetry used was specifically intended to be used within line of sight. As the UAV was used within line of sight, there is insufficient testing to determine if the UAV can perform outside line of sight.

Figure 2.36: FS-i6S Transmitter and FS-iA6B Receiver [22]

Beyond Line of Sight (BVLOS) is a new and emerging field. Before BVLOS, UAVs were restricted to only military use. Recently study has been conducted to find methods to ensure safe and reliable use of BVLOS UAVs. A study by Diego Guenzi et al [115] looked for feasible solutions for BVLOS capable UAVs using open source and easily accessible parts for aerial geohazard monitoring and surveying. Most airspace regulations require some sort of redundancy for critical engineering components to minimise the likelihood of failure. The main telemetry module used for this project is a RFD868 radio modem (Figure 2.37). Some features that the RFD868 is capable of is long range communication (greater than 40km) as well as being small and lightweight so it does not disrupt aircraft balancing. The RFD868 also has considerably higher transmission power (1 Watt or +30dBm), it is because of this feature that allows it to be feasible in high interference environments.

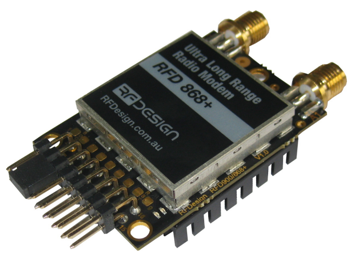


Figure 2.37: RFD868 Radio Modem [23]

The RDF868 serves as the main form of communication between the user on the aircraft, but several redundancies were put in place to ensure that the aircraft. The network redundancies used for this project can be seen below (Figure 2.38). In Guenzi's design the data received by the GCS is broken up to ensure that if one system fails then there are other routes to communicate with GCS. By spreading the transmission of data across three different methods, this enhances the UAVs reliability.

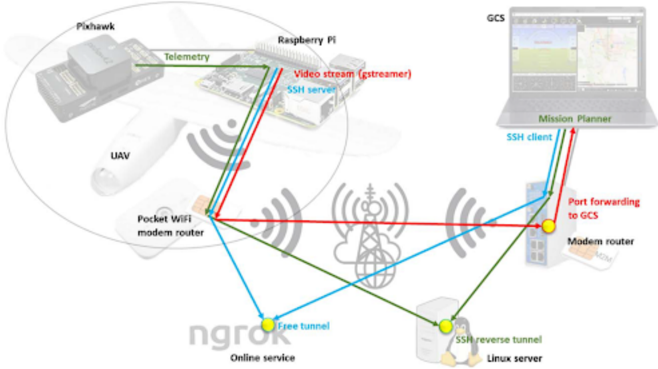


Figure 2.38: Telemetry Redundancies for BVLOS [24]

Another example of a BVLOS UAV is a geospatial surveying project was conducted by Anna Zmarz et al [24] of the University of Warsaw. The purpose of their BVLOS UAV was to survey sections of Antarctica that was untraversable due to the extreme Antarctic conditions. Zmarz's design involved a fixed-wing UAV that was used a YM6500 Satelline telemetry module (Figure 2.39) with a range of 25km [203]. The telemetry module was responsible for monitoring and controlling the flight path of the UAV and the signal was boosted via antennas mounted on the GSC as well as the UAV itself.The Satelline YM6500 uses the UHF band of radio waves and is typically used for long range communication. The data transmission speed is 19200bps depending on the setting of the radio module. The communication mode is set at half duplex, therefore only one can be transmitting and receiving at a time [25]. The telemetry module used for this scenario is suitable for surveying. The range, provided this module and the lack of traffic in the airspace, allows Zmarz's design to be optimised for the environment the UAV will be in.

Figure 2.39: YM6500 Satelline Module [25]

2.2.2 Autonomous System

Author: Aaron Su, Anthony Leung and Alexandar Nguyen

Introduction

In the past decade, due to the advancement in miniaturization of electronic components, the broad spectrum of unmanned aerial vehicles (UAVs) enabled applications has received the most attention and been extensively used for civilian and military purposes [204], including search and rescue, environmental protection, mailing and delivery, marine operation and other miscellaneous applications [205]. These applications can take place outdoor or indoor within challenging and complex environment [206]. Traditionally, UAVs in these applications require human operators to control within line-of-sight (LoS) and typically involve a remote crew of two or more personnel for safe flight and payload/mission management [207, 208]. However, manual operators are shown to be limited by human factor such as manual control capacity and bandwidth especially in stabilisation tasks [209]. Even experienced operators can find it challenging when manually controlling UAVs in cluttered and dynamic environments [210, 211], which further raises the concerns for operators in developing countries where limited flight training can be provided [212].

Therefore, UAVs capable of independent decision-making and operation are highly desirable in complex and dynamic environments [26] such as water sampling operation in Yamuna River, presented in Backgorund (Chapter 2.1). The significance of autonomy for unmanned aircraft system (UAS) is also highlighted by Young et al. [213], which include the ability to increase information collection and mission success rate while reducing the number of staff, risks related to human factors and mission cost. However, limitations of existing technology in avionics, computational processing, communication, and energy storage still pose significant challenges in achieving UAV autonomy [26], especially within urban environments of developing countries where unreliable or non-existent global navigation satellite system (GNSS) signal, insufficient telemetry infrastructure and other unpredictable interference during operations are commonly expected [214].

Framework

While the definitions of autonomous system remain ongoing research, several studies have attempted to define unmanned aerial system (UAS) autonomy. Kendoul [215] defined an autonomous UAS as a system that can accomplish assigned mission successfully without external system while adapting to operational and environmental conditions. Clothier et al. reviewed various definitions and scales of autonomy applied in micro aerial vehicles (MAVs) and UAS and categories them based on “independence” and “complexity” [216]. The International Civil Aviation Organization (ICAO) [] simply describes the Autonomous Aircraft System (AAS) as a system that operates without human intervention. In addition, Clough [217] proposed a differentiation criterion among automatic, autonomous, and intelligent systems. Clough defined an automatic system as one that simply executes command from external system. Adding on to this, an autonomous system possesses the ability to plan and make decision towards mission requirements, while an intelligent system extends further with the capability of reasoning actions and generate its own goals without any external instructions.

Many researchers have proposed frameworks for evaluating the level of autonomy (LoA). Most frameworks describe five to ten distinct LoA [213, 217, 218], with the lowest level being manual controlled and the highest level being fully autonomous for intelligent behaviour or swarm [215]. One of most cited framework developed by Huang [219] defined The Autonomy Levels for Unmanned System (ALFUS) with three orthogonal dimensions: (1)mission complexity (MC), (2)environmental complexity (EC), and (3) human independence (HI). Kendoul [215] further generalize the HI dimension as external system independence to include any external system of a self-contained UAS such as a ground station. This framework is widely adopted by researchers for evaluating autonomy level of UAS and many other similar multidimensional scales were proposed [26,215,220,221].

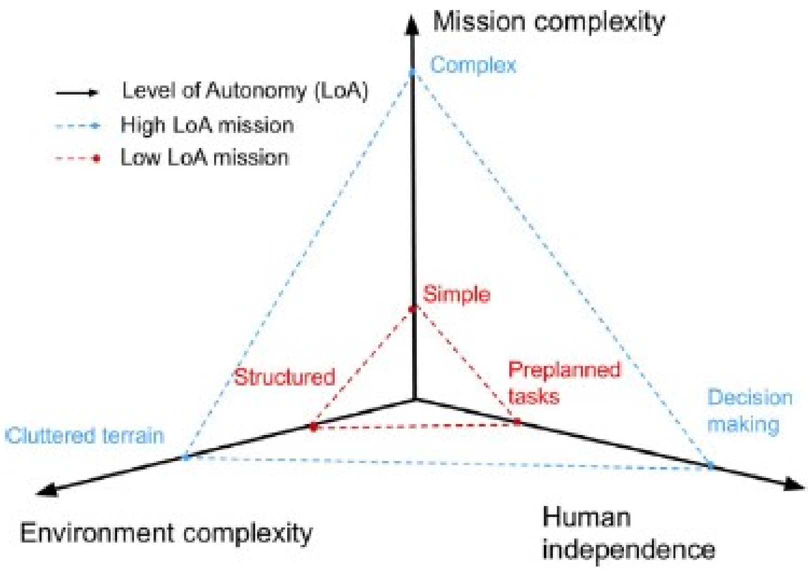


Figure 2.40: Autonomy Level [26]

As numerous researches and technologies have been developed for UAS over the past 20 years, it is necessary to categorise these technologies in a structural manner to facilitate their integration towards a comprehensive system design. Kendoul [215] argued that three functional technology areas namely guidance, navigation and control (GNC) are identified as the core components of an autonomous UAS and provided a survey of GNC system used to increase LoA for UAS. Elbanhawi et al. [26] extended this system to include more generic functions and finally proposed a comprehensive process involved in various level of UAS autonomy, with reference to the sense-plan-act (SPA) cycle defined within the discipline of artificial intelligence as shown in Fig. These frameworks present comprehensive analysis of technologies applied in autonomous UAS and thus are adopted as the foundation of this chapter. In addition, with the rapid development of computer vision and deep learning techniques in the past decade, associated technologies continue to succeed in solving more-than-ever complex problem in real time and open up possibilities for many new autonomous operations [?].

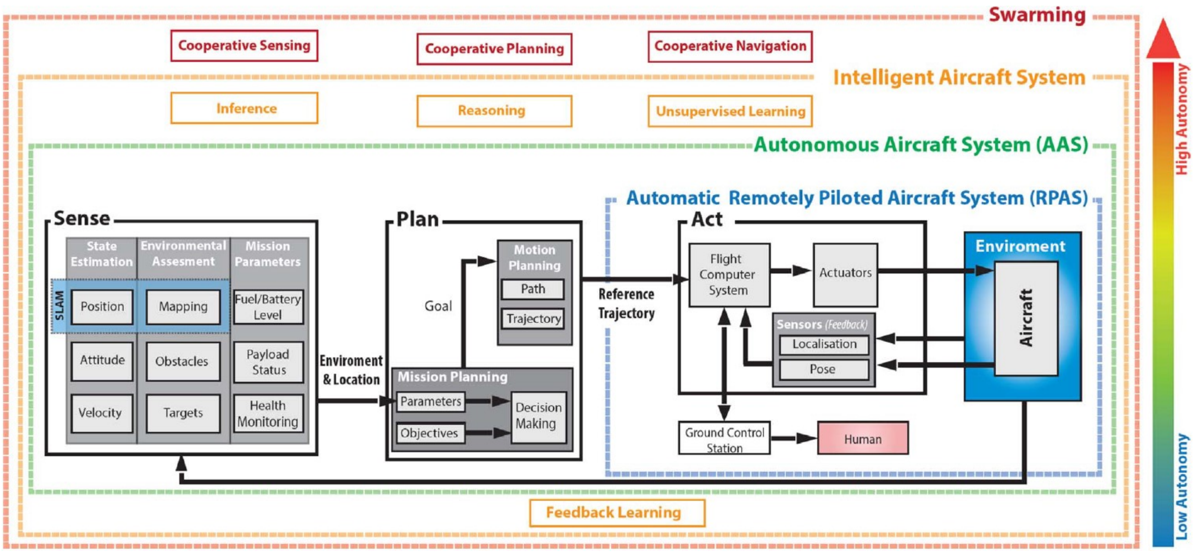
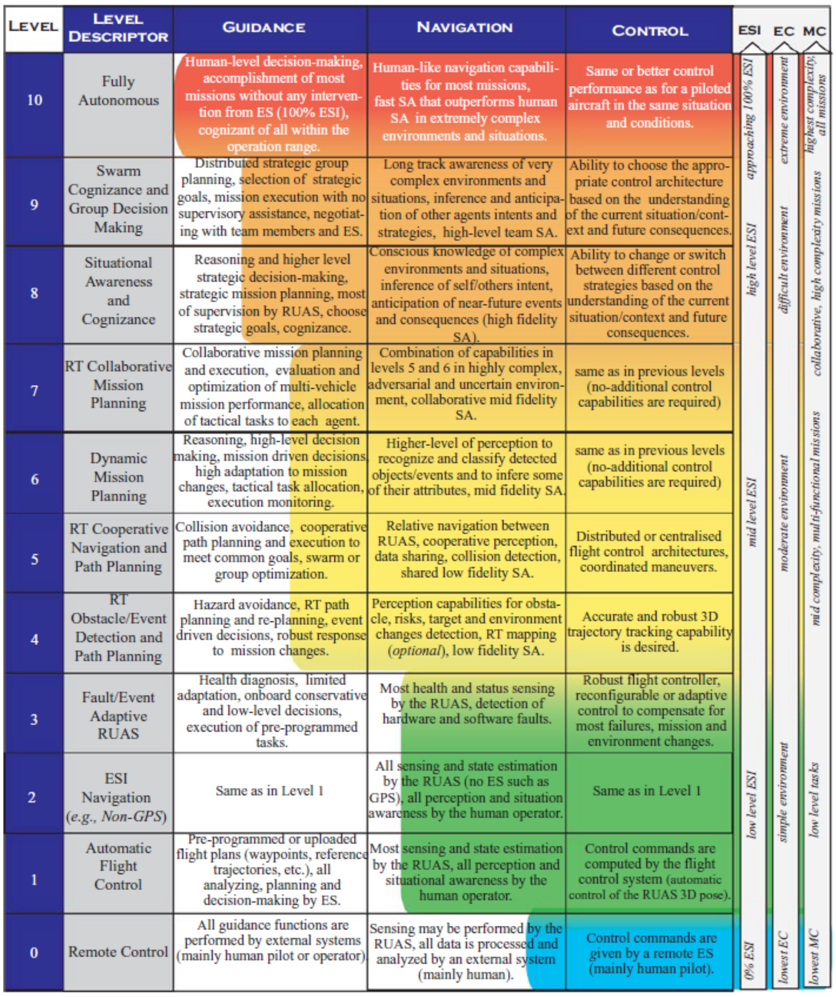


Figure 2.41: SPA cycle [26]

In this chapter, a comprehensive review of promising technologies for enabling autonomous UAV operations is presented, focusing on the cost and benefit analysis with specific reference to water sampling application in developing countries such as Yamuna River in India. Compared to the SPA cycle which defines the core functions in a sequential manner, the GNC framework [215] implements hierarchical classification of technologies which provides better separation of their scope. It categorizes technologies based on the autonomy level they provide, hence offer a fair comparison between technologies for the same hierarchical level as well as a guidance for deciding the level of autonomy to be used in the final design of the water sampling application. Therefore, the reviewed technologies are categorised based the level of autonomy they are associated (from lower to higher) following the Control-Navigation-Guidance scheme as shown in fig. 2.42 in the remaining sections.



Level	Level Descriptor	Guidance	Navigation	Control
10	Fully Autonomous	Human-level decision-making, accomplishment of most missions without any intervention from ES (100% ESI), cognizant of all within the operation range.	Human-like navigation capabilities for most missions, fast SA that outperforms human SA in extremely complex environments and situations.	Same or better control performance as for a piloted aircraft in the same situation and conditions.
9	Swarm Cognizance and Group Decision Making	Distributed strategic group planning, selection of strategic goals, mission execution with no supervisory assistance, negotiating with team members and ES.	Long track awareness of very complex environments and situations, inference and anticipation of other agents intents and strategies, high-level team SA.	Ability to choose the appropriate control architecture based on the understanding of the current situation/context and future consequences.
8	Situational Awareness and Cognizance	Reasoning and higher level strategic decision-making, strategic mission planning, most of supervision by RUAS, choose strategic goals, cognizance.	Conscious knowledge of complex environments and situations, inference of self/others intent, anticipation of near-future events and consequences (high fidelity SA).	Ability to change or switch between different control strategies based on the understanding of the current situation/context and future consequences.
7	RT Collaborative Mission Planning	Collaborative mission planning and execution, evaluation and optimization of multi-vehicle mission performance, allocation of tactical tasks to each agent.	Combination of capabilities in levels 5 and 6 in highly complex, adversarial and uncertain environment, collaborative mid fidelity SA.	same as in previous levels (no-additional control capabilities are required)
6	Dynamic Mission Planning	Reasoning, high-level decision making, mission driven decisions, high adaptation to mission changes, tactical task allocation, execution monitoring.	Higher-level of perception to recognize and classify detected objects/events and to infere some of their attributes, mid fidelity SA.	same as in previous levels (no-additional control capabilities are required)
5	RT Cooperative Navigation and Path Planning	Collision avoidance, cooperative path planning and execution to meet common goals, swarm or group optimization.	Relative navigation between RUAS, cooperative perception, data sharing, collision detection, shared low fidelity SA.	Distributed or centralised flight control architectures, coordinated maneuvers.
4	RT Obstacle/Event Detection and Path Planning	Hazard avoidance, RT path planning and re-planning, event driven decisions, robust response to mission changes.	Perception capabilities for obstacle, risks, target and environment changes detection, RT mapping (*optional*), low fidelity SA.	Accurate and robust 3D trajectory tracking capability is desired.
3	Fault/Event Adaptive RUAS	Health diagnosis, limited adaptation, onboard conservative and low-level decisions, execution of pre-programmed tasks.	Most health and status sensing by the RUAS, detection of hardware and software faults.	Robust flight controller, reconfigurable or adaptive control to compensate for most failures, mission and environment changes.
2	ESI Navigation (*e.g., Non-GPS*)	Same as in Level 1	All sensing and state estimation by the RUAS (no ES such as GPS), all perception and situation awareness by the human operator.	Same as in Level 1
1	Automatic Flight Control	Pre-programmed or uploaded flight plans (waypoints, reference trajectories, etc.), all analyzing, planning and decision-making by ES.	Most sensing and state estimation by the RUAS, all perception and situational awareness by the human operator.	Control commands are computed by the flight control system (automatic control of the RUAS 3D pose).
0	Remote Control	All guidance functions are performed by external systems (mainly human pilot or operator).	Sensing may be performed by the RUAS, all data is processed and analyzed by an external system (mainly human).	Control commands are given by a remote ES (mainly human pilot).

Figure 2.42: GNC Framework and Autonomy Level [26]

2.2.2.1 Flight Control System

Author: Anthony Leung

2.2.2.1.1 Controller

This section explores the differences between flight controllers in comparison to their price, features and quality suited for the uses of a Water Sampling Drone.

To integrate the entire system of the UAV, flight controllers are used to process information from exterior sub functions and compute within one central unit. An example block diagram for a quad copter is shown in fig. 2.43.

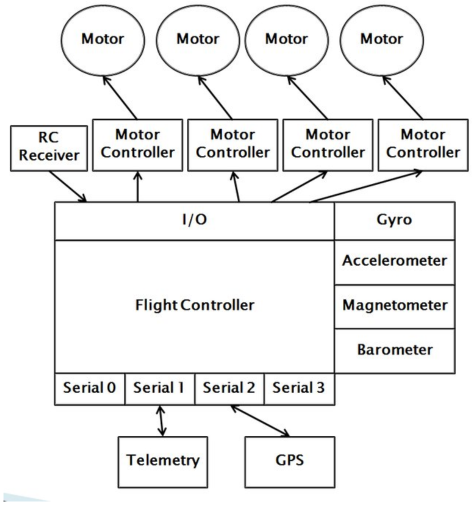


Figure 2.43: Quadcopter block diagram by [27]

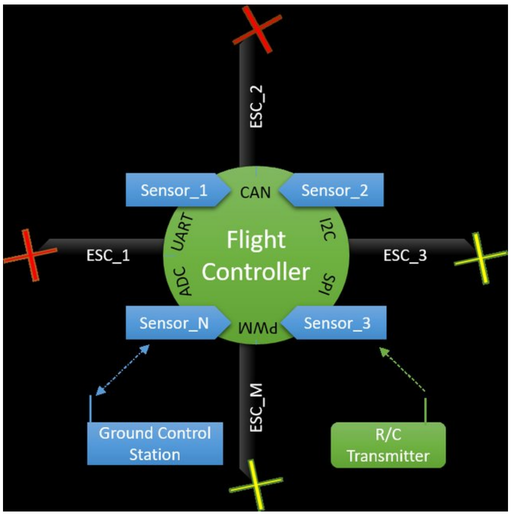


Figure 2.44: Generic block diagram of a UAV system [28]

As shown in fig. 2.43 the flight controller takes upon the responsibility to communicate with external peripherals such as the gyro-meter, accelerometer, magnetometer, barometer, telemetry, GPS, motor controllers and receivers. It is vital for the flight controller to be able to handle the information gathered from each of the resources and process them with speed and efficiency to ensure optimal functioning of the UAV. Fortunately, flight controllers are well developed and have even been commercialised for for some time. The two flight controllers that are often used are either closed or open source, with a wide variety currently in the market. This section aims to review the available architectures, uses and benefits of known controllers and apply them to the study of water quality sampling.

Definitions

Important definitions for flight controller components are listed in table 2.2.

Table 2.2: Table of Definitions for Specific Components.

Word/Acronym	**Definition**
ECU/ESC	Electronic Control Unit (ECU) and Electronic Speed Controller (ESC) usually relate to the motor components of a UAV system but is a general term for separately managed controllers.
UART	Universal Asynchronous Receiver/Transmitter (UART) is a stand-alone circuit used for transmitting and receiving devices such as GPS, Bluetooth or radio [222] .
XBEE	A personal network that is compared with WiFi. It uses 75% less power and transfer at 250kbits/s[a].
PWM	Pulse Width Modulation (PWM) is the common protocol used to control motors / radio through an analog signal[g].
PPM	Pulse Position Modulation (PPM) is similar to PWM however allows the management of multiple PWM channels within one[g].
DSM	Digital System Multiplexer (DSM) is a digital protocol that is robust against noise and interference[g].
SBUS	Serial Bus (SBUS) is a serial communication protocol being able to operate through a single cable[g].
CAN	Controller Area Network (CAN) is a robust communication bus that allows ECU's to transfer information with each other. Opposed to an SBUS which performs polling of different ECU's [**?**] .
I2C	Inter-Integrate Circut (I2C) uses a protocol that communicates from one 'master' to multiple 'slaves'. Intended for short distance communications [223] .
SPI	Serial Peripheral Interface (SPI) is a protocol that is effective for small peripherals, working on four lines for clock, data and select lines [224] .
IMU	Inertial Measurement Unit (IMU) is a device that measures force and angular rates, typically combined with an Accelerometer, Gyroscope and sometimes Magnetomers.
Gyroscope	Measurement device for angular rates.
Accelerometer	Measurement device for acceleration.
Barometer	Measurement device for air pressure.
Magnetometer	Measurement device for magnetic direction.
DAC	Digital to Analog Converter (DAC).
ADC	Analog to Digital Converter (ADC)
LVDS	Low Voltage Differential Signalling (LVDS) is a low cost method for transferring high-speed data (Gbits/s) through a copper wire [225].
OTG	On-The-Go (OTG) allows the connection for USB devices to connect and take control of the micro-controller.

Closed-Source Flight Controllers

Commercialised Flight Controllers are typically pre-programmed devices by the manufacturer which gives simplicity for the consumer to plug their components. This is often at a high cost to buy and stops users from adapting the device to their personal applications, which may require interior alterations [226]. These flight controllers are considered as 'closed source' and table 2.3 reveals the top four performing flight controllers in the market as of 2019.

Table 2.3: Weight and price of highest performing closed-source controllers [48]

No.	Flight Controller	Weight	Cost (AUD)	Source
1	Naza-M V2	95g	$249	[4]
2	DJI A3	386g	$1399	[5]
3	DJI N3 Quadcopter	132g	$499	[6]
4	Naza-M Lite	66.3g	$119	[7]

As shown in table 2.3, closed source flight controllers can be very costly and also dependant on the application of each controller. The biggest advantage for using these controllers is its simplicity, whereby users who have little programming knowledge are able to utilise special features such as returning to home functionality or even maintain flight with a failed motor [227]. A common feature of the flight controllers shown in table 2.3 is that they belong to the company of DJI, one of leading developers of drone technology using ARMv8 64bit core microprocessors in their controllers. The ARMv8 64bit core [228, 229] belongs in the family of microcomputers, which have the ability to process machine learning and artificial intelligence, potentially justifying why the DJI range of flight controllers are considered to be the best in the market.

Open-Sourced Flight Controllers

Open-sourced flight controllers give the ability for users to alter its interior components and have a large community alongside its platform. As an open source, these provide Printed Circuit Board (PCB), Hardware Description Language (HDL) source code, bill of materials, schematics and more aiding the own construction of manipulation of the design for personal use. In a 2017 and 2018 review of flight controllers, the differences of the most commonly used flight controllers were reviewed in [28] and [49]. These comparisons are summarised and filtered into table 2.4. With reference to definitions in table 2.2. The flight controllers have been differentiated by their in-built features. Considering the weight of those compared in table 2.4, The average weight for a flight controller is 34.88g and have a low power consumption; which is at maximum around 3W.

Table 2.4: Feature comparison of reviewed flight controllers [28, 49]

Platform	**Processor**	**Wifi**	**Bluetooth**	**UART**	**XBEE**	**PWM**	**PPM**	**DSM**	**SBUS**	**CAN**	**I2C**	**SPI**	**IMU**	**GPS**	**Gyroscope**	**Accelerometer**	**Barometer**	**Magnetometer**	**LVDS**	**OTG**	**DAC**	**ADC**	**Power Consumption (W)**	**Weight(g)**
Phoenix	ARM Cortex-A9									X			X	X	X	X			X				2.6	64
OcPoC	ARM Cortex-A9	X	X	X		X				X	X	X	X	X	X	X	X			X			4	70
PIX-HAWK/PX4	STM32F427			X		X	X	X	X	X	X	X	X		X	X	X	X				X	1.6	38
PIXHAWK2	STM32F427			X		X	X	X		X	X	X	X		X	X	X	X				X		39
Pa-parazzi/Chimera	STM32F767			X	X	X	X		X	X	X	X	X		X	X	X	X			X	X		
CC3D	STM32F103						X	X	X		X				X	X								8
Atom	STM32F103								X		X				X	X								4
APM 2.8	AT-MEGA2560			X							X				X	X						X		31
FlyMaple	STM32F103			X		X					X		X				X	X						15
PXFmini	Raspberry Pi												X				X	X				X		15
PixRacer	STM32F427						X	X	X	X			X		X	X	X	X						10.9
Pixhawk 3 Pro	STM32F427						X	X	X	X		X					X	X						45
Sparky2	STM32F405						X	X	X	X							X	X			X			13.5
Erle-Brain 3	Raspberry Pi																X	X				X		100

Micro-Processors

Micro-processors are the central units to flight controllers and differentiate by there capacity to operate, measured in bits, and the speed in which it operates, in clock frequencies (Hz). With a larger bit range, more difficult processes are able to be undertaken, such as neural networks, graphic interfaces and motor controls. As shown in table 2.4, majority of flight controllers utilise STM32 microchips, with some others using ARM Cortex-A, Raspberry Pi and ATMEGA. Majority of the flight controller models shown involve a microprocessor that belong to the company ARM. ARM encompasses the the following micro-processors:

- STM32: Micro-controller range [230]
- Cortex-A: Micro-computer range involving Operating Systems (OS) capability [231]
    - Utilised by Raspberry Pi [232]

The final micro-processor is the AVR's ATMEGA chip which is predominantly only within the micro-controller family. A qualitative comparison of the opposing brands are listed below in table 2.5.

Table 2.5: Comparison of AVR and ARM micro-processors. [50]

Criteria	**AVR**	**ARM**
Architecture	Harvard	Reduced Instruction Set Computing (RISC)
Community	This has a large surrounding community for support based widely used Arduino micro controllers.	Larger than AVR due to its application in computers, mobiles and many more.
Cost	Low	High
Features	Slow speed operation and low difficulty programming	High speed operation and high difficulty programming
Platform examples	ArduPilot Mega, Mikrokopter	Pixhawk, Sparky2, Chimera, CC3D, Atom, FlyMaple, PXFmini
Comments	AVR are typically used for controlling applications at a lower scale which form the basis of most DIY projects. It is cheap to buy and easy to program.	ARM processors have the extensive capability of being micro-computers, allowing functions such as deep learning and Artificial Intelligence.

Cost of Open-Sourced Flight Controllers

Outlined in table 2.6 are the prices found for the controllers found in table 2.4. As shown, as more features are in-built with the system, the price tends to increase to justify their uses. Few of the reviewed controllers did not have prices, as such devices were open-source controllers. These flight controllers were:

- Phoenix
- Paraparzzi/Chimera
- PXFmini
- Sparky 2
- Erle-Brain 3

All of the listed controllers cannot be purchased and requires fabrication. The controller schematics and PCB designs can be found on the code sharing web platform, Github.

Table 2.6: Selected flight controller prices as of 2019.

Flight Controller	**Little Bird ($)**	**Core Electronics ($)**	**Banggood ($)**	**Other ($)**	**Max Price ($)**	**No. Of Features**
OcPoC				599.00	599.00	13
PIX-HAWK/PX4	499.00	$ 434.57			499.00	14
PIXHAWK 3 PRO				249.99	249.99	7
PIX-HAWK2				238.00	238.00	13
PixRacer			120.37		120.37	9
Fly Maple	104.01	116.28			116.28	6
APM 2.8			48.41		48.41	5
CC3D	23.31				23.31	6
Atom			19.74		19.74	4

Prices were derived from the following websites [233–238].

2.2.2.1.2 Algorithm

Author: Alexandar Nguyen

This section explore current flight control algorithms that could be potentially utilised by UAV's as well as examining commonly used algorithms used in commercial and open source drones.

Background

Aircrafts are unstable vehicles because if there is any imbalance in their system, especially roll and pitch, it will cause linear and angular acceleration that may cause collision into buildings, trees, people, the ground etc. [239] The balancing of a quad-copter requires continuous reading of sensors to allow for adjustments in rotor speeds. These are usually done autonomously through a control system code.

Numerous control algorithms exist to control the flight and stabilisation of an Unmanned Aerial Vehicle, these include linear control systems, model based non-linear control systems and learning based flight Controllers [240]. A multitude of controllers utilise different forms of flight control as well as blending multiple algorithms together to produce a more optimal result depending on the desired function of the UAV.

Existing Control Systems
As stated previously, the three categories of flight control are, learning based flight control, linear flight control and model-based non-linear control, figure below lists the control systems that exist in the respective categories.

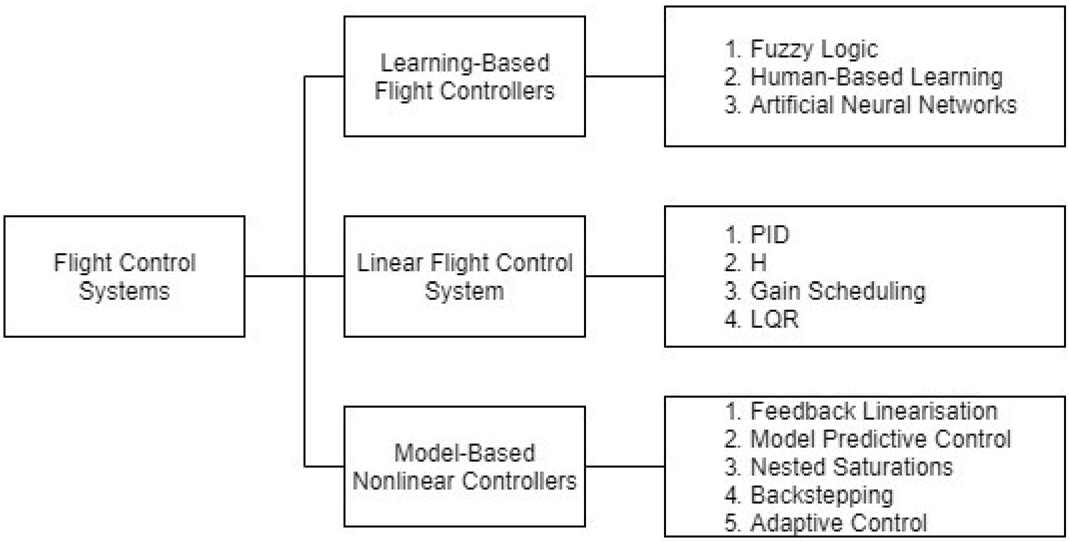


Figure 2.45: Flight Control Systems

Learning Based Flight Controllers
Main Characteristic of learning-based controllers is that they are not initially represented as a dynamic mathematical model. The nature of these controllers includes the need to iterate and train the system in order to get the desired results [136].

Fuzzy Logic:
The idea for Fuzzy Logic Control was to use the information and knowledge used by human pilots and translate them into rules that can be used by the fuzzy logic control system [240]. The controller doesn't work on binary logic but on the "degree of truth". Binary logic operates on either 1 or 0, where fuzzy logic is a real value between 0 and 1 [241]. An advantage fuzzy logic controllers have is it does not depend on having a well-developed mathematical model meaning it simplifies the process [241].

Human-Based Learning:
This algorithm learns based on the analysis of pilots execution of manoeuvres from flight data [240]. Its objective was to extract the input sequences and feedback mechanisms that pilots use to execute aggressive manoeuvres [240]. In Gavrilets study [242], they implemented this concept to develop and implement an intuitive control logic for autonomous aggressive flight.

Artificial Neural Networks:
Neural Networks are generally used to identify unknowns in the system and then combined with another control technique [240]. This controller requires no knowledge of physical parameters of the system meaning that the controller can be used for any quadrotor of different masses and inertia within the same class [241].

Linear Flight Control System
Linear Flight Controllers are on of the most utilised approaches for UAV control.

***PID*: **The PID (Proportional Integral Derivative) control system is one of the most widely used methods consisting of 2 loop control system with an inner and outer-loop system [240]. The inner loop controls altitude using single input-output PID and the outer loops is translation motion control using decoupled PID. PID is stated to be a time-consuming process but can be improved by identifying the dynamic model and tuning the PID controllers [240].

***H*:** This control method is able to handle uncertainties in parameters and able to handle un-modeled dynamics. This control demonstrates good tracking during manoeuvres as well as altitude control [240].

***Gain Scheduling*:** This is one of the most used designs for flight controllers for aerospace systems and used in many research projects [240].

***LQR (Linear Quadratic Regulator)*:** This is a popular control technique used for accurate orientation and position control, and can be used in conjunction with feedback linearization to achieve higher levels of trajectory tracking [240].

Non-Linear Flight Control System:
Quadrotors are underactuated, nonlinear and strongly coupled having six degrees of freedom which is controlled with only 4 input terms, x,y,z,roll. This has drawn a lot of attention from researchers to device nonlinear controllers to achieve autonomous control [240].

Feedback Linearization [240]:
This method changes the non-linear dynamics to a linear equivalent through feedback and incorporates transformation of variables and selection of appropriate input that cancels non-linearity in the system. System is represented as:

$$\dot{x} = p\left(x\right) + q\left(x\right)u, \quad y = r\left(x\right) \tag{2.1}$$

Where x is the system states and y denotes the output vector. This all helps formulate a control input, $u = \gamma(x) + \beta(x)v$, which provides a linear input-output mapping between new control input v and output y. This is a convenient tool however it requires full state statistics as well suffering from unstable zero dynamics.

***Model Predictive Control*:**
Also referred as Receding Horizon Control (RHC), this process requires a clear model of the plant to then predict the model's future behaviour to then track its error and minimize it [240]. This is an iterative process that can anticipate upcoming events to then yield control inputs accordingly [241]. This tracking began as a cost minimisation problem with input and output constraints which was solved with a gradient decent method [240].

***Nested Saturation*:**
This control system is for a system with actuator saturation in which is inevitable in feedback control systems. If ignored the controller will perform worse with degrading performance and instability [243]. This is more specifically for smaller UAVs that undergo aggressive manoeuvring, object avoidance and experiences external disturbances, overall causing frequent saturation. Nested Saturation systems are applied to the longitudinal, lateral, heave and yaw dynamics.

***Adaptive Control*:**
A robust control method which can handle un-modeled dynamics and uncertainties in parameters, due to vulnerability to modelling errors and uncertainties of dynamic inversion. Dynamic inversion is a nonlinear control technique that is equivalent to input-output feedback linearization. This model is effective when performing aggressive manoeuvres such as hover to hover, acceleration to deceleration and E-turn manoeuvres at high speeds [240].

***Backstepping*:**
This is a recursive method to control non-linear and linear systems. The design is based on an approximate mathematical nonlinear model and is utilised to stabilise controls [240]. Limitation of this method is applying to a real time quadcopter due to the need of information of all system states [241].The use of PID and Backstepping provides more robustness with external disturbances (i.e. Wind) compared to backstepping.

Algorithms in Selected Flight Controllers
The flight controllers, Pixhawk and Ardupilot, were suggested based on affordability and flexibility in the previous section. Upon further research, the types of controllers used in both systems are Proportional Integral Derivative Systems. PID systems are simple yet effective solution for stabilisation as well as being easy to implement [244]. It calculates the difference between the desired and measured variable value, an "error value" and tries to reduce the magnitude of error. These measured variables will be data obtained flight controllers, gyros and accelerators etc. and comparing it to specific values for specific purposes [136].

- P: depending on present Error
  (current - desired) * P_setting)
- I: is the accumulation of Errors
  (last_I_result + ((current - desired) * I_setting)
- D: predicted values of future errors based on the current rate of change
  ((current - desired) - (last_current_value - last_desired_value)) * P_setting

PixHawk
Multicopter Position Controller

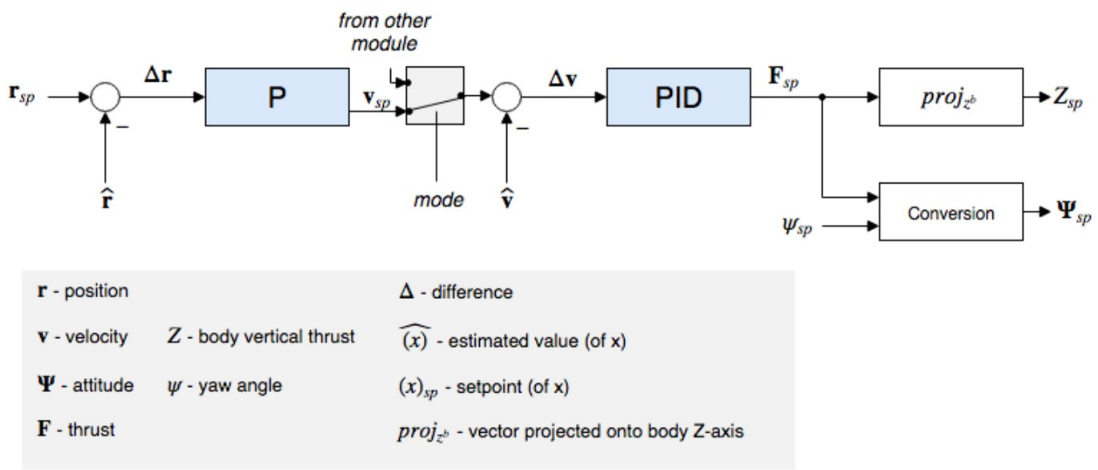


Figure 2.46: PixHawk Position PID Controller

State Estimations are performed on a low-level controller to obtain real time requirements of the system, this allows for the compensation of loss of visual localization data or loss of computer connection. Positions estimates are obtained from EKF.

The PID system utilized is a standard cascade of position velocity loop seen in fig. 2.46. This system has 2 different modes. The outer (position) loop is bypassed, depending on mode, (shown as a multiplexer after the outer loop). The position loop is only used when holding position or when the requested velocity in an axis is null. The integrator in the inner loop (velocity) controller includes an anti-reset windup (ARW) using a clamping method [245].

Ardupilot

Altitude Control

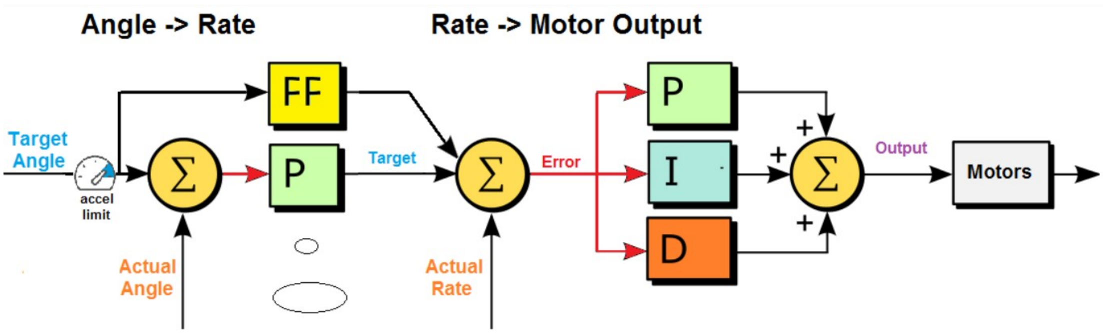


Figure 2.47: Ardupilot Altitude PID

Fig Nig 2 diagram displays a PID system used for Altitude Control for each axis.

1. A P (proportional) controller is used convert the angle error into a desired rotation rate.
2. PID controller is then used to convert the rotation rate error into a motor command [246]

Position Control

Very similar to the altitude control architecture, the P and PID combination is used for position control. The Ardupilot uses separate interfaces for horizontal control (X and Y axis) and vertical control (Z-axis). They are in different interfaces as some modes only require one either horizontal or vertical control, e.g. Altitude Hold, requiring only the Z-axis. Layered PID controllers are used:

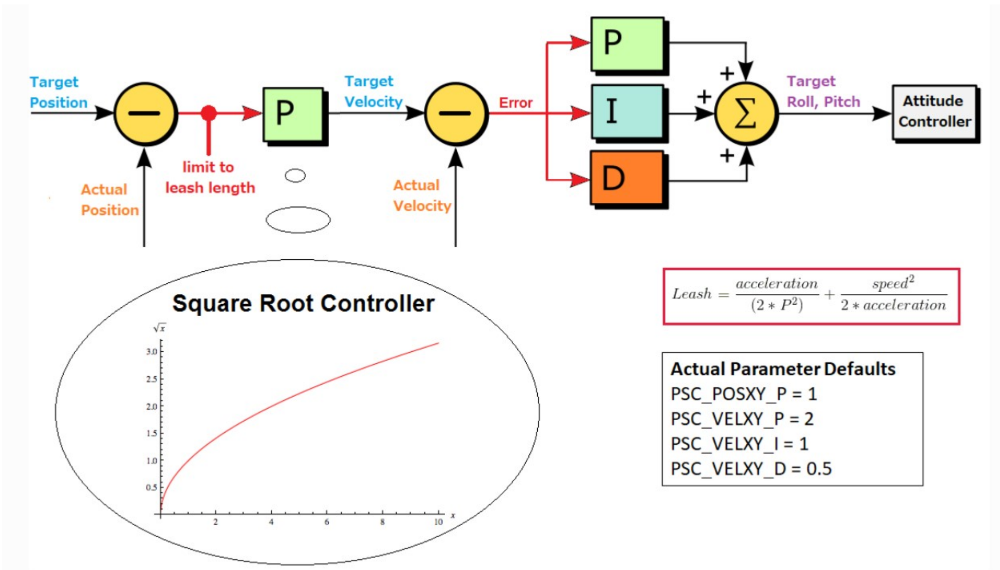


Figure 2.48: Ardupilot Altitude PID

For the XY axis interface, a proportional controller is used to convert the position error into a target velocity which is followed by a PID controller. This converts the error into a desired acceleration to then obtain a target lean angles which is sent to the altitude control module.
Similarly, the Z axis utilizes the same proportional controller which convers position error to a target velocity, in this case the rate at which the drone climbs. Again, this velocity is converted to a desired acceleration and enters a PID control system to provide desired throttle. The desired throttle is sent to the altitude control module [247].

Other PID systems are used in the Ardupilot which are used to achieve:

- Altitude Hold (as mentioned before)
  - Used to convert altitude error (difference between desired and actual) to a desired climb or decent rate
  - If set at a higher rate, it will be aggressively try to maintain altitude
  - If set to high, it results to a very jerky throttle response
- Throttle Hold
  - Usually doesn't really need tuning
  - Converts the desired climb or descent rate into a desired acceleration up or down.
- Throttle Acceleration
  - Converts the acceleration error into a motor output.
  - Ratio of 1:2 of P to I (I twice size of P), should be maintained if modify these parameters
  - These values should never be increased but for very powerful copters you may get better response by reducing both by 50% (i.e P to 0.5, I to 1.0).

In Cherub Dim's et al study [135], a qualitative and quantitative comparison between the 2 most widely used open source flight controllers, PixHawk and Ardupilot, was performed. The results are explored below.

Qualitative Result

- ***Hardware Compatibility*** **(accounting for various operating systems and/or device management software):**

  Ardupilot is compatible with more hardware compared to PX4. From **??** 2.2.2.1.2 it is concluded that Ardupilot focuses on having their software being compatible to closed and open source, where the PX4 is more focused on open source.
- ***Partner Companies*** **(Support from other Companies):**
  ArduPilot has more partner companies for each software developer, having 39 where PX4 has 24 however, the PX4 are partnered with larger companies, which weigh over the other 39 countries.

Control Algorithm Type	Note
Fuzzy Logic	Works under "depths of truth" rather than binary logic and sets rules based on information and knowledge used by human pilots. These types of controllers do not require a detailed mathematical model thus simplifying the creation process.
Human-Based Learning	Based on control data from pilots to extract behaviour and sequences utilised and integrated in the control algorithm.
Artificial Neural Networks	Like the fuzzy logic method, it does not need any mathematical models meaning that it can be used with any UAV type and it is generally used to identify system unknowns.

- ***User Experience* (Interface):** The Calibration process of PX4 is better as it is more interactive and more comprehensive, using pictures and graphics. Since it is more interactive it is also easier to calibrate as it can all be calibrated through the UI.

  The Ardupilot can be smoothly used right out of the box and is better for the change of parameters because in PX4 the PID have to be manually tuned. It also has a better interface even though it is more cluttered and not streamline as well as having more available features, PX4 has less refined with only limited features and flight modes. Ardupilot also allows the user to download and analyse data within the software and export into a MatLab file. PX4 requires use of external software.

Quantitative Analysis

- *GPS and Barometer Calibration (Accuracy)*
  Average Error of Barometer:
  - 6.7% Ardupilot
  - 2.6% PX4

  Average Error of GPS
  - 0.87% Ardupilot
  - 0.24% PX4
- *Flight Path (Time and Accuracy)*
  PX4 has better checkpoint accuracy, completing a predefined path in 0.476 second with an accuracy of 0.55% compared to the Ardupilot's 0.7%.
- *Loiter*
  The controllers were tested at a certain altitude to determine which software had the best latitude and longitude stability where the Ardupilot was proven to perform better
- *Return to Launch*
  The controllers' efficiency of returning to home position were tested where the main focuses were on duration and deviation. The PX4 was proven to perform faster averaging 9.3 seconds at a height of 15m, where the Ardupilot would slow down at a height of 10m. The Ardupilot would have more displacement from the

home position as well.

- *Altitude Control*
  PX4 was proven to have better performance and can elevate to differing heings with higher accuracy compared to Ardupilot. The Ardupilot is able to maintain its elevated high more stably compared to the PX4.

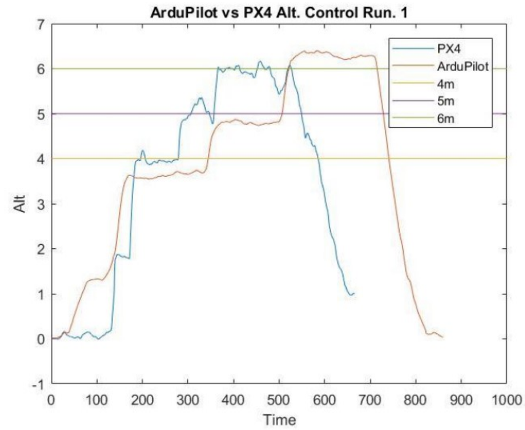


Figure 2.49: Altitude Control Ardupilot vs PX4

- *Battery Management*
  Ardupilot consumes more battery in-flight. PX4 was marginally better, can have a longer flight time, means that there is a distinct difference between the 2 software in terms of how the sensors communicate between each other.

Table 2.7: Final Results

Qualitative Test	**ArduPilot**	**PX4**
Hardware Compatibility	X	
Licensing		X
Partner Companies		X
User Experience	X	
Quantitative Test	**ArduPilot**	**PX4**
Flight Path Accuracy		X
Flight Path Time		X
Altitude Control		X
Loiter	X	
Return to Launch		X
Battery Management		X

Conclusion

With all qualitative and quantitative results considered, it is observed in table 2.7 that the PX4 is superior in almost all fields, having higher positional accuracy, being faster as well as being more efficient in battery usage. The loiter function would be crucial for the collection of water, where fluctuation in height may cause the sampling device to emerge from the body of water. In fig. 2.49 it can be seen that the PX4 causes more fluctuation in altitude thus being more undesirable, however alteration in the altitude control with the guidance of the online community can increase its accuracy and performance. Overall, the Pixhawk 4 flight controller will be chosen as the desired flight controller as it has many features, as seen in table 2.4, as well as being light weight, having superior performance and having a larger active community which can be utilised for future development of the flight controller.

2.2.2.2 Navigation System

Author: Aaron Su

Definition

Navigation System (NS): The process of data acquisition, data analysis, and extraction and inference of information about the vehicle's states and its surrounding environment with the objective of accomplishing assigned missions successfully and safely. [215].

Adopting Kendoul's [215] framework, the main functions of a navigation system for enabling autonomy, from lower to higher level, can be classified as Sensing, State Estimation and Perception as shown in fig. 2.50. This also represents the order of implementation when building an autonomous UAV application as lower level functions are commonly required as building blocks towards higher level autonomy. While countless technologies exist for navigation purpose, in this section, with reference to the requirement and limitation of portable water sampling application in developing countries, review is focusing on technologies that can be self-contained by UAV with limited external infrastructure or system needed.

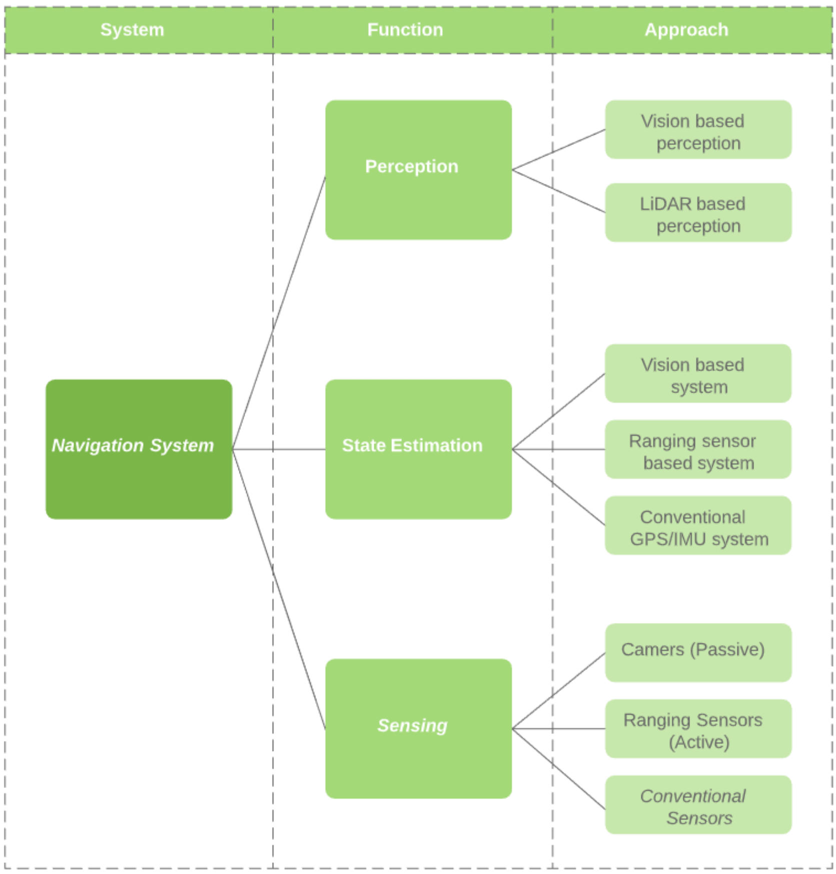


Figure 2.50: Classification of Navigation Systems

2.2.2.2.1 Sensing

Sensing is the first and lowest level functions of a navigation system. Technologies related to sensing generally involve the actual sensory device (hardware) and the mechanism/algorithm that respond to physical phenomenon or stimulus and enable the data acquisition process for the corresponding type of information. This is the fundamental functions required for application in any autonomy level, such as state estimation and perception.

An overview of the sensing technologies commonly used for UAV and a general analysis of their characteristics are presented in this section. These technologies include the conventional sensors that usually perform dead reckoning to estimate pose, and active ranging sensors and passive vision sensors (camera) that are also capable of mapping. The analysis will focus on market available sensing technologies. Detailed description of the mechanism and the state-of-the-art in research and development of these technologies are out of the scope of this survey.

Conventional Sensors

Conventional sensors are sensors that typically represent the minimum configuration for state estimation of UAS, including IMU (three gyroscopes, three accelerometers, and three magnetometers), global navigation satellite system (GNSS) and a barometric altimeter for attitude, position/velocity and height estimation respectively. Advancement in miniature technology has made a compact integration of GPS/IMU/altimeter possible, within an affordable price range. Therefore, they are employed in most of the commercial UAS nowadays.

The Inertial Measurement Unity (IMU), the core component of widely used Inertial Navigation System (INS), is an integrated sensor package that combines three orthogonal accelerometers, gyroscopes and sometimes magnetometer to produce a three-dimensional measurement of both specific force, angular rate and orientation for pose estimation Inertial-based sensors typically have high short-term precision. However, it is prone to suffer drifting readings due to its dead reckoning nature [**?**].

On the other hand, global localisation systems, such as global navigation satellite system (GNSS) and barometric altimeter [248] can be employed to assist IMU in generating state estimation with long-term precision. Although these systems can produce estimation of global position, they often lack accuracy, update rate or are easily affected by environmental change, e.g. indoor or dense urban area [249].

As INS and GNSS thrive in short term and long-term precision respectively, it is therefore a wise choice to integrate their complementary characteristics [205, 250–252]. Indeed, their integration with algorithm such as Kalman Filter [248,251,253] or automated tuning [254] has been dominant since 1990s, which results in substantial enhancement in pose estimation.

Ranging Sensors (Active)
Active ranging sensors typically involve wave emitting mechanism which is often referred to the concept of time-of-flight (ToF) sensing. Two types of ranging sensors are commonly used in UAS, namely sonic sensors (sonar) and optical sensors. Although the operation principle for both type of sensors remains conceptually similar, the differences in the media of their wave transmission result in their distinct characteristics.

Sonar
Sonar, also known as ultrasonic sensor, relies on emitting high frequency (40kHz upward) pressure waves and measuring the time taken for the wave to return to a receiver. Because of its ease of use and relative affordability, sonar is very popular among robotic applications. Although its range is mostly hardware-dependent, it is generally limited to 6m detection range as the resolution can rapidly decrease and become unreliable [255]. The use of sonar sensor is highly environment and application dependent, as angled object can redirect the pulse and lead to false readings. The change in pressure, wind speed, altitude and temperature can also alter the speed of sound and hence produce biased result. So far, sonar is mainly used in indoor application because of its limited range, high latency, and noise sensitivity. However, sonar can be particularly useful in proximity sensing for feature-less and optically reflective surface such as water surface.

Infra-Red
Infrared proximity sensors, similar to sonar, consist a transmitter and receiver to measure distance. A pair of LEDs are used to emit light and a phototransistor acts as a sensor to receive it. Although IR range sensors have many advantages such as being robust, requiring low power and being lightweight and compact, the detection range is very limited (1-5 m) and becomes less reliable at further distances. Due to its beneficial SWaP characteristics, IR sensors are often employed in an arrays structure to enhance their coverage. However, because the sun's radiation emitting IR, it is more preferable in low light conditions, such as smoked-filled or hazy environment.

LiDAR
LiDAR (light detection and ranging) is a ToF sensor that relies on coherent beams, where the intensity is dependent on the how reflective the surrounding objects are. Since LiDAR's are dependent on reflectiveness, utilising the phase shift between transmitted and received signals to provide 2D or 3D readings, external light sources such as sunlight may affect readings. LiDAR also consumes a considerable amount of power, compared to the pervious ToF sensors, as the sensing results in large data sets introduce high processing loads. Traditional LiDARs are power intensive and bulky, however miniature LiDars are more suitable for drone applications as they are more light weight and cheaper however they have smaller range, less accurate and are more sensitive to external light.

Cameras (Passive)
There are many types of imaging sensor cameras commonly used on UAV, such as monocular, stereo, thermal imaging and RGB-D cameras. These cameras work in unison with

computer vision programs in order to map surroundings, object track and detect as well as many other functions. Vision based navigation is rising in popularity as it is compact and requires less power compared to other methods, such as ultrasound and laser. Cameras provide information of surroundings, the motion of the vehicle, colour etc. however, cameras are sensitive to ambient light and scene texture. Also, due to cameras providing rich information, complex image processing algorithms would be required to perform real-time analysis on on-board microprocessors which can be computationally expensive, as other functions would run simultaneously. Furthermore, the field of view of a single camera is very limited for a UAV, the implementation of fish-eye lenses, EO sensors or multiple cameras will allow the UAV to fly through more dynamic environments at the cost of more computational power.

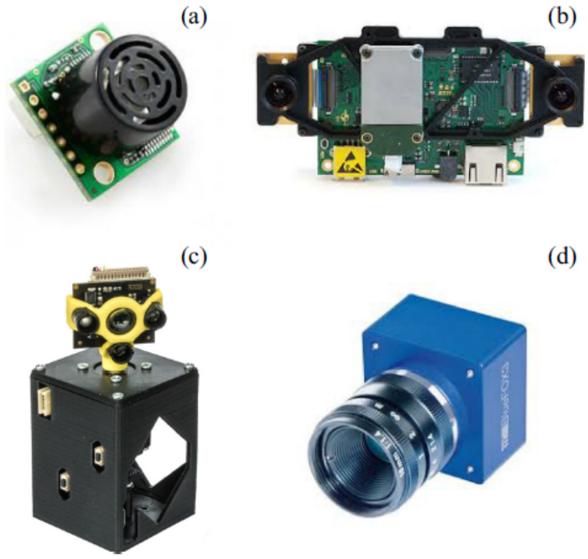


Figure 2.51: (a) ultrasonic sensor , (b) stereo camera, (c) LiDAR and(d) monocular camera. [26]

Sensors Fusion

Sensor fusion involve the process of data and information acquisition, filtering, correlation, comparison, association, and combination/integration [219]. As discussed for conventional sensors, sensors fusion is often applied to enhance the accuracy and reliability of the resulting estimation by continuous refinement. Different type of fusion were proposed in research, including fusion of conventional sensors with ranging sensor, conventional sensor with cameras, and even ranging sensors with cameras, which typically utilise various forms of Kalman Filter [256].

LiDAR can be integrated with IMU to provide robust and efficient indoor mapping and localization [257], or further integrated with GNSS to transit between indoor and outdoor avigation with a hybrid scan matching algorithm, achieving efficiency and robustness [258]. Camera can be incorporated with IMU [259] for outdoor operation, leading to reduction in payload mass and energy consumption. This fusion can also provide accuracy state estimation [260] as well as obstacle avoidance [261] due to the fast update frequency and rich information. There are also studies that propose an integration of camera and laser to enable flexible navigation strategies are required for safe and reliable operation [262]. Overall, sensor fusion technologies are highly dependent on the requirements of application, detailed algorithms are beyond the scope of this section.

2.2.2.2.2 State Estimation

State estimation for RUAS is defined as the process of tracking the vehicles 3D pose which could be relative to a frame or from an initial position. Generally state estimation is important for the development of flight control and autonomous UAVs as it forms the basis of tracking the vehicle. Typically, state estimation algorithms involve fusing data from various sources (onboard sensors, maps, etc). State estimation algorithms can be classified into three main categories based on the sensing technology. 1) conventional systems, 2) systems that rely on active ranging sensors and 3) vision-based sensors.

Note that algorithms allowing both localization and mapping at the same time (e.g. SLAM) are analysed in the perception section as these algorithms generally rely on the understanding of environment and hence is more tightly associated with higher level of autonomy.

Conventional IMU/GPS systems

UAVs normally rely on an onboard IMU and a GNSS module such as a GPS to provide the flight controller with altitude and position readings. An extended Kalman filter (EKF) is able to provide data fusion with different sensors to estimate the pose of the UAV. The pose can be estimated using one filter with all the state variables [263, 264] or by two cascaded EKFs [265], one for altitude and heading estimation and the other for position and velocity estimations. As the estimation for different states can be enhanced by incorporating more sensors. Height estimations can be further improved by incorporating altimeter measurements into the estimation process via fusing the reading into EKF or using another Kalman filter that fuses altimeter readings with vertical acceleration. Other alternatives for sensors data fusion include particle filters and complementary filters [266], but are less popular.

One disadvantage of GNSS-based navigation is its dependency on existing signals from satellites. There is a need to have a support and backup system in the event that GNSS readings are not available. Rural and wilderness areas may be denied GNSS signals that are needed for this form of navigation and therefore a backup system would need to be developed.

Ranging sensors based

Although active range sensors such as LiDARS, radars, ultrasonic and IR have generally been solutions for the perception component of navigation, the outputs from these sensors can be used for state estimation for flight controllers.

Ultrasonic and Infrared Sensors Based

Both ultrasonic and infrared sensors are designed for sensing obstacles normal to the direction of their emitting pulse, hence, three of each can be arranged perpendicularly to obtain its relative position within a confined space. Because of their relative limited detection range, their applications are commonly constrained to an indoor environment such as indoor hovering, take-off and landing [267]. Some outdoor applications were proposed by researcher such as stabilization and precise landing on small objects [268] and obstacle avoidance [269].

LiDAR

Similar to IR sensor, LiDAR can provide estimation of UAV's relative position through the ToF mechanism, however, in 2D or 3D rather than a single point. Thus, LiDAR is commonly used with Simultaneous Localization and Mapping (SLAM) algorithm to also provide understanding of the environment and thus will be discussed in the next section (perception).

Vision-based

Vision based systems are passive and are generally cost effective and draw very little power. The components needed for vision-based systems are small in size and have a low weight and can be easily incorporated into a UAV system with little adverse effect. Computer vision form the perception component of navigation and can be incorporated into state estimation for the flight controller. In this section, the most commonly used vision-based approaches and algorithms applied for UAVs state estimation without a map, also known as visual odometry (VO) is reviewed. This include the optical flow method and feature tracking method.

Bio-inspired Optic Flow

Bio-inspired image-processing can be used for visual guidance, this is known as optical flow. Through optical flow the translations and rotation in a series of consecutive images can be detected. This method of navigation was derived from flying insect's vision for navigation. The process can be described as the apparent visual motion seen by a moving observer. The motion is then perceived by the eye as a vector field representing angular speed of the object moving by the observer [270].

Figure 2.52: Optical flow from image sequence [29]

A limitation of any vision-based system is that it becomes highly dependent on the visual scene. Problems arise when there are adverse lighting conditions (glare/shadow etc), lack of distinct features or weather conditions can negatively affect the performance of this system. This as a result would limit the UAVs utility and restrict its operating range. Optic-flow navigation systems are computationally intensive and could result with latency for the onboard computer. Optical flow may also be constrained by the bandwidth of the input visual data [271] as higher input frequency is needed for UAV in order to account for aliasing/ error in data. Recently developments to optical flow solutions [272] have incorporated inertial measurements unit (IMU) with the optical flow measurements [273] to achieve UAV movement estimation and navigation.

Feature-based
In featured-based VO, the UAVs position relative to the internial or a known location is computed via integrating over time in the flow distances. The distance measurements are obtained via tracking visual features in an unknown environment using an imaging system. A typical VO algorithm can be broken down into the following components:

1) Detection of distinct features that can be tracked across successive images.
2) Feature correspondence or tracking between consecutive images.
3) Motion parameter estimation using feature correspondences.

The VO algorithm will need to compute a scale factor to determine the UAVs position and velocity. Error due to drift while travelling is another problem that will need to be addressed when using a VO-based system. This can be overcome by using IMU measurements to compensate for the rotation effects and drift to improve the estimation accuracy and robustness. Feature-based visual odometers that are based on monocular [274, 275], stereo [276], fisheye [277] and RGB-D [278] vision were proposed.

2.2.2.2.3 Perception

Perception capabilities typically involve environment mapping, obstacle detection and avoidance, target recognition and tracking. The ability to perform these tasks in real-time is essential for reaching autonomy level of 4. Two types of technologies are commonly used in contemporary perception applications, namely passive approach that mainly relies on cameras and active approach that involve range sensor such as LiDAR. In this section, perception systems are divided into (1) vision-based perception (passive) and (2) LIDAR-based perception (active). Algorithms within each category that enable various perception functionality are reviewed.

LiDAR-based
LiDAR is able of processing and providing accurate information of the surrounding environment with low computational power. Although it is computationally sound, LiDAR's have heavy power consumption as well as having higher weights which will significantly affect its mechanical performance. However, recently the miniaturisation of LiDAR sensors have been developed and are currently used on miniature quadroator UAS as their main perception sensor.

SLAM
LiDAR-based Simultaneous Localization and Mapping (SLAM), one of the most popular methods for robot perception, allows for precise estimation of UAV position through spatial relations between the vehicle and environment, thus providing functions of state estimation and perception at same time. Currently most studies conducted using LiDAR are with 2D scanning capabilities, where the reflection of the laser off the ground allows for height estimations. The position and velocity of the UAV can be estimated through the fusion of the IMU data and the pose estimation through Extended Kalman Filter (EFK).

Variants of SLAM for special purposes exist, such as Simultaneous Mapping and Planning (SMAP) that oriented towards obstacle detection and avoidance and Safe Landing Area Detection (SLAD) for precision landing. It utilises perception systems that simultaneously performing mapping and planning to overall build an environment. In addition to the utility that SLAM provide, SMAP also plan its obstacle-free path for exploration and goal-oriented navigation. SLAD on the other hand focus on safe landing area selection in challenging terrains. Compared to visual SLAD, LiDAR-based SLAD excels at providing accurate measurement in texture-less environments, complex terrains, or poor lighting conditions.

LiDAR and SLAM algorithms are successfully implemented in ground vehicles and indoor UAVs [279, 280] however not for outdoor devices without the aid of GNSS. This is due to large open environments often not have sufficient information to provide relative positional estimates.

Vision-based

As discussed in previous section, compared to the GNSS, LiDAR, ultrasonic sensors, and IR sensors, visual sensors can get abundant information of the environment. Meanwhile, they are relatively cheap with great SWaP characteristics. Therefore, vision-based perception has becoming a hot spot in the field of UAV navigation.

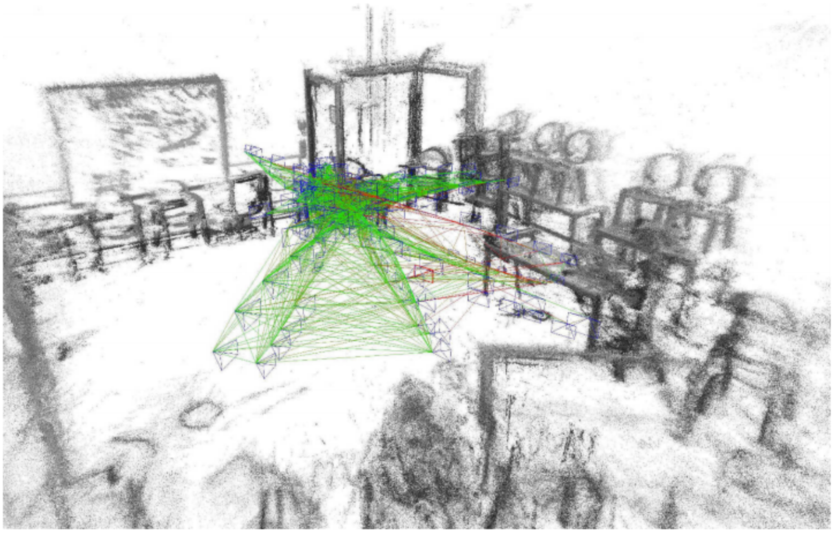


Figure 2.53: Visual SLAM [30]

SLAM

Map building systems have recently undergone a massive development due a interest in visual simultaneous localisation and mapping techniques (SLAM) [281]. As UAVs are decreasing in size, there is a need to limit the number of onboard peripherals required for perception. Traditionally, large complex systems such as laser radar and sonar were used but slowly are being phased out in commercial applications and replaced with simple cameras for perception. Due to the popularity in research, three types of methods were derived according to the image processing method, namely, indirect method, direct method, and hybrid method.

Indirect method extracts features from images for motion estimation and localization procedures. It commonly reconstructs only specific set of points to build a sparse scene map and hence requires low computational power, however, suffers from texture-less environment. Direct method on the other hand optimizes geometry parameters by analysing the entire image to find dense correspondences. Hence, it is robust under various images distortions at the cost of computational power. Therefore, a hybrid method that combine the advantages of two methods by applying them in a sequential manner, producing faster and more accurate result with smart-phone level processor. The main constraint is that a high frame rate camera is required therefore limits its use for onboard processing.

Obstacle detection and avoidance

Obstacle avoidance is a necessary part for autonomous navigation. With an inbuilt system to ensure that the UAV can avoid collision reliably, this can increase the level of autonomy. The basic principle for perception-based obstacle detection and avoidance is to first detect the obstacle and then compute the necessary action to avoid and steer clear away from the threat. The two main methods of obstacle detection currently used is SLAM based methods and optical flow methods.

In addition to state estimation, variants of optical flow algorithm that learn from insect behaviour can also estimate obstacle present in the images by identifying the corresponding light flow signal of obstacles. This allow UAV to recognise a direction where obstacles can be passed safely, known as a reactive approach.

A flaw of optical flow-based method is that it cannot determine distance to the object, this may pose a risk solely depending on this method for obstacle detection. SLAM methods on the other hand provide the UAV with a map of the environment, but in order to generate this map would require high computation power and reflection time [282].

Target tracking
Target tracking is currently an important research topic for micro and small UAVs. As micro and small UAVs are often used for targeted search and tracking tasks as their stability and high manoeuvrability optimises them for use.

Target tracking often involve a combination of computer vision technology and control vision technology. Traditionally, methods such as Mean Shift, Particle Filter and Kalman Filter, and Optical Flow algorithms based on feature point were used. However, due to the emergence of correlation filter (CF) and deep learning tracking methods, classical tracking methods have been gradually sifted out [283]. Currently, popular target tracking methods can be categorised into generative tracking and discriminative tracking.

The discriminative methods that train the classifier to distinguish the target and the background are argued to be more robust than generative method. CF based and deep learning-based tracking algorithms are some of the most current development of the discriminative methods. Although deep learning method has powerful model learning ability, better feature expression ability and the ability to acquire high-level semantic information, it often requires large training data and heavy computation burden. Meanwhile, CF is more suitable in the field of UAV visual tracking due to its fast computation speed in Fourier domain, simultaneous detection and positioning.

2.2.2.3 Guidance System

Definition

Guidance System: A system can be defined as the "driver" of a RUAS that exercises planning and decision-making functions to achieve assigned missions or goals. The role of a guidance system for RUAS is to replace the cognitive processes of a human pilot and operator. It takes inputs from the navigation system and uses targeting information (mission goals) to make appropriate decisions at its high level and to generate reference trajectories and commands for the AFCS at its low level [215]

The two main functions of a guidance system for enabling autonomy, from lower to higher level, can be classified as Path Planning and Mission Planning as shown in fig. 2.54. Numerous methods for path planning exist for UAVs, however, very limited study in mission planing for small size UAV can be found. Therefore, methods that are generally useful in performing mission planning tasks in robotics are considered.

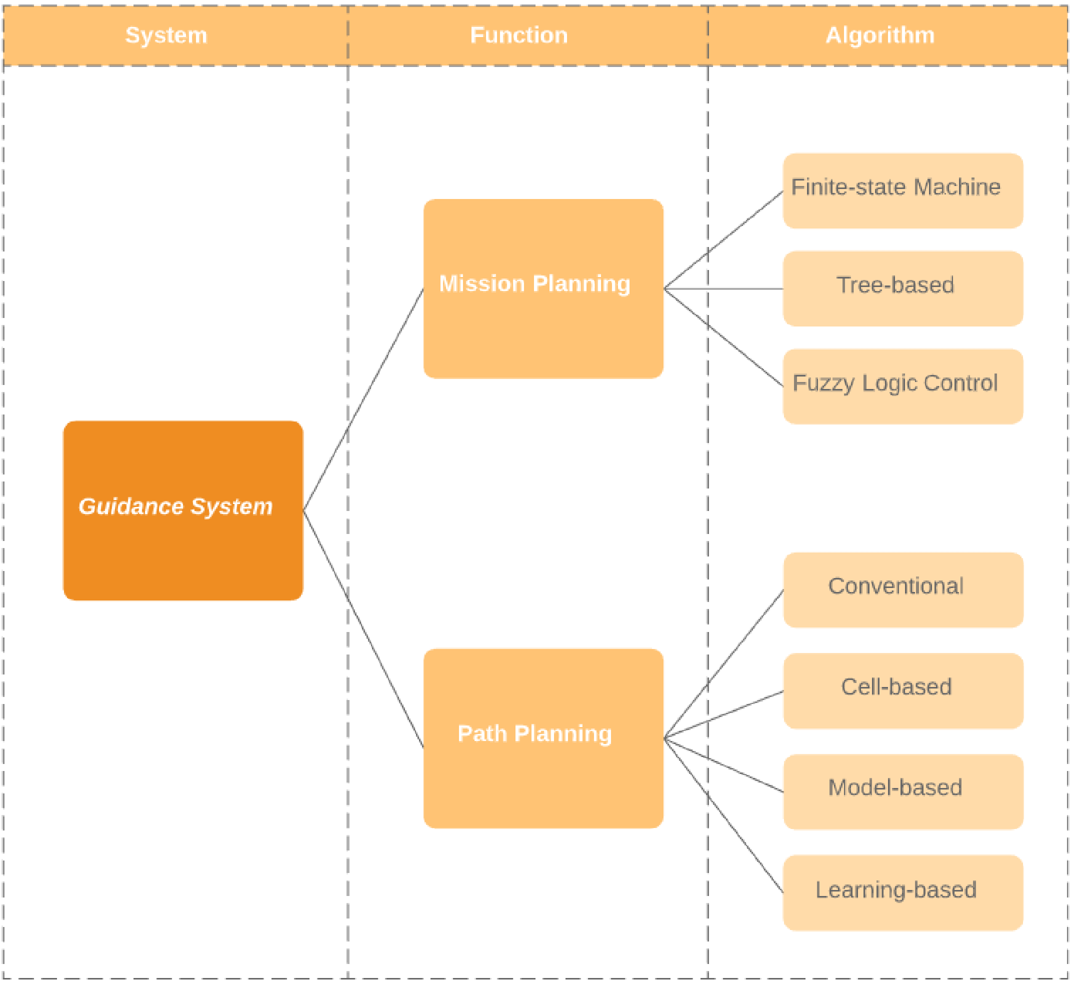


Figure 2.54: Classification of Guidance Systems

2.2.2.3.1 Path Planning

Path planning algorithms have always been in active research especially in the fields of robotics. Numerous path planning algorithms have been proposed for various operating conditions and there is no way to best describe the distinction among these algorithms using a single classification method. As these algorithms are constantly evolving, it is reasonable to utilize a recent framework proposed by Amarat et al [284] to help survey the state-of-the-art path planning developments and extract more relevant ones for target application (aerial water sampling) for deeper analysis.

In Amarat's study, the most recent development of path planning algorithms can be classified into conventional, cell-based, model-based, learning-based and hybrid as shown in the figure below. He also summarizes that, by comparison, conventional and cell-based algorithms have the advantages of fast convergence and easy implementation but lack of adaptiveness, whereas model-based provide optimal solution but too complex to work in real-time and similar to learning-based, which requires huge computational power and not suited for small size application such as UAV.

Therefore, conventional and cell-based path planning are the optimal options for micro-UAVs (MAVs). Within these categories, there is also a need for dynamic planning as global map is most likely not provided or dynamic obstacles would interrupt the operations. Hence, four types of simple but powerful algorithms that are commonly used in MAV dynamic path planning are reviewed, including D-star, Potential Field, the PRM series and the RRT series.Under each of these categories, numerous variants of each algorithm have been proposed in the last decade and therefore cannot be listed extatically. In this section, as a constructed global map is commonly not present in application such as aerial water sampling, the most popular algorithms used in single UAV dynamic path planning is reviewed.

D-Star (D)*

D* algorithm developed Stentz [285] is the dynamic version of A* algorithm. These algorithms are also known as heuristic search algorithm that aim to find the shortest path by creating a chronological map. On top of A*, D* can deal with partially or completely unknow dynamic environment by continuously update the map. D* algorithm provide sufficiently good performance at low computational cost. However, due to the its simplicity, a UAV path planning system that solely depends on D* might not be robust enough in more complex environment.

Potential Field

Potential Field algorithm convert the vehicle into a particle in a force field, where the goals generate attractive force and obstacle with repulsive force, aiming at leading the vehicle towards the goal while avoiding obstacles. This algorithm is characterised by its low computational complexity, however, has many drawbacks such as a high risk of converge to local minima and oscillating path in narrow regions [286].

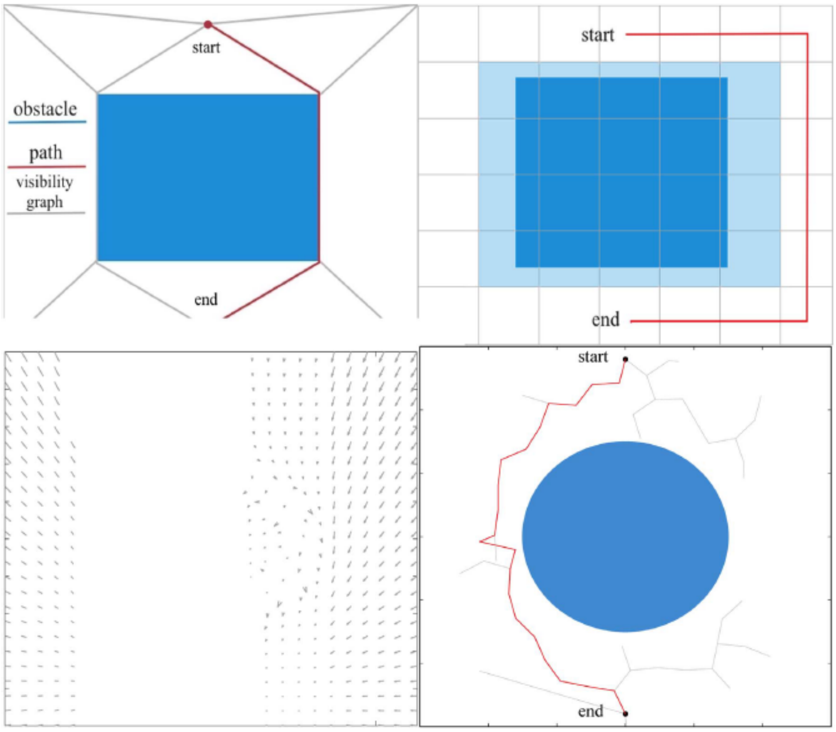


Figure 2.55: (top left) visibility graph, (top right) A* algorithm, (bottom left) potential-field and(bottom right) RRT algorithm. [26]

Probabilistic Road Map (PRM) series
Over the past decade, randomised-search algorithms have become popular in solving high dimensional planning problem [287]. PRM is first proposed by Kavraki and Latombe [288] which uses random sampling and discretization to generate states of continuous space, and then create a road map for shortest path. This algorithm is well suited for 3D environment planning due to its fast exploration performance in high dimensional space, however, is prone to be inefficient for narrow confined spaces and dynamic obstacles [215].

Rapidly Exploring Random Tree (RRT) series
Similar to PRM, RRT is also a heuristic randomization-based approach, first introduced by Lavalle [289], and have lots of recent developments [290, 291]. The distinction from PRM is that instead of randomly sampling the configuration space, RRT begins at a start location and randomly expands a graph or tree [215]. It outperforms PRM in high-dimensional space for efficiency and the ability to deals with dynamic obstacles or constraints, therefore, is most suited for autonomous MAVs. The only drawback due to its nature as a randomised planner, where only sub-optimal path can be generated from stochastic sampling [287].

Hybrid algorithms
In most of real-world applications, multiple layers of planning are often required [292–

294] and algorithms are often combined or tailored to the specific environment of the application [295], such as combine 3D PRM with A* [296], or Dijkstra's with visibility graph [297]. Therefore, to develop a path planner with robust performance, hybrid algorithm that combine forms of global and local planning algorithm is usually recommended.

In addition, to achieve a smooth control flow for UAV as shown in the figure, processes such as path smoothing, and following strategies are also to be considered. However, due to the inborn high manoeuvrability of RUAS and the minimal environmental complexity presented in the target region (Yamuna River), detailed analysis of these algorithms is out of the preliminary scope. On the other hand, comprehensive reviews for robotic path smoothing [298, 299] and UAV path following [300] have been presented and will provide reference for improvement of the system.

2.2.2.3.2 Mission Planning

Mission planning is often referred to as contextual intelligence. These can involve determining robot's behaviour such as exploring unknow environment [301], target tracking [302], waypoint navigation [303] and other vehicle actions (e.g. payload manipulations). In the context of UAV autonomy, this is the high-level planner for evaluating current situation and redefining the desired operation strategically. The assessment of situations typically includes mission-critical data, civil-aviation rules and regulations, time-varying environmental features and cost/reward of each plan/policy.

Due to the high complexity and high-level reasoning requirement, mission planning in recent year for commercial system is still mostly performed by human or with the complex multi-layer planning system that is particular tailored for each individual application, such as Apex developed by NASA [304], and were mostly used in robotic helicopters. In the field of MAVs, these methods would be considered too complex and not necessary for single purpose MAV. Therefore, simple decision-making algorithms are sufficient for most streamline MAV operation. The most commonly used decision-making algorithms in MAV include finite state machine, fuzzy-logic, and a recent developed tree-based framework [305].

Finite-state machines

Finite-state machines are commonly used for robotics and artificial intelligence where state and behaviour are modelled to help define a policy that maximise a reward [306]. A typical implementation is to combine with Markov-decision process and allow agent to deal with stochastic environment [307]. This algorithm has been successfully applied in several UAV applications [31, 308].

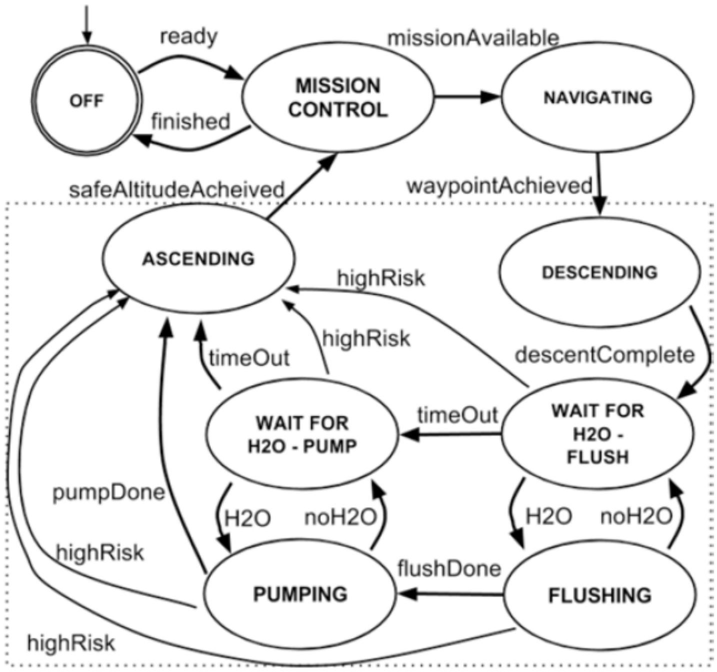


Figure 2.56: Finite-state Machine for aerial water sampling [31]

Tree-base
A tree-based mission planning method was introduced by Molina et al [305] that is built on the TML language developed by the same team. This language/algorithm convert each task into nodes in a tree-like structure that can be easily understood and edited by operator and thrive in handling parallel tasks. The framework also provides many utilities such as manager of actions and skills, action monitor, event detector and problem manager, and was successfully implemented in MAV for search and rescue mission [294].

Fuzzy-logic control
Fuzzy-logic control is also useful in mission planning due to its ability to mimic reasoning of human from rules modelled by linguistic representations. However, limited study has apply this in MAV operation [309].

Overall, although large study has been carried out for mission planning in large scale intelligent applications such as traffic control, it remains a frontier research area for mission planning implementation on MAVs. This is because the majority of MAVs applications is limited to simplified operation procedure without strategic re-planning required.

2.2.2.4 Water Sampling System

Author: Anthony Leung

2.2.2.4.1 Water Detection

Drones have been widely used for sampling in aquatic environments and have subsided many health risks compared to physical sampling by humans. The most common form is utilising a sampling bottle that is held at an aerial distance [310]. This sampling bottle is dangled by string and is completely mechanical, utilising either gravity or entrapment systems to withhold water inside the bottle which has been explored in section 2.1.3. An alternative method is to utilise drones that have the ability to perform both in air and on the surface of the water. This has been successfully been achieved with the UAV with floating attachments, giving buoyancy for the vehicle to land on water [311]. Both forms are able to retrieve water samples in their environment at a surface level.

Specific to the chosen location of Yamuna River is the characteristics of foam within its water. This has potential affects in the drones ability to retrieve water samples due to incorrect detection of its altitude, leading it to capture samples of foam rather than water. Effectively, some drones have been designed to be equipped with time-of-flight, temperature, pressure and conductivity sensors to identify the position of the vehicle's altitude an allow accurate depth measurements [310, 312]. This can be particularly useful in conditions in the Yamuna River, were foams are produced dependant on seasonal changes. With the ability to detect the water body's surface and the depth, the UAV can potentially reduce its issue of a mistaken aquatic sample.

To legitimately detect a water body and reduce the risk of capturing improper samples, a pressure or liquid level sensor unit must be incorporated into the drone design. Although the purposes of this chapter is to identify and determine water level of the sampling device, it has the potential applications such as an in-situ readings, which are valuable insights to water quality.

Liquid level

Liquid level sensors can be categorized by either pneumatic, optical or conductive. In table 2.8 it shows the difference of each liquid level sensor, surveyed from websites [51,52]. Each type of liquid level is compared with its ability to measure water levels, indicate foam or water, its compactness and whether it is relatively low in cost.

Table 2.8: Sensor types and features [51, 52]

Sensor	Description	Water Level	Foam indicator	Water indicator	Compact	Low cost	Comments
Pneumatic	Using a floating mechanism, this sensor measures depth by the difference in its equilibrium point. A shaft is wrapped with a buoyant cone that allows it to raise as it is pulled deeper into the water's body.	X				X	
Optical	Using light refraction measurements within a cone, this sensor detects the amount of light that has permeated into the water's body.		X	X	X		Life of 50,000 hours – durable.
Conductive	Using the conductivity of the water's body, this sensor completes an electric circuit when too electrodes meet due to the conductivity of the water.	X	X	X		X	
Ultrasonic	Uses the frequency of sound waves that are reflected from a surface back to the sensor. Different mediums will reflect different lengths of time.		X	X	X		This requires a fixed distance object away from sensor to detect mediums.

Conductive sensors are the cheapest of the range being as low as $5.51. Although cost effective, this sensor will not be able to perform accurately in the detection of water due to the characteristics of the foam. The foam in Yamuna River has heavy metals as indicated in [313] and since the sensor is based on its ability to conduct, the sensor may detect foam readings as water.

Pneumatic sensors rely on the device to be afloat in water, however in the Yamuna River this cannot be guaranteed to be the condition. Although pneumatic/float sensors are relatively cost effective with the range of sensors starting at $7.47 on Element 14 [314], this light weight and low power consumption device will not provide viable accuracy of detecting the medium of water. The sensor may stay afloat in the foam and respond with invalid readings.

Ultrasonic sensors may be a viable option to the solution of detecting water. The Non-contact Digital Water Level Sensor made by DFRobot was compared for this application [315]. This sensor is usually externally used for airtight bottles that require a liquid level sensor. Whilst extremely practical, this device may need waterproofing. The sensor is costed at $9.90.

Optical sensors can simply identify a water body. At $13.18 on Element 14 [316] this sensor will be perfect for detecting the water body's surface in the Yamuna River. However affordable, this only produces either a HIGH or a LOW result dependant of being submerged in water or not. This may also be disturbed by light shining onto the optical device, skewing its readings. Therefore using an optical sensor may not be viable due to the environmental circumstances.

Pressure Sensor

Pressure sensors work by the effect of strain gouges and can be effective for the use of finding the depth of water. One suitable product for detecting the accuracy in depth of water is the MS580301BA01-00 Pressure Sensor, detecting measurements of up to 1 bar, with absolute increments of 1.5 mbar. 1.5 mbar translates to approximately 1.5mm of water for accuracy and 1 bar translates to approximate 10 meters of water, which is perfect for the desired application in detecting water for up to 10 meters in depth. Furthermore, this sensor operates at 3V and 1uA, which is extremely low power for the uses of the drone. The complete sensor costs $26.23 on Element 14 [**?**]. This sensor has also been the selection of choice by [312]. This is shown in fig. 2.57.

Figure 2.57: Pressure sensor [32]

2.2.3 Power System

Author: Anthony Leung

2.2.3.1 Direct & Auxiliary Power Sources

Power is essential to perform the functions of a UAV. Without management of power, UAV's are prone to spontaneously failing, have short duration missions or even be underpowered when needed most. The advancements of power sources has grown rapidly in the past decade to extend the duration of UAV's with new sources such as the Hydrogen Fuel Cell. This section will highlight sources that have been used to either generate, provide or extend power usage to UAV systems, touching upon Li-Ion batteries, Photovoltaics, Fuel Cells, Super-capacitors and hybrid combinations of those listed. A block diagram of how the power source is used in a typical UAV system is shown in fig. 2.58. The management of power, or interchangeably the 'battery' source is central to the whole electronic system.

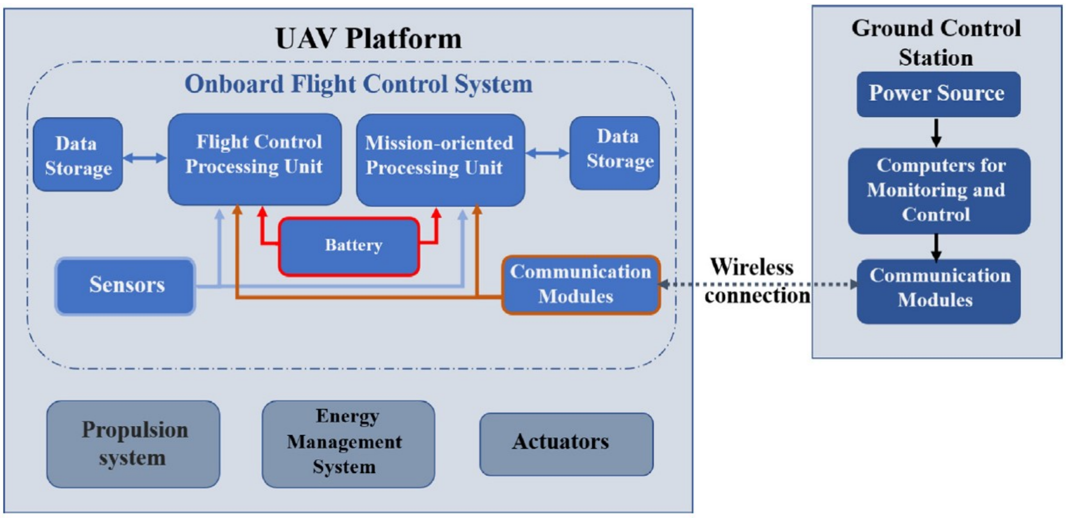


Figure 2.58: Block diagram of the power contribution towards the complete electronic system [33]

2.2.3.1.1 Li-Ion

Most drones utilise Lithium Ion batteries to operate with typically a Lithium Polymer (LiPo) battery which can only provide enough energy for 30 minutes [40, 42, 317–319]. LiPo batteries are characterized by a low 'gravimetric energy density'(or specific energy), which is the measurement of Watt hours per kilogram. A low gravimetric energy density means the system stores a low capacity of power per kilogram of weight. Alongside this, LiPo batteries have a fast discharge times and require long charging times [42]. To resolve this and extend operation times, often this would need additional LiPo sources however, this would increase battery size and resulting a larger effort to propel a UAV [319]. In fact, this direct relationship between the battery capacity need per weight has been graphed by [34] in fig. 2.59.

Figure 2.59: Relationship of capacity and battery weight [34]

Amongst the negative characteristics of current LiPo batteries, their uses have been advantageous for their fast discharge rates to induce an instantaneous current - propelling the UAV into flight as efficiently as possible. In fact, such papers adopting the newly advancements of fuel cells, still use some form of LiPo batteries [35, 40, 319] in their research and design - providing some outstanding results of flight performance. Fuel cells will be explored in the section of Fuel Cell. The advantages and disadvantages of LiPo batteries are summarised in table 2.9.

Table 2.9: LiPo battery advantages and disadvantages

Advantages	**Disadvantages**
- Instantaneous power for electrical devices, especially motor for propelling - Easily accessible for recharging	- Fast discharging rates resulting in up to only 30 minutes of operation - Requires constant recharging for multiple flights - Low gravimetric energy density, resulting in larger weights (kg) to store more capacity (Wh) - Slow charging

2.2.3.1.2 Solar Photovoltaic

Research into Solar Photovoltaics (PV) have been mostly applied to fixed wing UAV's, however more recently this has been adapted to large wingspan multi-rotor UAV's. Understanding how these systems operate may be beneficial in providing more efficient an environmental means of preserving the state of charge in batteries. These UAV's can be representative of the one shown in fig. 2.60. In most design cases, the PV is coupled with a LiPo battery to [36, 37, 320] recharge it on board.

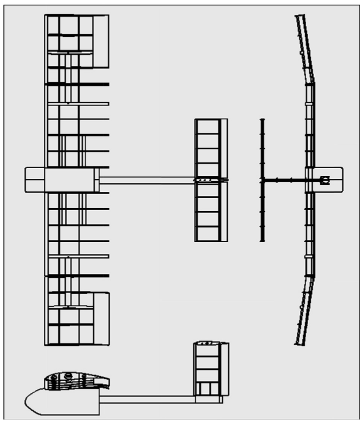


Figure 2.60: Three principle views of fixed wing UAV with an attached PV cell. [35]

To optimise angles to capture solar energy, several ideas have risen to capture sunlight through the optimum angles. The design found in [36], has contributed to research by developing a flight path algorithm to optimally attract the sun. The path of the UAV is in a slant 30 degree cylindrical shape. This is shown in the diagram of fig. 2.61.

Another design [37], had designed a Z-shaped wing to optimise the area to capture solar energy. In this design [320], the authors use learning algorithms to allow the UAV to understand its environment, improving knowledge of how to optimally capture energy capture solar energy.

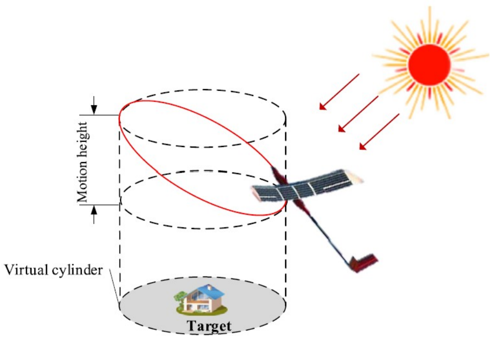


Figure 2.61: Flight path of for designed UAV to optimise sun's critical angle [36]

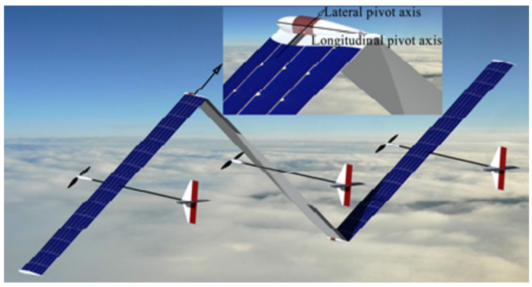


Figure 2.62: Z-shaped design of a fixed wing UAV [37]

Fully solar UAV's have been developed before by students of the National University of Singapore (NUS) and require no LiPo battery to function [38]. The drone occupies a surface area of $4m^2$, 148 individual solar cells and weighs 2.6kg. This is shown in fig. 2.63.

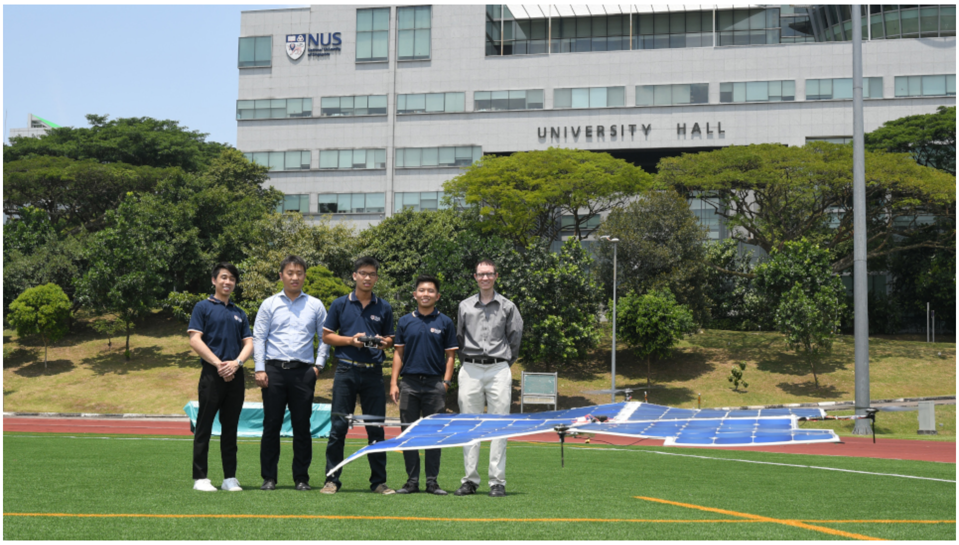


Figure 2.63: Solar quad-copter drone developed by NUS students [38].

Although various methods have been made for optimizing solar energy harvesting [36–38, 320], they are still limited by the amount of sun incident rays it can be exposed to. A summary of PV advantages and disadvantages have been outlined in table 2.10.

Table 2.10: PV advantages and disadvantages [33]

Advantages	**Disadvantages**
- Generates power through clean sources - Does not significantly affect aerodynamic efficiency	- Power generation is affected by temperature - PV are usually quite heavy - Expensive - Inefficient power output - Requires large surface areas - Affected by weather and day-night changes

2.2.3.1.3 Fuel Cell

Fuel Cell technology is currently the best long endurance power source for its ability to have a high gravimetric density (or specific power) [40]. High gravimetric densities allow a power source to last longer. The concept of fuel cells is by capturing the reaction from combining hydrogen and oxygen together, releasing a charge through the cathode and anode. This principle is shown in fig. 2.64 as hydrogen is fused with oxygen from the atmosphere, it releases an electric current. This is formally named as a Proton Exchange Membrane (PEM).

An additional advantage to this is within its process, being able to produce clean H2O along with its electrical potential. This technology has in fact been commercialised and optimised within these articles [40, 318, 319, 321–327].

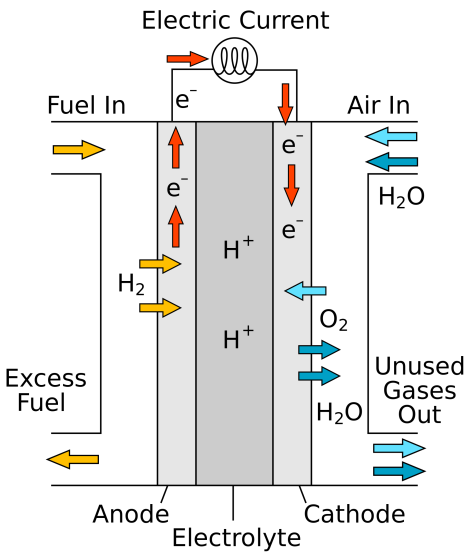


Figure 2.64: Diagram of a hydrogen fuel cell [39]

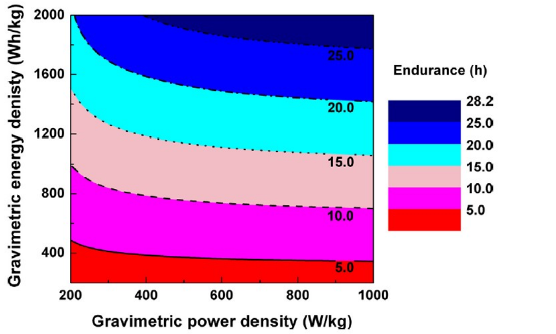


Figure 2.65: Gravimetric power and gravimetric energy densities for specific durations [40]

In 2018, companies such as Doosan and Protonex were able already able to produce PEM fuel cells that can store 600W, 1.2kW or 2.1kW [318, 324]. To use such a power source for UAV's, they often are coupled with a LiPo battery to produce the initial thrust. This is because fuel cells have a low specific power with its high specific energy; meaning it is provide a slow yet long lasting burst of power. Doosan's DP20 2.1kW system has a total system weight of 6.3kg and could give 2 hours of flight time for a UAV - compared to the standard 30min flights with just a LiPo battery [318]. In 2019, PEM fuel cells developed further to hold 2.4kW of power potential, by Intelligent Energy [322]. This power source had set the world record for having the first multirotor UAV to run for 12h, 7min and 5s with its 800W FCPM PEM battery.

Moreover, PEM fuel cells have the ability to run UAV's for more than the world record 12 hours in [40]. It was found that at gravimetric energy densities of more than 1800Wh/kg (600W/kg), UAV's have the ability to endure even longer distances and functioning for more than 24 hours. The conceptualised gravimetric energy and power density is graphed in fig. 2.65 by [40]. The UAV shown in fig. 2.66 displays how a typical fuel cell is mounted onto a quad-copter.

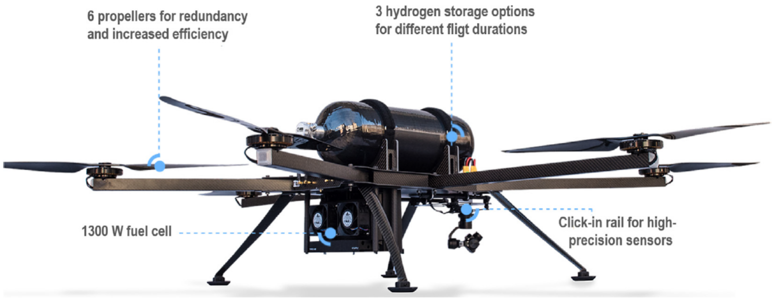


Figure 2.66: Hycopter: a hydrogen fuel cell quad-copter from HES [41]

A major disadvantage to using PEM fuel cells is their limited availability and expensive means of production. Fuel cell hydrogen is currently obtained from fossil fuel reforming and is quite demanding in its energy consumption requirements to produce hydrogen [328]. Currently technology is still being tested and examined to ensure the production of this energy source is cleaner, with experiments being conducted on $NaBH_4$ and MgH_2 [321, 328], however all of these sources have concluded with more research being needed for this area of study. A summary of PEM battery advantage and disadvantages are shown in table table 2.11.

Table 2.11: PEM fuel cell battery advantages and disadvantages

Advantages	**Disadvantages**
- Slow discharge, allowing it to power for longer periods - Fast refuel due to being a gas form - High gravimetric energy density, meaning it stores more power with less weight - Has the potential to power UAV's for 2, 14 or more than 24 hours depending on the select PEM fuel cell	- Hydrogen is not abundant and not easily accessible for recharging PEM fuel cells - A slow discharge rate means low instantaneous voltage/current, therefore it requires a LiPo battery for most takeoff on UAV's - Cost inefficient for both purchasing the battery and refueling of the battery - Hydrogen generation methods are currently a high impact to the environment and further research is required - Sizing can increase depending on power demands

2.2.3.1.4 Super-Capacitors

An auxiliary source of power is to use super-capacitors, given its ability to have fast charge and slow discharge rates. The system is typically coupled with a power supply, a LiPo battery that is then run through a circuit that prolongs the battery's useful life. This is represented in a block diagram shown in fig. 2.67.

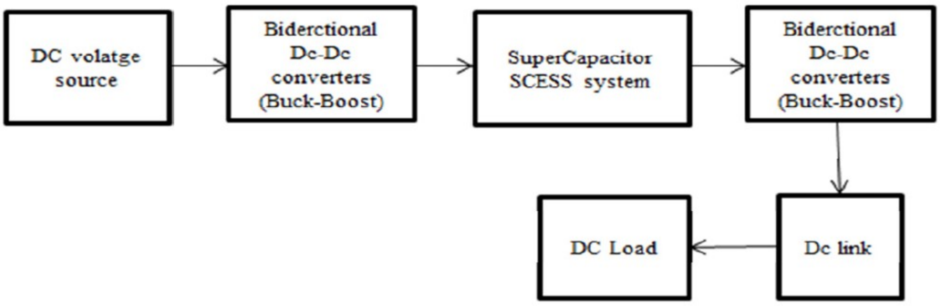


Figure 2.67: Block diagram of a typical circuit implementing a super-capacitor [42]

Using the polarization of an electrolyte solution, ions become separated and electrode are moved from layer to layer. The arrangement of such ions is shown in fig. 2.68.

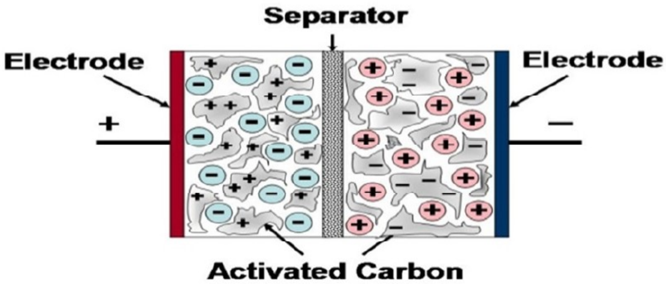


Figure 2.68: Diagram of a super-capacitor [42]

The advantages and disadvantages of super-capacitors are weighed in table 2.12. It is clear that the adoption of super-capacitors in a UAV system can be highly beneficial for improving performance with very little disadvantage, this has been proven by [41, 42] by simulation and experimentally.

Table 2.12: Super-capacitor advantages and disadvantages

Advantages	Disadvantages
- Charges within seconds to several minutes - Discharge time last several hours to a day - Twice as much power density than a LiPo battery - Extremely low energy density falling below 5 Wh/kg - Charging/Discharging efficiency from 85% to 98% - Cycle life measured in millions (LiPo is 200-1000) - Cost effective for its capability	- Requires an external supply of power

2.2.3.1.5 Hybrid Systems

Extending the features and capabilities of sources, hybrid systems are the most effective for prolonging flight duration's in terms of size, weight and efficiency. In [35], the authors adopted a hybrid power system to a fixed wing UAV which extended its flight time from 7.8 hours to 16.1 hours endurance. The system orients its power supply from a LiPo battery, fuel cell and a PV, managed by a Power Management System (PMS). The PMS is controlled with a micro-controller such as an Arduino, that switches supplies like so:

1. LiPo: For initial take off - giving a quick propulsive force
2. Solar PV: capturing solar energy when LiPo is not in use and utilised when solar energy is available
3. Hydrogen Fuel Cell: To supply consistent voltage throughout cruising phase when solar power is unavailable

The study also concluded of how operational costs and risks of damage can be reduced using this technology [35]. Furthermore, depending on weather conditions, PV power can add another 2 hours of endurance (65W to 116 W) to the UAV. In another design, this was coupled with super capacitor shown in fig. 2.69. The findings from this research found that the addition of a super-capacitor contributed in delivering peak power and power absorption during dynamic changes under different loading conditions [35].

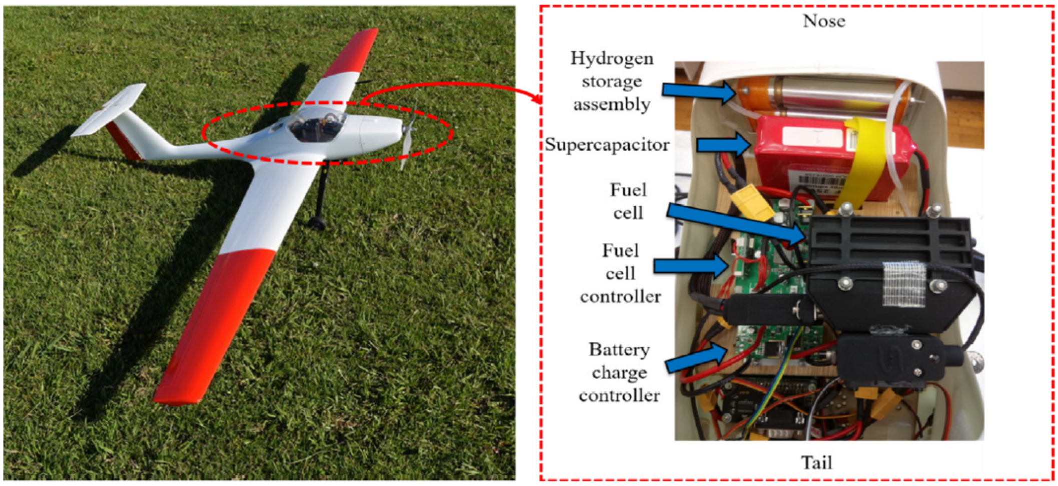


Figure 2.69: Hybrid UAV with PV, fuel cell, LiPo and a super-capacitor [41]

2.2.3.1.6 Remarks

Some other sources of power which were not considered within this research were Piezoelectric devices and Laser-beam in flight recharging [33, 41]. Although the piezoelectric effect can be useful in theory for harvesting electricity generated from vibrations of the UAV, Little to no direct research has been investigated for the implementation onto UAV's. This is potentially due to the restraints of standard piezoelectric devices, which can only provide in the range of milliwatts. This is extremely low for the application of drones as they require measurements of up to kilowatts [329]. Due to the low power output, Piezoelectric devices were not considered within this literature review.

Furthermore the notion of a laser-beam in-flight charging system is one that could power UAV's indefinitely [41]. It operates with a ground station concentrating a laser beam to the UAV and it would charge as it operates. The drawback of this solution is that the UAV's must fly at low-altitudes within sight. However useful, this was out of scope for the project of Water Quality Sampling as the design neither needs to last indefinitely or be able to fly within sight at all times. Thus, laser-beam in-flight designs were not scoped in-depth in this study.

2.2.3.2 Energy Management System (EMS)

To manage the entire system for power, it involves a Battery and a Power Management system. A Battery Management System (BMS) is one that is responsible for monitoring the usage of power, providing readings of voltage, current and the remaining useful life. A Power Management System (PMS) facilitates the switching of power sources within a hybrid battery system. Together, this makes the Energy Management System (EMS) and how it is connected to the propulsion system is shown in 2.70.This section will focus on prognostics and how to prolong the effective use of typical power sources for UAV's.

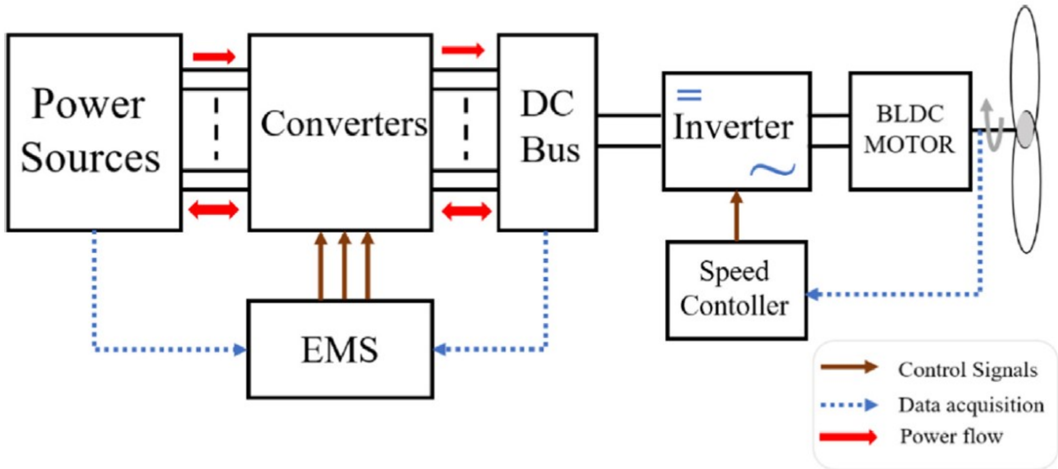


Figure 2.70: Block diagram of EMS within propulsion system [33]

Monitoring the usage of power is important in ensuring enough power is reserved for take-off, cruising and landing when operating the UAV. This is important for the UAV as it reflects how the system will respond under preturbances and work under increasingly heavier payloads. Voltage and current are the typical parameters read using a semiconductor and a Hall-effect sensor respectively. Such readings are called the State of Charge (SoC) and is shown on most electrical devices today. The difficulty is within determining the Remaining Useful Life (RUL) of a LiPo battery, which informs the time left until all resources are no longer effective for the system to run. A table of definitions is used to explain the inner-workings of a battery system in table 2.13.

Table 2.13: Prognostic definitions for determining battery parameters.

Acronym	**Definition**
SoC	State of Charge (SoC) is typically the percentage (%) of capacity remaining within the battery.
SVT	Safety Voltage Threshold (SVT) is the battery's voltage range before it reaches its End of Discharge (EoD).
EoD	End of Discharge (EoD) is the SoC where the battery begins to degrade internally, causing irreversible damages.
EoL	End of Life (EoL) is the SoC where the battery is at 0% and can no longer be reused.
RUL	Remaining Useful Life (RUL) is the range in time such that it reaches EoD.
Cycle Time/Life	The number of iterations before a battery degenerates to such that it becomes inoperative.

To understand, Li-Ion batteries are limited in their usage by whats called Safety Voltage Threshold (SVT). How a typical one-cell battery discharges is shown in fig. 2.71, revealing how the SoC is measured against voltage. The SVT is between 3.4V to 4.2V with any voltage prior to 3.4V incurs a rapid voltage drop leading to poorer battery performance.

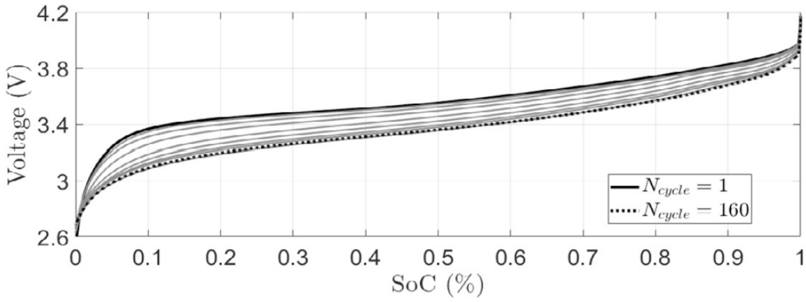


Figure 2.71: State of Charge of a one-cell battery [43]

If the battery does fall below 3.4V, which for this example is the End of Discharge (EoD), the battery cannot be reused and can lead to dangerous effects if persisted. Furthermore, as cycle values go from 1 to 160 in fig. 2.71, discharge rates become increasingly faster in time. A clearer example is depicted in fig. 2.72 of how cycles affect battery performances in terms of time to EoL.

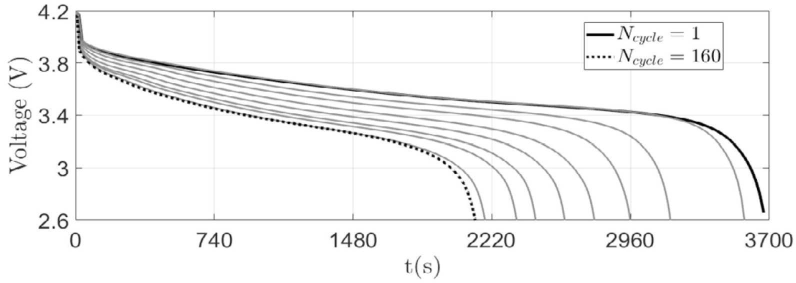


Figure 2.72: Time to EoL for increasing cycles [43]

The goal for prognostics is to predict the time remaining until the EoD to prevent any damages to the interior systems of the battery. The underlying principle for predicting RUL is to use machine learning algorithms. Several researchers [43, 44, 317, 330] have simulated, trialed and texted algorithms under different load conditions. Machine Learning can be done under three ways: supervised, semi-supervised and unsupervised. Supervised learning is done by training the algorithm with data before applying it to working systems. An example of this study is [317] in 2017 whereby four algorithms were taught how to predict the RUL of a Li-Ion battery. The algorithms tested were:

- Least Absolute Shrinkage and Selection Operator (LASSO)
- Multi-Layer Perceptron (MLP)
- Least Square Support Vector machines for Regression (LSSVR)
- Gradient Boosted Trees (GBT)

What S. Mansouri et al. from the study concluded was that a GBT algorithm would be best in predicting RUL with a precision average of 0.85 minutes. However, the experimented conducted did not experience any load fluctuations, which is typical in the environment of UAV from the drawing of devices such as motors and sensors.

Improving upon [317], in 2018 R. Schacht-Rodriguez at al. [43] implemented an Extended Kalman Filter (EKF) onto a hexa-rotor UAV. This is an example of Model-based Prognosis whereby the algorithm requires a determined model of the entire system for it to begin predictions. Comparing against first-order and second-order polynomials as prediction functions for battery performance, they were able to predict within 10 minutes, over a 20 minute flight mission, the accurate measure of RUL. This follows a SoC of 60%, meaning at 60% battery capacity, the EKF algorithm was able to determine the RUL with good accuracy. This is shown in fig. 2.73 whereby each line represents a prediction at time t_i.

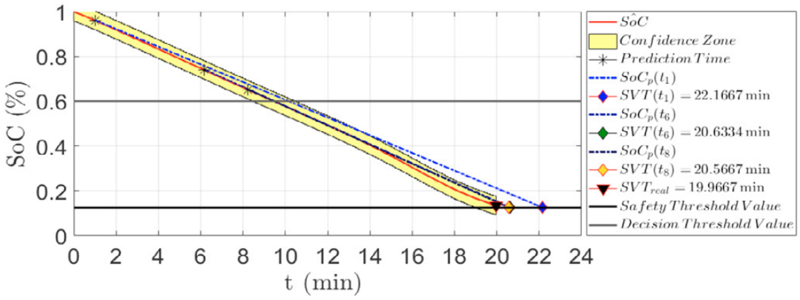


Figure 2.73: Prediction accuracy using EKF at times t_i [43]

However, this study was limited in its experimental testing and the environmental conditions of the UAV's flight testing was too controlled to formulate accurate judgements on the prediction method. It was also deemed computationally costly, which ultimately would take longer for micro-controllers to compute on-board.

In a study by M. Mishra et al. [44] in 2018, testing was conducted for different loading variations and a new suggested approach was far less costly. It was to use a Data-driven model, which gave more practical light on the application of UAV's. In this study, M. Mishra et al. used a Bayesian Hierarchical Model (BHM) which required no pre-determined model for its predictions. The model used a series of of log-normal scales which are filtered and weighted into a normal distribution. The major benefit to this model was its ability to predict with or without historical data and form an accurate judgement at 25% of its actual RUL. This is shown in fig. 2.74 whereby the accuracy improves as more data is accumulated into the system. This is represented by the reduction of error bands in purple and the red marker indicates the voltage at a particular time of the battery's RUL.

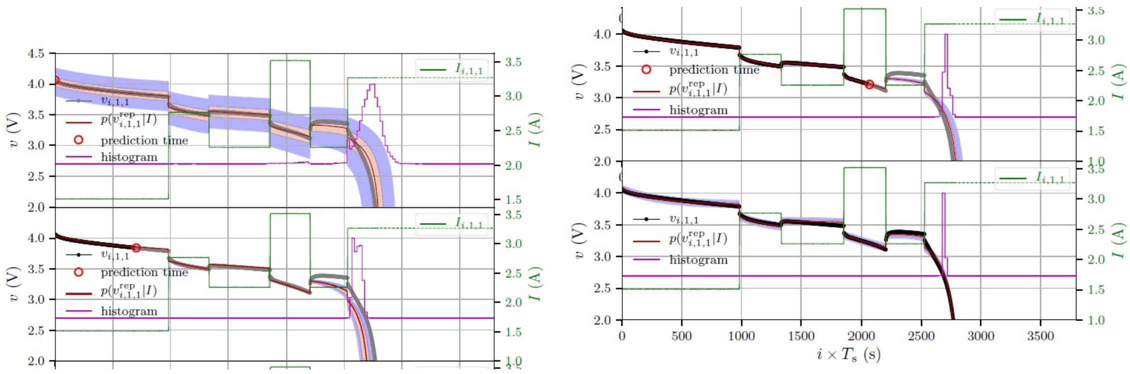


Figure 2.74: Prediction progression using BHM with reducing error bands indicated in purple [44]

Although the BHM algorithm excelled in its uses for prediction without pre-given voltage data, the experiment did utilise loading currents that were already expected in its estimation, which is not known in a typical UAV flight.

Finally, in a 2019 journal by N. Eleftheroglou et al. [330] the authors had resolved the limitations faced by the aforementioned researchers [43, 44, 317]. They had combined both model-based and data-driven algorithms, whilst experimenting further with a hybrid model. The study consisted of the three algorithms:

- Gradient Boost Trees (GBT)
- Bayesian Neural Networks (BNN)
- Non-Homogeneous Hidden Semi Markov Model (NHHSMM)

These were selected with knowledge of what had already considered by the researchers listed before. Furthermore, this study enhanced credibility by testing both predefined and manual paths, used real-time data of voltage measurements, experimented on 6 missions and tested on 10 different batteries. It was then compared with Precision, Mean Squared Errors, Mean Absolute Percentage Error, Cumulative Relative Accuracy and Confidence Intervals Convergence. The conclusion was that the algorithms NHHSMM and BNN outperformed GBT's, in its higher accuracy determined by the listed error determination methods. BNN has the added benefit of not needing to input the failure state observation into the system before running and thus, it was concluded that the best method to use for RUL is BNN. The comparison of predictions is shown is fig. 2.75 with confidence interval bands of 95%.

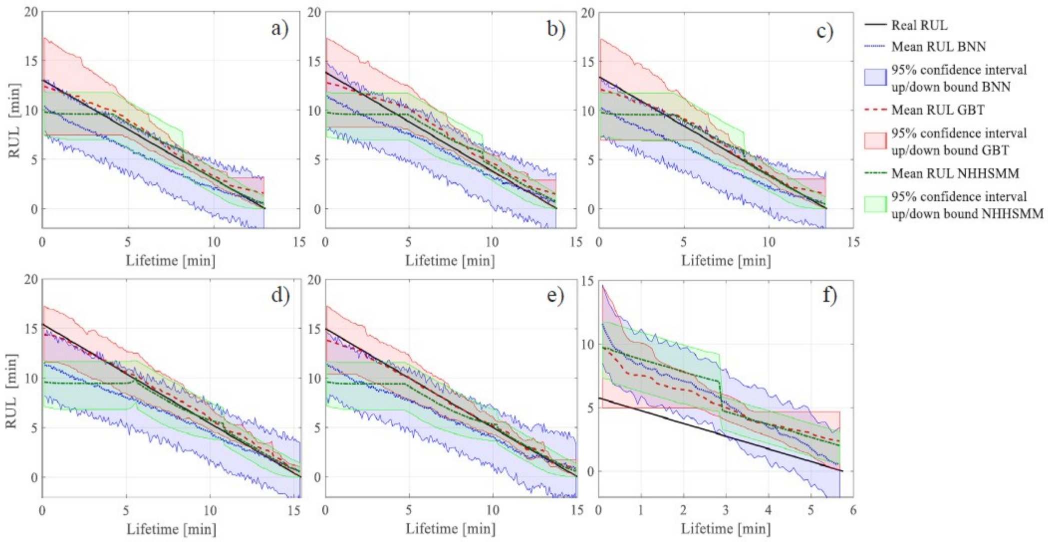


Figure 2.75: Battery predictions for 6 missions for GBT, BNN and NHHSMM

Chapter 3

Strategies

3.1 Mechanical System

3.1.1 Aerodynamic Problem

Author: Alex Peterlin

3.1.1.1 Interpretation

The propulsion system of our drone will play a crucial role in our ability to meet the various constraints of this problem space. If a poor design is chosen, our drone may be unable to fulfil one of the requirements to sample water. To address the propulsion system of our drone, two rotor configurations that are commonly used in the drone market were considered; single-rotor and quad-rotor. Single-rotor designs offer superior payload capacity and higher efficiency but only fill a small niche in the drone market, due to the mechanical complexity of scaling them down. On the other hand, quad-rotor drones offer high levels of control and improved stability. Currently, quad-rotor drones are the most popular drones on the market as they allow for smooth aerial photography and easy controllability. Quad-rotor drones are also being developed in new areas such as parcel delivery and surveillance. The main drawback of single rotor drones is their flying difficulty and the danger of the heavy spinning blade. Unlike quad-rotor drones, single-rotor drones require a large spinning blade to provide all the necessary lift, which can be dangerous if mishandled. Furthermore, the vibrations of single rotor designs are often seen as unfavourable for assignments that require a high level of accuracy and data acquisition whilst hovering or flying.

3.1.1.2 Objective

To design an efficient rotor configuration that will allow users to safely and reliably retrieve water samples in a reasonable time frame. The rotor configuration will need to have a medium payload capacity whilst minimising the power consumption required from the motors. This will reduce the amount of energy supply from the batteries, which will extend the flight time of the drone and reduce the overall costs of the system. The rotor configuration chosen will need to be safe to operate, reliable and have a low risk of malfunction. Lastly, the system will need to be easy to maintain or repair if a failure were to occur.

3.1.1.3 Methodological Approach

In the literature review conducted these two rotor configurations were explored to determine their strengths as well as their various applications in studies. Single-rotor drones see very little use in surveillance and sampling scenarios, while quad-rotor drones seem to be a viable option for many research applications that require a UAV.

While single-rotor drones are an efficient solution that offer high efficiency and prolonged flight time, their stability and ease of control prove a difficult hurdle to overcome when attempting to hover and collect samples. Quad-rotor drones are simply more tailored to activities that require a high degree of stability and accuracy to sample and transport volatile solutions. An ideal configuration would have a balance between efficiency and controllability, which the quad-rotor can accomplish. With its nimble design, a quad-rotor configuration would include improved stability as well as moderate payload capacity and flight time. Compared to a single rotor drone, the efficiency would be lower but this would be compensated by its superior manoeuvrability and reliability.

3.1.2 Structural Chassis Problem

Author: Henry Gourley

3.1.2.1 Interpretation

The functional requirements and constraints detailing this design recommend a chassis incorporating a water collection mechanism, sensors, extended flight time, manoeuvrability and cost effective implementation without compromising portability, robustness, durability and ease of use in developing countries. Several factors will be analysed to best accommodate these features including the number and orientation of propellers, material selection, construction methodology, component integration, failure detection and prevention and the length, material and cross-section of the chassis itself. Military, environmental and recreational drones have a range of functionalities for stealth, espionage, scanning and remote retrieval purposes. Integrating aspects of these designs has been identified as crucial in optimizing chassis capabilities [137].

3.1.2.2 Objective

Design or modify drone frame equipped with an integrated water collection mechanism capable of withstanding and transporting varying load profiles with repeated exposure to potentially harmful substances.

3.1.2.3 Methodological Approach

Defining methodology for critically determining the final chassis structure is important to optimize design parameters and best satisfy the functional requirements. Following the incorporation of other subcomponents including motors, propellers, batteries, water sampling mechanism, circuit boards and circuitry into the chassis design; Finite Element Analysis (FEA) and Computer Fluid Design (CFD) will be used to analyses the stresses and aerodynamic properties of the Tarot 650 Sport Quadcopter Frame to ensure it can meet the demands with an appropriate factor of safety.

CAD design and engineering drawing:

- CAD Tarot 650 Sport Quadcopter Frame geometry.
- Transport CAD files to FEA software for analysis (ANSYS Workbench).
- Modify CAD if necessary.
- Transport CAD files to CFD software for analysis.
- Following optimisation ensure engineering drawings align with Nepalese/Australian standards.

Stress analysis (FEA):

- Static structural analysis/ ACP (pre):
  - Delamination and debonding
- Modal analysis:
  - Natural frequencies of drone
- Joint analysis:
  - cyclical, fatigue, life expectation

Aerodynamic analysis (CFD):

- Simple analysis as drone will only travel in horizontal and vertical trajectories
- Will require:
  - Max possible horizontal and vertical velocity from propeller thrust
  - Wind profile of Yamuna river

3.1.3 Water Sampling System Problem

Author: Brandon Voon

3.1.3.1 Interpretation

Water quality assessment involves three different categories: physical, chemical and biological [60]. These categories are correlated to one another in the sense that biological growth and aquatic life such as fish and crustaceans, plankton and micro-organism requires the proper oxygen level, temperature range and pH level to strive [116, 331, 332]. Oftentimes, physical and chemical assessment can be conducted by in-situ monitoring using probes and sensors. These parameters include temperature, turbidity and presence of some chemical compounds [60]. Biological assessments on the other hand requires the use of more advanced instruments which are often stationary therefore, requiring the use of water samples [333]. They are usually used to identify nutrient level, isotropic composition, micro-organisms and pathogenic activities in the water [333]. Currently, grab sample is the most common kind of sampling method. This traditional method involves personnel manually collecting water from shores or from the side of boats. Such method results in a lack of accuracy due to water being mixed and disturbed during collection [334]. Besides, manual grab sampling lacks depth-specific water quality data [335]. In addition, grab sampling poses several risks to personnel such as coming in contact with infected water due to faecal contamination [336]. In order to mitigate these issues, the use of unmanned vehicles for water sampling have received heavy research and development.

Table 3.1: Water Quality Parameters [53–62]

	Water Quality Assessment	
	Parameters	**Description**
Physical	Temperature	Directly related to organisms' growth, metabolism and reproduction
	Colour	Mixing and agitation of water column
		Presence of mineral (iron or manganese) or algae and weed or sediments
	Sediments in water / turbidity	Co-related to the turbidity of water
		Particles affect aquatic system
		Reduce light penetration
	pH	Affect physiological functions of enzymes
		Increase toxicity of certain chemical compound
		Measures acidity and alkalinity of water
Chemical	Dissolved oxygen level	Vary with temperature, turbidity, biological activity (photosynthesis)
		Indicator of ecosystem condition
	Acidity	Can be caused by the presence of carbonates (buffer)
	Electrical conductivity (salinity)	Presence of ions causes electrical conductivity
		Understand surrounding land and water geography
	Nutrient concentration	Eutrophication
		Condition of water body (algae bloom)
	Heavy metals	Due to pollution by nearby industries
		Some aquatic animals bioaccumulate metals
Biological	Bacteria	
	Algae	Provides an ecological assessment (indication of water quality)
	Chlorophyll	A green pigment responsible for photosynthesis in algae or aquatic plants
		Give an indication of the volume of aquatic plants
	Phytoplankton	Microscopic plants
		Give indication of phosphorus and nitrogen in water body

3.1.3.2 Objective

To design/ modify and develop a water sampling system that can be mounted onto an unmanned autonomous vehicle at a low cost. The water sampler itself has to be resistant to chemical reactions with chemical and biological compounds found in water source to allow for a larger range of test to be conducted. The system has to be simple, robust and reliable as it will be deployed in developing countries to aid the issue of water scarcity. A simple system is required for easy maintenance and repair work to be conducted if required.

3.1.3.3 Methodological Approach

In the literature review section mentioned in section 2.1.3, various type of sampling mechanism has been discussed along with its application in real life. However, very few design involves the use of these sampling devices in an autonomous sampling environment. Therefore, the aim of this paper is to allow for a selection of sampler to be modified and employed for the use in autonomous water sampling.

The particular sampler of choice has not yet been decided upon as it depends on various other components within the sampling vehicle including shape and design of vehicle and available payload capacity.

Example of System requirement

1. Simple for easy maintenance and repair
2. Reliable
3. Made from inert material to allow for wide range of chemical and biological testing
4. Compact and portable

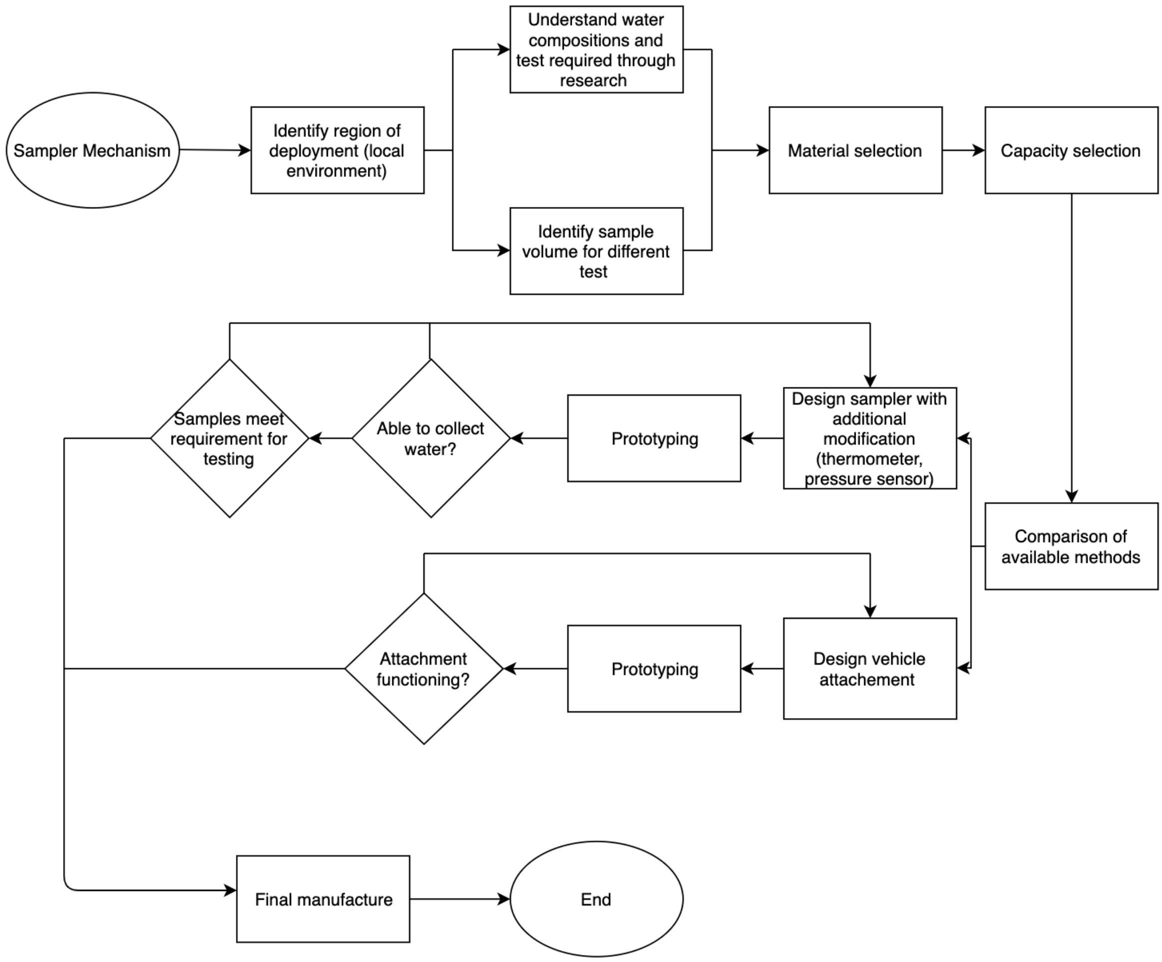


Figure 3.1: Methodology Flowchart

3.2 Electrical Hardware and Firmware

3.2.1 Power System Problem

Author: Anthony Leung

3.2.1.1 Interpretation

To fully maximise the capabilities of a UAV system it is critical for the power system to be designed optimally for water sampling missions. Since most UAV's can only last 30 minutes with a standard Li-Ion battery and without loads as mentioned in section 2.2.3.1, it is required to have a power system that is endurable and have its prognostics read. The remainign useful life is key to understanding the UAV's power capability to finish missions. Furthermore, a well-designed system limits the potential power issues causing failure during UAV missions.

3.2.1.2 Objective

To design and build a prognostic battery management system and a hybrid power system to maximise endurance for water sampling missions.

3.2.1.3 Methodological Approach

To determine which direct or auxiliary source of power to use, it must be closely compared to the constraint criteria. The selection between hydrogen fuel cells, solar photovoltaics, super-capacitors and Li-Ion batteries that must fit and abide C1 - C5 in table 1.6.After the selection of power sources, it is required to develop a system that administers the switching of sources using control algorithms. For this project either Fuzzy Logic or Rule-based Logic will be adopted as it is the simplest to implement [33]. From thereon, two machine learning algorithms will be tested. This is Bayesian Neural Network and Non-Homogeneous Hidden Semi Markov Model, which have been concluded as the best for remaining useful life predictions mentioned in section 2.2.3.1 and tested for its ability to compute prognostics. The complete process should follow fig. 3.2

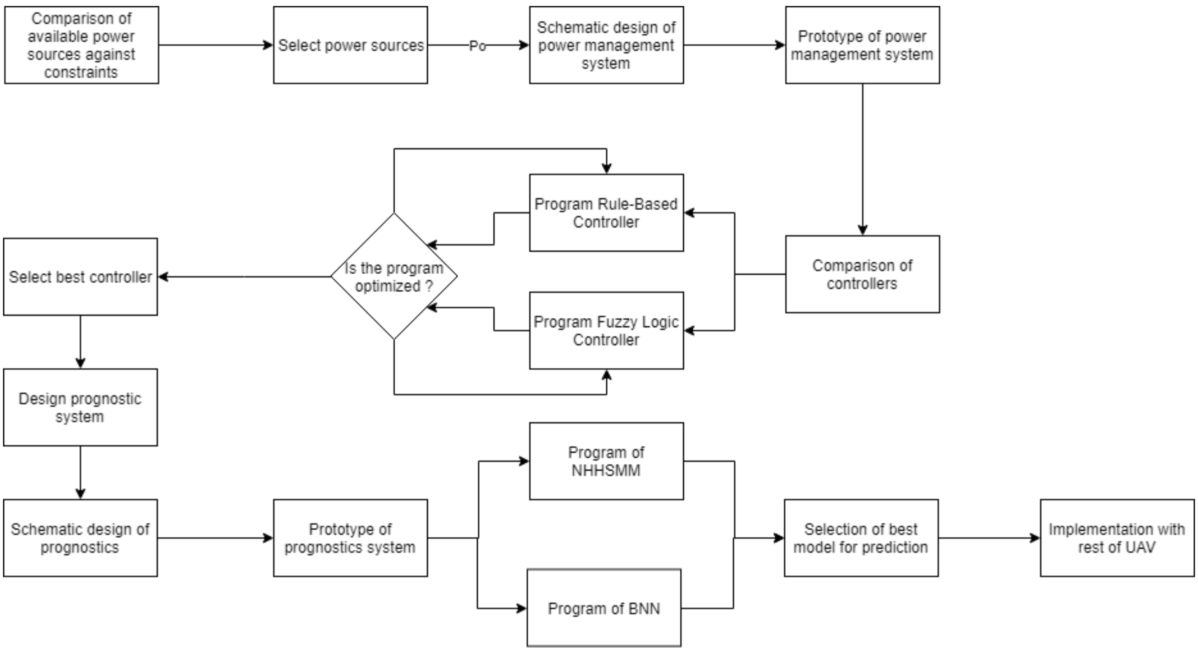


Figure 3.2: Methodological approach to power system problem

3.2.1.3.1 Design and prototyping

To design and prototype boards from programming, Altium will be used. Altium is a circuit design software that is adopted in most industries today. Circuit schematics will be constructed and prottyped for testing. Once the design is verified to be working, the schematic will be transformed into a Printed Circuit Board (PCB) which will be soldered with components and undergo firmware programming.

3.2.1.3.2 Solar Photovoltaic Energy Harvesting

The governing principle of calculating power from a single solar cell is given by [337]:

$$P = eAEcos\theta \tag{3.1}$$

Where:

- P is power in Watts
- e is the efficiency of the solar panel
- A is the area of the panel in m^2
- θ is the incident angle

This formula will be used in determine how much power can be obtained through the used of photovoltaics, with the given area available and efficiency of the chosen solar cell for the application of a water sampling UAV.

3.2.1.3.3 Rule-based Logic Controller

This controller uses an assignment of if-else statements for a given conditions and makes decision outputs. For the use of power management, it will be implemented to to control the switching of power selected power sources and is programmable in C++.

3.2.1.3.4 Fuzzy Logic Controller

Unlike a rule-based controller which uses binary decisions of true or false, Fuzzy Logic Controllers allow a range of conditions to make decisions. This requires mapping of decisions based on outcomes which satisfy measures of between 0 to 1 (not only 0 and 1). This is often software provided in Matlab.

3.2.1.3.5 Bayesian Neural Network

The concept of Bayesian Neural Network (BNN) is to esimate a problem using a non-linear regression task and is given in [330]. The prediction is obtain using the mathematical shown below.

$$[H]y(x_i) = f(x_i, \theta) + e_i \tag{3.2}$$

Where:

- $y(x_i)$ is the output Remaining Useful Life (RUL)
- $f(x_i, \theta)$ is the non-linear model that is trained
- x_i is the voltage vector
- θ is the number of model parameters of x_i
- e_i is the random noise with zero mean and variance measured by the data (Normally distributed)

Adapting the problem of water sampling should following the workings of N. Eleftheroglou et al. [330].

3.2.1.3.6 Non-Homogeneous Hidden Semi Markov Model

The idea of the Non-Homogeneous Hidden Semi Markov Model (NHHSMM) is to use a bi-dimensional stochastic process to form a sequence of conditionally independent random variables.

$$L(\theta, X^{(1:K)}) = \prod_{k=1}^{K} Pr(x^{(k)}|\theta) \xrightarrow{L'=log(L)} L(\theta, X^{(1:K)}) = \sum_{k=1}^{K} log(Pr(x^{(k)}|\theta)) \tag{3.3}$$

$$\theta^{\star} = argmax(\sum_{k=1}^{K} log(Pr(x^{(k)}|\theta)) \tag{3.4}$$

Where:

- $L(\theta, X^{(1:K)})$ is the likelihood function
- $x^{(k)}$ is the k-th voltage history
- K is the number of available histories
- $\theta^{\star}$ is the masimum likelihood estimator

This algorithm will be tested for prognostics for the water sampling UAV, more information of how this is implemented is found in [330].

3.2.2 Flight Control System Problem

Author: Alexandar Nguyen

3.2.2.1 Interpretation

Completing research on Flight Controllers and current flight control algorithms, no current gaps were evident as the flight controllers developed are currently very mature, especially open-sourced controllers which have large community forums. This is seen in the feature comparison in table 2.4 where many controllers house multiple in-built essential systems such as IMU, GPS, UART etc. as well as being relatively light weight. The open source flight controllers, Ardupilot and Pixhawk were studied and both utilise a PID control system. The PID system, as stated in previous sections, is a simple yet effective method for controlling PWM levels for the quad-rotor motors however, it was stated that it's a time consuming process.

3.2.2.2 Objective

From the previous section, it is understood that flight controllers are sufficiently developed, where common open-sourced controllers are effective in altitude and position control. Thus, the experimentation of the control algorithm rather than the controller itself will be conducted. Currently, the controllers operate in a PID system, where the first loop controls altitude and the second translation motion. The incorporation of another control system on top of the PID system will be experimented on in the furture.

3.2.2.3 Methodological Approach

As stated above, the comparison between control algorithms will be conducted to determine the most optimal for our design. A performance comparison will be conducted assessing the:

- Flight Time
- Altitude Control
- Loiter Accuracy
- Positional Accuracy

These values will be recorded and weighted accordingly to overall aid in the selection of specific algorithms.

3.2.3 Autonomous System Problem

Author: Aaron Su

3.2.3.1 Interpretation

This section describes the strategy adopted by this research towards building a solution for the autonomous system of UAV. Section 3.1 provides an in-depth interpretation of autonomous system problem; section 3.2 states the objective of this research with detailed goals. section 3.3 discusses the methodology to be used in the study, and the stages by which the methodology will be implemented. As presented in section 2.2.2, manual controlled UAV for beyond line of sight (BLOS) often requires high technical proficiency from long period of training to be able to operate safely. Even when these requirements are met, little operation mistakes can still easily lead to significant damage or crashing in cluttered and dynamic environment within where UAVs are typically operating. This is particularly concerning for operators in developing countries as sufficient training might not be possible and the cost of failure is very high. Hence, autonomous operation comes into rescue. To begin with, basic level of autonomous UAS operations may be carried out with the presence of satisfactory GPS availability. However, these operations that rely on conventional sensors such as IMU and GPS are not robust and accurate enough to handle situations in cluttered or GPS-denied environments. Figure A typical scenario is a water sampling problem in developing country, in which MAVs may fly among various regions such as urban area, forest, steep or rough terrains or other cluttered environments with GPS blocking or without any GPS signal. In this case, an UAS solution with higher autonomous capabilities to handle various tasks in such complex environments yet cost-effective, is highly demanded.

3.2.3.2 Objective

To design and build an autonomous system for UAV that are optimal for water sampling problem in developing countries. In details, these require the system to be robust and reliable, where only methods that are tested and validated in various real-world environments are considered; operational, where minimum training is required for the safe operation of the system under different conditions; cost-effective, where lower-cost hardware should be employed to achieve the required sensing and processing capabilities; transferable, where system can be easily setup and deployed on scale; and weight-efficient, where less bulky or heavy hardware should be preferred.

3.2.3.3 Methodological Approach

In the preliminary stage, the research initiated with a literature review of the area of autonomy related to UAV via multiple online sources with primary focus on scholarly articles. Literature was gathered from broad survey or review type articles to research and development in specific field through keyword-based search. Framework and benchmark were selected to help collect, classify and evaluate technologies that are promising for autonomous UAV operations. As the research focuses on portable aerial water sampling in developing countries, reviews were further refined towards small size UAV, also known as micro-UAV (MAV). Technologies enabling autonomy of MAV from lower to higher level were reviewed within the Guidance, Navigation and Control (GNC) scheme. Additionally, sources that detail methods of computer vision and deep learning illustrate the promising capabilities of vision-based system due to the rapid development of related algorithm and miniature of hardware.Finally, a design process that follows the system engineering approach was carried out to select the optimal configurations of navigation and guidance systems.

3.2.4 Communication System Problem

Author: Dylan Dam Author: Dylan D

3.2.4.1 Interpretation

After conducting research on present UAV telemetry solutions, a current gap can be seen for feasible solutions that are also cost effective. For the telemetry solution there are certain constraints that our design needs to abide by (Table 3.2) and the performance metrics that the UAV is expected to be able to do can be seen in Table 3.2.

To better visualise the gap in current design proposals, a matrix would be used to demonstrate the which constraints and metrics are met between all design solutions studied (Table 3.3). Based off the constraints and metrics imposed by our team, a distinct pattern can be seen. UAVs that generally meet the P6 and C7 metric generally do not meet C1, C3, P4 and P7 outcomes. The technology implemented by Guenzi and Zmarz that allow for BVLOS flight are required to meet certain airspace regulations in order to minimise the margin of error. In order to incorporate these redundancies into their designs required more investment into sensors and software to ensure reliability. For the UAVs that do not have BVLOS capabilities, they generally are more technologically transferable/ feasible for developing countries at the expense of BVLOS capabilities.

Table 3.2: Constraints and Performance Parameters Required by UAV Telemetry

Index	Constraints
C1	Suitable for use in developing countries
C3	Robust
C4	Reliable
C5	Maintainable, repairable and sustainable
C6	Remotely Operable

Index	Performance Metrics
P1	Functions successfully in real environment
P2	Societal Impact
P3	Environmental Impact
P4	Technologically Transferable
P5	Meets in-country legislation requirements
P6	Able to navigate on water away from line-of-sight
P7	Feasibility

Table 3.3: Comparing Performance and Constraints for Studied Design

UAV Design	Kopran	Ore	Srivastava	Guenzi	Zmarz
C1	X	X	X		
C3	X	X	X	X	X
C4				X	X
C5	X	X	X		
C7				X	X
P1	X	X	X	X	X
P2	X	X	X	X	X
P3	X	X	X	X	X
P4	X	X	X		
P5	X	X	X	X	X
P6				X	X
P7	X	X	X		

3.2.4.2 Objective

Based off the last section, a strategy must be implemented in place to bridge the gap between the two types of design. It is important to note that Guenzi and Zmarz's design for the UAV are fixed wing UAVs. Generally, fixed wing UAVs are more energy efficient and consume less energy compared to rotary-wing UAVs. However, rotary-wing UAVs are able to sample water at specified locations accurately as they can ascend and descend without a traditional take-off/landing which justifies its use. A disadvantage of rotary-winged UAVs are that they generally consume more power and therefore have a less effective range compared to fixed-wing UAVs. It is because of this inherent inverse relationship between the power consumption and distance traversed by rotary-wing UAVs a redefinition is required for BVLOS.

The UAV is expected to traverse through Indian airspace and therefore need to abide by Indian regulations for BVLOS operations. Based off the Directorate General of Civil Aviation (DGCA) [338], a set of guidelines for BVLOS operation for small/micro UAVs. Under the DGCA the maximum allocated airspace for experiment is 20sq km with a maximum altitude for 400ft (120m) above ground level for "Green Zones" under Digital Sky airspace monitoring. The permitted flights may be permitted in "Yellow Zones" but would require approval by the aviation board. Therefore based on this, the BVLOS capabilities will be defined as being able to traverse in 20 sq km with mild-high interference from natural barriers such as trees and mountains. The basic requirements stipulated by the DGCA are that all UAVs must have at a minimum these capabilities (Table 3.4). These constraints will be noted as DGCA Constraints or DGCAC.

Table 3.4: Directorate General of Civil Aviation Constraints for BVLOS Mission

[338]

DGCA Constraints Index	DGCA Constraint Description
DGCAC1	Capabilities for autonomous operations
DGCAC2	Sufficient endurance for long range operations
DGCAC3	Capabilities to withstand adverse weather
DGCAC4	Capability to transmit identity and live trajectory information.
DGCAC5	Detect and Avoid System in place
DGCAC6	UTM unit to provide population data, terrain, obstacle data, airspace traffic data and meteorological data, Notice to Airmen information about airspace as well as GNSS serviceability.

Given the DGCA's constraints on the UAV, this provides a quantifiable metric as the expected performance of the UAV. DCGA1-6 correspond with our parameters C3,C4,C7,P1 and P6. However, metrics such as technologically transferable and maintainable are our team's specific defined metrics that need to be met. Therefore, based on the information gathered the UAV should be able to transmit a high volume of data between the GSC and the UAV as well has have a minimum broadcast range of 20sq km as required by the DGCA, but at the same time needs to be cost effective and technologically transferable/feasible in low socioeconomic regions to comply with our own set metrics and constraints.

3.2.4.3 Methodological Approach

After defining the metrics that will be used to assess what would be required of the telemetry module, it is important to weigh the different performance parameters to determine which is most important. As stated above, the performance parameters that will be assessed for each module would be its range, transmission speed, sensitivity to interference (suitability in rough terrain) as well as cost. The evaluation of the modules would be conducted in a matrix in order to clearly see superior models. (Table 3.5).

Table 3.5: Example of Telemetry Module Evaluation Matrix

Module	**Range**	**Transmit Speed**	**Sensitivity**	**Cost**	**Score**
Module 1	Score*Weight	Score*Weight	Score*Weight	Score*Weight	Row Total
Module 2	‘’	‘’	‘’	‘’	‘’
Module 3	‘’	‘’	‘’	‘’	‘’
Module 4	‘’	‘’	‘’	‘’	‘’
Module 5	‘’	‘’	‘’	‘’	‘’
Module 6	‘’	‘’	‘’	‘’	‘’
Module 7	‘’	‘’	‘’	‘’	‘’
Module 8	‘’	‘’	‘’	‘’	‘’
Module 9	‘’	‘’	‘’	‘’	‘’

The scores that are given out for the evaluation matrix is ranges from -1 to 1. Scores are generally given a -1 if they fail to perform at a minimum what is required for BVLOS flight, 0 if they perform just the bare minimum and +1 if capabilities exceed what is required. However, this scenario means that all metrics are equally as desirable, but in reality some traits are much more important. The most important trait for the module is the range (without added peripherals like antennas) and the cost of the module.

The basis of this study is to determine a cost effective BVLOS capable telemetry system. Next transmission speed is also important since large amounts of data need to be transmitted with little latency this metric would be the next most desirable after range and cost. The reason that speed is placed after range and cost is because modules, if they're cheap and can transmit far, can be duplicated and data be broken up as shown in Guenzi's design. The last trait is sensitivity, as the terrain that the UAV is to be operated may contain sufficient sources of interference, it is important that the module is not sensitive to interference to prevent data loss. However, most modern telemetry solutions are fairly robust and reliable, but if modules have an added feature to help reliability it would benefit our design as a whole. The complete weighting of each metric can be seen below:

- Range Weighting Score: **3**
- Cost Weighting Score: **3**
- Sensitivity Weighting Score: **1**
- Transmission Speed Weighting Score: **2**

A baseline should be established to compare telemetry modules with against. For each of the traits except range the average would be taken. As DCGA has provided information on the max range of the UAV, the range would be based off that. The datum for comparison can be seen below (Table 3.6).

Table 3.6: Telemetric Comparison Table

Telemetry Metric	**Average**
Range	3km
Cost	$50
Sensitivity	-100dBm
Transmission Speed	250kbps

Through establishing a datum point of what is to be expected of the telemetry module, further study can be done on existing modules in the market to gauge their capabilities.A comparison would be conducted on several off the self RF modules to determine which one is best suited for our design. This study will be conducted in the next section.

Chapter 4

Preliminary Design Avenues and Considerations

4.1 Mechanical System

4.1.1 Aerodynamic Design

Author: Alex Peterlin

From the literature review conducted in section 2.1.1, two drone propeller configurations were considered and their current applications in parcel delivery and surveillance were researched to determine their feasibility in meeting the constraints of water sampling. A summary of the main advantages and disadvantages of single and quad-rotor drone types has been conducted in table 4.1.

,

Table 4.1: Advantages and Disadvantages of Singlerotor and Quadrotor drone configurations

	Advantages	**Disadvantages**
Singlerotor	-Long endurance and prolonged flight time (with gas power) -Heavier payload capacity -Higher efficiency -Reduced power consumption -Easy and quick refuelling -Higher energy density	-Dangerous (due to single blade) -Expensive -High flying difficulty -Vibrations caused by engine
Quadrotor	-Ease of operability -Hover flight -Good accessibility -High level of stability -High degree of control -Fail-safe of additional propellers	-Limited flight time with current battery technology -Moderate payload capacity -Long recharging time

Single-rotor drones (helicopters) have the highest efficiency configuration out of all the propeller drones. As single-rotor drones only operate using a single large blade, they are able to spin at a slower speed and consume less power. This allows the drone to operate at a higher efficiency, which helps extend its flight endurance and payload capacity compared to other drone models. Furthermore, single-rotor drones have the option of being powered by gas engines, which further prolongs their flight time, and allows controllers to quickly refuel them. While gas engines do increase performance due to the higher energy density of fuel, they also create a lot of vibrations due to their explosive engine strokes. Vibrations increase the already high-flying difficulty of the drone as it is harder to stabilise whilst hovering, and also interfere with sensitive measuring equipment that may be attached to the drone. While these drones are very efficient, they are more expensive and much harder to fly than their multi-rotor counter parts.

Quad-rotor drones provide enhanced stability and ease of operation. By using four rotors to balance itself in the air, quad-rotor drones possess a higher degree of control over single-rotor drones as they incorporate electronic stabilisation to aid the controller in guiding the drone. This allows for higher precision sampling whilst hovering. Moreover, quad-rotor drones have a lower risk of injury and malfunction due to the additional propellers. While the propeller blades of quad-rotor drones need to spin at a much faster rate to maintain lift, they are much smaller and therefore possess less kinetic energy, which reduces the risk of causing damage to the surroundings. Unfortunately, due to current battery technology, quad-rotor drones have a limited flight time and also require a long period to recharge. This limits the amount of flights or tests that can be performed in a single run, which could reduce preciseness of the measurements taken.

As our drone has a higher priority on stability and ease of control, the quad-rotor drone would be the most ideal rotor configuration for water sampling. Due to its high degree of control whilst hovering, controllers would be able to reliably and safely retrieve water samples for analysis using current battery technology.

4.1.2 Structural Chassis Design

Author: Henry Gourley

Based on literature review findings, several recommendations will be discussed for Thesis B. Cost and design considerations suggest the Tarot 650 Sport Quadcopter Frame is the most suitable frame selection. According to preliminary investigations, a light weight carbon fibre frame capable of lifting a 3kg payload capacity should be sufficient. Foldable arms also enable increased portability and ease of use for untrained personnel. The frame's centre of mass is its geometrical centre. Maintaining this symmetry when components are added is crucial in maintaining flight stability control.
To ensure a durable and robust drone, this design will custom build an easily accessible waterproof housing for the drone's central body. Circuitry radiating towards propeller motors will run through hollow watertight tube arms. The chassis will also incorporate flotation units attached to the drones ground support legs [129]. This will allow the drone to rest upon the water's surface in calm conditions whilst sampling is undertaken, increasing the longevity of battery life and providing a safety net against critical failure over water bodies. Finite Element Analysis (FEA) and Computer Fluid Design (CFD) will be used to analyses the stresses and aerodynamic properties of the Tarot 650 Sport Quadcopter Frame to ensure it can meet the demands with an appropriate factor of safety.

4.1.3 Water Sampling System Design

Author: Brandon Voon

4.1.3.1 Water Sampling Standards

Water samples can be used for various purpose, study and analysis. The test for different water parameters requires different volume of water samples and a general outline for water sampling and preservation method was given below based off different governmental and non-profit (WHO, UNICEF, UNESCO and United Nations) bodies [339–343].

Table 4.2: Standards

Type of test	Sample size	Test	Preferred storage bottle	Washing	Preservatives
Microbiology Samples	250mL	E.coli	Polyethlyene bottle	Sterile	30mg Sodium Thiosulphate
Chemistry samples	250mL and 1000mL	Trace metal	HDPE bottle	Acid washed	1% Nitric Acid
	1000mL	Standard water analysis Nutrient pH Anion Conductivity	HDPE bottle	Detergent	NIL
Fluoride	250mL	Fluoride	HDPE bottle	Detergent	NIL
Chlorine	500mL	Chlorine level	HDPE		NIL
Pesticide	1000mL	Pesticide	HDPE bottle	Solvent	80mg Sodium Thiosulphate
Mercury	500mL	Mercury	Glass	Acid washed	2ml 20% potassium dichromate with 4M nitric acid / litre

The acid washed method uses Hydrochloric acid (5% by volume in distilled / deionised water) or Nitric acid (10% by volume in distilled / deionised water)

4.1.3.2 Comparison of Conventional Water Sampling Methods

A comparison of all the conventional sampling methods discussed above was conducted in table 4.3,4.4. Several of these parameters compared were done based on the knowledge on the product specifically.

Table 4.3: Advantage and Disadvantages of each Sampler Type

Sampler	Advantage	Disadvantage
Niskin Bottle	- Placed in a rosette system for multi sampling at same depth (up to 36) [344] - Can be used in a chain system for multiple depth sampling [345] - Varying capacity available - Thermometer can be attached to measure water temperature in a pressure resistant glass housing [345, 346]	- Manual closing mechanism using messenger - Weight - Unable to study dissolved gas composition in water [158] - Require cleaning before re-deployment [347, 348] - Disturbing and mixing of water column upon collection of water [349]
Go-Flo Bottle	- Placed in a rosette system for multi sampling at same depth - Can be used in a chain system for multiple depth sampling - Varying capacity available - No contamination from different water column - Can be used for trace metal sampling due to material used - Thermometer can be attached to measure water temperature in a pressure resistant glass housing [346]	- Manual closing mechanism using messenger - Weight - Require cleaning before re-deployment - Disturbing and mixing of water column upon collection of water
Van-Dorn Bottle	- Vertical and horizontal bottle orientation - Allows for shallow water body sampling - Can be used in a chain system for multiple depth sampling - 2 - 8L sampling capacity [350] - Two types of bottles available (alpha & beta) - Beta bottle can be used for trace metal sampling - Clear bottle allows for immediate observation of water samples	- Manual closing mechanism using messenger - Weight - Require cleaning before re-deployment - Disturbing and mixing of water column upon collection of water
Bailer	- Comes in disposable and biodegradable option - Comes in all sizes - Low cost - Light and Dense non aqueous liquid can be sample using bailer [182, 351] - Easy to transport [182]	- Aeration of water sample during collection (VOC unable to be tested) [352] - Agitation of water [351] - Check valve failure due to suspended solid [182, 351]
Suction Lift Pump	- Relatively cheap [353] - Portable [353] - Peristaltic pump can be used in small diameter bore hole sampling [354] - Variable speed control [354]	- Require priming [353] - Vacuum causes water to lose some dissolved gas [355] - Peristaltic pump limited to shallow application [354] - Changes in solution chemistry [354]
Sub-mersible Pump	- Height pumping rate [353] - Priming not required [353] - Reliable [353, 356] - Easy to use [353]	- Results to single point of failure [356] - Damage from slit or sediment [195, 196, 355] - Inefficient in shallow well [353]

Table 4.4: Qualitative Comparison of Samplers.

	Niskin Bottle	**Go-flo bottle**	**Van Dorn Bottle**	**Bailer**	**Suction lift pump**	**Submersible pump**
Cost*	Low	Medium	Low	Low	Vary	Vary
Ease of deployment	Medium	Medium	Medium	High	Low	Low
Ease of maintenance	High	Medium	High	High	Low	Low
Weight of bottle + sample	(4kg+1.2L) to (43kg+30L)	(5.6kg+1.7L) to (147kg+100L)**	(7kg+2L) to (12kg+5L)***	Varies	Varies	Varies
Mechanism complexity	Medium	High	Medium	Low	High	High
Robustness	Medium	Medium	Medium	Low	High	High
Maintenance	Easy	Medium	Easy	Easy	Hard	Hard
Sustainability	Medium	Medium	Medium	Low	High	High

(*) [114, 357–359].(**) [360]. (***) [361, 362].

Table 4.5: Description of Compared Parameters

Comparison Parameters	**Description**
Ease of deployment	Requires the use of additional input (electricity, messenger) to complete the water sampling procedure
Ease of maintainability	Number of parts to build up the entire mechanism
Mechanism complexity	Number of parts
Robustness	Expected lifetime of entire mechanism
Ease of cleaning and replacement	Effort required to remove the parts to allow for cleaning inside the bottle / pump
Sustainability	Efficiency during deployment over time - This is subject to regular cleaning and maintenance

4.1.3.3 Stratified Sampling

Multi-depth sampling are usually conducted for quantitative and sedimentary sampling as this provides a more accurate representation of the water body of interest. Sedimentary sampling are divided into two types: suspended and bottom sediments. Besides, multi-depth sampling will also be of interest when a water body has distinct stratified layer [363].

Collecting water samples at different depths has several effect on the overall analysis of the water body. If the water body of interest contains different water stratification at different depth, water should be collected at each distinct layer to allow for a more complete representation of the water body [343]. This in turns provides a more comprehensive detailed analysis on the water body. However, for shallower, well mixed water body, a single sample is sufficient. Surface and bottom sampling can also be conducted for shallower water body for a better representation but, should be taken with care to prevent the stirring of bottom sediments as this causes a bias in result.

For stratified sampling, random water samples will be collected within each layer and the depth should be noted. This ensure that there are no overlap of layers and analysis [363].

The Yamuna river is known for its thick toxic foam present on the top layer that is derived from industrial waste and other pollutants, hence it is important to collect a sample on the surface level. Additionally, deeper samples should also be collected to allow for a thorough understanding of the water body as this portrays the actual condition of the water.

4.1.3.4 Discussion

For the purpose of deployment in developing countries, where clean water source is limited, water monitoring and analysis plays an important role in bridging this ever lasting issue. As such, the sampler itself plays an important role in providing an accurate analysis of the water body. Several different methods for water sampling has been mentioned and compared above. The water discussed will include Yamuna river located in India, Bagmati river in Nepal and Buringanga river in Bangladesh. A drone will be used for the purpose of autonomous water sampling as mentioned in section 1.2.

Heavy metal and chemicals from pesticides and fertilisers are one of the most common contaminants found in these rivers. As such, in order to conduct water analysis for heavy metals and chemical composition, inert materials should be used for sampling. Based on the currently available sampling method mentioned above, the most suitable method would be the Beta Van-Dorn bottle due to the type of material used that will not leech chemicals. Other sampling methods could also be used but requires some degree of changes in terms of its material and mechanism to prevent leeching or reaction with the water. Additionally, as the Van-Dorn bottle is horizontal, shallower water could be sampled although this depends upon the site location. If multiple samples at different depth is required, the Van-Dorn bottle can be attached in a chain system in which the triggering of the first bottle will cause a second messenger to be released for the second bottle.

The trigger mechanism uses a messenger that will be sent down the tether to come in contact with the closing mechanism of the bottle. However, as the messenger travels down and enters the water, the speed will be significantly reduced due to buoyancy.

This could be a potential issue for mission as it cost time and money to re-conduct the sampling. Based on several water sampling studies conducted, this issue has not yet been raised and is probably due to their sampling depth. To take this into account, several steps could be taken.

1. The sampling depth could be limited based on the weight of messenger and water current condition.

2. Modifying the closing mechanism to adjust its sensitivity.

3. Re-design a new closing mechanism that would work for deeper water sampling.

This could be used as a point of reference for other sampling method that uses a messenger for its closing mechanism.

Additionally, as sampling will be conducted using a drone that will be hovering above the water, some form of attachment has to be designed for the purpose of attaching the Van-Dorn bottle to it. The easiest method to this is by allowing the bottle to dangle freely below while in flight. Although this could be a potential solution, it also poses risk to the vehicle as well as any personnel below it. This could be improved by using a winch system that can lower and raise the bottle at the site. Whereas for the messenger, it can be attached beside the winch with a servo motor with a rod acting as a support to the loop on the messenger to prevent it from sliding down. However, once triggered the rod retracts, allowing the messenger to fall freely. The servo motor rod and messenger will not be an issue to the raising and lowering of the sampler due to the tether being in the middle of the messenger and the messenger loop being attached to the rod. The use of winch also allows the drone to fly within the safe flight zone in the region without the free dangling bottle causing a problem during manoeuvre. The dependance on the winch also shifts the center of gravity of the drone nearer towards its centre when compared to a free hanging bottle several metres away from the vehicle. As a drone will be used, payload capacity plays an important role therefore, has to be taken into serious consideration if any of the above modifications were to be designed and employed. The ability to identify the position of the bottle relative to the water and at a known depth is also critical, due to the serious pollution issue in the Yamuna river that causes thick foam to form on the surface, this could be a potential challenge when trying to determine if the bottle is sampling foam or water. To solve this issue, a pressure sensor or water conductivity sensors can be attached on the outside of the bottle. This gives the operators a better idea on the position of the bottle relative to the water. The ability to attach sensors as such also allows for in-situ monitoring of certain water parameters.

The use of other methods such as Niskin, Go-flo and bailer are also acceptable methods. However, as mentioned by Suter et al, the presence of a valve / spout on the Niskin and Go-flo bottle for the release of water content can cause a variation in reading for microbial analysis. This is because of the position of the spout not being directly at the bottom of the bottle hence not all the water collected is used for analysis. This allows for micro particles to sink to the bottom of the bottle. Although, the end stopper allows for the water content to be poured out, this method usually causes cross contamination. Thus, a potential solution for the Niskin bottle is to modify one side of the end stopper to allow for drainage. As the end stopper of a Niskin bottle has a long handle, it can be hollowed out to allow for a ball valve to be attached midway. This ensures that any lanyard connection for the closing mechanism is not affected. Water will then be drained from the side of the hollow end stopper through the valve. Besides that, the bottle could be gently shaken before drainage to allow micro particles to be released from the bottom, this provides for a more accurate representation of a real water condition in which micro particles and sediments are constantly moving within the water body and not stagnated on the bottom.

Cross contamination is often an issue faced during analysis. This occurs in different stages within the sampling and analysis phase: before sampling and after sampling. Before sampling contamination are usually due to contaminated bottles being used. After sampling on the other hand, involves water coming into contact with any outer surface of the bottle. This could occur because the bottle is not completely covered and sterilised during transport. Besides another possible source of contamination is during the filtration process. This is when sampled water are poured out to be filtered. This can happen when water is present in the valve or on the surface, hence when the valve is opened for drainage, stagnant water at the valve will also be collected for analysis. However, water at the valves or at the surface had already been exposed to air and other contaminants before being drained, filtered and analysed. To ensure that drained sample are accurate and reliable, the valve can be opened to allow for free flow before any actual samples are being collected for filtration and analysis. Besides, ensure that all bottles are being covered during transportation to prevent for contamination. Contamination during the filtration process on the other hand is hard to mitigate as the sources of error are very subjective and depends heavily on the laboratory and lab personnel. As for before sampling contamination, ensure that all samplers used are properly cleaned and sterilised.

Bailer on the other hand has the simplest mechanism of them all. This method allows for more water to be collected due to its ability to collect water without the use of additional mechanism or complicated attachments. This can simply be fitted onto the drone either by free hanging or by a winch that can be lowered and raised from the water body. Additionally, bailers comes in two types: reusables and biodegradable. The bio-degradable bailer could be a potential solution for water sampling at the above mentioned river due to its material.

Pumps on the other hand are generally complex. It requires power to operate, which is one of the most important factor when it comes to selection of methods. One of the benefit of using the submersible pump over other sampling methods is the ability to analyse dissolved gas composition. All the above mentioned methods are not capable in collecting water samples for the purpose of dissolved gas analysis due to its closing mechanism that allows for gas to expand and release when ascending. Both the suction lift and submersible pump are a more technological oriented alternatives of water sampling and are very different in terms of the water parameter analysed later. This is because of its operating characteristics. Besides that, the strong centrifugal force generated tends to change water chemistry and in some case cause a loss of dissolved gas and other Volatile Organic Compound (VOC). However, very little improvement could be done due to its complex mechanisms. Therefore it is critical to understand the parameter of interest before selecting a particular method. For the deployment on an unmanned vehicle (drone), storage method has to be taken into account as these storage has to be in accordance to the water sampling guidelines to prevent inaccurate or false results.

The most important aspect that should be taken into account before the deployment of any sampler is to understand the parameters of interest, depth of water as well as surrounding environment. Even though, all the methods are proven to be reliable and acceptable to some extend, different methods are still preferred over others in some conditions and having a thorough knowledge on these, allows for a more efficient water sampling mission. It is important to understand the capabilities of each method as there is no one particular method that can overcome all the issues faced. These are just one of the many trade-offs of using different methods and has to be fully understood before use.

Table 4.6: Potential limitations and solutions

Potential Limitation	**Potential Solution**
Sunken micro particles not poured out during the release of water content for sampling	- Modifying one side of the end stopper to allow it to act as a valve / shifting position of valve - Gently shaking the bottle to allow particles to be released from the bottom
Cross contamination / leeching of chemicals	- Discard some water before actual collection and filtration - Thoroughly clean bottle before redeployment - Change material of sampler
Messenger deployment failed to close bottle	- Redesign of mechanism - Modify sensitivity of closing mechanism
Free hanging bottle	- Winch system

Below outlines a potential solution to the above mentioned application.

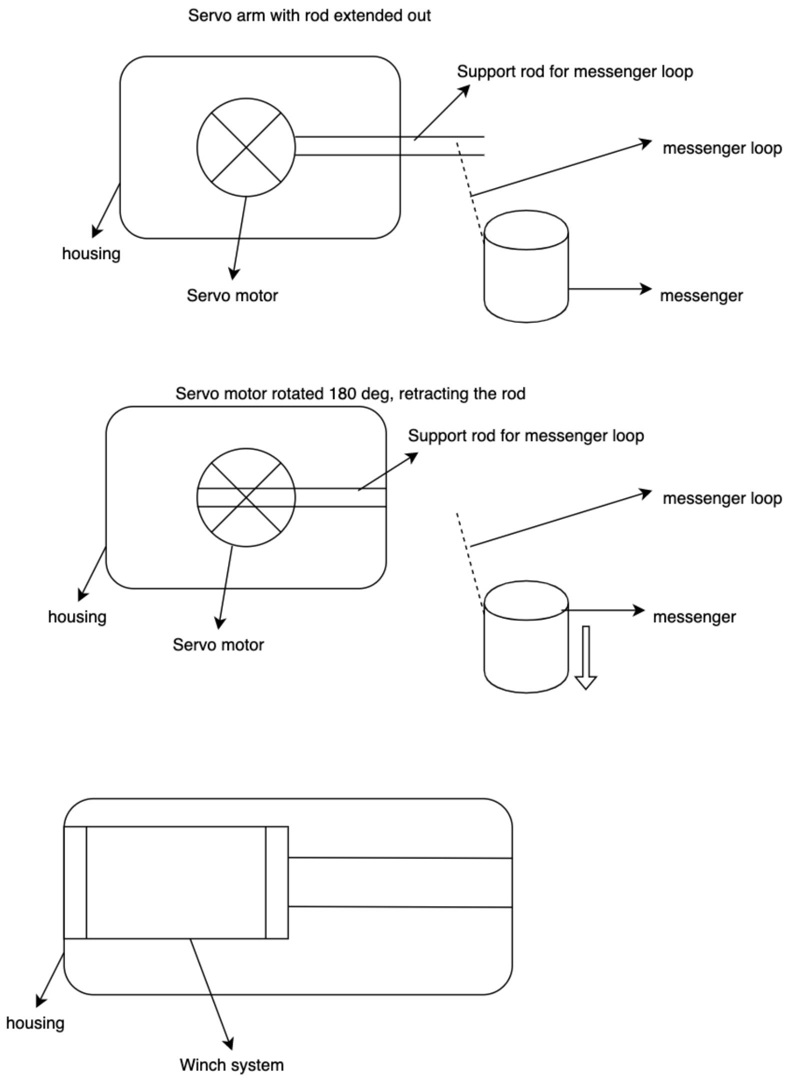


Figure 4.1: Servo motor position and winch

The winch and servo motor will be attach side by side. The messenger release mechanism works by rotating the arm 180 degrees, retracting the arm where the messenger will be attached to via a loop. The bar will completely retract back into the casing allowing the messenger to drop freely. In order to prevent the loop to slide off the bar during flight, a small groove will be made to allow the loop to sit snugly within. As these are just potential solutions to the issues mentioned above, many of the aspects regarding the winch and the release mechanism are still in the discussion phase. These improvements will receive further improvements once all the other components of the vehicle is confirmed: payload capacity and size in particular. However, basic calculation for the torque required by the servo motor assuming the total length of the arm and the bar to be 13cm is attached in the Appendix A.

4.2 Electrical Hardware and Firmware

4.2.1 Power System Design

Author: Anthony Leung

As mentioned in section 3.2.1.3, power sources must be uniquely selected such that it fits the use of the chosen developing country, India. A relative comparison of each power source reviewed in 2.2.3.1 is qualitatively compared in table 4.7. From table 4.7 the choice of implementing a super-capacitor into the power system is a reliable, robust and cost effective solution for extending the capabilities of battery usage. However, a primary power source is required and the most reliable form is to incorporate a LiPo battery which has high efficiency and easily refueled amongst the longer charging intervals. Unfortunately, it has a nature of being quickly discharged throughout missions as mentioned in section 2.2.3.1. Therefore, an environmental and sustainable option is to add a small solar photo-voltaic to the system. This will recharge the LiPo during mission times and with the three elements working together, safety is increased and the entire system can reliable for completing water sampling tasks. Hydrogen fuel cells will however, not be used in the water sampling project. This is due to it's refuel-ability being expensive and not abundant, both a high cost and unreasonable to be using for developing countries.

Table 4.7: Relative comparison of features of power sources

Power Sources	**Fast recharging**	**Lightweight**	**High Efficiency**	**Long flight endurance**	**High power density**	**Low response to load variation**	**Compact sized**	**Low weight**	**Cost effective**	**Easily refueled**	**Low Maintenance**	**No. of Advantages**
Hydrogen Fuel Cell		X		X	X	X	X	X				**6**
Solar PV		X		X						-	X	**3**
LiPo			X				X	X	X	X	X	**6**
Supercapacitor	X	X	X	X	X	X	X	X	X	-	X	**10**

A block diagram of the system is shown in fig. 4.2, involving a power source management and prognostics system. To implement these features, a micro-controller will be used to facilitate and compute the switching of power sources and run algorithms to predict the remaining useful life. To select the controller to be used for the applications of a power management system will depend on the processing demand of the tested controller and algorithms mentioned in section 3.2.1.3. As there is limited information of how computationally demanding these applications use, micro-controllers will be selected during the design phase.

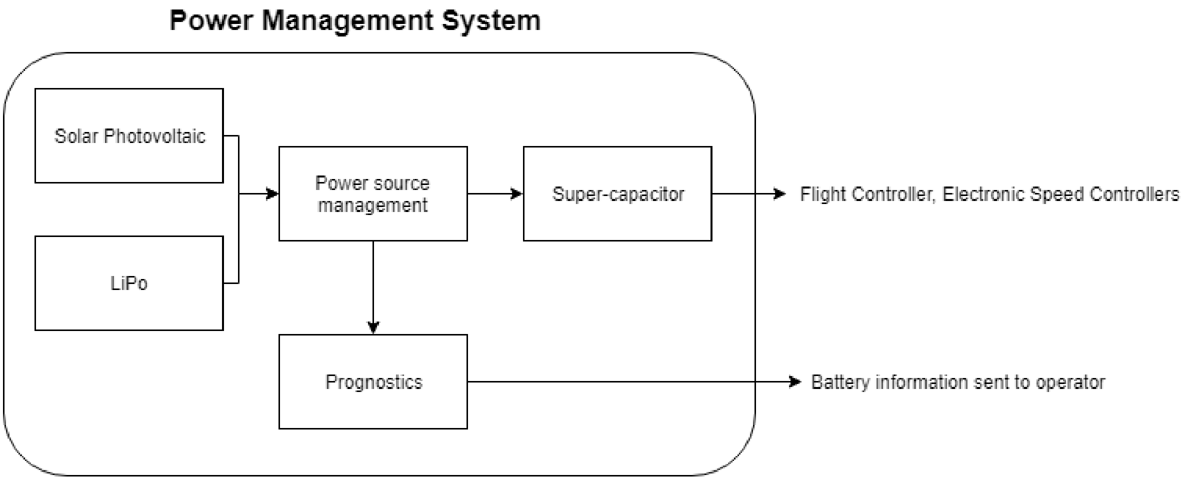


Figure 4.2: Block diagram of expected power system

In terms of costing, rough estimation for components are shown in table 4.8. These a relative estimates to build the entire system however they are subjected to change actual implementation.

Table 4.8: Cost of power components

Product	**Price ($)**
URUAV 11.1V 10000mAh 30/60C 3S Lipo Battery XT90 Plug for FPV RC Quadcopter Agriculture Drone [364]	81.05
Super-capacitors (Highest - dependent on application) [365]	20.00
Arduino Mega 2560 [366]	24.41
Solar Panel (9v 220mA) [367]	13.14
Total	138.60

4.2.2 Flight Control System Design

Author: Alexandar Nguyen

This section of the report will outline the initial design considerations for the UAVs flight controller and the proposed methodology. As stated in section 3.2.2.3 the preliminary designs would not entail the design of the controller itself, but the control algorithms that allow for altitude control and position control. No specific design has been chosen as of yet however the in-built PID controller in the Pixhawk 4 has proven to be accurate and robust to a certain degree, as seen in section 2.2.2.1.2 in the Quantitative Analysis, where the flight path accuracy was 0.55%. Again, as stated in section 3.2.2.3 different control algorithms will be tested against each other through the simulation engine within the PX4 program to determine the best performing algorithm for our situation.

4.2.3 Autonomous System Design

Author: Aaron Su

In this section, a preliminary design of the navigation and guidance systems for autonomous aerial water sampling in developing countries, such as Yamuna River in India, is proposed. The design process follows the system engineering approach inspired by Sadraey [368], which primarily consist of requirement definition, functional analysis and allocation, and design synthesis at the preliminary stage.

4.2.3.1 Requirement Definition

The design requirements primarily evolved from the UAV's mission statement that have been stated in section objectives. In addition, these requirements should also consider the regulations posed by the local government to perform BVLOS operations legally. For India government, the requirements for BVLOS remotely piloted aircraft (RPA) are highlighted in the table below, which further emphasises the need of high-level autonomy for BVLOS operation. Moreover, by combining the constraints provided by the customers, the high-level design criterion can be identified as performance, usability, cost-effectiveness, transferability, weight-efficiency, and the mission fitness for water sampling.

Table 4.9: Government Requirements

a	Micro and Small RPAS only permitted
b	Capability for autonomous operations
c	Sufficient endurance for long range operations
d	Capability to withstand adverse weather
e	Capability to transmit identity and live trajectory information
f	Carriage of barometric sensor on board

The operation procedure and environment should also be clearly identified in the context of Yamuna River in India. For autonomous aerial water sampling, the operation procedure typically follows location selection, take-off, navigation around obstacles, altitude control above water at target location, return navigation and landing. On the other hand, the environment of Yamuna River can be characterised as mostly open space, with limited urban structures at lower altitude and floating rubbish on water surface. Occasionally, people or boats can be present in the river as well as toxic floating foam, which pose high risk to the operation of the UAV.

Therefore, the designed configuration should be capable of executing the entire operation procedure in this environment meeting at least the satisfactory levels of the design requirements.

4.2.3.2 Functional Analysis and Allocation

Conventionally, the design configuration of an autonomous UAS can be decomposed into three primary functional components, namely Guidance, Navigation and Control [368]. By analysing the design requirements and operation context, it can be seen that an UAS with an autonomy level [215] between 3 to 4 is the minimum requirement for this application. In other words, the functional requirements should at least contain a Guidance System capable of real time path planning and robust response to mission changes; a Navigation System capable of robust state estimation, and obstacles, risks, target and environmental changes detection; a Control System capable of robust flight control and provide adaptive control modes in different situations.

Therefore, the design configuration alternatives for Guidance System and Navigation System will be selected, aiming at satisfying the design requirements and criterion at an optimal condition (Control System has been discussed in previous section and hence will not be included here).

Guidance System

In Guidance System, algorithms can be applied to accomplish path planning and mission planning purposes.

For mission planning, due to the limited options provided from the literature, Finite State Machine (FSM) and Tree-based framework are the only ones that are sufficiently validated under real-world environment. By comparing these two methods, Tree-based algorithm is more suitable for parallel tasks transition in complex mission, whereas FSM provides simple and controllable structure with robust response to situation change in a streamline operation. Therefore, as water sampling procedure does not involve parallel operation, simple FSM can be selected as the mission planning algorithm to reduce complexity.

For path planning, D-star, potential field, rapid exploring random tree (RRT), probabilistic road map (PRM) are candidate algorithms for 3D dynamic path planning. As the operating environment of aerial water sampling is typically high-dimensional and unknown, randomised search algorithms such as RRT and PRM are preferred for reducing the computation complexity and robustness. As discussed in the literature review, RRT outperforms PRM in efficiency and dynamic response for high-dimensional space. It also fits perfectly in exploration-like operation, such as one required by water sampling for

Table 4.11: Characteristics of Perception approaches

	Pros	Cons
LiDAR-based	- Accuracy - Computational efficiency - Not affected by lighting condition	- Limited use in outdoor space (medium range) - Heavy and bulky
Vision-based	- Versatile - Long range - Light and cheap	- Computationally heavy - Easily affected by light condition

navigating in previous unknown environment between waypoints. Therefore, RRT will be selected as the primary path planning algorithm in the guidance system.

Navigation System

In Navigation System, as the perception level of autonomy is required, configurations of sensing, state estimation, up to perception should be selected. The correlation between commonly used sensing device and their general capabilities in each navigation function is presented in table.

Table 4.10: Sensor capabilities

Sensors	**LiDAR**	**Camera**	**Ultrasonic**	**Infrared**	**GPS/IMU/Barometer**
Perception	High	High	-	-	-
State Estimation	High	Medium	Low	Low	Medium

As higher autonomy system usually implies certain degree of lower autonomy capabilities. Hence, it is more logical to select configuration of system from higher to lower level. Therefore, it can be easily seen that only LiDAR and Camera are capable of both perception and state estimation function. Therefore, the selected configuration should be either LiDAR-based or Vision-based. A more detailed pro and cons for each system is listed below.

It is worth noting that, although both systems have certain degree of state estimation capability, they are mostly restricted to local state estimation, meaning only relative position can be estimated when the mission begins. Therefore, it makes more sense if their global position can be also provided by using GPS, allowing a reliable periodic update of their true position. Indeed, this is also required by the government regulation as geo-fencing rules should be applied.

IMU is also a fundamental sensor that is usually installed. From the advancement of miniature technology for electronic components, most powerful IMUs can already be made in very small size for a relatively low price. By combining the IMU state estimation using Kalman Filter, the overall estimation can be largely improved with negligible cost. Therefore, the inclusion of IMU should be considered in most case.

In aerial water sampling, it is critical to estimate the relative altitude above water during certain operation, such as hovering or landing on water surface. As water surface is usually featureless and reflective, and target water surface altitude BVLOS cannot be confidently predicted, therefore, camera, LiDAR and GPS/altimeter in this situation all become unreliable. Hence, ultrasonic sensor can be useful as it will not be significantly affected by these properties and its detection range is perfectly within the requirement for landing operation [31].

Other sensors such as barometer, although not necessary in the target mission, is required by the government regulation. Infrared on the other hand, operate in a similar manner as LiDAR, hence is reductant in LiDAR-based system. However, infrared can be used in assisting landing operation in vision-based system to increase precision, but the necessity of extra component should be further analysed. Finally, the government regulation also requires the capability for recognizing bright colour and flashing lights, as well as FPV backup control, hence, a basic level camera should also be equipped in LiDAR-based system.

Overall, configurations that are LiDAR-based or vision-based are proposed, with inclusion of additional sensors that are necessary or optional. These configurations can be shown in the morphological matrix below, where sensor in grey are optional or to be determined by sampling mechanism.

Table 4.12: Configuration Alternatives

Function		**Configuration Alternatives**	
		Vision-based	LiDAR-based
Perception		Cameras	LiDAR + Single Camera
State Estimation	Global Position	GPS + barometer	GPS + barometer
	Attitude and Velocity	IMU	IMU
	Distance Above Water	Ultrasonic sensor	Ultrasonic sensor
	Landing Assistance	Infrared	(Deflected LiDAR)

These configurations can be evaluated against the design requirements in a Pugh's matrix shown below, where the design in [31] is chosen as standard, and the weights.

Table 4.13: Pugh's Matrix

Design Criterion	Weights	Standard	Vision-based	LiDAR-based
Performance	6	DATUM	+	+
Usability	8		+	+
Cost-Effectiveness	7		-	-
Transferability	5		S	-
Weight-Efficiency	7		S	-
Mission Fitness	9		+	S
Total+			3	2
Total-			1	3
Overall Score			2	-1
Weighted Total+			23	14
Weighted Total-			7	19
Weighted Overall Score			14	-5

Therefore, from the matrix, it is clearly shown that Vision-based configuration is a better configuration for the target application, regarding all the design criterion. It also indicates that LiDAR-based system is evaluated lower than the existing design from [31], due to the fact that LiDAR is a relatively complex device that often introduce extra weight, cost and setup effort. Indeed, LiDAR-based system is mostly used indoor for precision operation and struggle to provide effective measurements in open outdoor space [279, 280].

For vision-based system, various algorithms can be applied to perform state estimation and perception. As presented in the review section, optical flow or feature-based algorithms can be used to perform odometry from image sequences. This can be combined with information provided by GPS/IMU/barometer using Kalman Filter, resulting in highly robust and reliable estimation of pose. This will allow the UAV to conduct most of the operations reliably within the water sampling mission when external influence (e.g. obstacles) is limited.

In case any obstacles are present in the operational area of the UAV, obstacle avoidance can be performed using either visual SLAM or optical flow. However, visual SLAM is highly computationally intensive, and its mapping capability is not required in the target application (water sampling). Therefore, the simple but powerful optical flow is considered more suitable in this case. In addition, for precision landing or target recognition, correlation filter (CF) or deep learning algorithms can be applied. However, these capabilities are not considered compulsory with respect to the current mission definition, hence will not be included in preliminary design until entire system and operation configuration is determined.

4.2.3.3 Design Synthesis

After all configurations for each GNC systems have been selected, a design synthesis can be performed to link all components into an integrated system as shown in figure below.

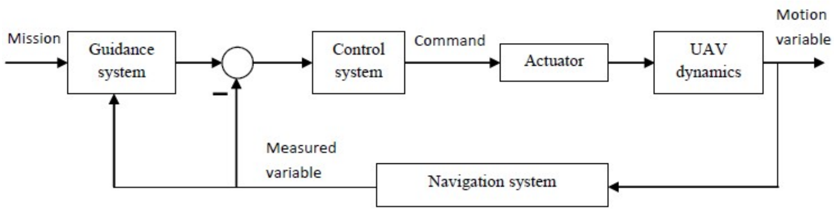


Figure 4.3: Autonomous System Flow Chart

The synthesis for a complete system typically involves defining the hardware structure and software structure. The hardware structure can be directly derived from the selection of sensors and is shown below.

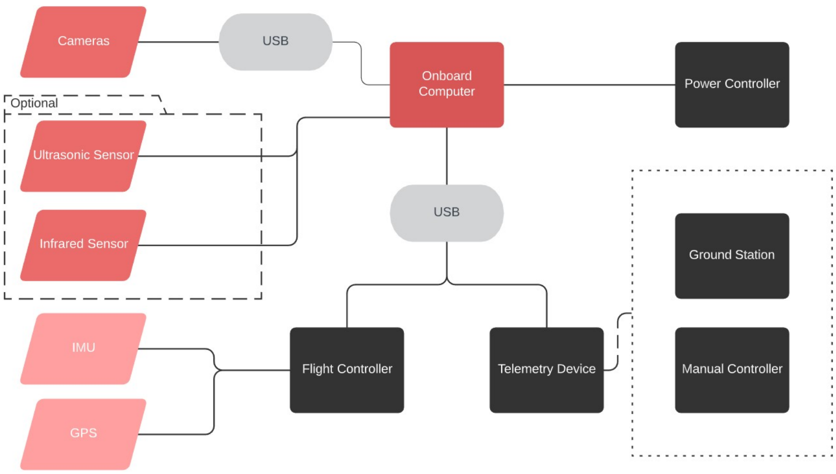


Figure 4.4: Hardware Structure Design

Where the components in red are devices involved in Guidance and Navigation systems and components in black are other functional components discussed in other systems (previous chapters).

It is worth noting that all sensor outputs have to be processed by an onboard computer which has much higher computational power requirement than microcontroller. This is because sensor data processing typically involves parallel thread and high memory requirement especially for image processing. Light weight but powerful LINUX based computers are commonly equipped, which has wide range of price from \$60 (Raspberry Pi 4) to \$500 (Jetson TX2). Therefore, the choice of optimal on-board computer cannot be made at this stage due to the complexity of the system and difficulty in estimation the accurate computational power needed. However, a software structure will still be proposed in figure assuming enough computational power can be provided by the selected onboard computer.

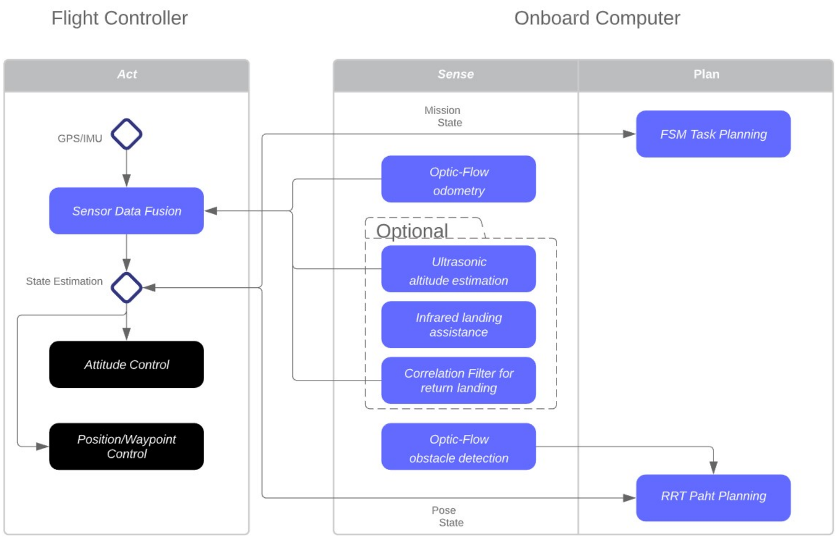


Figure 4.5: Software Architecture Design

Note that sensor data fusion is incorporated into flight controller to balance the computation load on both processors, and components in black were discussed in flight control section. It can also be seen that the previous assumption is reasonable as the algorithms are chosen to minimize the computational requirement so that the necessary processing tasks loaded in onboard computer remain minimum.

Finally, by integrating the hardware and software structure, the preliminary design is completed and is expected to achieve the objectives in preliminary level. However, at this stage, the design remains a high-level representation of the components involved and is subject to change when further analysis is carried out in later stage.

4.2.3.4 Limitations

The main limitation of this design is the trade-off between cost and performance. As camera and vision-based algorithms are involved, both direct cost and computational cost increase significantly when more cameras and more powerful computer are employed. However, to ensure fast response and optimal field of view, more cameras and faster computer are often required. Therefore, a balance between cost and performance must be achieved by carefully refine the design requirements and communicate with target customers.

4.2.4 Communication System Design

Author: Dylan Dam

Author: Dylan D

This section of the report will be employing the proposed methodology for analysing telemetry modules currently available in the market. The hopes of this chapter is to narrow down on 3-5 possible solutions. The reason why a set of modules would be selected as opposed to one is manufacturing claims something differ to the actual chips performance, therefore having back-up selections is important to avoid any setbacks.

Table 4.14: Radio Telemetry Solution Study

Module	Range	Transmit Speed	Sensitivity	Cost
Digi Xbee 3 Pro [369]	3.2km	250 Kbps	-103dBm	$65
RF-LORA-868-SO [370]	16km	300 Kbps	-130 dBm	$21
APC220 RC Module [371]	1.2km	57.6Kpbs	-113dBm	$65
LoRa MESH Radio Module - 868MHz [372]	3km	115.2 Kbps	-148 dBm	$73
HopeRF RFM95W [373]	3km	300 Kbps	-148 dBm	$25
SparkFun Transceiver nRF24L01+ [374]	100m	2 Mbps	-82 dBm	$22
Semtech SX1262DVK1PAS [375]	40km	300 Kbps	-148 dBm	$540

Based on the study of different RF modules, the following evaluation matrix will be used to determine which module is best suited for our teams application (Table 4.15).

Based off the evaluation matrix, two RF modules will be considered for the design for UAV telemetry. The HopeRF RFM95W and the RF-LORA-868-SO are potential candidate for the design solution as they fulfil most of the requirements of the project.

Table 4.15: Evaluation Matrix of Radio Study

Module	Range (Weight 3)	Transmit Speed (Weight 2)	Sensitivity (Weight 1)	Price (Weight 3)	Score
Digi Xbee 3 Pro	0	0	1	-1	-2
RF-LORA-868-SO	1	1	1	1	9
APC220 RC Module	-1	-1	1	-1	-7
LoRa MESH Radio Module - 868MHz	0	0	1	-1	-2
HopeRF RFM95W	0	1	1	1	6
SparkFun Transceiver nRF24L01+	-1	1	-1	1	1
Semtech SX1262DVK1PAS	1	1	1	-1	3

4.2.4.1 Overview of Preliminary Design

When establishing a Ground Control Station, the monitoring the flight monitoring/ flight controlling would be conducted on a laptop. Which would provide the telemetry module data that needs to be sent to the UAV. The laptop would connect to the telemetry module and then from there the RF modules would transmit the data to the UAV. The general breakdown of the telemetry module can be seen below.

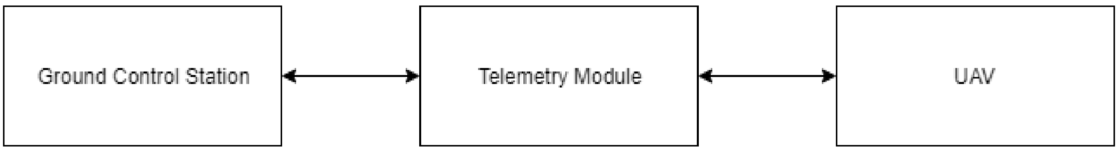


Figure 4.6: General Breakdown of Telemetry Module Function

Essentially, the telemetry module serves process information that needs to transmit data as well as read incoming data. The full duplex nature of the telemetry module allows the Ground Control Station to receive up to date information regarding the state of the UAV as well as detected obstacles. A preliminary design sketch of the telemetry module is provided below to detail the parts that would be required for the module to function. The telemetry module comprises of an outer shell which is designed to allow the components to be mounted onto it for transportation. The outer shell aims to protect the internal wiring and components when operating in the field. The outer shell will have ports for power and data uplink as well as an LED array for troubleshooting. The outer shell houses the microcontroller unit which has the sole purpose of handling incoming and outgoing data. The microcontroller unit is connected to the RF module which is connected to an antenna for transmission. A breadboard junction would be used to power the LEDs as well as connecting the RF modules to the microcontroller. The benefit of this design is that the RF modules can be duplicated to break up the data

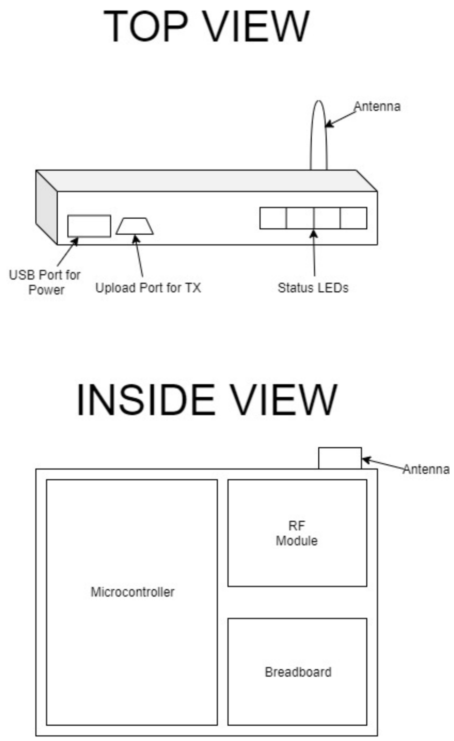


Figure 4.7: Preliminary Telemetry Module Design

processing with minimal risk of interference of data.

4.2.4.2 Electrical/Software Plan

The design mentioned above will contain an electrical and software component that will need to be implemented. The electrical wiring would be planned out on a software called "Fritizing" the purpose of Fritzing is to determine the input and outputs of all parts and determine with pins are required for the module. An example of a preliminary plan for the wiring of the telemetry module can be seen below:

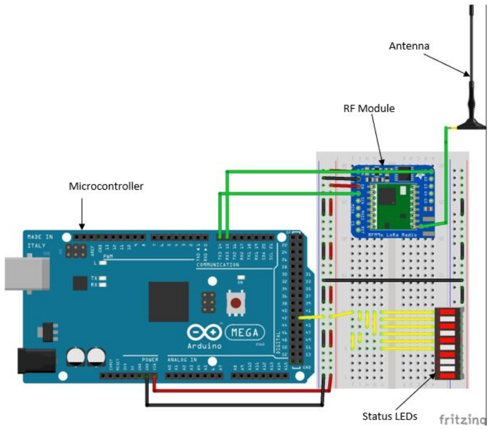


Figure 4.8: Preliminary Module Wiring

The green lines would represent the data lines for receiving and transmitting. The yellow lines are status LEDs that will connect to one of the digital I/O ports on the micro controller. The microcontroller would send off a string of 1's and 0's which would be encoded to mean a specific error has been detected.

The software component would then be split into two components. The microcontroller software and the visual UI for the user. The general pseudo code for the microcontroller would be continually running the following loop:

- Check RX port for receiving data.
- Check TX port for data that is to be transmitted
- Idle

The code implemented would allow for full-duplex communication between the ground station and the UAV itself. This ensures that the design of the telemetry module is "black boxed" (4.6) and is not dependent on any other systems. The sole purpose of this module is to send and receive information. However, the flight UI software is more complicated. The purpose of the flight UI can be summarised into the following dot-points.

- Display Flight Data
- Track the Position of the UAV
- Display the State of the UAV
- Selecting Operating Mode for UAV (Manual/Autonomous)

The data that the UI must receive and display as per requirement of the DCGA are the altitude, velocity and position of the UAV as well as obstacles in its trajectory/surroundings. This information is assumed to be encoded on board by the navigation module and is only received and processed via the telemetry module. However, if the the data that is required by the navigation module is the operating mode as well as movement information. If the module is operating in autonomous mode then way points needed to be sent to the UAV for the navigation module to plan a flight path and if manual mode is selected than movement commands need to be sent to the module to process into the appropriate movement. The current software than is capable and meets the requirements for the team's needs is Mission Planner by Ardupilot.

The open source nature of Mission means that the software is free and is generally highly customisable to fit our specific needs and requirements.

4.2.4.3 Hardware Design

The purpose of using Fritzing to design the components is to determine the approximate dimensions of the shell that is to house the electronics. The outer shell is to be made out of PLA plastic and 3d printed. As shell only serves to house and provide some protection to the module there is more emphasis on creating something lightweight and cheap for use. The outer shell would be drawn on Solidworks and then exported to a "slicing" software to generated the appropriate G-code for the 3D printer.

Figure 4.9: Mission Planner UI by ArduPilot [45]

Chapter 5

Preliminary Conclusions, Outcomes and Future Work

5.1 Mechanical System

5.1.1 Aerodynamic Design Progression

Author: Alex Peterlin

To meet the system constraints of this particular assignment, after consulting the available literature on research drones, the quad-rotor configuration has been selected as the most suitable design due to its high stability and payload capacity capabilities. Whilst the payload capacity of our water sampling device is yet to be decided, it is reasonable to assume it will not exceed a limit which requires the implementation of more rotors. This is mainly because for each extra rotor we add to our configuration, it will significantly increase the power requirements of our batteries and simultaneously lower our drones flight time. In the next phase of our work, prototype testing will need to be conducted to ensure the modification of a sampling device on our drone does not drastically shift its gravity of centre, thereby reducing stability and overall controllability of our drone.

5.1.2 Structural Chassis Design Progression

Author: Henry Gourley

After consideration of literature and self determination of market and customised drone frame options feasibility it is recommended the Tarot 650 is used going forward. Preliminary investigations suggest the Tarot 650's Specifications in terms of maximum payload capacity and durability are sufficient in meeting requirements. Foldable arms also ensure ease of portability, proving essential within a developing nation context. It is suggested to house board circuitry, batteries and the water sampling mechanism within the frames center, enclosed within a customised, waterproof casing designed without compromising accessibility and repairability standards. Flotation units will be attached to drone legs to mitigate the likelihood of critical failure and potentially allow the drone to rest upon the water's surface in calm condition when collecting samples. Finite Element and Aerodynamic analysis will be conducted to determine regions of high stress concentration poor flowability. The customised central housing will be optimized through numerous iterations to maximise performance characteristics.

5.1.3 Water Sampling System Design Progression

Author: Brandon Voon

For the deployment in developing countries, where clean water source is limited, water monitoring and analysis plays an important role in bridging this ever lasting issue. However, before the design and prototyping of any sampling solution, it is important to fully understand the capabilities of the vehicle used, particularly its payload capacity and stability. Additionally, sampling site has to be thoroughly surveyed to ensure proper and safe deployment to both the operating personnel as well as the sampling vehicle.

As of now, no specific sampling methods will be chosen for the purpose of this paper. However, recommendations were made for the deployment in Yamuna river, Bagmati river and Buringanga river. Additionally, it also known that several additional modifications will be made to the sampler of choice to allow for sensors to be installed for in-situ measurements. The type of sampler, capacity and attachment to vehicle will be further designed once all aspects of the vehicle has been confirmed.

5.2 Electrical Hardware and Firmware

5.2.1 Power System Design Progression

Author: Anthony Leung

Through the state of available literatue, it was found that UAV's were commonly limited by the amount of power that was available - lasting only at best 30 minute for missions on a single battery's charge. This inhibited how UAV's complete missions, as it deters its performance to thrust propellers, traverse and even cause sporadic failures. However, literature has shown ways to extend this performance by consider hybrid systems and algorithms to maximise the amount of power available and prognostics to know when power ceases to be effective. This report has decided to use a hybrid system that incorporates a LiPo, super-capacitor and solar photovoltaics to be more reliable, robust and sustainable. This will be managed by either a rule-based or a fuzzy controller. Furthermore to make the system more robust, a Bayesian Neural Network or a Non-Homogeneous Hidden Semi Markov Model will be used to predict the remaining useful life of the chosen battery. The complete system intends to be the most suited for developing countries, well-costed, and maintainable as well as the constraints already listed.

For future, testing will be required for the aforementioned designs to fully understand the advantages and disadvantages of each method. This will be then filtered and the best methods will extracted to be implemented in Thesis B.

5.2.2 Flight Control System Design Progression

Author: Alexandar Nguyen

For a more cost-effective, flexible and sustainable controller, open-sourced controllers were researched. This narrowed the desirable controllers to two widely known controllers, Pixhawk and Ardupilot where the Pixhawk Controller was chosen as the desired flight controller as it out performs the Ardupilot controller as well seen in table 2.7. However, as of now, no specific flight control algorithm has been decided and the comparison between the different algorithms and the inbuilt PID system will be the main focus of the section of Flight Controllers' future work. Further future work would entail the understanding of the PX4 software, as well as the testing of the inbuilt control algorithms and other types of algorithms within the PX4 simulation, to provide a conclusive algorithm used for our design.

5.2.3 Autonomous System Design Progression

Author: Aaron Su

From the literature review of the contemporary technologies for Navigation System and Guidance System, it is found that vastly different system configurations exist, and no single system design can be qualified the best under various operating environment. In this report, the characteristics of the technologies within each of the system in different autonomy level were analysed and compared with the consideration of water sampling context.

Design requirements were identified by analysing both the customer needs and government regulation in the target area (Yamuna River). Design configurations were selected following the system engineering approach to establish a well-rounded system that address all identified design criterion. Finally, a system design that include the hardware and software structures was proposed, which was considered the optimal solution for autonomous system in the context of water sampling in developing country.

For later stage design, the detailed specifications of each sensor will be selected, and electronics will be assembled and tested. Software environment will be setup on the onboard computer with the proper middleware (e.g. ROS) and framework (e.g. PX4) to accelerate integration and testing. Algorithms will also be implemented within the system and performance will be evaluated according to the designed software architecture. Life-cycle refinement will be applied, to replace or improve certain component in the system, in order to achieve an optimal configuration regarding the design requirements.

5.2.4 Communication System Design Progression

Author: Dylan Dam

Author: Dylan D

The goal of this study was to determine currently telemetry solutions that are used for different UAVs. The study begins board by studying five different implementations of UAVs within their respective research purpose and finding a gap in current solutions. Based on the gap in research, being the lack of cost effective telemetry solutions, our currently methodology was adopted. Through the methodology, a preliminary design was formulated that can meet our team's criterias as well as fulfil the requirements by Indian airspace. The DCGA provided a set of requirements that the UAV was expected to be able to perform, this included the max airspace allocated for our UAV as well as the data that the UAV is expected to present on the flight tracker. With Indian airspace regulation and our own methodology in mind, a study was conducted on different off the shelve RF modules to determine which select few are meet most of our teams requirements. The next section of the thesis deals with a preliminary design and a breakdown of the entire process to prepare for the next semester.

5.3 Outcomes

The proposed designs of specific components comply with the problem statement and constraints. The selection of a UAV sampling device over other traditional sampling methods eliminates direct vehicle contact with water as well as eliminating the need to traverse difficult land terrain while still being amphibious. Furthermore, the added feature of fold-able arms allows the vehicle to be compact and provide extra portability which proves essential for developing nation context. The UAV will have a quad-rotor configuration providing robust stability and payload capacities. Through the implementation of autonomy and flight control the inaccuracy of human error is eliminated and the use of precise sensors and flight control algorithms provide a more reliable system. Other algorithms such as the Bayesian Neural Network or Non-Homogenous Hidden Semi Markov Model, which allows for the prediction of remaining operable battery life, further provides robustness to the overall UAV system as it allows the user as well as the computers to predict of remaining battery life is capable of performing an immediate sampling procedure. The implementation of a hybrid power system which incorporates LiPo, super capacitors and solar photovoltaics expands on the reliability and robustness of the system as well as being sustainable. Lastly, long range radio waves were selected to communicate with the UAV as they have penetrating capabilities allowing operations at distances that fall within out of line of sight operations.

5.4 Timeline and Gantt Chart

The timeline for this project has been made to account for delays and absences within the team. This also includes 2 day buffers and also involve early start and early finish procedures to allow ample time for group members to comfortably complete their task in time, sparing 2 weeks before Thesis B is assumed to be due. The task start date is the 30/11/2019 and the finish date is 10/04/2019. The complete project is expected to run with three iterations, with developments improving on previous iterations to ensure the designed project is robust and reliable. The iteration due dates of these are expected to be 1/03/2020, 26/03/2020 and the final iteration is the expected finish date. This Gantt Chart is provided on the following page

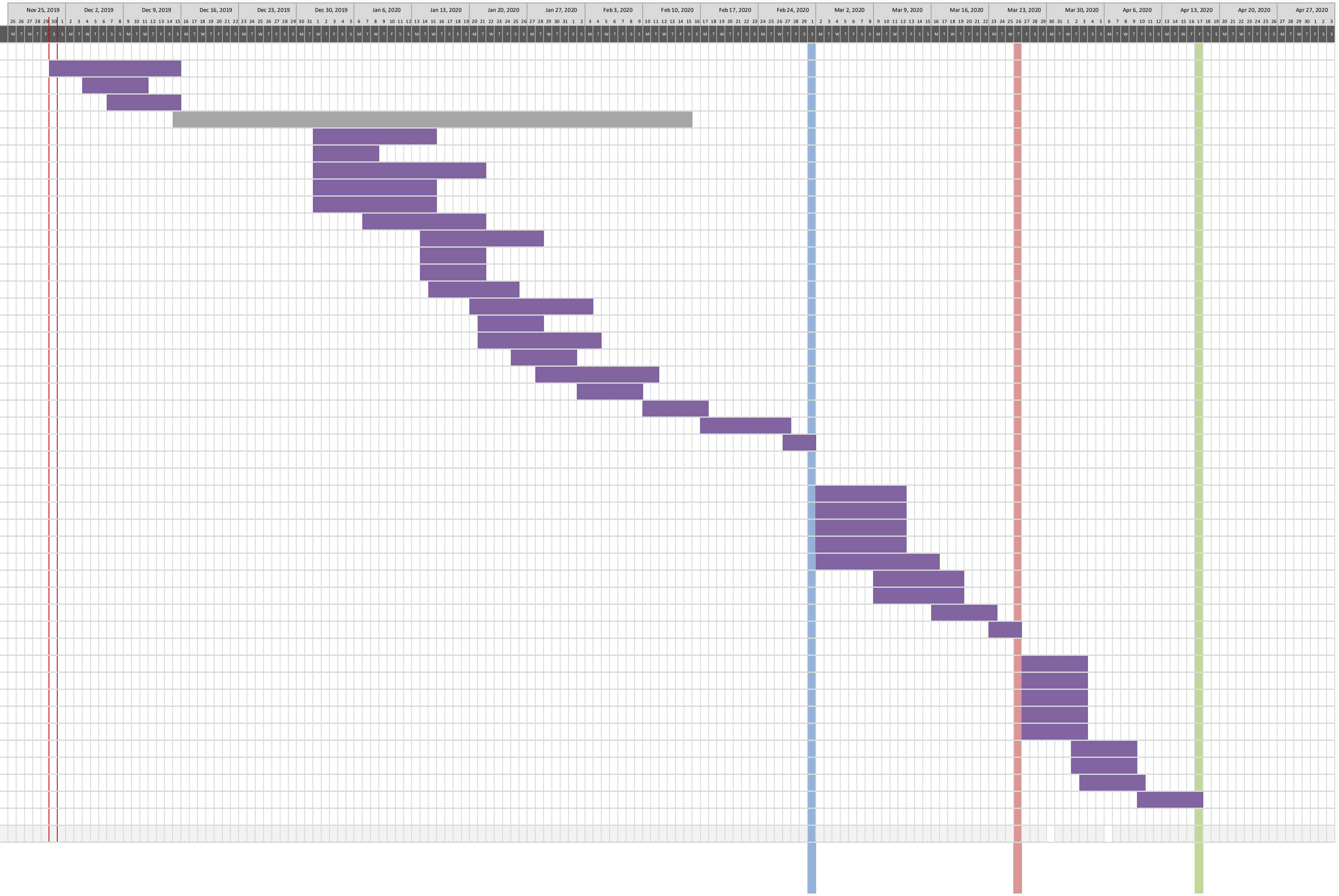
Thesis B

Group 22
Project Lead

Project Start: Sat, 11/30/2019
Display Week: 1/01/00

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

TASK	Componen	ASSIGNED TO	PROGRESS	START	END
Iteration 1					
Flight controller design and selecti	El	Alex N	0%	30/11/19	15/12/19
Flight control protyping	El	Alex N	0%	4/12/19	11/12/19
Flight control firmware developme	El	Alex N	0%	7/12/19	15/12/19
Alex N Unavailable Period		Alex N	100%	15/12/19	15/02/20
Autonomy design and selection	El	Aaron S	0%	1/01/20	15/01/20
Autonomy prototyping	El	Aaron S	0%	1/01/20	8/01/20
Power design and selection	El	Anthony L	0%	1/01/20	21/01/20
Sampling design and selection	M	Brandon V	0%	1/01/20	15/01/20
Telemtry design and selection	El	Dylan D	0%	1/01/20	15/01/20
Autonomy firmware development	El	Aaron S	0%	7/01/20	21/01/20
Aerodynamic design and selection	M	Alex P	0%	14/01/20	28/01/20
Power management prototyping	El	Anthony L	0%	14/01/20	21/01/20
Telemtry prototyping	El	Dylan D	0%	14/01/20	21/01/20
Sampling design prototyping	M	Brandon V	0%	15/01/20	25/01/20
Power management firmware dev	El	Anthony L	0%	20/01/20	3/02/20
Autonomy firmware testing	El	Aaron S	0%	21/01/20	28/01/20
Telemetry firmware & software d	El	Dylan D	0%	21/01/20	4/02/20
Sampling method testing	M	Brandon V	0%	25/01/20	1/02/20
Chassis Design and selection	M	Henry G	0%	28/01/20	11/02/20
Telemetry design testing	El	Dylan D	0%	2/02/20	9/02/20
Chassis prototyping	M	Henry G	0%	10/02/20	17/02/20
Complete system integration	Al	ALL	0%	17/02/20	27/02/20
Accessment and improvement	Al	ALL	0%	27/02/20	1/03/20
Aerodynamic prototyping	M	Alex P			
Iteration 2					
Autonomy improvement design	El	Aaron S	0%	2/03/20	12/03/20
Flight control improvement desigr	El	Alex N	0%	2/03/20	12/03/20
Telemetry improvement design	El	Dylan D	0%	2/03/20	12/03/20
Power improvement design	El	Anthony L	0%	2/03/20	12/03/20
Sampling improvement design	M	Brandon V	0%	2/03/20	16/03/20
Chassis improvement design	M	Henry G	0%	9/03/20	19/03/20
Aerodynamic improvement design	M	Alex P	0%	9/03/20	19/03/20
Complete system integration	Al	ALL	0%	16/03/20	23/03/20
Assessment and improvement	Al	ALL	0%	23/03/20	26/03/20
Iteration 3					
Autonomy improvement design	El	Aaron S	0%	27/03/20	3/04/20
Flight control improvement desigr	El	Alex N	0%	27/03/20	3/04/20
Telemetry improvement design	El	Dylan D	0%	27/03/20	3/04/20
Power improvement design	El	Anthony L	0%	27/03/20	3/04/20
Sampling improvement design	M	Brandon V	0%	27/03/20	3/04/20
Chassis improvement design	M	Henry G	0%	2/04/20	9/04/20
Aerodynamic improvement design	M	Alex P	0%	2/04/20	9/04/20
Complete system integration	Al	ALL	0%	3/04/20	10/04/20
Assessment and improvement	Al	ALL	0%	10/04/20	17/04/20
Insert new rows ABOVE this one					



Appendix A

Moment Calculation for a Servo Arm

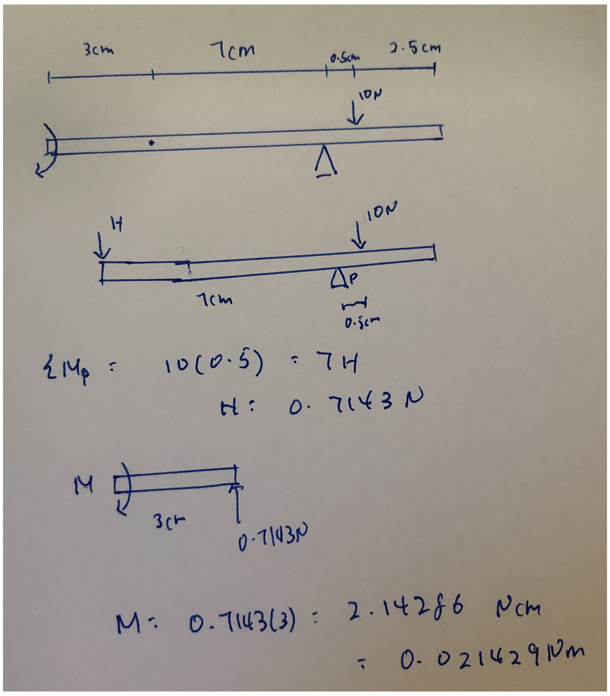


Figure A.1: FBD: Force and Moment analysis

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