ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

ROBOTIC FISH FOR MONITORING WATER POLLUTION

M.Sc. THESIS

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Department of Control and Automation Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

SU KİRLİLİĞİNİ DENETLEMEK İÇİN ROBOTİK BALIK

YÜKSEK LİSANS TEZİ

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Mohammed Javed Ansari, an M.Sc. student of ITU Graduate School student ID 504161131, successfully defended the thesis/dissertation entitled "ROBOTIC FISH FOR MONITORING WATER POLLUTION", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission: 14 January 2022
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To my mother and father,

FOREWORD

The basis of this study roots to disccussions of several ideas with my advisor, Prof. Dr. Mustafa Dogan, who has always been so supportive to me since the first day I got introduced to him. He always inspired me to work on Robotic Fish, being the underwater world very less explored. I cannot thank Prof. Dogan enough for the way he supported, inspired, and motivated me, whether be it with the thesis or outside.

With all those things that I was going through during this study, I could not have been able to do it was there not a very supportive background. I acknowledge the support my parents, friends, and families showed all this long.

There are innumerous persons that in a way or other contributed to the completion of this study, but I cannot skip naming Rayene and Hadeeyah for the beacon they always held.

January 2022 Mohammed Javed ANSARI

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ABBREVIATIONS

ADC	**:** Analog to Digital Converter
AUV	: Autonomous Underwater Vehicle
GPS	**:** Global Positioning System
HOV	: Human Occupied Vehicle
I2C	: Inter Integrated Circuit
PLA	**:** Polylactic Acid
PWM	**:** Pulse Width Modulation
ROV	: Remotely Operated Vehicle
SPI	: Serial Peripheral Interface
TPU	**:** Thermoplastic Poly Urethane
UART	: Universal Asynchronous Reception and Transmission (UART)
UWAC	: Underwater Wireless Acoustic communication
UWC	: Underwater Wireless Communication
UWOC	: Underwater Wireless Optical Communication
Wi-Fi	**:** Wireless Fidelity
WLAN	**:** Wireless Local Area Network

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ROBOTIC FISH FOR MONITORING WATER POLLUTION

SUMMARY

The vast majority of the earth's surface is covered by water. Some parts of the ocean are so deep that even Mount Everest would be lost into them as if it never existed. Water bodies, irrespective of fresh or salty, big or small, all of them host some of the most unique ecosystems. Mankind is known to have set its sails into the oceans for time immemorial now. But it has only been possible in recent years that they have dived inside by the means of HOVs, ROVs, and AUVs. And still, most of it remains unexplored. Every living thing from a unicellular amoeba to Antarctic blue whales including every single plant needs water to survive. Otherwise, the earth would be as barren as any other planet known so far. The key to fact that life exists on the earth is water. But unfortunately, the amount of garbage of all kinds being dumped into the sources of water pollutes them and in a long run adversely affects and endangers the living things on planet earth. As our very existence depends on water, it’s indispensable to monitor and take essential steps to preserve the water quality accordingly.

Not only does water avail a sustainable condition for the terrestrial inhabitants, but also is a habitat to a huge number of species within. One of the most well-known species among these aquatic animals is fish. In this work, a brief study of types of fishes along with their structural definition is carried out to determine how they propel and swim in the water with their fin and then eventually use the discoveries to biomimetically design and implement a robotic fish capable of exploring water and taking certain readings with inbuilt sensors. The thus obtained readings can be used to monitor water. The robotic fish here tries moving in the water replicating the motion behaviors of a fish.

This study consists of 5 different parts. Chapter 1 provides a brief introduction of the whole idea and the classification of fish according to their swimming behavior. Fishes swim in the water using their fins. They use their fins to produce a propulsive force that pushes them forward. Depending upon which part of the fish and how it pulsates fishes can be categorized into different classes. These classifications help study fishes better. A detailed categorization on the basis of various grounds is further discussed in this chapter. A common approach to classify fishes is based on the modes of propulsion that a fish applies while swimming i.e. whether undulatory or oscillatory methods of generating propulsive forces. These two categories of fish swimming modes are BCF (body and/or caudal fin) locomotion, and MPF (median and/or paired fin) locomotion. A thing common in these modes of propulsion is that the caudal fins play the most important role in producing the propulsive force generation. In this study, a “Carangiform & Fusiform” model has been adapted for replication. The first chapter also gives a brief description of “Biomimetics” along with some of its popular applications in various fields. Later in this chapter, the overall implementation of this work has been mentioned.

Chapter 2 discusses works of a similar kind. It also comprises the methods used in other similar works. The caudal fin drive mechanism can be of single, multiple, or compliant type. It is already known that the caudal fin plays the most important role in swimming and maneuvering. And the stiffness of the joint that connects the caudal fin to the body of the fish is equally important for efficient swimming. Unlike other similar works, Turfi uses a single joint method with a soft caudal fin.

The outer cover of Turfi was designed using SolidWorks. The 3D model was later printed using a 3D printer. The outer body of Turfi was divided into 2 halves while designing. The first half enclosed all the electronics (including the SD card module, battery, sensors, processor, and driver circuits) and the motors. The pectoral fins are controlled using micro servo motors that help Turfi in maneuvering and the caudal fin is driven using a dc motor attached to a reduction mechanism. The other half of Turfi is the caudal tail and its mechanism that creates the oscillatory motion in the caudal fin by the means of the dc motor. The caudal fin drive mechanism converts the rotary motion of the dc motor to oscillatory motion. The front enclosure part was 3D printed using Polylactic Acid (PLA) because of its stiffness. The posterior i.e., the caudal fin was made using Thermoplastic Polyurethane (TPU). TPU is best known for flexibility. Making the caudal fin with TPU gives the caudal fin a soft and flexible structure thus making the propulsion wavy and smooth.

The ESP32 used as the processor is also embedded with a WiFi module. ESP32 is programmed to create an Async WiFi server. The asynchronous server allows Turfi to take the readings and store them on an SD card even when offline. And when connected can deliver all the data collected at once. This helps Turfi to navigate and collect data irrespective of its connection to the base station. Turfi while navigating underwater takes the sensor readings and stores them into an SD card. After the completion of navigation, Turfi resurfaces and connects with the base station using WiFi and sends all the readings made during the navigation. Turfi later. These readings can be accessed using an IP provided by ESP32. These details are discussed in Chapter 3.

As this study progressed further it was seen that Turfi can be programmed in various ways to accomplish different tasks. In the 4th Chapter, the results of two different tests are included. In the first test, Turfi was programmed to take readings at a certain depth (i.e., 20cm). A PID controller using PID Library by Brett Beauregard was used to track the depth based on the readings from the depth sensor. The second test was similar to the first one except that Turfi was instructed to take left and right turns.

5th Chapter concludes this work by describing the complexity of multi-fin locomotion underwater. It also briefly explains how Turfi can be developed in order to accomplish further. Upgrades such as a camera to record underwater, sensors to measure pH, oxygen level, salinity, etc. can be attached to Turfi. These sensors can help Turfi monitor underwater in a more detailed way. An exit mechanism is also proposed in this section. The exit mechanism would help Turfi resurface in case the battery is below a certain level or once the navigation is complete. Once atop, the whereabouts of Turfi can be known using GPS.

There have been works of similar nature done priorly. But most of them tend to focus on a descriptive analysis of the swimming behavior of a fish and then replicating it. In this work, the scope has been slightly widened by adding the sensors to make required readings. One major hindrance similar to the ones of previous works i.e., limitation to wirelessly communicate well is experienced while working on this project as well.

Thus, a different approach is applied in this study. In this approach, Turfi is instructed to follow a certain navigation route. While navigating underwater, Turfi also stores the sensor readings on an SD card. These data can be retrieved wirelessly from Turfi over WiFi. Thus, obtained data can be used for further processing.

SU KİRLİLİĞİNİ DENETLEMEK İÇİN ROBOTİK BALIK

ÖZET

Dünya yüzeyinin büyük çoğunluğu sularla kaplıdır. Okyanusun bazı kısımları o kadar derindir ki Everest Dağı bile sanki hiç yokmuş gibi o derinliklerde kaybolur. Su kaynakları, tatlı veya tuzlu, büyük veya küçük fark etmeksizin, hepsi en eşsiz ekosistemlerden bazılarına ev sahipliği yapıyor. İnsanoğlunun çok eski zamanlardan beri okyanuslara yelken açtığı bilinmektedir. Ancak son yıllarda HOV'lar, ROV'ler ve AUV'ler gibi teknolojinin gelişmesi ile birlikte robotik araçlarla okyanusun derinlerine ulaşılmak mümkün olmuştur. Bu teknolojik gelişmelere rağmen okyanusların çoğu hâlâ keşfedilmemiş durumdadır. Gerek tek hücreli bir amipten gerekse Antarktika mavi balinalarına kadar her canlı, hatta her bir bitki de dahil olmak üzere hayatta kalabilmek için suya ihtiyaç duyar. Eğer su olmasaydı, dünyamızda da şimdiye kadar bilinen diğer gezegenler gibi yaşam olmazdı. Yeryüzünde yaşamın var olduğunun anahtarı sudur. Ancak ne yazık ki su kaynaklarına atılan her bir çöp kirliliğe sebep olmakta ve uzun vadede dünya üzerindeki canlıları olumsuz etkilemekte ve tehlikeye atmaktadır. Varlığımız suya bağlı olduğundan, su kalitesini bu doğrultuda izlemek ve korumak için gerekli adımları atmak vazgeçilmezdir.

Su sadece karada yaşayanlar için sürdürülebilir bir koşul sağlamakla kalmaz, aynı zamanda içindeki çok sayıda canlılar için bir yaşam alanıdır. Bu su canlıları arasında en çok bilinen türlerden biri balıktır. Bu çalışmada, yüzgeçleriyle suda nasıl ilerlediklerini ve yüzdüklerini izleyerek esinlendiğimiz balık türlerinin kısa bir incelemesi yapıldıktan sonra biyomimetik olarak suda gezebilen ve dahili sensörler ile belirli okumalar yapabilecek robotik bir balık tasarlanmıştır ve su kirliliği ölçmek için kullanılmıştır. Bu şekilde elde edilen sensör okumaları suyun kalitesini ve durumunu izlemek için kullanılabilir. Buradaki robotik balık, bir balığın hareket davranışlarını taklit ederek suda yüzmeye çalışmaktadır.

Bu çalışma 5 farklı bölümden oluşmaktadır. Bölüm 1, tüm fikrin kısa bir girişini ve balıkların yüzme davranışlarına göre sınıflandırılmasını sağlamaktadır. Balıklar yüzgeçlerini kullanarak suda yüzerler. Yüzgeçlerini, kendilerini ileriye doğru iten bir itici güç üretmek için kullanırlar. Yüzmek için balığın hangi kısmını kullandığı ve nasıl titreştiğine bağlı olarak balıklar farklı sınıflara ayrılabilir. Bu sınıflandırmalar balıkları daha iyi bir şekilde incelemeye yardımcı olur. Çeşitli gerekçeler temelinde ayrıntılı bir sınıflandırma bu bölümde daha ayrıntılı olarak tartışılmaktadır. Balıkları sınıflandırmak için yaygın bir yaklaşım, bir balığın yüzerken uyguladığı itme modlarına, yani itici kuvvetler oluşturmak için dalgalı veya salınımlı yöntemlere dayanmaktadır. Bu iki balık yüzme modu kategorisi, BCF (vücut ve/veya kuyruk yüzgeci) hareketi ve MPF (orta ve/veya çift yüzgeç) hareketidir. Bu tahrik modlarında ortak olan bir şey, itici kuvvet üretiminde en önemli rolü kuyruk yüzgeçlerinin oynamasıdır. Bu çalışmada "Carangiform & Fusiform" modeli taklit edilmektedir. Birinci bölüm ayrıca, çeşitli alanlardaki bazı popüler uygulamalarıyla birlikte "Biyomimetik" hakkında kısa bir açıklama vermektedir. Bu bölümün ilerleyen

kısımlarında, bu çalışmanın genel uygulamasından bahsedilmiştir.Bölüm 2, benzer türden çalışmaları tartışır. Aynı zamanda diğer benzer çalışmalarda kullanılan yöntemleri de içermektedir. Kuyruk yüzgeci tahrik mekanizması tekli, çoklu veya uyumlu tipte olabilir. Kuyruk yüzgecinin yüzme ve manevra yapmada en önemli rolü oynadığı zaten biliniyor. Kuyruk yüzgecini balığın gövdesine bağlayan eklemin sertliği de verimli yüzme için eşit derecede önemlidir. Diğer benzer çalışmalardan farklı olarak Turfi, yumuşak kuyruk yüzgeci ile tek eklem yöntemi kullanır.

Turfi'nin dış gövdesi SolidWorks kullanılarak tasarlanmıştır. Tasarlanmış 3D model daha sonra bir 3D yazıcı kullanılarak basılmıştır. Turfi'nin dış gövdesi tasarlanırken 2 aşamalı yapılmıştır. İlk aşamada tüm elektronik komponentler (SD kart modülü, pil, sensörler, işlemci ve sürücü devreleri dahil) ve motorlar birlikte çalışacak şekilde entegre edilmiştir. Göğüs yüzgeçleri, Turfi'nin manevra yapmasına yardımcı olan mikro servo motorlar kullanılarak kontrol edilir ve kuyruk yüzgeci, bir indirgeme mekanizmasına bağlı bir DC motor kullanılarak tahrik edilir. Turfi'nin diğer yarısı ise arka kuyruğu ve bunun dc motor vasıtasıyla kuyruk yüzgecinde salınım hareketini yaratan mekanizmasıdır. Kuyruk yüzgeci tahrik mekanizması, DC motorun dönme hareketini salınımlı harekete dönüştürür. Ön muhafaza parçası, sertliği nedeniyle Polilaktik Asit (PLA) kullanılarak 3D olarak basılmıştır. Arka, yani kuyruk yüzgeci, Termoplastik Poliüretan (TPU) kullanılarak yapılmıştır. TPU en iyi esneklik ile bilinir. Kuyruk yüzgecinin TPU ile yapılması, kuyruk yüzgecine yumuşak ve esnek bir yapı kazandırarak, tahriki dalgalı ve pürüzsüz hale getirir.

İşlemci olarak kullanılan ESP32 de bir WiFi modülü ile gömülüdür. ESP32, bir Async WiFi sunucusu oluşturmak üzere programlanmıştır. Eşzamansız sunucu, Turfi'nin okumaları almasına ve çevrimdışıyken bile bir SD kartta saklamasına izin verir. Su üstünde bağlandığında, toplanan tüm verileri bir kerede teslim edebilir. Bu, Turfi'nin baz istasyonuna olan bağlantısından bağımsız olarak gezinmesine ve veri toplamasına yardımcı olur. Turfi, su altında gezinirken sensör okumalarını alır ve bir SD karta kaydeder. Navigasyonun tamamlanmasından sonra Turfi yeniden yüzeye çıkar ve WiFi kullanarak baz istasyonuna bağlanır ve navigasyon sırasında yapılan tüm okumaları gönderir. Turfi daha sonra. Bu okumalara ESP32 tarafından sağlanan bir IP kullanılarak erişilebilir. Bu ayrıntılar Bölüm 3'te tartışılmaktadır.

Bu çalışma ilerledikçe, Turfi'nin farklı görevleri yerine getirmek için çeşitli şekillerde programlanabileceği görüldü. 4. Bölümde iki farklı testin sonuçlarına yer verilmiştir. İlk testte Turfi, belirli bir derinlikte (yani 20 cm) okumalar alacak şekilde programlandı. Derinlik sensöründen alınan okumalara dayalı olarak derinliği izlemek için Brett Beauregard'ın PID Kitaplığını kullanan bir PID denetleyicisi kullanıldı. İkinci test, Turfi'nin sola ve sağa dönüşler yapması talimatının verilmesi dışında birincisine benzerdi.

5. Bölüm, su altında çok kanatlı hareketin karmaşıklığını tanımlayarak bu çalışmayı sonlandırıyor. Ayrıca, daha fazlasını başarmak için Turfi'nin nasıl geliştirilebileceğini de kısaca açıklar. Turfi'ye su altında kayıt yapmak için kamera, pH, oksijen seviyesi, tuzluluk vb. ölçmek için sensörler gibi yükseltmeler eklenebilir. Bu sensörler Turfi'nin su altında daha detaylı izlemesine yardımcı olabilir. Bu bölümde ayrıca bir çıkış mekanizması önerilmiştir. Çıkış mekanizması, pilin belirli bir seviyenin altında olması durumunda veya navigasyon tamamlandığında Turfi'nin yeniden yüzeye çıkmasına yardımcı olacaktır. Bir kez tepesinde, Turfi'nin nerede olduğu GPS kullanılarak bilinebilir.

Daha önce de benzer nitelikte çalışmalar yapılmıştır. Ancak çoğu, bir balığın yüzme davranışının tanımlayıcı bir analizine ve ardından onu uygulamaya odaklanma eğilimindedir. Bu çalışmada, gerekli okumaları yapmak için sensörler eklenerek kapsam biraz genişletildi. Bu proje üzerinde çalışırken, önceki çalışmalardakine benzer büyük bir engel, yani kablosuz olarak iyi iletişim kurma kısıtlaması yaşandı. Bu yaklaşımda Turfi'ye belirli bir navigasyon rotasını izlemesi talimatı verilir. Turfi, su altında seyrederken sensör okumalarını da bir SD kartta saklar. Bu veriler WiFi üzerinden Turfi'den kablosuz olarak alınabilir. Böylece elde edilen veriler daha sonraki işlemler için kullanılabilir.

1. INTRODUCTION

Water constitutes around 60% of the human body. And water makes up around 71% of the entire globe itself. Chemically, water is two parts Hydrogen and one-part oxygen. From metabolism within the human body to determining the climate of the planet, water plays a vital role. Our very existence depends on water. Talking further of its importance, let us not forget that several space expeditions costing trillions of dollars are carried out just to find traces of water in outer space.

It is quite obvious that life is very related to the availability of water. So much so that if there were no water, there won't be life. And this is proven by the barren planets discovered so far.

While only 15 percent of terrestrial life has been discovered. Life underwater in this regard seems to be completely untouched. With a known species of around 226,000, only around 5% of marine life has been discovered so far. Thus, in the underwater, there remains a whole different world which mankind is yet to learn and discover. [1],[2]

Talking of water available on earth, it’s such an irony when we try to examine how it is neglected and polluted even though our very existence is directly dependent on it. Water is capable of dissolving anything more than any other liquid known. This is what makes water known as the “universal solvent. But this is also the reason what makes water vulnerable to pollution. Although water is so important, the ongoing disposal and dumping of tonnes and tonnes of pollutants (degradable and non-degradable) deteriorate the quality of available water day by day.

Attributing the existence of life on earth merely to water would quite not be justified because there are other numerous factors related to it. And among them is a favorable climate. Nonetheless, the climate itself is very closely related to the water cycle. Specifically, the ocean currents which are also known as the “Conveyor Belts” of the planet play a vital role in keeping the planet sustainable. The ways that the ocean plays a role in affecting the weather and climate of the entire planet are by storing solar radiation, distributing heat and moisture around the globe. And these ocean currents directly depend upon various factors such as the wind on the surface, temperature, density, etc. [3]

As the temperature is one of the determinants of the ocean current, with the rise in temperature of ocean water it can be noted that the ocean current is being affected and so is the climate and the weather.

This thesis emphasizes designing and prototyping a biomimetic-based robotic fish that is capable of taking data underwater and then storing it in an SD card. The data thus received can be retrieved for further use to tackle water pollution.

1.1 Aquatic Life

With the fact that the majority of the planet i.e. over 70% is covered by water, the number of aquatic lives, their species, and vegetation are far beyond that the humans have discovered or maybe even imagine. In other words, the aquatic ecosystem covers more than 70% of the earth's surface. Out of this, more than eighty percent remains unmapped, unobserved, and unexplored. It is also predicted that only 5% of the existing aquatic life has been discovered. [4]

The decrease in presence of light and the amount of pressure that water exerts with the increase in depth can be attributed as the reasons for making "deep-sea" unexplorable. With the advent of underwater rovers, people seem to be interested in knowing more about the underwater world.

1.1.1 Fishes

Fishes are scaly-scaled aquatic animals. And they breathe using gills. Gills are the differences that make a shark a fish and a whale a mammal. Fishes are not just the most common aquatic animals but also with a total number of living fish species discovered (about 32,000), they outnumber all other vertebrate species (amphibians, reptiles, birds, and mammals) combined. [5]

1.1.1.1 Fish Morphology

Fishes can be found in numerous shapes and sizes. They can range from a Dwarf Pygmy Goby (9 mm) to an enormous Whale Shark (up to 18 meters). And their shapes can be unexpectedly surprising such as an elongated tape, a rug mat, etc. Fishes over time have adapted to cope with the surroundings they are found in. The streamlined and torpedo-shaped fishes are found in open water where they tend to swim fast and straight, whereas fishes with a flat body such as stingrays are found at the seabed to wait for the prey. Similarly, fishes with long snout mouths suck and hunt their food from narrow reefs and cracks. Fishes with larger mouths gulp their food while those with smaller mouths nibble. A detailed description of the classification of fishes based on their morphology can be accessed via FishBase; the most extensively used global online database on fishes that over time has "evolved into a dynamic and versatile ecological tool" that is widely cited in scholarly publications. [6]

The ‘Morphology’ table of FishBase, based on the lateral body shape and cross-section, classifies the fishes into the following six body shape groups in Figure 1.1:

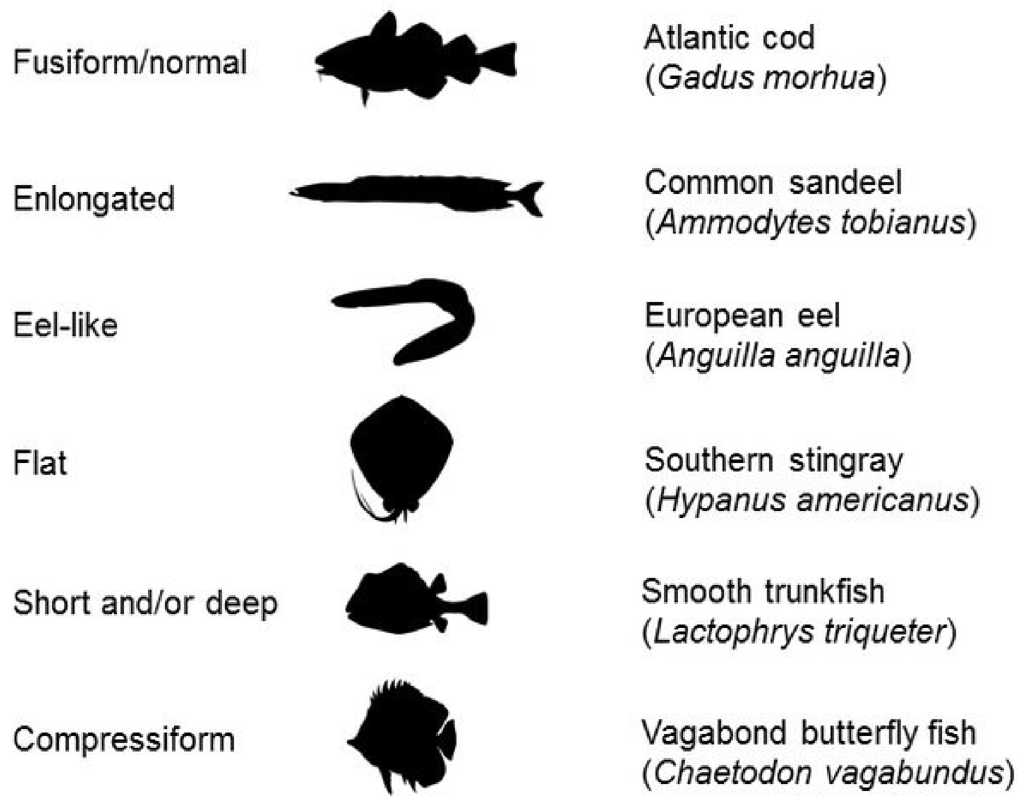

Figure 1.1: Body shape of fish according to six categories with species examples of each category. Pictures from www.phylopic.org under a Creative Commons Public Domain Dedication 1.0 License [7].

1.1.1.2 Locomotion in Fishes

It is quite obvious that fishes swim in order to move from one place to another. Fishes use the propulsive movement of the caudal (tail) fins to push them forward, while the rest are generally involved in guiding, stability, control, and maneuvering. The classical plan of Breder divides fish into categories based on their mode of locomotion named after exemplar species. [8],[9],[15]

Another approach to classifying the modes of fish propulsion is to locate fishes along a continuum from undulatory to oscillatory methods of generating propulsive forces.

In another approach, the classification of the modes of fish propulsion while swimming can be done by determining whether it is undulatory or oscillatory methods of generating propulsive forces. These two categories of fish swimming modes are body and/or caudal fin (BCF) locomotion, and median and/or paired fin (MPF) locomotion. [11]

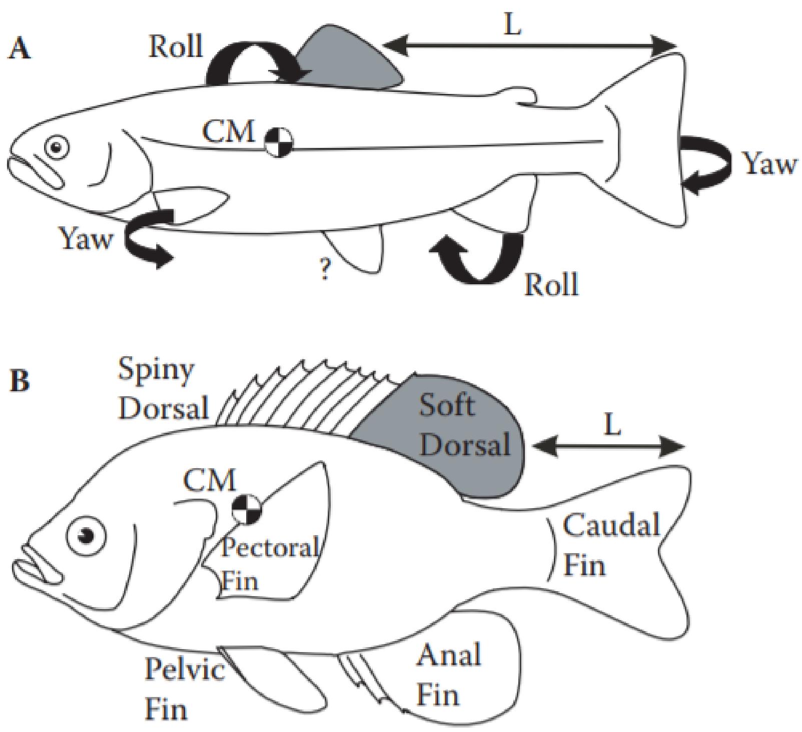

Figure 1.2: Body shapes in two representative teleost fishes namely, (A) trout (e.g., the Oncorhynchus mykiss) and (B) bluegill (e.g., Lepomis macrochirus) illustrating the major median and paired fins and their positions [10].

The body part of the fish that is involved in generating propulsive forces determines whether the fish is a BCF or an MPF swimmer. In BCF, a fish contracts and releases its body and/or caudal (tail) fin as if a wave to generate propulsive force that thrusts itself forward. Meanwhile, MPF swimmers use their median and/or pectoral fins to do so. Fishes are generally are know to be BCF swimmers. The BCF propulsion can be further categorized as shown in Figure 1.3 below:

Figure 1.3: Modes of BCF propulsion; (a) anguilliform, (b) subcarangiform, (c) carangiform, (d) thunniform and (e) caudal fin motion in thunniform locomotion [12],[14].

a) Anguilliform: Fishes with a slender and elongated body such as eel produce high amplitude undulations to propagate forward. Anguilliform swimmers can swim backward by changing the direction of propulsive wave propagation.
b) Subcarangiform: The subcarangiform swimmers are similar to anguilliform except that the undulations are only in the forward direction and more on the posterior part of the body. E.g. Trouts are subcarangiform.
c) Carangiform: Carangiform swimmers are faster than the former two groups. The undulations are concentrated mostly in the very rear of the body and tail (Caudal fins). Carangiform swimmers generally have rapidly oscillating tails.
d) Thunniform: The thunniform group comprises extremely fast swimmers such as Tuna. The entire undulations are in the tail and the joint connecting the main body to the tail. Thunniform swimmers possess large and crescent-shaped tails.
e) Ostraciiform: The ostraciiform group depicts very negligible body waves while swimming. The locomotion involves only caudal fin oscillation to create propulsive thrust. This group includes Ostraciidae.[9]

These can be summarised as shown in the Figure 1.4.

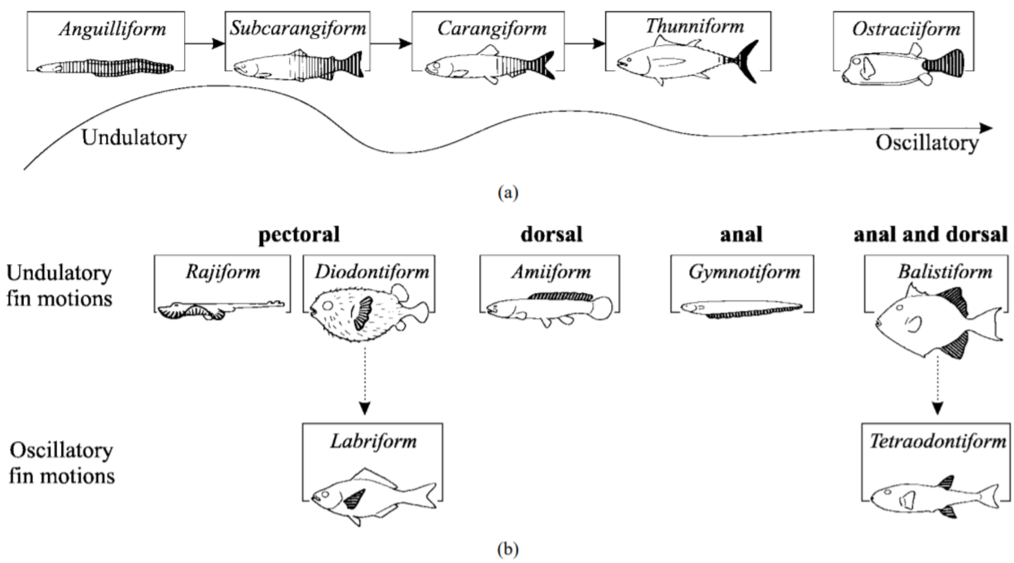

Figure 1.4: Different swimming modes of (a) BCF propulsion and (b) MPF propulsion. Shaded areas are involved in propulsive thrust generation [14].

1.1.2 Fishes & water quality

Irrespective of the salinity fishes are found in almost all aquatic habitats. They can be seen in fresh, salty, and brackish water as well. Further, over time fishes tend to adapt to their surrounding. However, sudden changes in the water *viz.* temperature, amount of dissolved oxygen, density, the number and the amount of other solutes, etc. might affect fishes adversely [13]. Those fond of keeping fishes as pets in an aquarium tend to acknowledge that fishes go through trauma and sometimes death if the entire water in the tank is changed suddenly, or the temperature changes suddenly, and for other reasons as well.

As a matter of fact, a similar practice is reported to be applied by Byzantines in their cisterns in Istanbul (the then Constantinopolis). Cisterns of Constantinopolis stored water and served to its dwellers. These cisterns also hosted freshwater fishes. The keepers of these cisterns used to keep an eye on the number of fishes in the cistern. If the number increased the water of the cisterns was believed to be favorable for consumption and vice-versa.

1.2 Biomimetics

Literally, the word biomimetics is comprised of two ancient Greek words i.e. bios (meaning life) and mīmēsis (meaning imitation). Thus, in short, biomimetics can be defined as an interdisciplinary field of science in which principles from engineering, chemistry, and biology are being combined to create systems or machines that mimic biological processes preexisting in nature.[16][17]

For time immemorial humans have been borrowing ideas from nature to solve their problems and enhance their solutions. One of the most famous applications of biomimetics was applied at Shinkansen Bullet Train that had high speeds but the sound levels were beyond environmental standards. Something that made the situation worse was a loud "tunnel boom" created due to the compression of air at the front of the train as it traveled through a narrow tunnel during the exit. The bullet-shaped nose was part of the problem. Eiji Nakatsu, an engineer and also a birdwatcher, used his knowledge of the splashless dive of kingfishers. The other source of the noise was the Pantograph. Engineers were able to reduce the pantograph's noise by adding structures to the main part of the pantograph to create many small vortices, inspired by the wings of an owl.

The more streamlined Shinkansen train not only travels more quietly but also made it travel 10% faster and use 15% less electricity.[18]

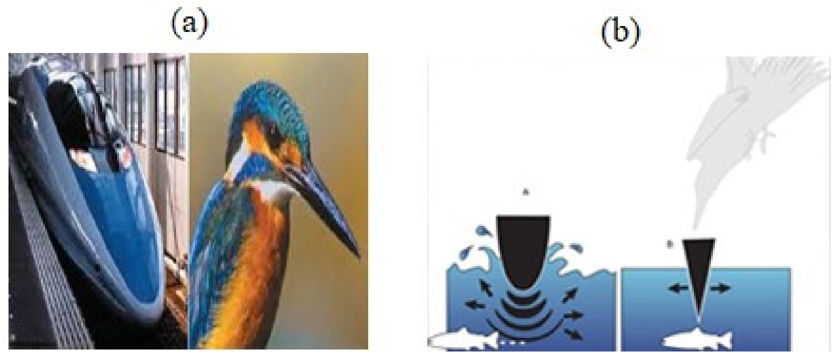

Figure 1.5: (a) Resemblance of a bullet train's nose with kingfisher's beak. (b) splashless dive of sharp beak into water.

A successful bio-inspired engineering solution should possess the following three key objectives: [19]

a) to search for smart biological solutions in the design, synthesis, and integration of complex materials and systems;

b) to learn about their composition, structure, properties, tunability, and mechanisms of formation; and

c) to identify new bio-inspired synthetic strategies and to apply this knowledge to the fabrication of novel, superior materials, and devices.

Biomimetics can provide a simple and sustainable solution to some of the most complicated problems. The capabilities of biomimetics can be summarized as boundless. However, it is often complicated to directly implement biomimicry because of its complexity. Biomimetics is relatively a new field and the lack of direct and descriptive methodology in this interdisciplinary field often leads to unfeasible solutions [17].

1.3 Implementation

In this thesis, the design of a biomimetic-based fusiform fish to carry out Carangiform propulsive locomotion is carried out. For reference, the fish is named Turfi. Turfi is designed and expected to roam underwater and collect data i.e. for time being temperatıre of water at a given depth. There are two sensors for now in Turfi; a Alternatively, the depth can be converted to the pressure exerted on the pressure sensor. The sensor readings are then stored in an SD Card which can be retrieved later and be processed further.

2. LITERATURE REVIEW

Exploring and studying underwater cannot be as easy as it is done on the land. Mainly because of lack of visibility due to the absence of light, extreme water pressure, and weak communication techniques available, it makes the underwater world as explorable as land. And for the same reasons underwater doesn't have navigational maps like that of land. But in recent, underwater has gained more and more interest. Underwater is being studied by the means of rovers and finned or propeller-based robots.

The robotic fishes, depending on the type, can be one of these generally; a) single joint, b) multiple joint, and c) compliant joint. All these types have their pros and cons. Even though the robotic fishes are evolving but it has been studied that they are yet far behind a real fish in terms of structure, maneuvering, and performance. One of the biggest challenges that underwater rovers or autonomous robots face is communication. Most of them are still wired. The wireless ones use electromagnetic waves and/or underwater acoustic communications. On one hand, electromagnetic waves have a faster transmission rate but are unfortunately subjected to drastic attenuations in water. 433 MHz is the most preferred signal for electromagnetic communication. Although this completely disappears within tens of meters of depth. Contrarily, underwater acoustic communication is capable of penetrating far deeper. But it has shortcomings such as slow communication speed and it gets easily refracted to the seabed as the water gets colder with the increase in depth. [20]

3. DESIGN AND IMPLEMENTATION

This chapter consists of detailed information about the complete methodology (including algorithms, materials, and approaches) used to accomplish the task. While designing Turfi some constraints were kept into consideration. They are:

- The entire locomotion will be based on the Caudal (tail) fin driven by a dc motor with gear reduction and the pectoral fins driven by small servo motors
- Turfi can be programmed to follow two different routines to take the reading underwater i.e. free mode in which Turfi will roam around through random depths and coordinates and then take a temperature log.
- Turfi is designed to preferably move in a straight path. Maneuvers like rising, plunging, and turning left or right will be guided by the pectoral fins.

3.1 Algorithm Used

The primary working principle of this project can be summarized using the following diagram:

Alternatively, the overall process can be represented in a block diagram as following:

Both Figure 3.1 and Figure 3.2, depict the summarized overview of this work. As mentioned in section 2.2 the robotic fish would be directed with means of pre-defined route loaded into the microcontroller, which will control the movement accordingly. When en route the microcontroller shall read the data from sensors and store it.

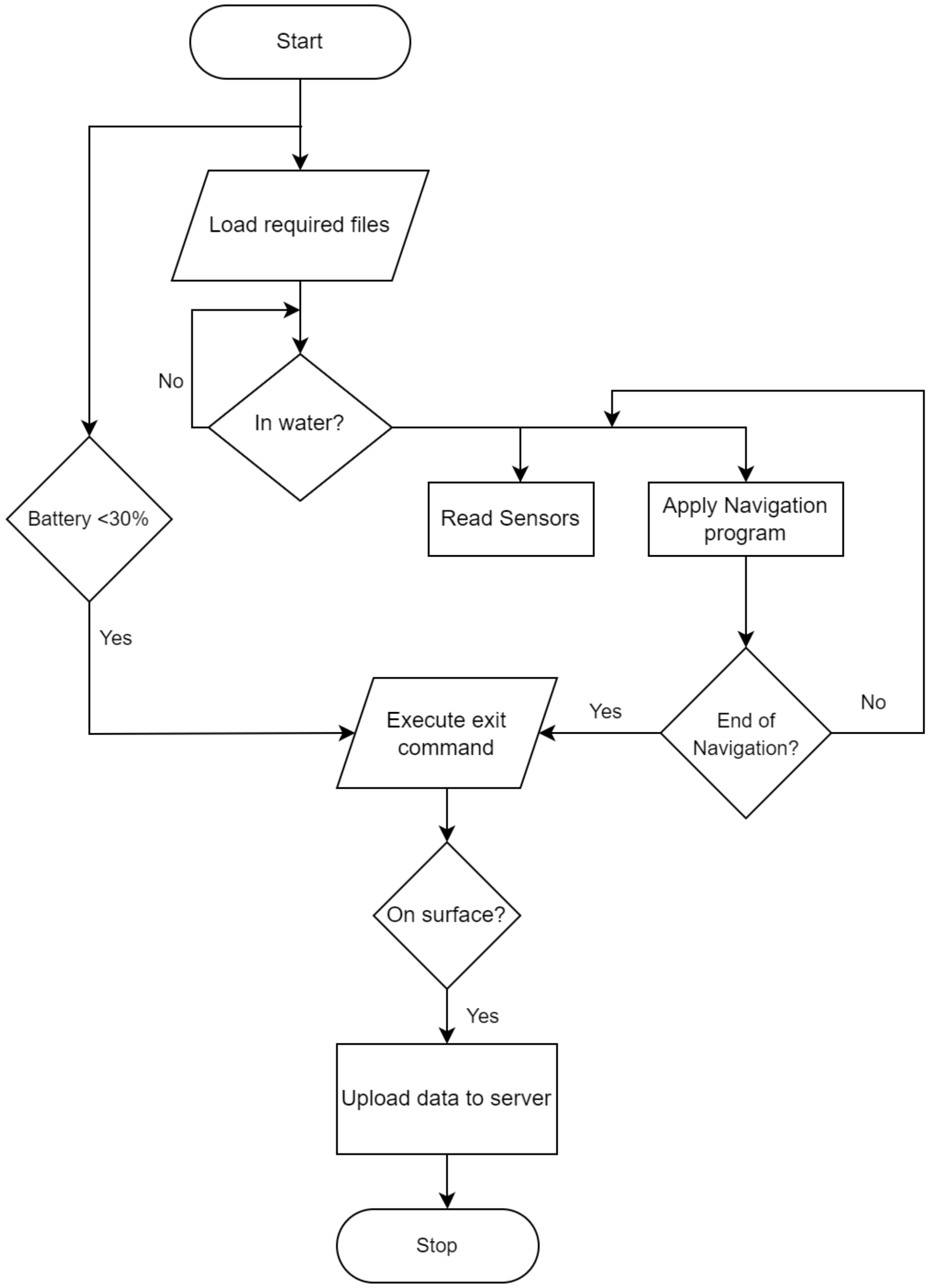

Figure 3.1: Flowchart showing the overall process.

3.1.1 Propulsion

As discussed in previous chapters, the flexing carangiform locomotive behavior has been imitated into action with modeling of the body and the tail fin. The whip-sweeping movement of the tail fin causes the fish to move forward. [21][22] Swimming efficiency of the carangiform kinetics, in terms of the drag force reduction, has a higher Reynolds number (Re) compared with other kinetics; for example, a carangiform swimmer typically swims at high Re around 105 while an anguilliform swimmer swims at Re around 104 in nature (Borazjani, 2008)[23].

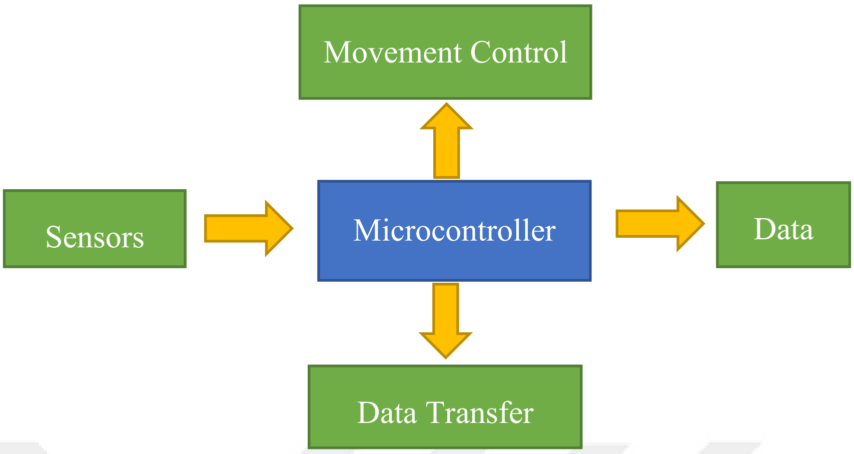

Figure 3.2: Block diagram of overall process.

3.1.2 Guiding

While the tail fin causes the robotic fish to throb forward, the side fins help dive or raise underwater while the fin on the top helps it turn left or right. These fins are to be controlled by employing servomotors.

Further, in previous works, it can be found that the guiding and locomotion are sonar-based controls. The attenuation underwater is so high that a scuba-driver swims alongside to guide the robotic fish. To overcome this, here we propose a concept pre-defined route for the fish to surf and collect data for water quality monitoring.

3.1.3 Measurement

The main objective of this work is based upon the different measurements to avail the conditions to determine the water quality. These measurements can be done with different sensors that are attached to the robotic fish.

3.1.3.1 Temperature

The phenomenon of variation of the temperature at different depths in larger water bodies is the thermocline. The change in temperature trend, there results in a change in the ocean currents. Ocean currents have a profound influence on climate [7]. Thus, temperature monitoring can even help us keep track of climate change too. Underwater temperature sensors are used for this purpose.

3.1.3.2 Pressure & depth

The pressure in liquid increases as the depth increases. This can be calculated with underwater pressure sensors. With these sensors on the robotic fish, temperature logs at the given depths can be prepared.

3.2 Designing the Fish

3.2.1 Rough sketch

Figure 3.3 shows a rough sketch of the internal contents of the main body compartment. It depicts the placement of internal components (sensors, battery, motors, etc.)

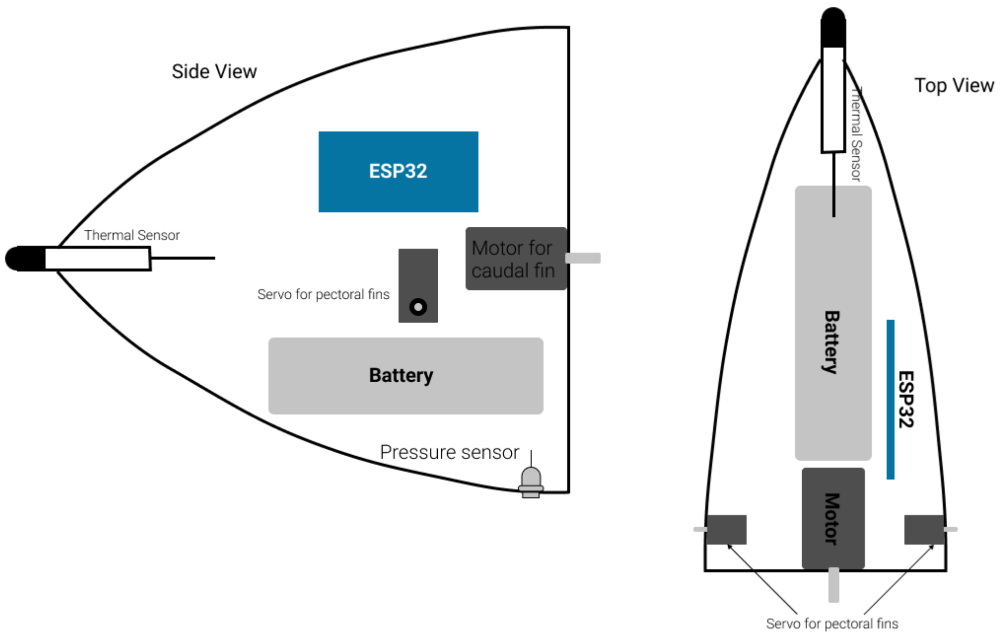

Figure 3.3: Rough sketch showing positions of the internal components.

3.2.2 3D design

Turfi's outer shell is designed using SolidWorks. The design is comprised of 3 different parts. The main enclosure compartment, the caudal fin & its drive mechanism, and the pectoral fins. can be seen in figure 10 (b).

3.2.2.1 Main enclosure compartment

The enclosure compartment is the main body of Turfi. The enclosure compartment encloses all of the other components and also acts as the base for the caudal fin. The main enclosure compartment also has the thermal sensor, pressure sensor, a Li-Po battery, a microcontroller circuit, a dc motor, 2 servo motors, an SD card module and a dc motor driver circuit.

After the completion of the design of the main compartment, it was 3D printed using Polylactic Acid (PLA) filament. The main compartment is divided into symmetric left and right parts. Both right and left parts when brought together form an enclosure for all the components within. Before putting Turfi into the water, it must be confirmed that these two attached halves are completely watertight, else all components inside could be damaged.

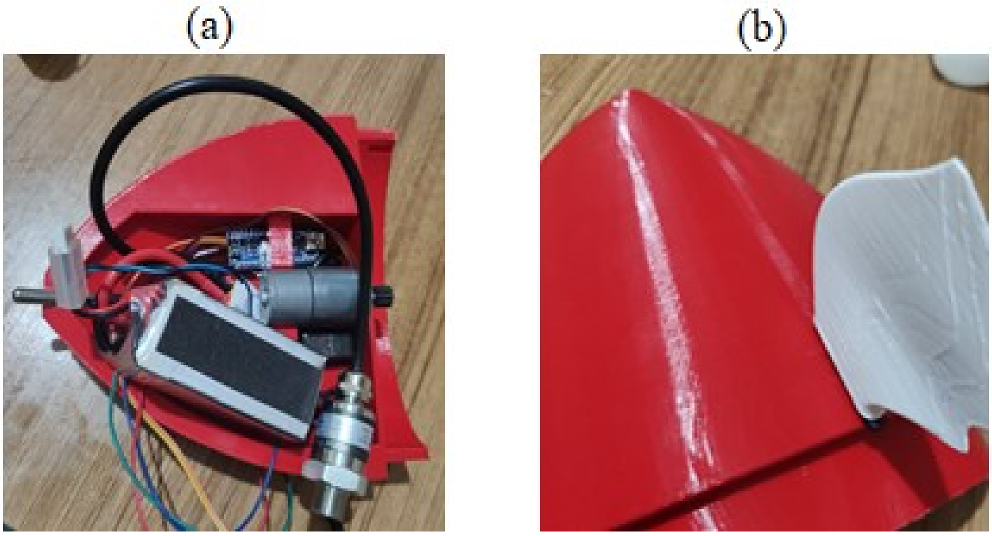

Figure 3.4: (a) Internal components of main compartment. (b) Main compartment supporting the pectoral fins.

3.2.2.2 Caudal fin

The Caudal fin was designed using SolidWorks as well and then later printed using Thermoplastic Poly Urethane (TPU) filament. While PLA is stiffer, TPU is best known for its flexibility. TPU was chosen for the caudal fin to give it a wavy form while swimming. The caudal fin drive mechanism can be seen in Figure 3.5.Similarly, in Figure 3.6 the 3D printed caudal fin. The pectoral fins are attached to either side of the main compartment. The pectoral fins were also designed using SolidWorks and later printed using PLA filament.

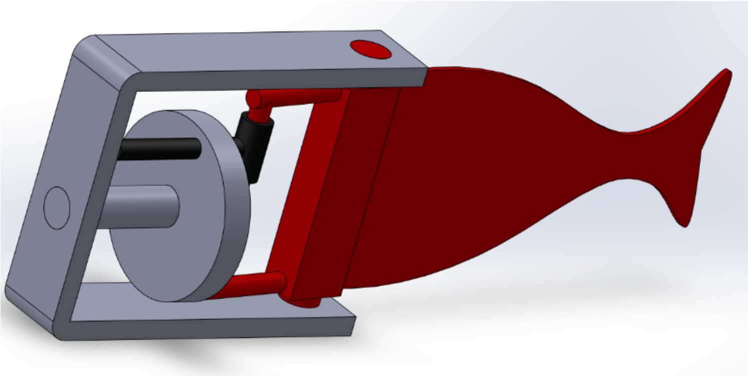

Figure 3.5: Driving mechanism of the caudal fin.

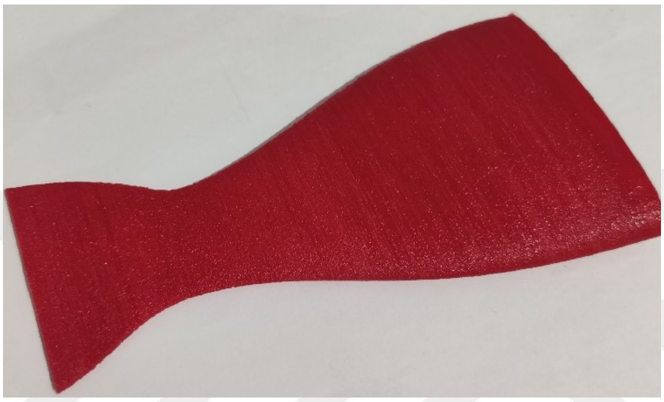

Figure 3.6: 3D printed caudal fin with TPU filament.

3.3 Components Used

Building Turfi required a combined working structure comprising of designing the model, 3D printing, coding, and electronics. The 3D design was made using SolidWorks. Later, this model was 3D printe. The electronics components, including the mickrocontroller board and motor control circuit along with the sensors, motors, and the battery was encased inside this 3D printed covering. The microcontroller was coded using Arduino IDE. The components used in Turfi are enlisted and briefly explained in the following sections.

3.3.1 ESP32

ESP32 is a feature-rich MCU with integrated Wi-Fi and Bluetooth connectivity for a wide-range of applications. All the other peripherals of Turfi are connected, monitored, and controlled by the ESP32.

With an operational temperature range of –40°C to +125°C, the ESP32 can perform reliably in industrial conditions. ESP32 can dynamically eradicate external circuit defects and respond to changes in external conditions with the help of advanced calibration circuitries. ESP32 is a low-power processor designed for mobile devices, wearable electronics, and IoT applications. It uses a combination of proprietary software to achieve ultra-low power consumption. In addition, ESP32 has cutting-edge capabilities including fine-grained clock gating, several power modes, and dynamic power scaling.

The ESP32 has antenna switches, RF baluns, power amplifiers, low-noise receive amplifiers, filters, and power management modules built in. With minimal Printed Circuit Board (PCB) requirements, the ESP32 provides priceless functionality and variety to your applications.

The ESP32 may function as a standalone system or as a slave device to a host MCU, eliminating communication stack overhead on the primary application CPU. Through its SPI / SDIO or I2C / UART interfaces, the ESP32 can connect to other systems and provide Wi-Fi and Bluetooth capability. [25]

The module used in Turfi is ESP32 DEVKIT V1 DOIT (30 pins version). The sensor data is collected using the analog pins of the module then stored on an SD card with the help of an SD card module. Later, the collect data is transferred to the base station using the WiFi connectivity of the ESP32 DEVKIT V1 module.

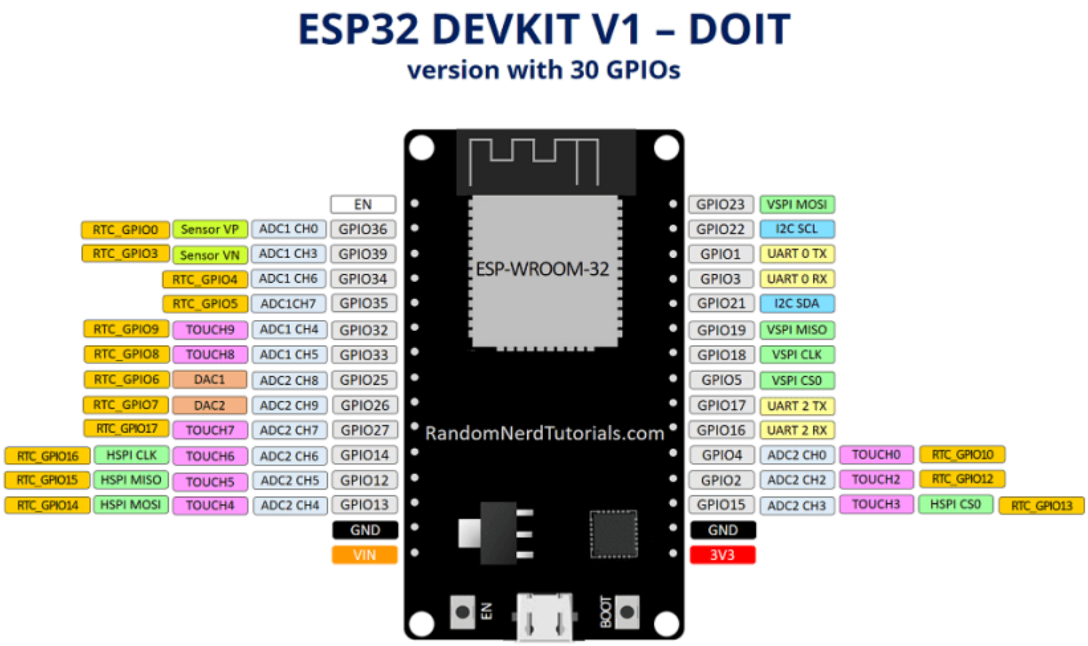

Figure 3.7: Pinout diagram of the ESP32 DEVKIT V1 [25].

3.3.2 SD card module

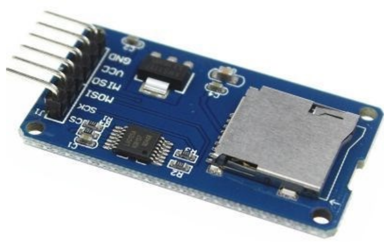

Figure 3.8: SD card module [26].

The SD card module is also enclosed with the main enclosure compartment. This module is connected to the microcontroller board and communicates with the microcontroller using SPI protocol. The data obtained from the sensor readings are stored in an SD card using this module.

3.3.3 Temperature sensor

The temperature sensor used in Turfi is a water-proofed tube-like version of a one-wire DS18B20-compatible sensor. DS18B20 is a 1-Wire digital temperature sensor from Maxim IC. It shows degrees in Celsius with a resolution of 9 to 12-bit precision, from -55 to 125 (+/-0.5). Each of these sensors has a unique 64-Bit Serial number etched into it that allows a huge number of sensors to be used on one data bus. [27] The temperature sensor is mounted at the nose of Turfi, slightly protruding out so that it can take the temperature readings efficiently.

Figure 3.9: (a) Position of temperature senor at the tip of Turfi. (b) Temperature sensor.

3.3.4 Analog water pressure sensor [28]

The water pressure sensor used in this project is by DFRobot Gravity that has a 3-pin interface. It supports standard 5V voltage input and 0.5~4.5V linear voltage output. It has a normal operating pressure of ≤2.0 Mpa. And is capable of working in the temperature range of -20~85°C. The pressure sensor is attached to the bottom of Turfi which means a depth of around 12 cm would be read every time Turfi is put into water.

3.3.5 DC motor with reduction gear

A dc motor with a reduction gear mechanism is used to drive the caudal fin for the propulsive force generation. The speed of the motor is controlled using PWM signals from the microcontroller.

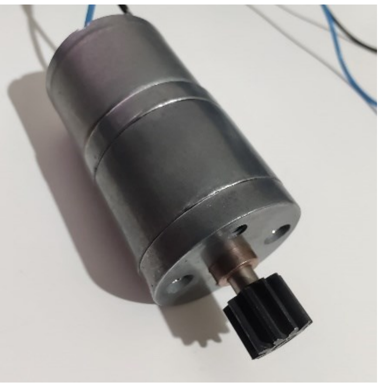

Figure 3.10: DC motor for caudal fin propulsion.

3.3.6 Servo motors for pectoral fin control

Two generic 9g micro servo motor is used to control the pectoral fins of Turfi. These motors help Turfi do maneuvers like turning left or right and rising or plunging.

3.3.7 Li-Po battery

Turfi is powered using a 4s Li-Po battery. The microcontroller, the SD card module, and the sensors are powered using the same battery but through a 5V voltage regulator.

3.3.8 DC motor driver circuit

A simple amplifier circuit is used to control the dc using the control signal from the microcontroller.

4. EXPERIMENTAL RESULTS

4.1 Test Scenario

4.1.1 Test 1

The robotic fish (Turfi) that was modeled and prototyped as explained in chapter 3, was tested to make some readings in an open pool. Turfi was programmed to maintain a depth of 20cm and a straight path to take the temperature measurements. To maintain a uniform depth of 20cm the measurements from the depth sensor were used and then a PID controller was employed to control the depth. In case Turfi dipped any lower than the given depth the pectoral fins were brought into action which would guide Turfi to rise as if the flaps of an airplane. Similarly, while swimming if Turfi rose higher than the given height the pectoral fins would guide it to dip lower unless the required height was attained. The test was run for about 3 minutes. The thermal sensor measurements were taken every 5 seconds and logged into a text file on an SD card using the SD card mode. The log file was retrieved later which can be seen in section 4.2.

4.1.2 Test 2

Another test was carried out in all the conditions that were the same as that of Test 1, except in Test 2 Turfi was programmed to change its direction randomly every 20 seconds by randomly turning one of the pectoral fins for 2 seconds. The left pectoral fin was rotated 90 degrees to make Turfi turn left and so was done on the right pectoral fin while turning right.

4.2 Data Collection

This section includes the test results obtained from the first test. The test results of the first test are shown in Table 4.1.

Table 4.1: Results from Test 1.

Depth (in cm)	Right Pectoral Fin Angle (in degrees)	Left Pectoral Fin Angle (in degrees)	Temperature (Celsius)
12,52	90	90	14
14,92	90	90	13
15,54	89	89	12
16,65	90	90	13
18,58	60	60	12
19,24	20	20	12
19,67	10	10	12
20,06	0	0	14
19,99	-5	-5	13
19,10	0	0	14
19,19	8	8	12
20,57	-4	-4	13
19,44	10	10	13
20,68	-6	-6	12

In Table 4.2, the outcomes of the second test are shown:

Table 4.2: Results from Test 2.

Depth (in cm)	Right Pectoral Fin Angle (in degrees)	Left Pectoral Fin Angle (in degrees)	Temperature (Celsius)	Turn
12,20	90	90	12	
14,90	90	90	13	
16,28	89	89	12	
19,06	90	90	11	
19,28	90	0	12	Right Turn
20,37	20	20	12	
20,02	10	10	12	
20,02	0	0	13	
19,60	-5	-5	12	
19,96	0	90	14	Left Turn

Table 4.2: Results from Test 2.

Depth (in cm)	Right Pectoral Fin Angle (in degrees)	Left Pectoral Fin Angle (in degrees)	Temperature (Celsius)	Turn
21,95	8	8	12	
21,00	-4	-4	12	
20,90	10	10	12	
19,81	-6	-6	12	

ESP32 was programmed to act as an ASYNC server using ESP32's ASYNC library. The ASYNC server allows Turfi to collect data and swim normally even when it is not connected to the WiFi. Once Turfi is asurface the data collected during the pursuit underwater can be retrieved easily over WiFi.

The figure below shows a sample data collected from Turfi using WiFi.

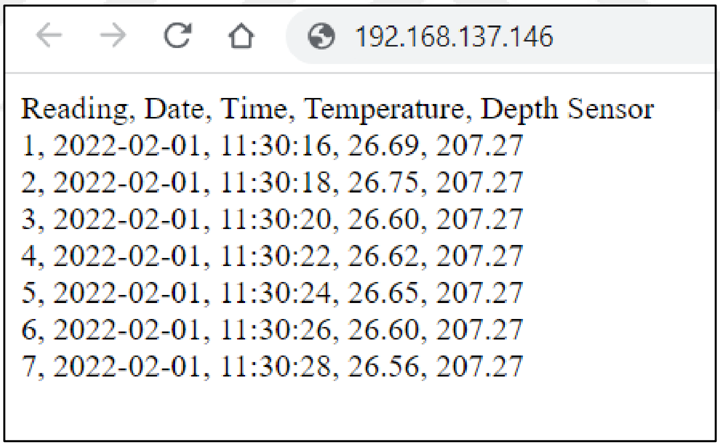

Figure 4.1: WiFi data collection.

5. CONCLUSION AND FUTURE WORK

In today's world, exploration on the land in darkness without a GPS, a map, a compass, or at least without a reference is unimaginable. And it is tougher to do so in a more viscous medium. With the help of a robotic fish such as Turfi, a better understanding of the water bodies around us can be achieved. It would help make water more explorable.

As the project progressed, an overwhelming number of new enhancements and upgrades to better the prototype were marked.

To prevent Turfi from drowning in the sea bed an exit mechanism using inflatable bags similar to that of airbags can be used. Let us say, Turfi is programmed to roam freely and autonomously collecting data and when the voltage of Turfi drops lower than a certain level (30%), the exit mechanism would come into action pushing Turfi afloat.

Though this would mean not much when Turfi is under the water. But it can be programmed to come out to the surface of water periodically so that the last seen location of Turfi can be known. Another application could be, once the exit mechanism is activated GPS signals the server of it availability for retraction.

When Turfi resurfaces after taking the necessary readings under the water, it can be made to connect with a server

An attached camera would help Turfi take stills and videos of the places that it explores. This would help collect more detailed data under the water.

As a matter of fact, there are other factors that affect the quality of water, adding sensors that can measure salinity, pH, oxygen level, etc. would collect more detailed data under the water.

If attached with pistons that are actuated electromagnetically, it would help Turfı collect water samples from deep waters for further study. This could be used to fight hazards such as oil spills, mucilage, etc.

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