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Extending Maneuverability of Internally Actuated Underwater Gliders, An Attempt to Develop an Open Platform For Research and Education

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EXTENDING MANEUVERABILITY OF INTERNALLY ACTUATED UNDERWATER GLIDERS, AN ATTEMPT TO DEVELOP AN OPEN PLATFORM FOR RESEARCH AND EDUCATION

By

Saeedeh Ziaeefard

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Mechanical Engineering- Engineering Mechanics

MICHIGAN TECHNOLOGICAL UNIVERSITY

2018

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This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Mechanical Engineering- Engineering Mechanics.

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Dedication

To my mother..

Who never had the chance to see the outcome of her ultimate sacrifice. I would not be here or be the person I am without her.

Contents

List of Figures

List of Tables

Preface

This work proposes new approaches in extending maneuverability of underwater gliders and develops open platforms for research and education. ROUGHIE, Research Oriented Underwater Glider for Hands-on Investigative Engineering, was developed to study and validate new flight patterns to increase agility of glider systems utilizing internal actuation. GUPPIE, a Glider for Underwater Problem-solving and Promotion of Interest in Engineering, was developed to promote robotics and engineering design process in pre-college STEM education.

Part one of this dissertation, comprised of five chapters, is dedicated to maneuverability of internally actuated buoyancy driven autonomous underwater vehicles (AUVs) or Underwater Gliders (UGs). In this work we study the kinematics and dynamics of the ROUGHIE and introduce new approaches to connect basic flights and generate advanced flight patterns. Advanced flights are modeled in Matlab-Simulink and the results are validated with experimental tests performed at Michigan Tech's indoor dive tank.

Part two of this dissertation, composed of three chapters, is devoted to a pre-college STEM education program that promotes engineering design process utilizing robots

that help people improve human life (Co-robots). GUPPIE is an example of a co-explorer robot used for environmental monitoring. The focus of this research is to investigate effects of hands-on and theme-based robotic programs on motivation, level of interest, and change of attitude towards STEM learning and related careers. Co-robots program, implementation methods, and assessment results are presented to discuss the effectiveness of this approach.

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I also like to thank Jamey Anderson and Christopher Pinnow at Great Lake Research Center for their technical guidance, marine transportation assistance, and other nautical provision during this research. In addition, I am thankful to Students Development Complex at Michigan Tech, allowing my research team to utilize swimming pool and dive tank in the last four years.

Last but not the least, I would like to thank my family: my sister Maryam and my husband Evandro for supporting me spiritually throughout my research.

Nomenclature

This table provide information on the abbreviation and nomenclature used throughout this dissertation.

(x_e, y_e, z_e)	Inertial reference frame
(x_b, y_b, z_b)	Body fixed reference frame
(x_f, y_f, z_f)	Flow frame
$\mathbf{R}_{eb}$	Rotation matrix transforming body frame with respect to inertial frame
$\mathbf{R}_{bf}$	Rotation matrix transforming flow frame with respect to body fixed frame
m_s	Linear sliding mass block
m_r	Common rail rotary mass
m_b	Buoyancy mass
m_f	Offset trimming mass
m_h	Glider hull mass
$\tilde{m}$	net buoyancy
m_t	Glider total mass
$\bar{m}$	Displaced water mass to calculate net buoyancy
g	Gravitational force constant

$_{m}$	Water density
Vol_t	Vehicle total volume
CB	Center of buoyancy
CG	Center of mass
ϕ	Vehicle roll angle
θ	Vehicle pitch angle
ψ	Vehicle yaw angle
α	Attack angle
β	Side-slip angle
$\mathbf{V} = [u, v, w]^T$	Translational velocity in the body frame
$\Omega = [p, q, r]^T$	Vehicle angular velocity in body frame with respect to flow frame
τ_{Rest}	Restoring force and moments
τ_{Damp}	Damping force and moments
τ_{Add}	Added mass force and moments
τ_{Cor}	Coriolis force and moments
T_t	Total kinetic energy of glider system
T_{ms}	Kinetic energy of sliding mass
T_{mb}	Kinetic energy of buoyancy mass
T_{mr}	Kinetic energy of rotary mass
T_{mh}	Kinetic energy of hull mass
$\mathbf{I}_s$	Inertia of sliding mass

$\mathbf{r}_s$	Position of sliding linear mass in body frame
$\mathbf{V}_b$	Buoyancy mass block velocity
$\boldsymbol{\Omega}_b$	Angular velocity of buoyancy mass in the body frame
$\mathbf{I}_b$	Inertia of buoyancy mass
$\mathbf{r}_b$	Position of buoyancy mass in body frame
$\mathbf{r}_r$	Position of rotary mass in body frame
r_{rx}	Position of rail in $x-$ direction
R_r	Roll mass semi-circular eccentric radius
γ	Vehicle internal roll angle
$\mathbf{I}_r$	Inertia of roll mass
$\mathbf{M}_A$	Added mass
$\mathbf{I}_A$	Added inertia matrix
$\mathbf{C}_A$	Cross term in $\mathbf{M}$ depending on the surrounding fluid in the body frame
$\mathbf{p}$	Translational momentum
$\mathbf{q}$	Angular momentum
$\mathbf{F}_{ext}$	External force applied to the vehicle in the flow frame
$\mathbf{T}_{ext}$	External momentum of the vehicle in the flow frame
$\hat{\mathbf{k}}$	Unit vector points to the gravitational force direction
$\mathbf{L}_r$	Distance from the roll mass' center of gravity to the center of inertia frame

$\mathbf{L}_b$	Distance from buoyancy mass' center of gravity to the center of inertia frame
$\mathbf{L}_l$	Distance from the linear sliding mass' center of gravity to the center of inertia frame
$\mathbf{F}_h$	Hydrodynamic force
$\mathbf{T}_h$	Hydrodynamic torque
$\mathbf{b}$	Vehicle position in inertia frame
$\boldsymbol{\nu} = [\mathbf{V}^T \quad \boldsymbol{\Omega}^T]$	Generalized translational and angular velocity in body frame
$\boldsymbol{\mu} = [\mathbf{P}^T \quad \mathbf{Q}^T]$	Generalized translational and angular momentum in body frame
R_t	Turn radius of glider
ω_3	Angular velocity of glider along a circular helix

Abstract

Increasing maneuverability of internally actuated Underwater Gliders (UGs) is inevitable due to high demands in underwater surveillance and reconnaissance missions where agility and stealthiness are the keys to success. High maneuverability is needed to provide the opportunity for optimal trajectory planning, planar motion smoothness, and re-planning adapting to the dynamic environments.

This work explores extending the maneuverability of underwater gliders through coupled improvement in mechanical design, efficient use of internal actuation, and motion planning strategy utilizing flight concatenation. The existence of five flight patterns "advanced flight", inspired by air gliders, enabled solely by utilizing internal actuation are investigated: Circle, Oval Turn, U-turn, S-Turn, and Figure-8. A feedforward-feedback switching controller is utilized to connect the steady-state flights through transition stages that features a neutrally buoyant state.

These advanced flights are categorized into two main groups: 1) continuous curvature and 2) switching curvature maneuvers. Circle, Oval Turn, and U-Turn belong to continuous curvature family maintaining a continuous increasing or decreasing heading angle. S-turn and Figure-8 are classified as switching curvature since the heading angle of the vehicle changes in transition points, switching into opposite convex or

concave outlines.

The advanced flights can be completed by any underwater glider that is mechanically capable of tight helical motion as long as the controller is capable of performing a smooth transition between steady state flights. Advance flights will increase the capability of underwater glider system in tracking optimized complicated paths in 3D space and improve fleet cooperative navigation and coordination.

Chapter 1

Part1: Extending Maneuverability of Underwater Gliders

It is foreseen the undersea world will be dominated by underwater vehicles in the next decade similar to the drones in the sky. Underwater Gliders (UGs) are type of Autonomous Underwater Vehicles (AUVs) that travel through water by changes of buoyancy. Utilizing wings, the vertical motion is translated to horizontal motion generating a saw-tooth profile. The resulting saw-tooth motion is slow but highly efficient, making gliders attractive for several oceanographic uses such as water quality measurement, ocean mapping, and search and rescue missions.

Underwater gliders are attractive vehicles in military missions due to their low acoustic signature which makes them virtually undetectable [1]. In military related missions such as surveillance, reconnaissance, inspection and identification, payload delivery, and time-critical strike missions, maneuverability becomes crucial when following complex paths specially in near shore operation is required [2].

This work focuses on extending maneuverability of underwater gliders utilizing a novel internal roll mechanism and a real-time controller. A series of advanced flight maneuvers utilizing basic flight concatenation are proposed here. Flight sequence and characteristics of each maneuver has been studied and the existence of such flight patterns are experimentally validated.

1.1 Introduction

In the past decades, Underwater Glider (UG) development reached its technical maturity, culminating with the current state-of-the-art commercial UGs that excel in long endurance missions and deep water deployments [3, 4, 5, 6]. By 2004 the legacy gliders, Slocum electric [7], Spray [8], and Seaglider [9], were successfully deployed for ocean data sampling missions.

Since then, several calls has been made to improve underwater gliders mission scope,

operational performance, and mobility [10, 11, 12]. To improve mobility of underwater gliders increasing maneuverability, the ability to perform smooth and small radius turning motion, becomes a necessity. Existing gliders control the heading through either the use of external rudder or internal roll actuation to induce turning motion, similar to a bank turn in aircraft. External actuation has typically resulted in tight turns in underwater vehicles with hybrid AUV-Glider system design [13, 14, 15, 16, 17, 18, 19, 20].

While this solution seems practical, power consumption management and external appendage maintenance present challenges in time exhaustive missions [21]. The current state-of-the-art technology fails to provide a solution that increases the maneuverability of internally actuated gliders without the need for external actuation. Recent examples of underwater vehicles in this context are, Slocum G2 [22], Sandshark [18], Gavia [14], Seawing glider [23], Grace [24] a robotic fish , Folaga [25], MAERS [15], and USM glider [26].

On the other hand, underwater fleet development, coordinated motion control, and cooperative navigation contributed largely in increasing maneuverability of underwater vehicles. Although multi-vehicle coordination has been broadly studied to optimize control and navigation, individual vehicle maneuverability performance received limited consideration [27, 28, 29, 30, 31, 32, 33, 34].

An alternative solution to increase maneuverability of underwater vehicles is concatenation of basic flights generated by internal actuation. Internal actuation has historically not been capable of performing turning motion required for shallow water operation, with most internally actuated gliders achieving turn radii on the order of 30-50 meters [35, 36]. Utilizing a vehicle that is capable of performing small turn radius with real time controller and capability of concatenating basics flights can be a possible solution to underwater gliders maneuverability problem.

1.2 Approach

To propose a solution to increasing maneuverability of underwater gliders system, at Nonlinear and Autonomous System Laboratory (NASLab), Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE)[37] was developed to offer a low-cost platform capable of performing small radius turning motion. In addition, this improved capability created exciting opportunities to investigate new flight patterns similar to those of air gliders through connecting basic flights. With the novel design of the internal rotary actuation in the ROUGHIE the goal is to generate new flight patterns in absence of external actuation.

Underwater gliders typically are designed to perform two steady state flights, wings-level (straight) and helical flight (spiraling). In internally actuated vehicles such as

ROUGHIE, spiralling motion is produced by changing glider's roll angle which induces a centrifugal force that drives the vehicle into helical trajectory. Literature suggests that it is possible to generate turning motion in internally actuated underwater gliders by concatenating basic steady flights using Dubin's segments [32, 35, 38].

Mahmoudian proposed an analytic solution to optimal path planning in 3D motion for an underwater glider. Zhang studied the numerical solution of helical motion to investigate control parameters involved in spiraling motion for underwater gliders [23]. Use of internal actuation to generate helical motion in underwater gliders was previously reported in [39, 40].

Recent studies report concatenation of steady flights to increase the maneuverability of underwater vehicles such as the anti-helical motion[41], combining the saw-tooth and spiraling motion[42], and investigating the 3D Dubin's motion[43, 44, 45]. These efforts lead the path towards more efficient and maneuverable vehicles by exploring Dubin's like 3D trajectories underwater, nevertheless use of external actuation seems necessary to achieve this path.

In this work five distinctive advanced flight patterns are proposed: 1) Circle, 2) Oval Turn, 3) U-turn, 4) S-Turn, and 5) Figure-8. These advanced fight maneuvers are categorized into two main groups: 1) continuous curvature and 2) switching curvature maneuvers. Circle, Oval Turn, and U-Turn belong to continuous curvature family

maintaining a continuous increasing or decreasing heading angle. S-turn and Figure-8 are classified as switching curvature since the heading angle of the vehicle changes in transition points, switching into opposite convex or concave outlines.

Advance maneuvers can facilitate motion planning by extending maneuverability and increase capability of underwater glider system in tracking complicated paths. Fleet cooperative navigation and coordination can improve vastly with advanced maneuvers in motion planning arsenal enabling the vehicles to find optimized path in 3D space.

The remaining of part one of this work reviews ROUGHIE's mechanical and electrical design as well as system upgrades in Chapter 2, vehicle kinematics and dynamics, modeling, and controller design in Chapter 3, underwater glider traditional flights, proposed advanced maneuvers, flight sequence and characteristics, and simulation results in Chapter 4, and presents experimental validation in Chapter 5.

Chapter 2

ROUGHIE Design and Upgrades

The Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE) has been designed through a series of revisions over the past few years [46, 47]. The current revision of ROUGHIE2.0, shown in Figure 2.1, builds upon lessons learned over the years of building and testing new models [48].

The ROUGHIE is small (1.2 m long) and light weight (15 kg); the small size enables launches from shores, docks, and in standard size pools, eliminating the need for expensive launching equipment. It specializes in littoral waters operation 3 m to 100 m. Table 2.1 shows the main characteristics of the ROUGHIE. The ROUGHIE can be equipped with various high quality scientific and navigational sensors, albeit with an increased cost to the vehicle.

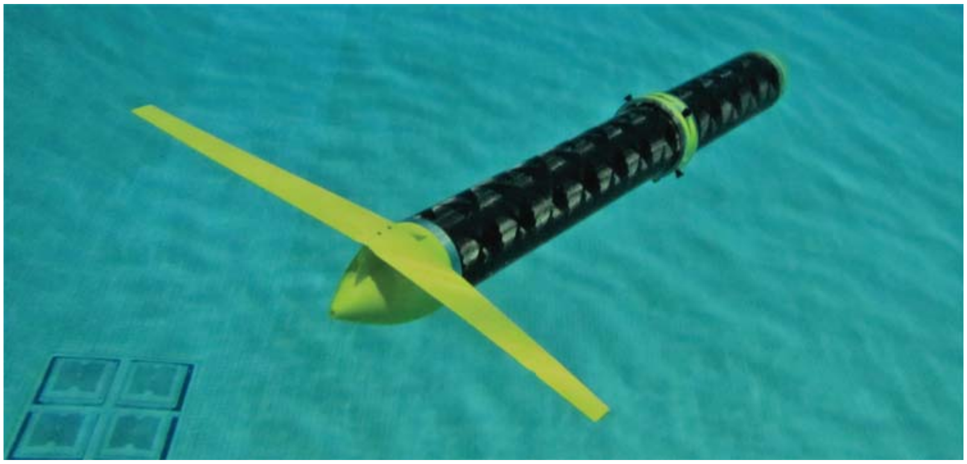

Figure 2.1: The ROUGHIE in carbon fiber hull, photo is taken during a pool test

Table 2.1
ROUGHIE Specification

Length	Mass	Depth Rating	Endurance	Speed
120 cm	15 kg	30 m	60hrs	1kn

The design focused on moderate endurance and littoral water deployment missions. Littoral in this concept refers to shallow waters between 3 to 100 meter. At the time of the vehicle design it was predicted that most of the glider function tests will be performed in the enclosed waters such as swimming pool and the Portage Canal of the Lake Superior. Thus, it was ensured that the functionality and maneuvering tests can be performed in the depth range of 3 to 10 meter. Better performance is expected in deep water due to excess time of flight for reaching steady state. This spatial constraint worked pushed for development of a depth controller that respond faster to feedback received from pressure sensor to prevent collisions and adapt to shallow water environment.

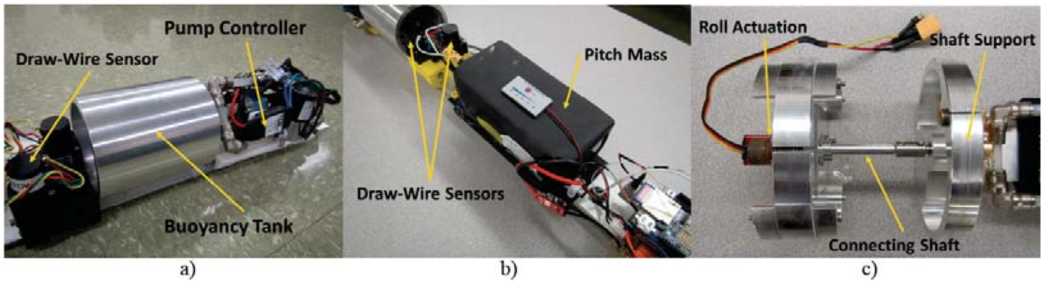

Figure 2.2: The ROUGHIE's internal mechanisms: a) The ballast system pumps water in and out of the tank to change the glider's buoyancy; b) The linear sliding mass module adjusts the desired pitch angle by moving the linear mass resulting in changing the center of gravity and creating a pitch moment; c) The rotary module pivots the main rail with respect to the hull, causing the hull (and hence the wing) to rotate.

To achieve high maneuverability the ROUGHIE was designed to perform turn maneuver with small radius. A large lift force was required to induce large heading angle so that the glider can perform a small circle. With the fixed-wing design, the only possible way to create large lift was to induce a large rolling moment. This was obtained by rolling the majority of the glider's internal components through a common rail that rigidly hold all modules except the roll module, Figure 2.2. This rail also serves as the main cable tray of the glider. 90% of vehicle internal mass is located on the common rail which is suspended between the front and rear end caps and mounted off-center towards the bottom of the vehicle. This off-center location enables the modules to be mounted on top creating a very large eccentric mass relative to total vehicle mass. By rotating this mass the glider rolls with respect to its fuselage.

The ROUGHIE features a fully modular design that allows easy integration with

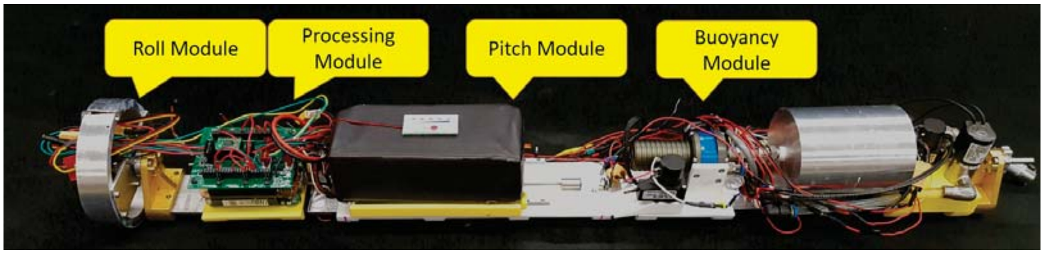

Figure 2.3: Upgraded ROUGHIE features a fully modular design that allows easy integration with various sensors or processing platforms.

various sensors or processing platforms. The mechanical design of the ROUGHIE is built around a modular layout mounted on a common rail that provides internal structural support. This design strategy makes ROUGHIE a multipurpose glider rather than a mission specific vehicle. The ROUGHIE can be divided into four different modules separately connected to the main power board: pitch module, roll module, bouncy module, and processing module. The rail-based and modular design of the ROUGHIE allows easy customization to accommodate different configurations and orientations.

Starting at the front of the glider is the roll module as illustrated in Figure 2.3. This module consists of the mounting hardware required to interface from the hull to a commercial-off-the-shelf (COTS) servo that has its shaft in line with the center of the hull. The servo attaches to the rail through a metal 3D printed connection arm that offsets the rail rotation from the hull center.

The three remaining modules are mounted on the rail. Physical connections from the modules to the rail are accomplished with a universal mount that is integrated into

the different 3D printed modules. 70% of all the custom made parts in the ROUGHIE are 3D printed mostly in low stress situation. By using 3D printing we are able to minimize the cost of the vehicle, achieve highly complex geometries for specialized parts, and perform rapid design updates including adapting the modular layout to new configurations.

The first module mounted on the rail is the buoyancy module that provides locomotive force in the dive plane by driving changes in glider net buoyancy. The buoyancy module uses a COTS micropump capable of supporting up to 100 m of head to pump water from the front port into the ballast tank. A normally closed solenoid valve is used in-line with the pump to interrupt the flow ensuring that water does not flow when the pump is not powered. Immediately behind the pump is the ballast tank and ballast tank mount. The ballast tank is a custom-machined cylinder capable of adjusting the ROUGHIE's net buoyancy by 375 g and is sealed by a 3D printed piston with a double o-ring sealing design to prevent jamming. 3D printing the piston allows the piston and draw wire attachment point to be integrated into one part that can be printed at very low cost. The ballast tank mount provides rigid attachment for the two draw wire sensors used for determining system center of gravity and ballast amount. In the previous design the buoyancy tank was located near the center of buoyancy. The new location of the buoyancy tank assists with the initial pitching angle of the glider in addition to sink an rise motion in vertical plane.

Aft of the buoyancy drive module is the pitch module. The pitch module is a sliding linear mass consists of a 3D printed base plate that rigidly holds the linear mass, a 3D printed linear mass control plate, a linear bearing, a power screw, and a micro DC gearmotor. The linear mass is a 25.9 V 12.6 Ah lithium-ion polymer battery that serves as power source for the ROUGHIE and is attached to the linear mass control plate via adhesive. The control plate enables the battery to attach to the draw wire cable, linear bearing, and power screw nut. A linear bearing provides smooth motion between the linear mass control plate and the base plate which is controlled using the power screw. Actuation of the power screw is accomplished with two micro DC gear-motors through a high reduction gearbox. These dual locomotion increases the speed of sliding twice as fast. The motors rotate in opposite directions.

Towards the rear of the ROUGHIE is the processing module. This module is an electronics stack that builds upon a 3D printed mounting plate. On-board electronics for communication and guidance, navigation and control (GNC) is built through an ATmega2560-based Arduino Mega as the processing platform; this solution was selected based on its low-cost and ease of programming and extensive line of COTS stackable expansion shields. The processing center is equipped with sensor suite including *Attitude and Heading Reference System* (AHRS), *compass*, *GPS*, *X-Bee radio communication*, and *pressure gauge*. A battery voltage and current sensing circuitry is implemented on the main interface to measure the battery state of charge during missions to avoid failures due to low battery charge. Preliminary experiments

suggest that the ROUGHIE's endurance is over 72 hours in the swimming pool where constant change of vehicle trajectory is required due to the shallow depth. Durability of this vehicle exceeds this value when in deeper water.

The ROUGHIE utilizes three custom printed boards. The power board derives all operating voltages from the battery using high efficiency DC-DC converters. A second custom printed board enables bidirectional pumping by switching the two outer phases of the pumps motor controller. This board is located near the buoyancy module to eliminated excess wiring and power cabling. The electronics stack connects to wet sensors such as pressure gauge and scientific payload via a pressure-rated bulkhead connector through the rear end plate. The third board interfaces all the sensors and actuators to the main processor.

The *AHRS* and *GPS* are integrated in a single unit and are used by the ROUGHIE to estimate its current pose (yaw, pitch, and roll) and location, respectively. The pose data is used in the control loop for pitch, roll, and heading feedback, and the GPS unit provides location data when the glider surfaces. This information is conveyed to the processing platform over a universal asynchronous receiver/transmitter (UART) serial communication interface.

The *pressure* sensor monitors the external pressure and is used to determine ROUGHIE's depth. It requires a 5 volt supply and provides an analog output proportional to the sensed pressure, which is read with one of the processing platform's

analog inputs. This depth feedback is logged using the internal SD card data-logger and also can be used by the controller to determine the appropriate times to descend or ascend.

The *draw-wire* sensors employed in the ROUGHIE are used to provide the control system with positional feedback of the ballast tank and the linear mass. These sensors use a small retractable cable to actuate an internal potentiometer, translating changes in linear motion to changes in resistance. We apply a voltage to the outer legs of the potentiometer and measure the voltage of the wiper with an analog input on the processor to determine the wire's position. Draw wire sensors on board ROUGHIE measure the location of the buoyancy tank piston and the linear mass linear position. These data are used to calculate the glider center of gravity CG at any time.

Figure 2.4: An ECO-Puck chlorophyll-a sensor in aluminum casing attached to the ROUGHIE's exterior. It connects to the internal electrical system via a waterproof cable through the rear end cap (not shown in this image).

At early stages of the vehicle operation, low-cost sensors such as hobby level IMU

(in order of \$100 USD)were used for data gathering. Due to low resolution of those devices the data was not precise enough for the controller thus it was challenging to tune the controller. Thus higher quality sensors (in order of \$1000 USD) were selected learning that to develop a low cost vehicle the quality of the main sensors can be compromised to some extent as long as it does not jeopardize the vehicle basic functionality and performance.

One of the main upgrades of the ROUGHIE2.0 was increasing the payload from 5 kg to 8 kg only by extending the length of the vehicle. This payload capacity can be used to equip the ROUGHIE with ocean sampling sensors to collect data in lakes and harbors. Currently ROUGHIE is equipped with a Wetlabs ECO Puck fluorometer shown in Figure 2.4 to measure the concentration of chlorophyll-a in open-water experiments. This COTS single-wavelength *fluorometer* has been used with the ROUGHIE to highlight the versatility of our modular design. This sensor was externally mounted to the glider using a custom aluminum casing. A waterproof cable connected the sensor to the internal electrical system through a waterproof bulkhead connector mounted on the rear rail end, and the sensor's output was measured by the processor's analog input.

The ROUGHIE had two hull configurations: one transparent acrylic hull for low pressure pool testing to ease debugging, and one aluminum hull for high pressure testing. In both configurations the ROUGHIE was sealed using o-ring crush seals between the

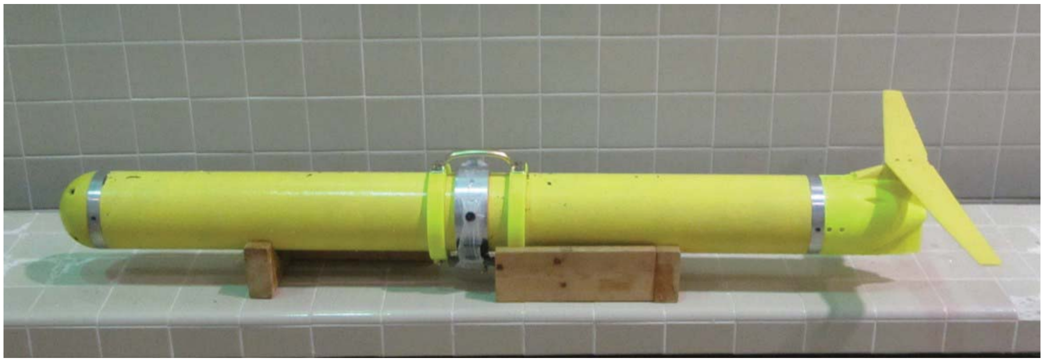

Figure 2.5: Yellow color was selected for glider fuselage and tail for its high visibility in open water mission deployment and retrieval.

end caps and metal joining plates. In the recent upgrade of the ROUGHIE a carbon fiber hull was used for high pressure testing to provide a smooth sealing surface and resolve the constant sealing issues of the ROUGHIE. After upgrading the fuselage and using a standard double O-ring sealing method, the ROUGHIE never experienced an external leakage. The fuselage is painted in yellow for higher visibility. A handle has been attached to the vehicle for ease of transportation and grip point for glider retrieval. Figure 2.5 illustrates the glider ready for water test.

Chapter 3

ROUGHIE's Dynamic Model and Motion Control

The ROUGHIE is considered simple structured glider with a cylindrical fuselage, aerodynamic front and end caps and one set of airfoil shaped fixed wing at the back of the glider. Its an internally actuated underwater glider with internal rotary and linear mass actuation to control the vehicle orientation [37, 48].

To understand the dynamics of the ROUGHIE, the vehicle was modeled as a system of mass blocks. This system is composed of fixed linear sliding mass block (m_s), varying buoyancy mass (m_b), evenly distributed glider body mass (m_h), and asymmetric trimming mass (m_p). Within the ROUGHIE a common rail carries the rotary mass

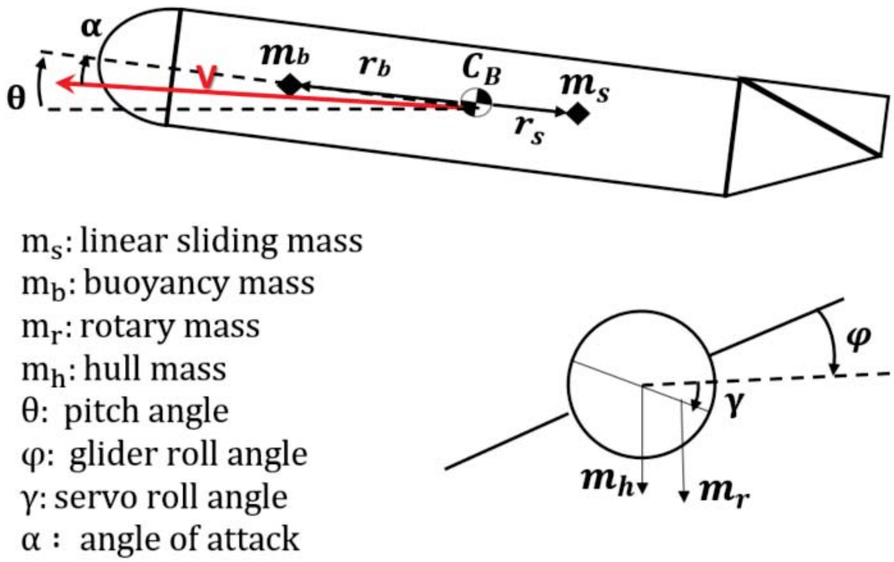

Figure 3.1: ROUGHIE point mass model

(m_r) which is consists of the buoyancy mass, sliding mass and %90 of the vehicle hull mass. Figure 3.1 illustrates the mass model of the ROUGHIE. The total mass of the vehicle is noted as $m_t = m_h + m_s + m_b + m_p$.

For modeling purposes, we divide the vehicle body mass into two individual masses, $m_h = m_{f_1} + m_{f_2}$. m_{f_1} includes internal main rail, two carriages and all the components mounted on the rail except for sliding mass (battery). m_{f_2} is composed of glider hull, front and rear cap, front and rear end plates, rotary servo and its supporting mount, tail wing, pressure sensor, and GPS antenna (located in the front cap) in the main configuration.

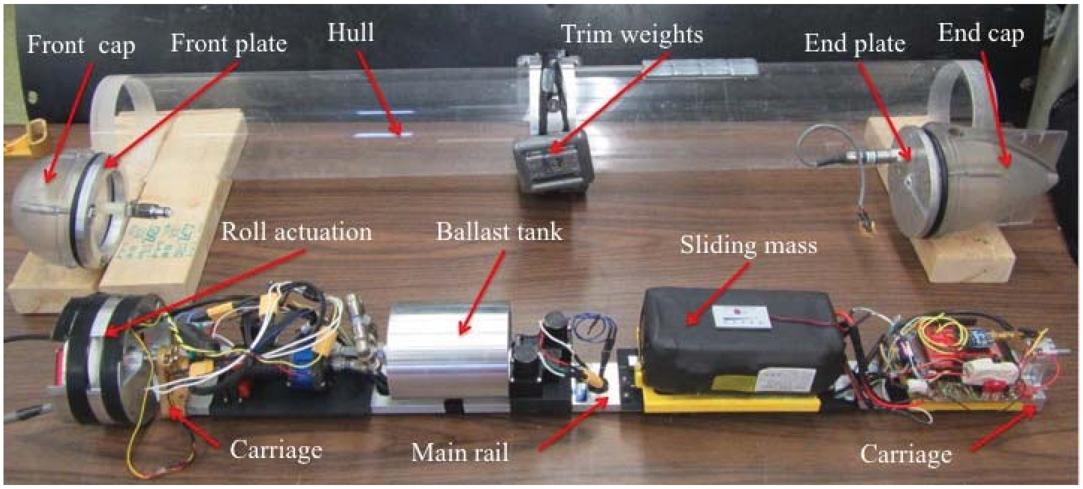

Figure 3.2: ROUGHIE glider internal mass layout

The total mass of the vehicle then is expressed as,

$$m_t = m_s + m_b + m_{f_1} + m_{f_2} + m_p. \tag{3.1}$$

The displacement of fluid due to the presence of the vehicle is defined as $\bar{m}$, thus the net mass can be expressed as $\tilde{m} = \bar{m} - m_t$. This term determines positive or negative buoyancy for the vehicle. The vehicle sinks in the water when it is negatively buoyant ($\tilde{m} < 0$) and rises when it is positively buoyant ($\tilde{m} > 0$). When $\tilde{m} = 0$ the state is known as neutral buoyant and the vehicle remains at the same depth/water level. Change of net mass is controlled by m_b which is the buoyancy tank mass. The distance of m_b to the vehicle CB is represented by r_b.

The buoyancy change m_b is a control input to the vehicle motion controller. In ROUGHIE heave and pitch motion are coupled during the transition phase, and at

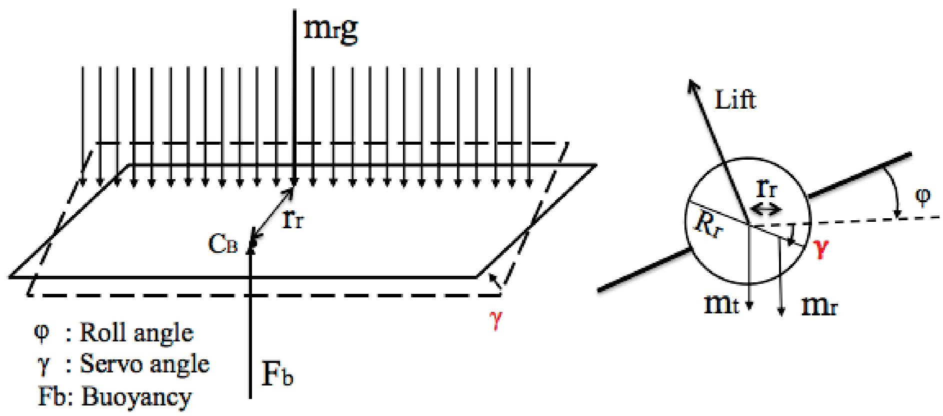

Figure 3.3: Point mass model in novel roll mechanism

the beginning and the end of the glide where changes of net buoyancy is required to glide up, down and during hovering. In the steady state segments of the flight, the heave and pitch motion are decoupled meaning that buoyancy mass maintain its value and $\dot{m}_b = 0$.

In the longitudinal plane, the vehicle uses a rail-based rotary mass (m_r) configuration illustrated in Figure 3.3 to maintain the roll angle for turning flight. This mass is composed of sliding point mass, buoyancy mass and part of vehicle internal component mass that is mounted on the common main rail, $m_r = m_b + m_s + m_{f_1}$. The motion of the glider is practically established by different configurations of these masses towards each other and their orientations in the system. The glider center of gravity is the mass centroid of the vehicle and it's position is given by,

$$\boldsymbol{r_{CG}} = \frac{m_s \boldsymbol{r_s} + m_b \boldsymbol{r_b} + m_p \boldsymbol{r_p} + m_f \boldsymbol{r_f}}{m_s + m_b + m_p + m_f}, \tag{3.2}$$

where $\boldsymbol{r}$ is the distance between each mass to the vehicle CB. Note that $\boldsymbol{r_f} = 0$ since the hull mass is considered uniformly distributed and always coincide with the vehicle center of buoyancy.

3.1 Reference Frame

To analyze the motion of the vehicle in 6 DOF, two reference frames are defined. One is fixed on the vehicle body, referred to as *body fixed frame*. The orientation of body reference frame axes coincides with the principal axis of the vehicle inertia axis and with its origin O_b at the symmetry plane of the body. Thus longitudinal axis x_b stretches from aft to fore, the transverse axis y_b directs to the starboard and the normal axis z_b points downward to the earth gravity direction.

The motion of the vehicle is described relative to an inertial reference frame. For marine vehicle the earth fixed inertia frame (North-East-Down) is an appropriate reference since the earth motion on low speed marine vehicle is negligible. The coordinates of the *inertial frame* is noted as (x_e, y_e, x_e) with its origin O_e at the origin of the earth inertia frame. The orientation of a coordinate frame with respect to the other can be expressed by a rotation matrix using three rotation angle knows as Euler angles roll (ϕ), pitch (θ), and yaw (ψ).

$$\mathbf{R}_{eb} = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & c\phi c\psi + s\phi s\psi s\psi & -s\phi c\psi + c\phi s\theta s\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix}, \tag{3.3}$$

where $c. = cos$ and $s. = sin$.

A third reference frame noted as *flow frame* is defined within the body frame with its x_f axis in direction of the vehicle velocity and its z_f axis located in $x - z$ plane of the body fixed frame. To obtain the flow frame, the body fixed framed is rotated around its y_f axis with angle of attack α and rotating the new frame around the $z-$ axis with side slipping angle of β, yields the following rotation matrix,

$$\mathbf{R}_{bf} = \begin{bmatrix} \cos\alpha\cos\beta & -\cos\alpha\sin\beta & -\sin\alpha \\ \sin\beta & \cos\beta & 0 \\ \sin\alpha\cos\beta & -\sin\alpha\sin\beta & \cos\alpha \end{bmatrix}. \tag{3.4}$$

The velocity of the vehicle with respect to the fluid then is expressed in flow frame as the vector $[\bar{V}, 0, 0]$. Angle of attack, α, and side-slip angle, β satisfy

$$\tan(\alpha) = \frac{w}{u}, \tag{3.5}$$

$$\sin(\beta) = \frac{u}{|V|}, \tag{3.6}$$

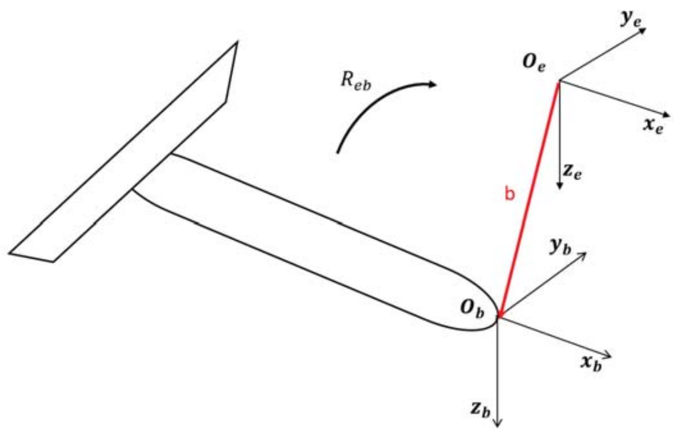

Figure 3.4: Vehicle position and orientation with respect to reference frames

where u, v, and w are the glider's translational velocities in the body frame with respect to the flow frame.

3.2 Kinematics

The position of the body fixed frame "b" changes with time with respect to the inertia frame "e" during the motion of the vehicle. If the distance between the two frame in space is denoted as vector **b** as illustrated in Figure. 3.4, then the linear velocity of the vehicle with respect to e-frame is time derivation of the vector **b**. Linear velocity in body frame is expressed as,

$$V_b = R_{eb}\dot{\mathbf{b}}. \tag{3.7}$$

If orientation of the body fixed frame with respect to inertia frame changes with time

then the rotation matrix R_{eb} is time varying. The angular velocity of "b" with respect to "e" defines as,

$$\dot{R_{eb}} = \omega \times R_{eb}. \tag{3.8}$$

The angular velocity in body frame is expressed as,

$$\omega = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta\sin\phi \\ 0 & -\sin\phi & \cos\theta\cos\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix}. \tag{3.9}$$

To describe the motion of the vehicle, the following vectors are used based on notations in Fossen [49]. η is the generalize position of the vehicle in body fixed frame with respect to the inertia frame,

$$\eta = \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix}, \eta_1 = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \eta_2 = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}. \tag{3.10}$$

ν is the generalized velocity of the vehicle in body frame with respect to the inertial

frame where ν_1 denotes the speed and ν_2 refers to angular speed,

$$\nu = \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}, \nu_1 = \begin{bmatrix} u \\ v \\ w \end{bmatrix}, \nu_2 = \begin{bmatrix} p \\ q \\ r \end{bmatrix}. \tag{3.11}$$

Generalized position and generalized velocity are related through the Jacobin matrix of the position,

$$\dot{\eta} = J(\eta)\nu, J(\eta) = \begin{bmatrix} J_1(\eta_2) & 0 \\ 0 & J_2(\eta_1) \end{bmatrix}. \tag{3.12}$$

3.3 Dynamics

For ROUGHIE τ is sum of different components of hydrodynamic forces and moments acting on the vehicle with respect to the body fixed frame,

$$\tau = \tau_{Rest} + \tau_{Damp} + \tau_{Add}. \tag{3.13}$$

τ_{Rest} denotes the restoring forces and moments due to the weight and buoyancy of the

vehicle and is dependant on the position and orientation of the vehicle. The center of mass (CG) is located under the center of buoyancy (CB) at the presence of non-zero roll and pitch angle, hence stabilizing the vehicles during its motion.

$$\tau_{Rest} = \begin{bmatrix} m_t g \\ CG \times m_t g \end{bmatrix} - \begin{bmatrix} \rho_m \mathrm{Vol}_t g \\ CB \times \rho_m \mathrm{Vol}_t g \end{bmatrix}, \tag{3.14}$$

where CG and CB are the vehicle center of gravity and center of buoyancy in body fixed frame respectively. ρ_m is the water density, $\mathrm{Vol_t}$ is the vehicle volume and g is the earth's gravitational acceleration. The restoring force on the vehicle results in a righting moment that causes vehicle to pitch up or down. At the neutrally buoyant point, the CG and CB are vertically aligned so that the resultant of restoring torques becomes zero.

τ_{Damp} denotes all potential damping acting on the fuselage and due to the vehicle appendages. τ_{Damp} is a function of the relative velocity of the vehicle with respect to the fluid and the position of the appendages δ. Note that the hydrodynamic forces and moments are part of the damping forces expressed as,

$$\tau_{Damp} = -D(\nu, \delta)\nu = (\frac{1}{2}\rho A \begin{bmatrix} C_D \\ C_C \\ C_L \end{bmatrix} \nu)\nu, \tag{3.15}$$

where ρ is the water density, A is the surface, and C_D, C_C, and C_L are the hydrodynamic coefficients of drag , cross terms, and lift force [50]. These coefficient are estimated based on basic hydrodynamic laws and look-up tables for cylindrical fuselage, half sphere nose cone and wings separately. These coefficient are function of shape, vehicle speed, angle of attack, and position of the force acting on the body with respect to the flow frame [51].

The ROUGHIE has a symmetric body with a NACA0012 wing at the aft of the vehicle. In modeling of the ROUGHIE this method was utilized due to its simplicity and absence of exact hydrodynamic coefficients due to lack of imperial testing. The drag and lift coefficients were calculated for the fuselage, then summed up to calculate the resulting forces and moments of the whole vehicle, neglecting the interaction of all the surfaces. These values are left multiplied by rotation matrix from flow frame to body frame.

τ_{Add} denotes the added mass forces and moments due to the inertia of the fluid around the vehicle which are functions of the vehicle acceleration with respect to the surrounding water.

$$\tau_{Add} = -M_A\dot{\nu} - C_A(\nu)\nu, \tag{3.16}$$

where M_A is the added mass and added inertia matrix and C_A is the cross term

matrix of the vehicle.

The motion of a rigid body in 6 DOF is defined as [49],

$$M_{RB}\dot{\nu} + C_{RB}(\nu)\nu = \tau, \tag{3.17}$$

M_{RB} is the mass and inertia matrix of the vehicle defined as,

$$M_{RB} = \begin{bmatrix} m_t I_3 & -m_t \times CG \\ m_t \times CG & I_b \end{bmatrix}, \tag{3.18}$$

where I_3 is 3×3 identity matrix and I_b is vehicle inertia matrix with respect to O_b in body frame.

$$C_{RB} = \begin{bmatrix} 0 & -[M_{RB11} M_R B_{12}] \times \nu \\ [M_{RB11} M_{RB12}] \times \nu & [M_{RB21} M_{RB22}] \times \nu \end{bmatrix} \tag{3.19}$$

where C_{RB} is the cross term inertia matrix of the vehicle.

The Coriolis force vector τ_{Cor} is defined as,

$$\tau_{Cor} = -C_{RB}(\nu)\nu - C_A(\nu)\nu. \tag{3.20}$$

Equation (3.17) yields to,

$$(M_{RB} + M_A)\dot{\nu} = \tau_{Rest} + \tau_{Damp} + \tau_{Cor}. \tag{3.21}$$

The final kinematics and dynamic equations of the vehicle is a 12 states dynamic system with 3 control inputs,

$$\dot{\eta} = J(\eta)\nu, \tag{3.22}$$

$$\dot{\nu} = [M_{RB} + M_A]^{-1}(\tau_{Rest} + \tau_{Damp} + \tau_{Cor}). \tag{3.23}$$

The control inputs are the variable buoyancy mass, the position of the linear mass and the internal roll angle of the common rail. This non-linear system is simulated in MATLAB/Simulink with 15 dimensional input vector including the system states and inputs. The vehicle characterization is passed to the system using a separate function and computes the derivatives of the system states. These derivatives are then integrated over time to evaluate the system's behaviour.

To calculate the trajectory of the ROUGHIE, the algorithm needs two inputs, the pressure and attitude which can be fed to system from the vehicle modeling and sensory data. The depth is determined by data provided from a pressure sensor and an AHRS provides the glider's pitch (θ), yaw (ψ), and roll (ϕ) angles. The following equations summarize the method used to calculate the position and speed of the glider

at each time step.

$$w = -\frac{z_i - z_{i-1}}{\tan(\theta)} \tag{3.24}$$

$$u = w \cdot \sin(\psi) \tag{3.25}$$

$$v = w \cdot \cos(\psi) \tag{3.26}$$

$$\triangle(x) = u \cdot \triangle(t) \tag{3.27}$$

$$\triangle(y) = v \cdot \triangle(t) \tag{3.28}$$

$$x_{i+1} = x_i + \triangle(x) \tag{3.29}$$

$$y_{i+1} = y_i + \triangle(y) \tag{3.30}$$

The vertical position of the glider is derived by

$$\dot{z} = w \cdot \cos(\theta) + u \cdot \sin(\theta). \tag{3.31}$$

3.4 Motion Control

To control system's behaviour an efficient motion controller is needed. When the depth of a glide or time of a glide are restricted due to shallow water application or high maneuver missions, hybrid feedforward-feedback approach suggested in [52] is a computationally affordable solution to the nonlinear control problem. A block

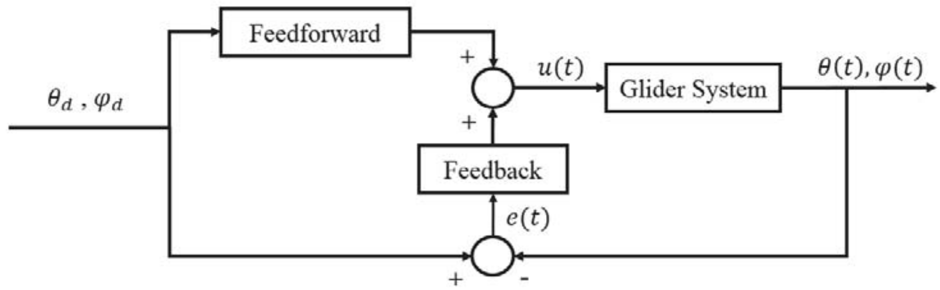

Figure 3.5: Hybrid feedforward-feedback controller to control the pitch angle (θ) and roll angle (ϕ) of the glider. The controller begins by sending the actuators to an initial position calculated by the feedforward block, based on the desired pitch and roll angles, θ_d and ϕ_d, respectively. Attitude feedback from the IMU sensor is then used to compute the error, $e(t)$. Finally, the compensating signal, $u(t)$, is then sent to the actuators (pitch module, buoyancy module, and roll module) to achieve the desired pitch and roll angles. Depth is directly controlled by a bang-bang controller using the pressure sensor feedback to the buoyancy drive.

diagram of the feedforward-feedback controller design is illustrated in Figure 3.5.

The ROUGHIE is restricted to operate in shallow water thus it has less depth or appropriate time to achieve steady state using only feedback control. In addition to that since the vehicle is designed to be highly maneuverable a switching control strategy also seems necessary to drive the vehicle to different segments or stages of flight as quick as possible. A switching control method has been used to choose between controllers at different stages of the flight.

The heave motion is controlled by the amount of water fed into the buoyancy system. The trajectory angle or pitch angle is preliminary controlled by the effects of net buoyancy and using a linear sliding mass to tune the trajectory angle. The heading is controlled indirectly through the roll angle of the vehicle in internally actuated

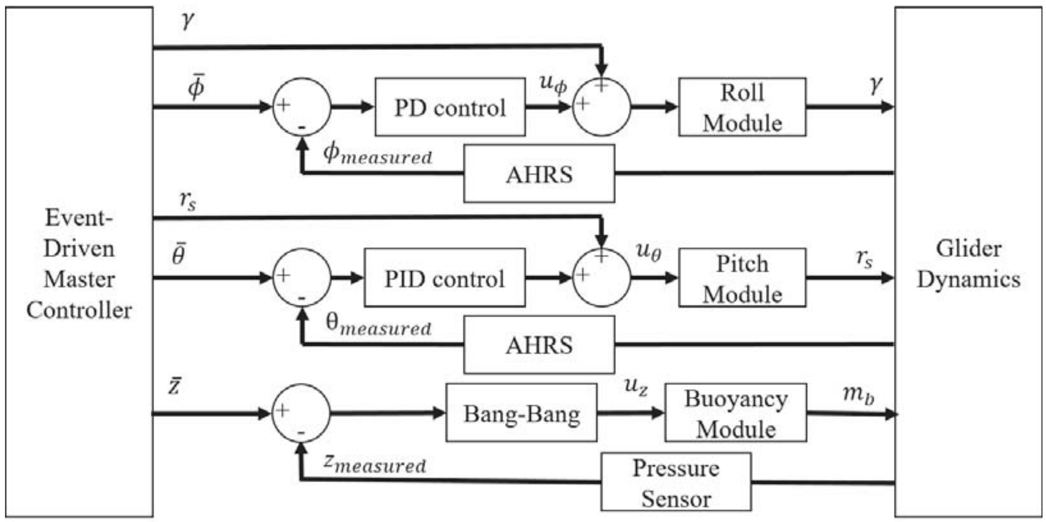

Figure 3.6: Multi-layer control strategy used in ROUGHIE. The Event-Driven Master Controller interprets the desired trajectory into actionable pitch ($\bar{\theta}$), depth ($\bar{z}$), and roll ($\bar{\phi}$) targets for the low level controllers.

underwater glider. Figure 3.6 shows multi-layer controller in ROUGHIE.

As an example when performing wings-level flight in shallow water, the hybrid approach uses the feedforward element to shift the ballast piston and sliding mass to predefined positions to initiate the glide and accelerate vehicle convergence rate to the desired trajectory. Then, during steady glides the controller utilizes feedback to compensate for errors and improve performance. The switching control acts in transition between different phases of a glide or connecting different flight patterns together. Figure 3.7 illustrates ROUGHIE switching states at transition point. As soon as the vehicle is in steady state the controller switches to hybrid control, thus driving to the desired trajectory for the next glide segment.

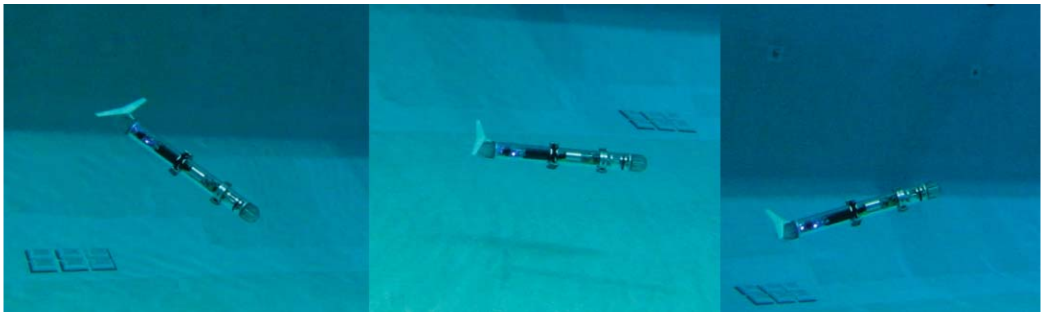

Figure 3.7: Saw-tooth trajectory in transition phase. The ROUGHIE travels on a downward glide by increasing the ballast mass using water intake and shifting the linear sliding mass to the forwards of center of gravity (CG) (left frame), then achieves neutral buoyancy (middle frame) before beginning an upward glide discharge the water using the pump and shifting the sliding mass behind the CG to achieve nose up trajectory (right frame).

3.4.1 Pitch Control

The ROUGHIE follows a saw-tooth pattern traditionally acquired by underwater gliders to propel in the water by altering the net buoyancy of the vehicle. The attitude in vertical plane is controlled through the shifting of the linear sliding mass position - consists of vehicle battery pack and a linear lead screw-motor actuating system- which in return shifts the CG of the vehicle with respect to the center of buoyancy and creates clockwise or counterclockwise pitching moment and tunes the glider attitude.

A draw wire potentiometer measures the position of the sliding mass. This value is used as an input to the motion control algorithm (PID controller in the original configuration) to adjust vehicle pitch angle. Both ballast system and pitch mass are

trimmed to neutrally buoyant at the the beginning of the mission in order to have the vehicle neutrally buoyant with $0°$ pitch.

The buoyancy module causes the bulk of the pitching motion due to the forward location of the ballast tank while the pitch control module performs fine adjustments to the vehicle pitch and rejects disturbances. To perform wings-level glides the buoyancy module pumps to a predetermined level and the pitch control module drives the pitch mass towards known positions for feedforward control.

Once the ROUGHIE has established steady gliding motion due to feedforward, the feedback controller is enabled to compensate errors and finely tune the pitch angle and reject any disturbances that are encountered. Feedback control utilizes IMU feedback of the vehicle pitch angle to adjust the pitch mass location. The combination of buoyancy and attitude change allows ROUGHIE to perform different dive strategies.

The glider's equations of motion are derived by calculating momenta from the vehicle-fluid system's total energy and applying Newtons laws [49]. The steady flight equilibrium happens when the derivatives of translational momentum and angular momentum are equal to zero. The kinematics of the vehicle thus becomes,

$$\dot{x} = u\cos\theta - w\sin\theta, \tag{3.32}$$

$$\dot{z} = w\sin\theta + u\sin\theta, \tag{3.33}$$

$$\dot{\theta} = q. \tag{3.34}$$

Where θ is pitch angle, q is the pitch rate and u and w are vehicle speed in surge and heave direction in body frame respectively. x, z are the position of the glider in inertial frame. Roll and yaw angles are assumed negligible in steady state glides restricted to the vertical plane, thus the pitch angle of the vehicle and and depth rate can be evaluated separately.

Let $W = m_t g$ be the weight of the vehicle, $B = \bar{m}g$ be the buoyancy restoring force, and $\Delta B = W - B$; with the origin of the body frame taken at the centre of buoyancy for convenience (CB), and (x_{CG}, z_{CG}) be the coordinates of the vehicle centre of gravity (CG) in the body frame, $\Delta x = x_{CG}$ and $\Delta z = z_{CG}$.

As discussed in Fossen [49], in steady state flight, when u is constant, the longitudinal model can be further simplified to consider only pitch and heave motion in vertical

plane diving mode. The kinematic equations for the pitch heave model becomes,

$$\dot{z} = w \sin\theta + u_0 \sin\theta, \tag{3.35}$$

$$\dot{\theta} = q. \tag{3.36}$$

The dynamic equations can be expressed as,

$$M \begin{bmatrix} \dot{w} \\ \dot{u} \end{bmatrix} + C \begin{bmatrix} w \\ u \end{bmatrix} = - \begin{bmatrix} \Delta B \cos\theta \\ -\Delta z B \sin\theta - \Delta x B \cos\theta \end{bmatrix}. \tag{3.37}$$

The right hand side in Eq. 3.37 is the hydro-static lift in the body frame computed with roll angle $\phi = 0$. The hydro-static lift is the control action on the vehicle, since the combined action of the ballast and of the sliding linear mass changes ΔB, Δx, and Δz.

Let $\bar{z}$ be the desired depth, and $\bar{\theta}$ be the desired pitch. We can define the following error function

$$e_z = z - \bar{z} \tag{3.38}$$

$$e_\theta = \theta - \bar{\theta} \tag{3.39}$$

The control objective in 2D glide control is to reach the target glide angle and desired depth, determining the control law in terms of pitch angle (θ) and net buoyancy $\bar{m}$

to guarantee the stable reaching of the desired trajectory. The reaching of the target trajectory is equivalent to the asymptotic convergence to zero of the variables e_θ and e_z.

The buoyancy mass, m_b, is a control input to adjust the heave rate $\dot{z}$. m_b changes by pumping water in and out of the ballast tank. The position of the ballast piston $\mathbf{r}_b$ is measured by the draw wire potentiometer, hence the buoyancy mass is calculated at every time step. This also causes a pitching moment about the center of the gravity of the vehicle.

By defining the following control law:

$$u_z = m_b sign(e_z) \tag{3.40}$$

$$u_\theta = k_{p_\theta} e_\theta + k_{i_\theta} \int_0^\tau e_\theta d\tau + k_{d_\theta} \dot{e}_\theta + \bar{m} \tan\theta, \tag{3.41}$$

where k_{p_θ}, k_i, and $k_{d_\theta}\dot{e}$ are positive control gains. Note that the term $\bar{m}\tan\theta$ is the feedforward part of the controller and depend on the initial net buoyancy and pitch angle. This value is unbounded as θ approaches $\pm\pi/2$, close to the vertical dive direction.

With the control law defined above, the position control is implemented as a proportional controller based on the error between desired and measured orientation. The feedforward term in the controller design guarantees robustness of the controller

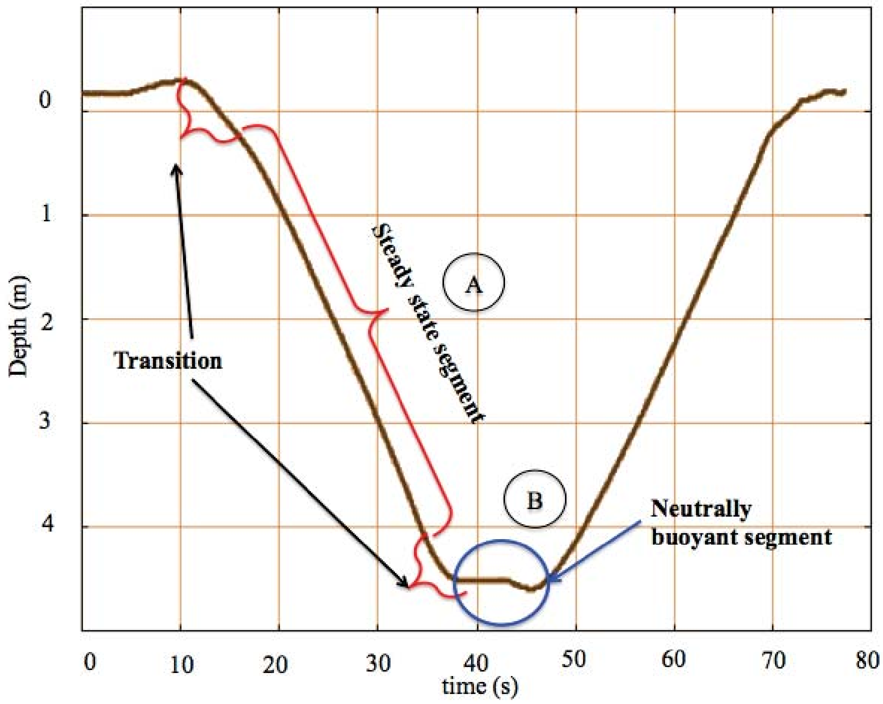

Figure 3.8: During each glide cycle the ROUGHIE uses a switching control strategy depending on the current glide state. In segment (A) a hybrid feedforward-feedback controller is used. In segment (B) a neutrally buoyant state is commanded using feedforward control.

with respect to uncertainties in the system. Hybrid feedforward-feedback controller controls the pitch angle (θ) and roll angle (ϕ) of the glider.

The controller begins by sending the actuators to an initial position calculated by the feedforward block, based on the desired pitch and roll angles, θ_d and ϕ_d, respectively. Attitude feedback from the IMU sensor is then used to compute the error, $e(t)$. Finally, the compensating signal, $u(t)$, is then sent to the actuators (pitch module, buoyancy module, and roll module) to achieve the desired pitch and roll angles. Depth is directly controlled by a bang-bang controller using the pressure sensor feedback to

the buoyancy drive. This control law is valid during the level flight segment of the glide. As illustrated in Figure 3.8 the a glide is composed of an ascent and decent steady state flight segment. The middle segment or the transition point is highly nonlinear and this control law is not valid entering or exiting the transition segment.

To compensate for the non-linearity, the switching controller utilizes a feedforward approach during the transition segment to smoothly connect the two wings-level straight flights by driving the vehicle in a neutrally buoyant state. With this technique the saw-tooth motion is physically altered in the transition stage. Instead of an instant transit from glide down to pull up, a neutrally buoyant state is added right before the pull up segment of the glide.

In this case, the vehicle loses downward momentum and reaches to a temporary equilibrium point at $\theta = 0$, then enters the second part of the glide cycle. Thus a robust switching controller is sufficient to control diving motion with good approximation considering the low speed of underwater glider.

3.4.2 Roll and Heading control

Controlling the heading angle of the vehicle in the horizontal plane is a more complicated task. In underwater gliders with no external actuator (or active rudder) like ROUGHIE, a roll induced heading angle approach is used, similar to a level turn

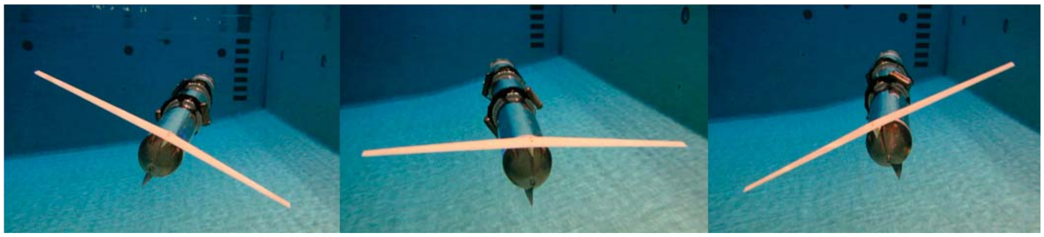

Figure 3.9: The ROUGHIE roll mechanism and roll controller is capable of rolling the vehicle +/- 60 degrees which results in a turn radius down to 3m.

performed by aircraft. By rolling the glider clockwise/counter clockwise, the hydrodynamic lift force applied on the wing from water induces a positive/negative yaw angle on dive/rise glide. Figure 3.9 depicts 3 states of roll in ROUGHIE. This strategy can be used to generate spiraling motion and turning maneuvers in internally actuated underwater gliders.

Similar to the 2D gliding, the hydro-static lift is the control action on the vehicle. The lift force on the rolled wing has a horizontal component that acts as centripetal force and causes the glider to change its heading and turn. By maintaining this horizontal force the glider stays in a helical motion upward or downward depending on its orientation in the vertical plane.

Heading control is achieved in two different ways in the ROUGHIE, either a direct feedforward approach or a hybrid feedforward- feedback approach [53], Case 1: The γ angle is sent directly to the servo as control input and is used for either system identification or feedforward-based inverse mapping implementation. Case 2: The γ

angle is obtained through feedforward-feedback control of ϕ and it is used for long-term turn control, or if the system has not been properly characterized following changes to the vehicle structure.

If $\bar{\phi}$ is the desired roll angle and $e_\phi = \phi - \bar{\phi}$ is the roll angle error, then Case 2 control becomes,

$$u_\phi = k_{p_\phi} e_\phi + k_{d_\phi} \dot{e}_\phi + k_\gamma \gamma \tag{3.42}$$

where k_{p_ϕ} and k_{d_ϕ} are controller parameter, k_γ is rotary servo's correction factor. In roll controller, the feedforward component is calculated based on the required turn radius and the feedback component is computed from feedback via the internal AHRS. Using the switching controller in turn maneuver, the glider is able to link different maneuvers in a single mission.

The roll controller uses a reverse mapping feedback controller to control roll angle of the vehicle directly, which in turn affects the yaw angle of the vehicle. The roll controller is active for disturbance rejection and maintains the mean value of the roll angle as desired by the user. The ROUGHIE's internal rotary mechanism can be used as an alternative or backup system for current AUVs' turning solutions since at low speed efficiency of rudder decreases and it can not control the heading as expected.

3.4.3 Switching Controller

Concatenation of the steady wings-level flight and helical flight for underwater gliders enables complex paths to be followed without the use of external actuators. Connecting flight strategy enables internally actuated vehicles to perform sensitive missions where high performance and stealthiness are required. Depend on the mission planning and the maneuver being used, the controller selects a sequence of wings-level, helical, and neutrally buoyant stages. The switching controller changes the state of the controller between feedforward and feedforward-feedback depend on the segments that the vehicle drives into.

The switching controller can choose between seven different combinations of flights every time it drives the vehicle into the next flight. For example if the vehicle is performing a downwards wings-level flight, it can transition into 1) upward wings-level flight, 2) upwards right hand side helical, 3) upward left hand side helical, 5) downward right hand side helical, 6) downward left hand side helical, or 7) neutrally buoyant for hovering missions.

To perform maneuvers, the feedforward-feedback switching controller can drive the vehicle through switching phases with smooth transition. For smooth transition, the controller utilizes the neutrally buoyant state to lower the acceleration of the

vehicle at the transition segment, allowing the system enough time to change the flight parameters to new values. The control is challenging specially when the only means of flight manipulation is internal actuation. This means controlling the resultant hydrodynamic forces utilizing vehicle structure, change of buoyancy, pitch, and roll. This switching approach toggles the feedback element of the hybrid controller off during transition periods and the feedforward element drives the glider to a neutrally buoyant state. As soon as the vehicle is in steady state, the controller switches to hybrid control, thus driving to the desired trajectory for the next glide segment by changing or maintaining the vehicle heading angle.

Chapter 4

Motion Planning Strategy Through Flight Concatenation

4.1 Basic Flights

Underwater gliders use change of buoyancy to propel through water. The buoyancy and gravity force interaction creates heave motion. In order to move forward through water they use wings to translate vertical motion to horizontal motion by generating lift force.

The main characteristics of these vehicles are: low power consumption, low acoustic signature, and high mission endurance.

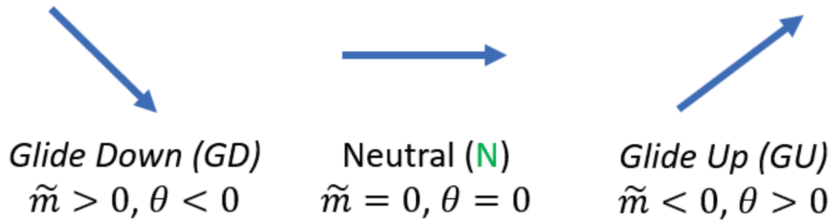

Figure 4.1: Wings-level flight- 3 stages

Typically, glider motions is divided into two distinctive basic flights: 1) wings-level flight or saw-tooth motion and 2) helical flight or spiraling motion.

4.1.1 Wings-level Flight or Saw-tooth Motion

Saw-tooth motion is the result of changing the vehicle pitch angle θ, keeping the roll angle zero, while the glider sinks and rises through adjusting buoyancy. Figure 4.1 illustrates three possible states of the wings-level flight solely based on buoyancy change. The control parameters in wings-level flight are buoyancy ($\tilde{m}$) and location of the sliding mass. Using wings-level flight underwater gliders can explore undersea in saw-tooth shape motion efficiently. Figure 4.2 illustrates saw-tooth motion performed by ROUGHIE in dive tank.

In shallow water, the main challenge in wings-level flight is maintaining symmetric flight and reaching steady state while avoiding the bottom. Utilizing faster internal actuators for buoyancy and sliding mass system aids achieving faster steady flight in

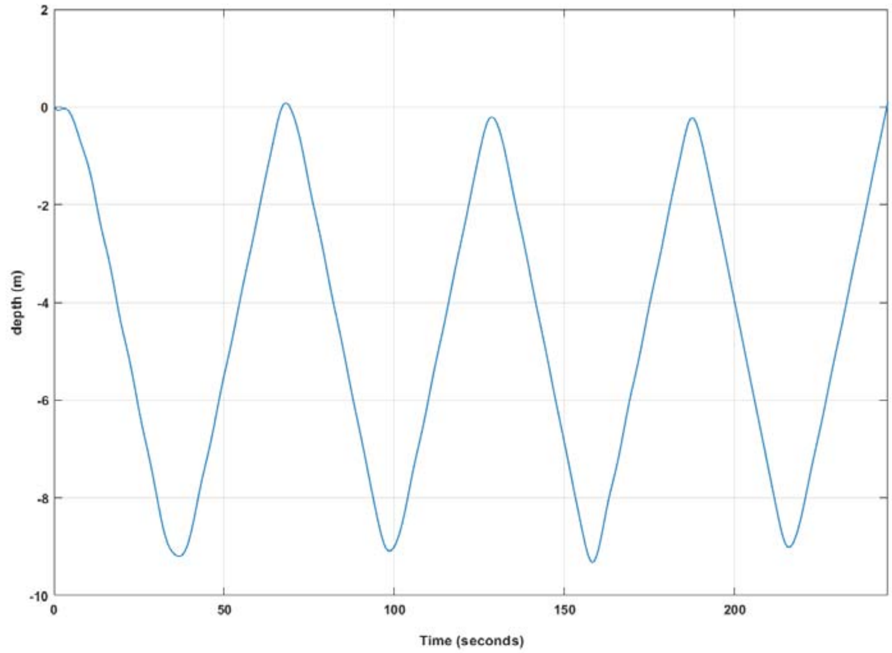

Figure 4.2: Saw-tooth variation of wings-level flight

shallow water due to the quicker response of the actuator to the controller's command. Adding a neutrally buoyant state facilitates smooth transition between glide-down and glide-up. This addition to the saw-tooth flight creates a corrugated shaped motion illustrated in Figure. 4.3. The neutrally buoyant state enables "hovering" capability in underwater gliders without any external means of station keeping.

4.1.2 Helical Flight or Spiraling Motion

Helical flight occurs when the vehicle initiates a banked turn with roll angle ϕ. The control parameters are position of rotary mass system which impacts internal roll angle γ and net mass $\tilde{m}$ that remain unchanged during the helical flight.

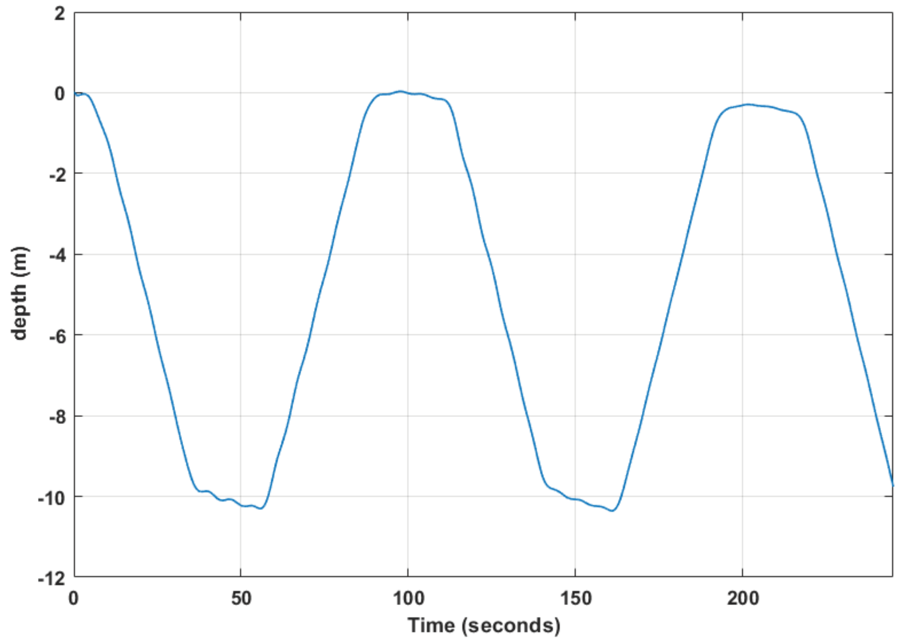

Figure 4.3: Corrugated variation of wings-level Flight

This provides opportunities for traveling efficiently without any actuation expenditure for water column oceanographic investigations. The helical descent and helical climb are extremely useful for vertical gradient data collection in ocean sampling and vision based imagery in mapping while probing a 360° water column [54].

While the vehicle is rolled, the horizontal component of the lift force act as centripetal force, opposes inertia, and drives vehicle in circular turning trajectory. The vertical lift component, continues to act in z direction opposing gravity during descent and buoyancy while ascending correspondingly traveling in downward and upward helical pattern. Figure 4.6 illustrates four different banked turn directions.

Underwater gliders can perform helical motion either in clockwise or counterclockwise

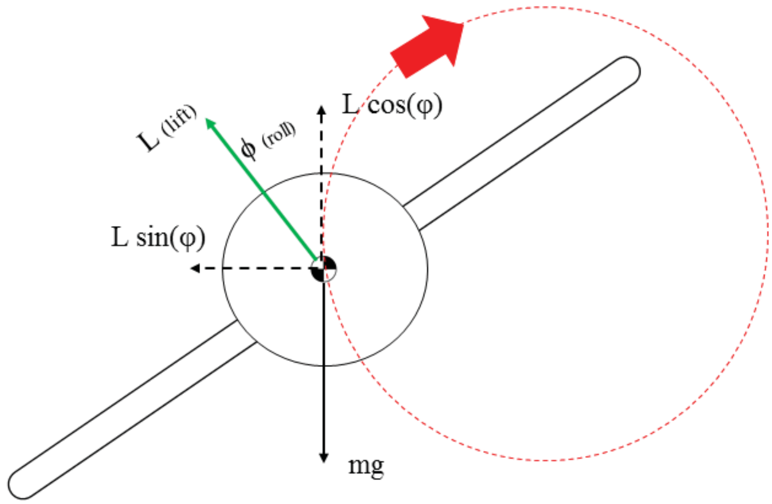

Figure 4.4: Turn motion dynamics and force assignment: turn right.

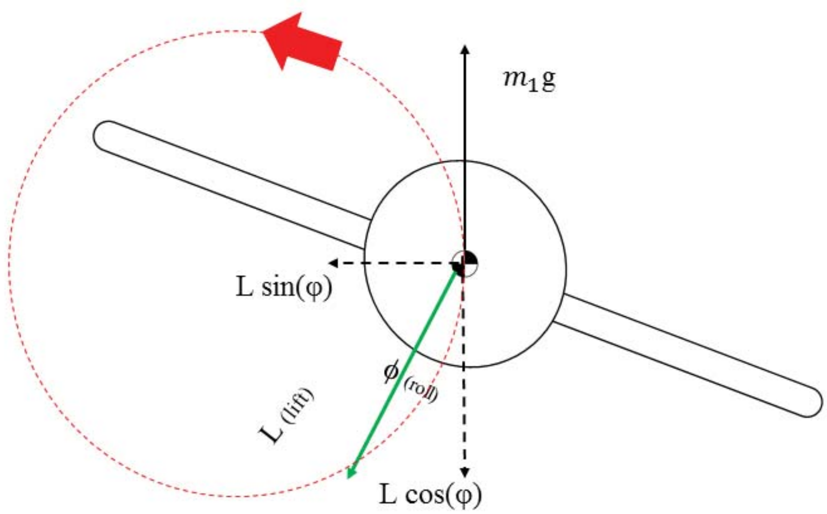

Figure 4.5: Turn motion dynamics and force assignment: turn Left.

screwing motion. The force assignment of the turn is shown in Figure 4.4 and Figure 4.5. Where m and m_1 are vehicle mass and depend on the vertical position of the glider in the water there are different by amount of buoyancy mass changes at the top or bottom of the glide.

The radius of the helix is depend on the vehicle roll angle ϕ, which in turn is related

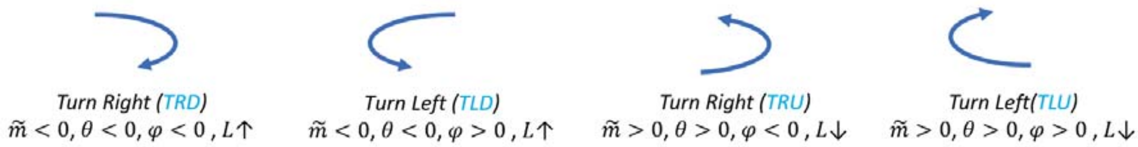

Figure 4.6: Clockwise and Counter Clockwise banked turn referred to as right turn and left turn with respect to the flight variables $\tilde{m}$, ϕ, and θ. L depicts the direction of the vertical component of the lift force.

to the horizontal component of the lift force. The rate of turn at a given speed is proportional to roll angle, larger roll angle results in smaller turn radius.

The top view and side view of ROUGHIE's helical profile at $\phi = 35°$ is illustrated in Figure 4.7 and Figure 4.8. The radius of the helix is depend on the vehicle roll angle ϕ, which in turn is related to the horizontal component of the lift force. The rate of turn at a given speed increases as the roll angle increases and results in a smaller turn radius.

4.2 Advanced Flights

To investigate ability of underwater glider in performing complex maneuvers, a parsing like technique was chosen to divide a hypothetical flight time history to different blocks where the vehicle performs similar complex flights. Each block contains a series of concatenated flight refer to "advanced flight" which can be repeated in specific mission over the operation time. The objective is to firstly investigate what are the potential advanced maneuvers and secondly, how to connect the advanced maneuvers

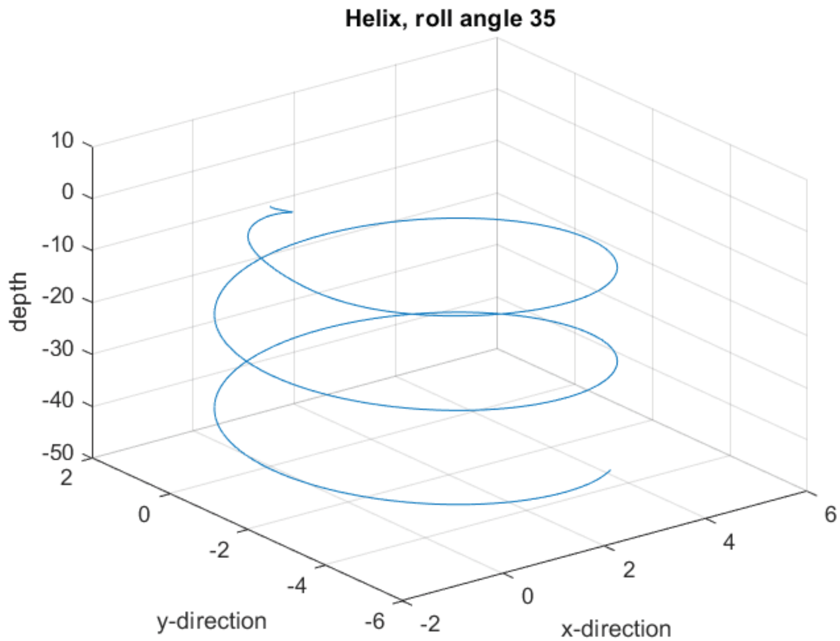

Figure 4.7: Helical flight is a screwing motion along a vertical axis, 3 dimensional view.

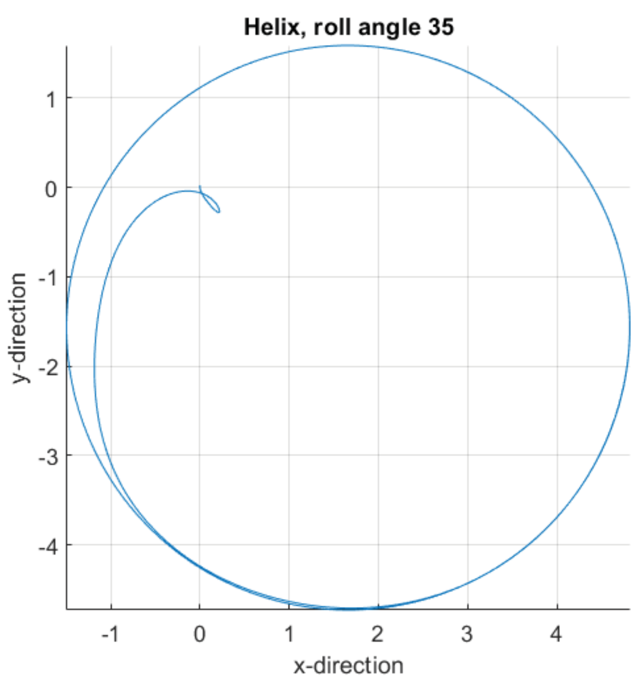

Figure 4.8: Top view of helical motion is a circle.

together.

Advanced maneuvers are dependent on the ability of the vehicle to perform helical turns at different rates and directions and the ability to enter and exit each basic flights. To investigate possible flight patterns, inspired by air gliders, five distinct maneuvers were chosen for further studies: 1) Turn around a point/ Circle; 2) Rectangular/ Oval Turn; 3) 180° Turn/ U-Turn; 4) S-Turn/ Symmetric and Asymmetric; and 5) Figure 8.

These maneuvers belong to two different family of flights: a) continuous curvature heading consists of Circle, Oval-turn, and U-Turn maneuvers, and b) switching curvature heading comprise of S-Turn and Figure-8 maneuvers. For the purpose of generating these flight by other vehicles all five of these maneuvers are explained in detail here.

The rest of this chapter presents mechanism of performing each advanced maneuver. A cartooning style drawing is illustrated to describe the composition of the basic flights in each complex flight. Simulation result of ROUGHIE model performing these maneuver is presented and finally the sequence of concatenating flights in each maneuver is represented in tabular form. Table 4.1 lists the notation used to describe the basic flight characterization in this section.

Table 4.1
Steady state flight notation

Notation	Definition
GD	Glide down
GU	Glide up
N	Neutrally buoyant
TR	Turn right
TL	Turn left
TRD	Turn right down
TRU	Turn right up
TLD	Turn left down
TLU	Turn left up
/	Exit with
+	Connect

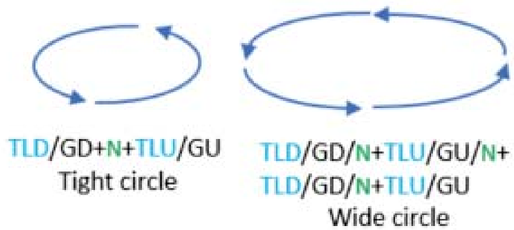

Figure 4.9: "Circle" flight sequence and expected patterns.

4.2.1 Turn around a point/Circle

This maneuver consists of number of helical turns in consecutive dives to follow a circular path. The vehicle follows a closed loop trajectory which resembles a circle in $x-y$ plane illustrated in Figure 4.9. Two variation of circles are due to the magnitude of the desired radius and turning rate.

To achieve a smaller circle a larger rolling angle is required, however the vehicle can complete the circle in less that two glide cycles. In circle maneuvers with larger

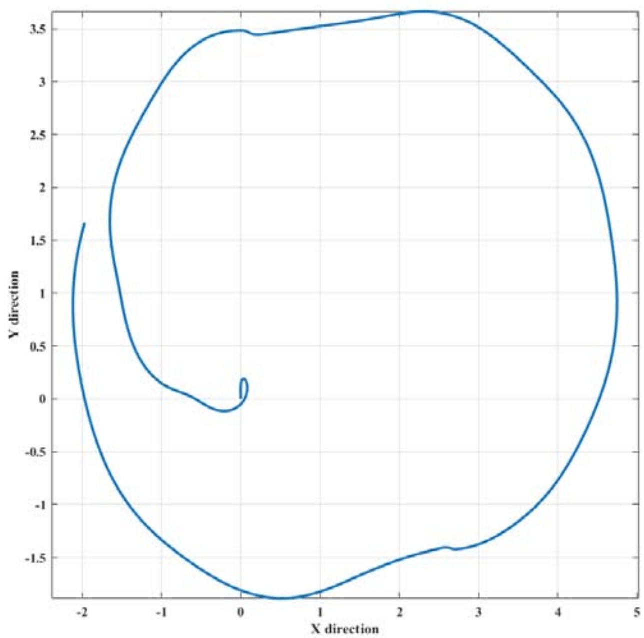

Figure 4.10: Top view of Circle maneuver in simulation with approximately 3m radius.

radius small roll angle and higher number of glide cycle are required when operating in shallow water.

To start the circle, the vehicle initiates the turn, CW or CCW. In internally actuated underwater vehicles this motion is achieved by rolling the fuselage CCW or CW respectively. Next step is gliding downward while holding the roll angle orientation thus maintaining the the turning direction.

This motion creates a partial arc of the circle. Since underwater gliders use change of buoyancy to locomote, in next stage the vehicle glide upward. To follow the circular path while gliding up the vehicle must roll to the opposite side. If the circle is not complete, due to the turn radius, then the vehicle repeats these two stages.

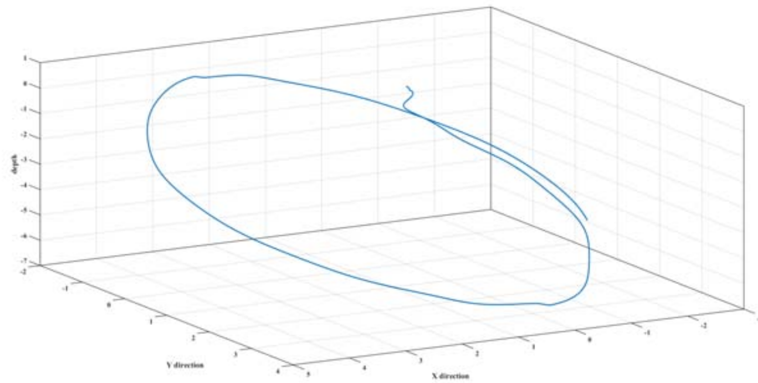

Figure 4.11: 3D View of Circle maneuver in simulation, the ROUGHIE model performs a tight circle in one glide cycle.

To smoothly connect the stages, especially if depth limitation is presented, a neutrally buoyant state can be utilized. In neutrally buoyant state the vehicle slows down and practically acts similar to braking. To successfully perform advanced maneuvers the neutrally buoyant state was used as “switching” stage to connect the flights.

To simulate the circle maneuver, two input controls were manipulated, 1) net buoyancy ,$\tilde{m}$, for depth control and 2) roll angle ,ϕ, to induce the turn motion. Figure 4.11 and 4.10 illustrate the circle maneuver simulation result with $\phi = 30°$ resulting in turn radius of approximately 3 meters. It is observed that the circle is not fully rounded where the neutrally buoyant state is applied. The sequence of performing the circle is illustrated in Table 4.2.

Table 4.2
Circle flight sequence

sign ϕ	value ϕ	sign θ	Glide	Turn direction
+	ϕ_1	-	down	left
-	ϕ_1	+	up	left
+	ϕ_1	-	down	left
-	ϕ_1	+	up	left

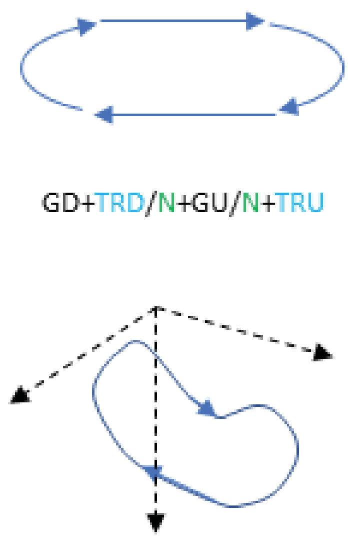

Figure 4.12: "Oval Turn" flight sequence and expected pattern, 3D and top view

4.2.2 Rectangular/ Oval Turn

The top view of this maneuver resembles an oval or rectangular shape. The oval turn is similar to circle except that the motion starts with downward wings-level flight creating the straight segment of the rectangle as illustrated in Figure 5.11. Then the vehicle performs a half circle to follow the arc segment of the oval.

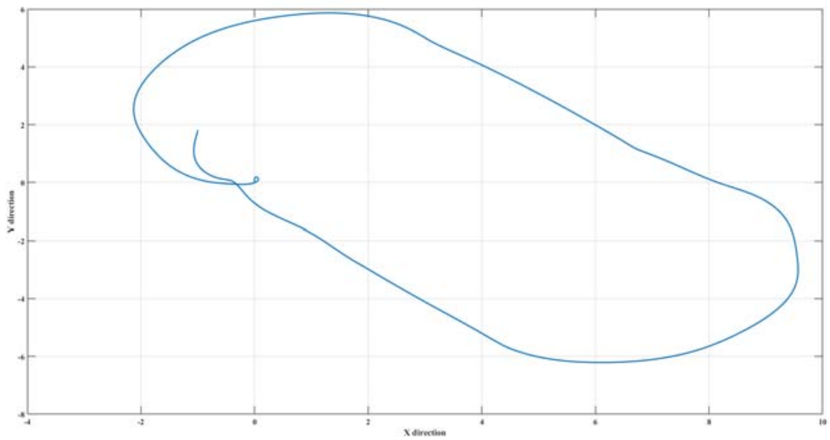

Figure 4.13: Oval turn simulation result

To connect these two segments the switching stage is utilized. To complete the oval the vehicle glide up in the same manner, performing wings-level flight connected to a half circle.

This maneuver is suitable for ascend and descend where depth limitation and narrow passages are the main challenges. Depend on the desired geometry of oval turn different values of roll angles in each arc segment can be utilized to construct a shape between oval and rectangle.

To simulate the oval turn, the control signal is similar to circle with the addition of straight line between the circular motions. Figure 4.13 illustrates the oval turn in simulation. The result shows good agreement with expected pattern. Table 4.3 illustrates the flight concatenation sequence for oval turn.

Table 4.3
Oval turn flight sequence

sign ϕ	value ϕ	sign θ	Glide	Turn direction
	0	-	down	N/A
-	ϕ_1	-	down	N/A
	0	+	up	N/A
+	ϕ_1	+	up	right

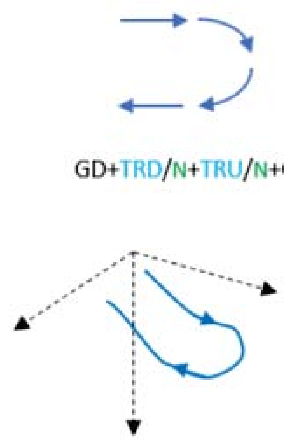

Figure 4.14: 180° Turn or U-Turn flight sequence and expected pattern, Top and 3D view.

4.2.3 180 ° Turn/ U-Turn

To change the heading, underwater gliders can use turn motion to change course. By concatenating two partial helices similar to circle maneuver glider is capable of performing U-Turn.

Initiating a CW or CCW turn by activating the roll actuator, the vehicle rolls to right or left and glides downward until the half of the desired heading angle $\psi_d/2$. Using the switching state, then the vehicle connects the second turn in opposite direction

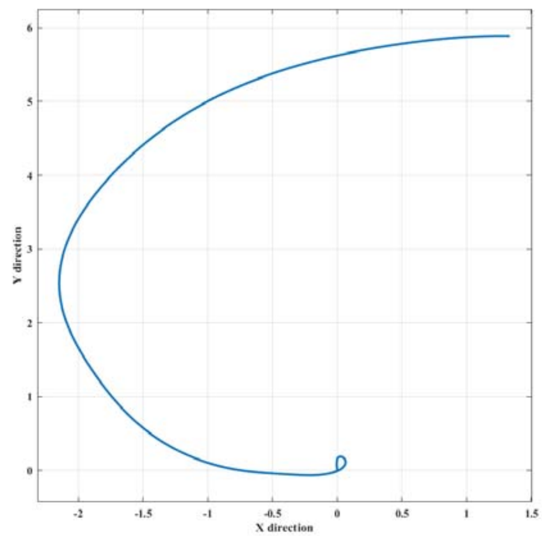

Figure 4.15: U-turn can instantly change the vehicle heading.

Table 4.4
U-turn flight sequence

sign ϕ	value ϕ	sign θ	Glide	Turn direction
+	ϕ_1	-	down	left
-	ϕ_2	+	up	left

by rolling to the opposite side.

This maneuver can be initialized at any stage of the vehicle path regardless of the previous flight. For example in Figure 4.14 the U-turn is connected to wings-level flight before and after changing the heading.

Figure 4.15 illustrates simulated U-Turn maneuver. Although this maneuver is demonstrated for complete U-turn, the heading angle can be set to any desired value other than 180° or complete U-Turn. Table 4.4 depicts the sequence of U-Turn flight.

4.2.4 S-Turn

Maneuvering between obstacles in collision-free path finding manner enables underwater vehicle to be highly desirable for mine countermeasure missions. Planning such paths in an unknown environment requires conducting consequent curved trajectories with varying radius.

S-Turn, one of the more sophisticated advanced manoeuvres investigated in this study can help the vehicle to smoothly glide between obstacles. This maneuver connects circular segments in snake shape trajectory. Each block of S-Turn consists of two circular arcs which can vary in radius.

To construct a S-Turns, the vehicle rolls to one side and initiates a turn. It then descends until it reaches the desirable heading angle. In next stage, the vehicle maintains its roll angle in the same direction and ascend to complete the S-Turn.

If in this stage the vehicle rolls to opposite side in it will construct a circular path as explained previously. Thus throughout this motion the vehicle does not change its roll angle orientation and holds a positive or negative roll at all time. The change of net buoyancy direction flips the orientation of the curvature at each stage.

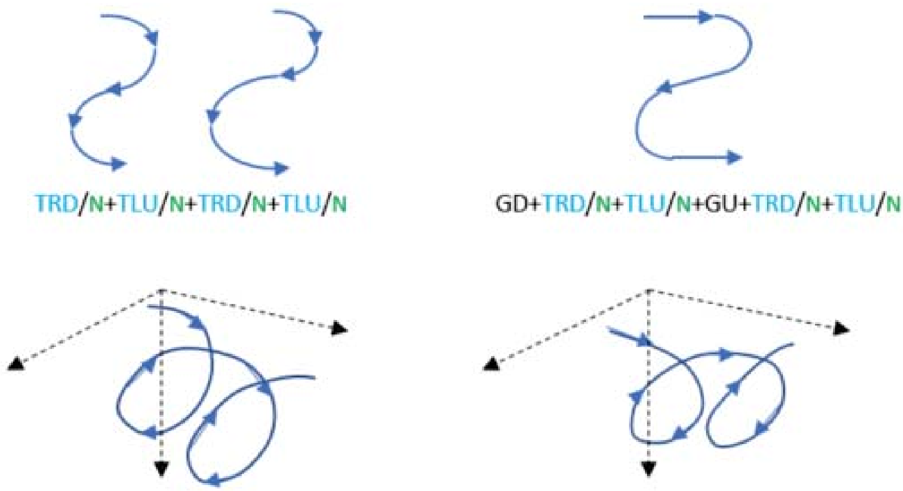

Figure 4.16: S-Turn flight sequence and expected patterns, To and 3D views.

There are three variations of S-Turn maneuver: symmetric S-Turn, asymmetric S-Turn, and delayed S-Turn.

Figure 4.16 depicts these variations. The concave and convex segments are connected through switching state for smooth transition.

Maintaining the magnitude of the roll angle thus fixed turn radius constructs "symmetric" S-Turn. If the vehicle changes the magnitude of the roll angle while maintaining the orientation, then the radius of the curve changes and "asymmetric" S-Turn is achieved. Vehicle finishes this maneuver in the same heading as starting point ensuring the objective of the flight was to avoid the obstacle and returning to the previous path heading after exiting this maneuver.

In simulation the S-Turn was modeled utilizing input signals to manipulate $\tilde{m}$ and

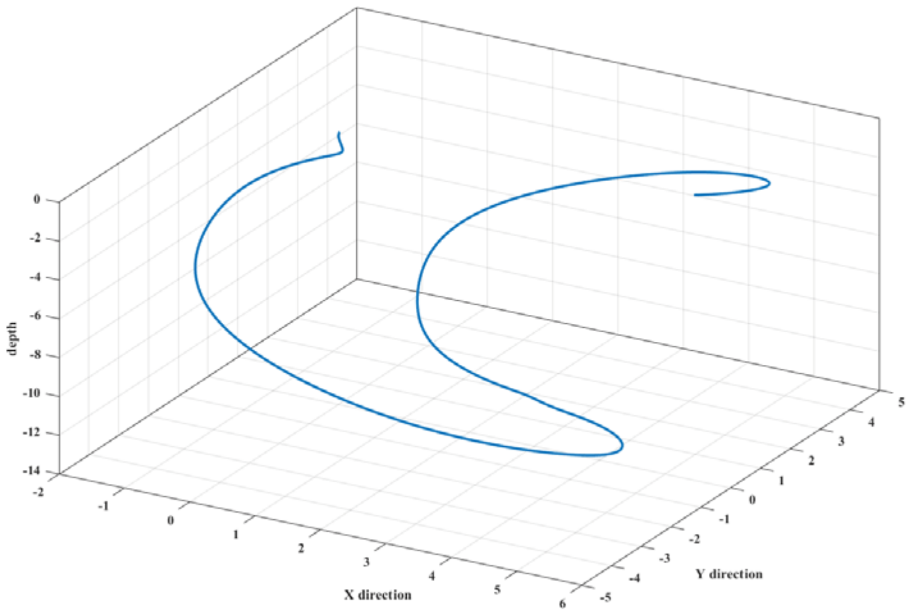

Figure 4.17: S-Turn simulation result, 3D view

γ. In ROUGHIE γ is the angle of the common rail that carries %90 of the vehicle internal mass. Changing this angle results in changing the vehicle center of mass in lateral direction which causes the rolling moment acting on the vehicle body. Figure 4.17 and 4.18 illustrate the simulation results of S-Turn.

Utilizing an obstacle avoidance algorithm and determining the desired turn radius for collision-free path, the controller actuates the roll mechanism to achieve the desired inducing turn motion with desired turn radius in internally actuated underwater gliders such as ROUGHIE. Table 4.5 and 4.6 depicts the flight sequence in symmetric and asymmetric S-Turn respectively.

Delayed S-Turn is similar to symmetric and asymmetric flight with except the first portion of the maneuver is a wings-level flight. This strategy helps the vehicle to

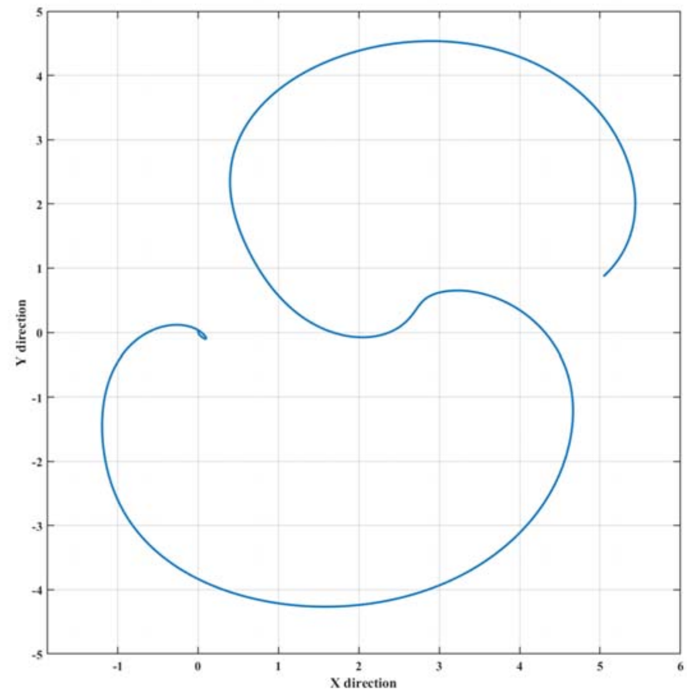

Figure 4.18: S-Turn simulation result, top view

Table 4.5
Symmetric S-Turn flight sequence

sign ϕ	value ϕ	sign θ	Glide	Turn direction
-	ϕ_1	-	down	right
-	ϕ_1	+	up	left
-	ϕ_1	-	down	right
-	ϕ_1	+	up	left

Table 4.6
Asymmetric S-Turn flight sequence

sign ϕ	value ϕ	sign θ	Glide	Turn direction
-	ϕ_1	-	down	right
-	ϕ_2	+	up	left
-	ϕ_1	-	down	right
-	ϕ_2	+	up	left

reach steady state pitch angle before entering the curved segment. A possible use of this maneuver is to create lawn mower type patterns where straight segments are required in order to sweep the mission area.

4.2.5 Figure-8

In some missions vehicle might be required to re-visit previous location such as a previously investigated object. A Figure-8 shape trajectory can be used to maneuver the vehicle around and about an object in a circular trajectory manner. Two opposite direction S-Turn maneuvers were combined as depicted in Figure 4.19 to generate Figure-8 flight. In this maneuver the vehicle S-Turns back to the starting point after exiting from the first S-Turn.

To establish this maneuver the vehicle starts an S-Turn flight in the desired direction. At the end of the second curve and to loop back to the starting point, the vehicle rolls to opposite direction similar to circle maneuver. Then second set of S-Turn flight is performed to reach to home position.

To simulate the Figure-8 two control inputs were used. Roll angle signal, 20 to -20, and net buoyancy $\tilde{m}$ to construct 4 glide cycles. It was observed simulating Figure-8 is more accurate since the heading angle ψ at each time is computed based on the vehicle model. Figure 4.20 shows the simulated Figure-8 maneuver.

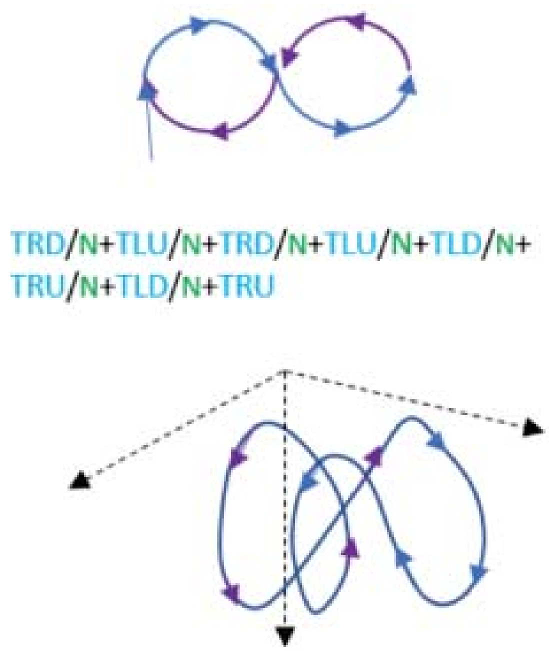

Figure 4.19: Figure-8 flight sequence and expected pattern, Top and 3D views

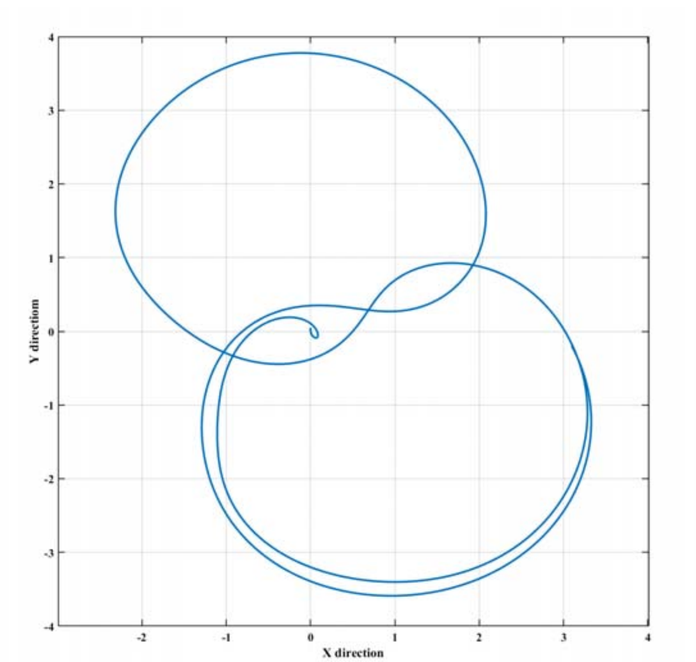

Figure 4.20: Figure*8 Simulation result, two interlocking circles shown in top view

Table 4.7
Figure-8 flight sequence

sign ϕ	value ϕ	sign θ	Glide	Turn direction
-	ϕ_1	-	down	right
-	ϕ_1	+	up	left
-	ϕ_1	-	down	right
-	ϕ_1	+	up	left
+	ϕ_1	-	down	left
+	ϕ_1	+	up	right
+	ϕ_1	-	down	left
+	ϕ_1	+	up	right

Table 4.7 presents the flight sequence for Figure-8 maneuver. Note that the challenge is to find a sequence that results in two intertwined circles at the end of the maneuver. If asymmetric S-Turn was chosen then the flight back requires an asymmetric S-Turn in reverse sequence to match the radius of the curves.

These flight patterns provides opportunities for optimal trajectory planning for underwater vehicles utilizing underwater glider systems. Advanced flights can assists increasing smoothness of planar motion and gradient of diving in studying optimal trajectory [55]. Utilizing concatenated flight patterns path re-planning adapting to the dynamic environments helps increasing the autonomy of these vehicles [56].

Chapter 5

Experimental Validation and Conclusion

The design of the ROUGHIE allows the internal manipulation of the vehicle center of mass thus enabling the ROUGHIE to perform the advanced maneuvers. To observe the possibility of these maneuvers different control input signals were applied to the vehicle model and the response were recorded to examine the advanced maneuvers patterns based on simulation. A series of experiments were also conducted to validate the maneuvers patterns and the vehicle capability to perform such flights. The ROUGHIE has been deployed on over 300 hours of basic systems characterization tests out of which 160 hours were dedicated to roll characterization, turning motion control, and validating advanced maneuvers [53, 57].

The characterization tests were performed in an indoor swimming pool located in Michigan Technological university' Student Development Complex. This tank is 15.84m long, 11.88m wide, and 4.27m deep at its deepest point. The small test area imposes additional constraints on the ROUGHIE motion as it is required to perform very tight maneuvers at shallow depth. These constraints increase the level of difficulty and introduce new challenges that mirror those that currently impede underwater glider use in littoral underwater zones.

The dimension of the swimming pool restricted the turn radius and gliding depth. The ROUGHIE displayed the capability of preforming small radius turns down to approximately 3 m in the limited depth of 4 m. This tight turn assisted tuning the vehicle control parameter to execute advanced maneuvers in enclosed shallow waters of dive tank. S-Turn and Figure-8 maneuvers consumed most of the test hours due to their complicated nature in a GPS denied environment.

A series of Open water deployments also were conducted in the Portage Canal, Upper Peninsula, Michigan. Achieving reliable glides in shallow water was the main objective during vehicle characterization in open water testing. Experimental data sets presented here are obtained while tuning the controller parameters to achieve reliable glide cycle in shallow water as well as validation of existence of advanced maneuvers for internally actuated underwater vehicles.

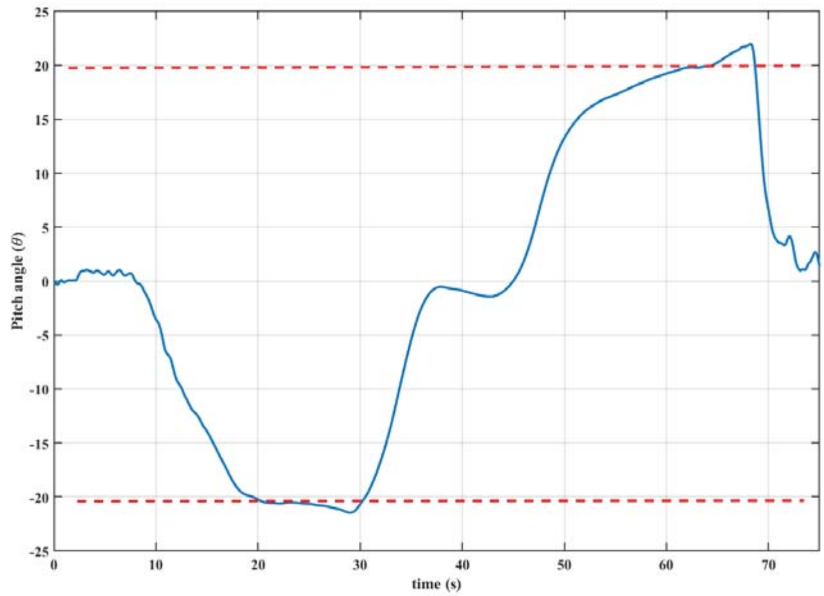

Figure 5.1: The controller drives the vehicle to $\phi = \pm 20^o$ in up/down glide in one glide cycle. The transition at the bottom of the glide is delayed by a station keeping behaviour to provide the initial condition for the pull up where the vehicle reaches equilibrium point at pitch angle equal to zero starting at approximately $t = 38s$.

5.1 Basic Flights

The experiments were designed to evaluate the performance of the vehicle in performing wings-level flight in shallow water. The challenge was to achieve a symmetric glide cycle with approximately similar glide angle in both direction.

5.1.1 Switching Controller

Since the depth is limited the glider does not have necessary dept or time to reach to the desirable pitch angle on the way back to the surface. A technique was required to slow down the vehicle in descent and drive it to ascent.

To solve this issue, the switching controller was utilized to drive the vehicle to a neutrally buoyant state which was achieved by driving the actuators to a pre-defined position using the closed loop feedforward controller. The smooth transition in inflection between the down glide and up glide illustrated in Figure 5.1 generating a symmetric glide cycle. When the vehicle pulls up, the controller switches back to feedback-feedforward mode, assisting the vehicle to reach to the steady state. As expected, the hybrid controller rapidly approaches the desired glide angle and is computationally affordable for shallow water missions. The ROUGHIE uses a bang-bang based depth controller which maintains the distance of the vehicle from the water surface and the bottom of the dive tank.

To examine the robustness of the presented feedforward-feedback controller a series of indoor pool tests have been conducted in the prototyping stage. Figure 5.2 depicts vehicle resulted glide paths with three control approaches, pure feedforward (open loop) to examine vehicle behaviour in absence of feedback, pure PID (closed

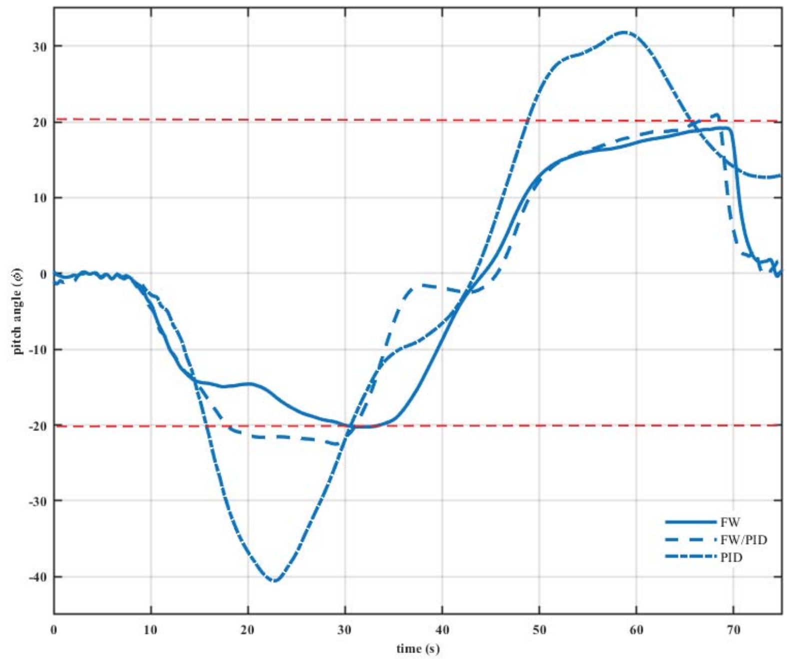

Figure 5.2: Experimental control validation of the ROUGHIE Feed-Forward Feedback controller. Desired glide = +/-20°.

loop feedback) to observe system overshoot, and hybrid controller composed of both feedforward and feedback.

With the results obtained from the open loop feedforward controller we can tune the hybrid controller parameters. The feedforward element of hybrid controller decreases the settling time and eliminate the overshoot providing a more robust controller.

In an effort to evaluate the functionality of the vehicle while carrying scientific payloads, an open water test was conducted in the Portage Canal of Lake Superior in Houghton, Michigan. A Wetlabs ECO Puck fluorometer as illustrated in Figure 2.4 was attached to the exterior of the vehicle, connected to the rear watertight bulkhead

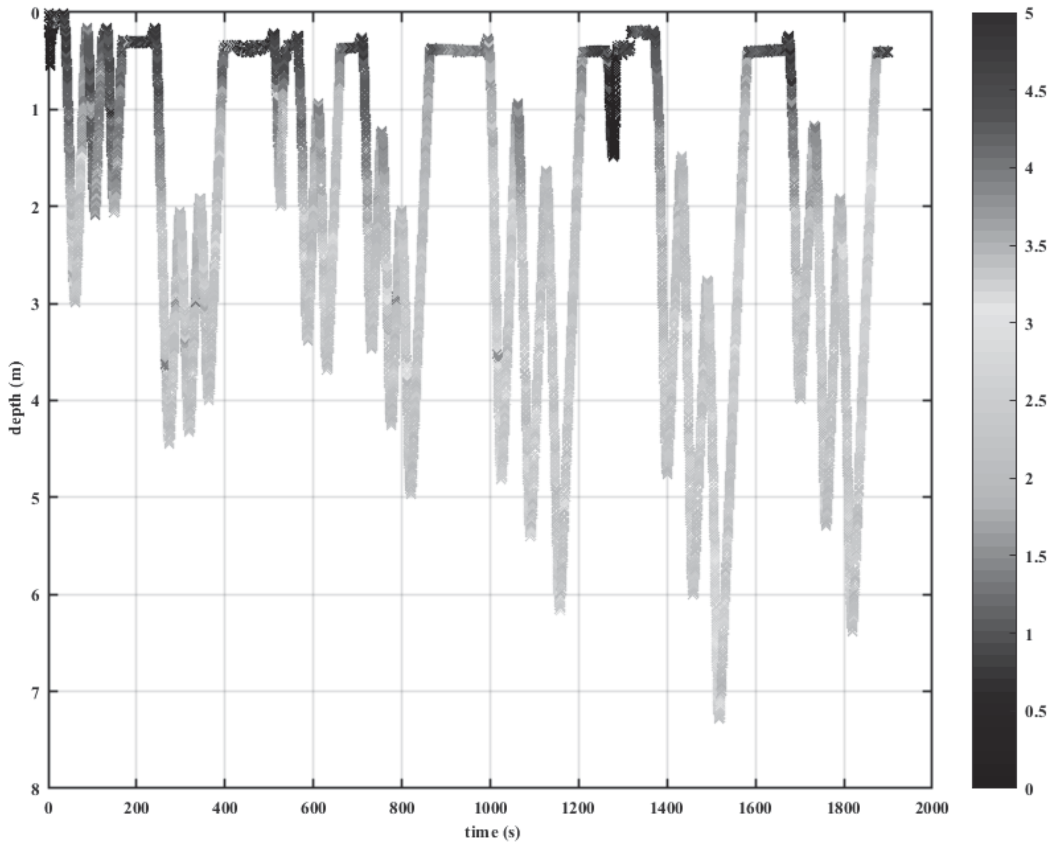

Figure 5.3: Scientific payload validation of the ROUGHIE: ECO Puck deployment in Portage Canal. The ECO Puck measures chlorophyll-a concentration in water. The results collected reflect the expected concentrations for the test location.

with a SEACON connector for power supply and transmit data. Data collected during ECO Puck deployment is shown in Figure 5.3. During this mission the ROUGHIE sampled the water over 30 minutes by completing clusters of three dives, increasing to depths up to 7 m.

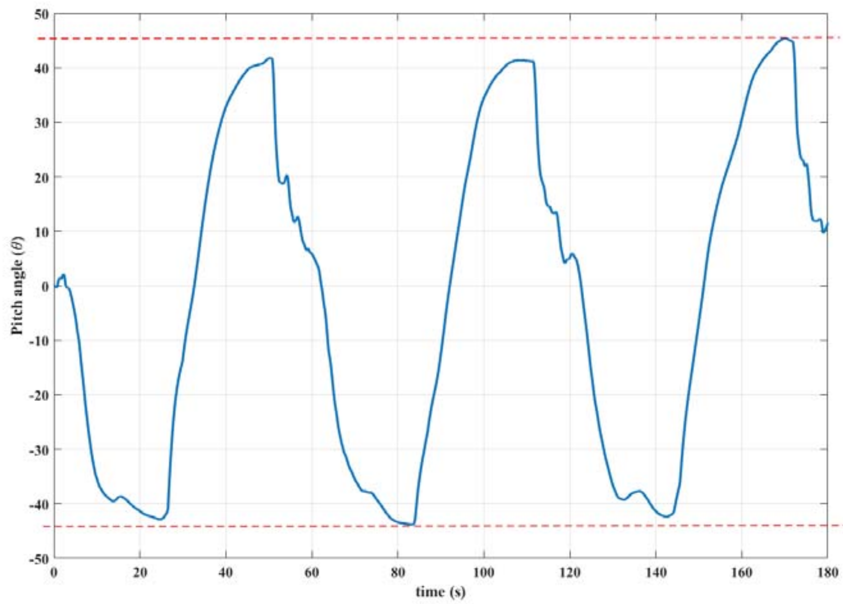

Figure 5.4: Maximum trajectory angle in vertical plane.

5.1.2 Pitch, Roll and Heading Controller

To characterize ROUGHIE's flight maximum attainable pitch angle test was performed. In this test, the linear mass module was sent to the maximum allowable distance (maximum value in feedforward controller) from vehicle CG, thus creating maximum pitching moment. The results, in upgraded configuration, shows that ROUGHIE is capable of reaching trajectory angle of 45° illustrated in Figure 5.4.

To characterize roll behavior and controller response, a series of roll testing was conducted at the dive tank. The ROUGHIE was configured at neutrally buoyant state and lowered to a depth greater than the wing span underwater. Then, roll controller

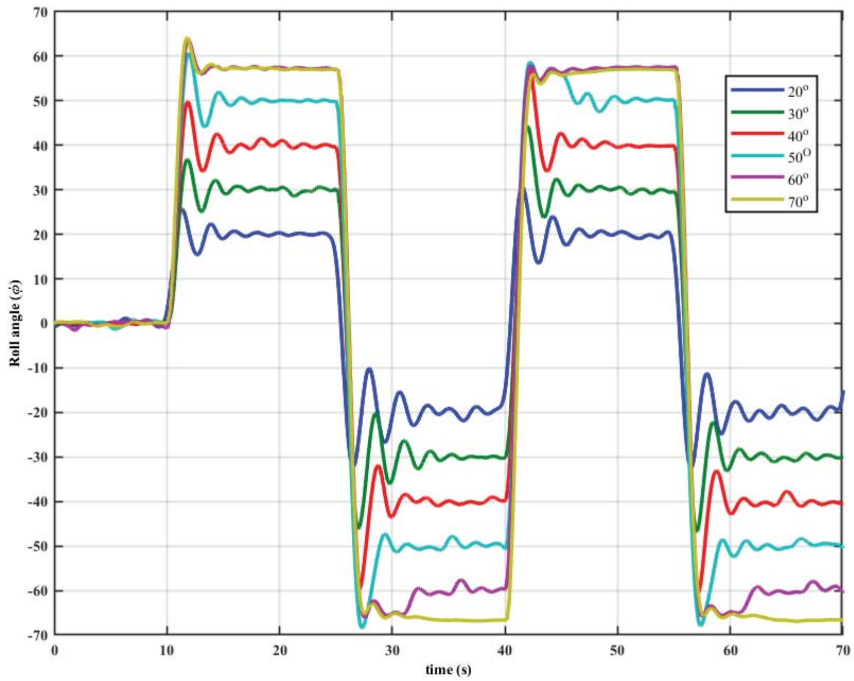

Figure 5.5: ROUGHIE roll response (ϕ) to commanded servo roll angle (γ), pure feedforward (Case 1) control. The dynamic response in vehicle roll angle is recorded using an AHRS sensor. As shown the system rapidly approaches a steady state roll angle that is slightly less than the internal servo angle due to the trimming method used.

fed the rotary module different roll angles from 0-70 ° clockwise and counter clockwise in sequence of 10 °.

The results of pure feedforward roll control (Case 1) for multiple roll angles, illustrated in Figure 5.5, show that the ROUGHIE is able to effectively achieve various roll angles using the internal servo-based roll mechanism, and can achieve a roll in excess of 60 degrees. Note that in some cases the roll response shown in Figure 5.5 is not symmetric about 0 degrees, which is an artifact of the trimming weights added to the ROUGHIE instead of the scientific payload. While these weights were manually

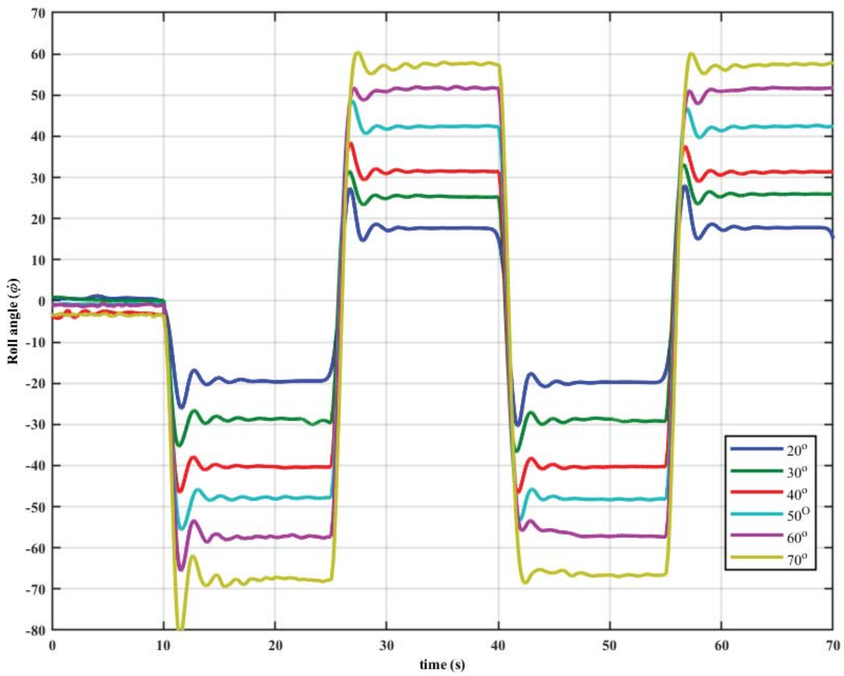

Figure 5.6: ROUGHIE roll response using to commanded ϕ using the feedforward-feedback (Case 2) control. The controller is capable of maintaining accurate roll angles through natural disturbances.

arranged as symmetrically as possible, there is some inherent error in their placement.

As an additional characterization of the roll system, we completed the same experiment with the hybrid feedforward-feedback roll controller (Case 2). Figure 5.6 shows the resulting vehicle roll angles. The addition of feedback control to the roll controller compensates for the presence of asymmetric trim weight. Comparing Figure 5.5 and Figure 5.6, the hybrid controller is able to achieve the target vehicle roll (ϕ) well within error limits up to approximately 50°.

After upgrading the ROUGHIE, the module was restricted to +/- 60° for safety reasons and prevention of system jam and failure. Roll tests were performed again

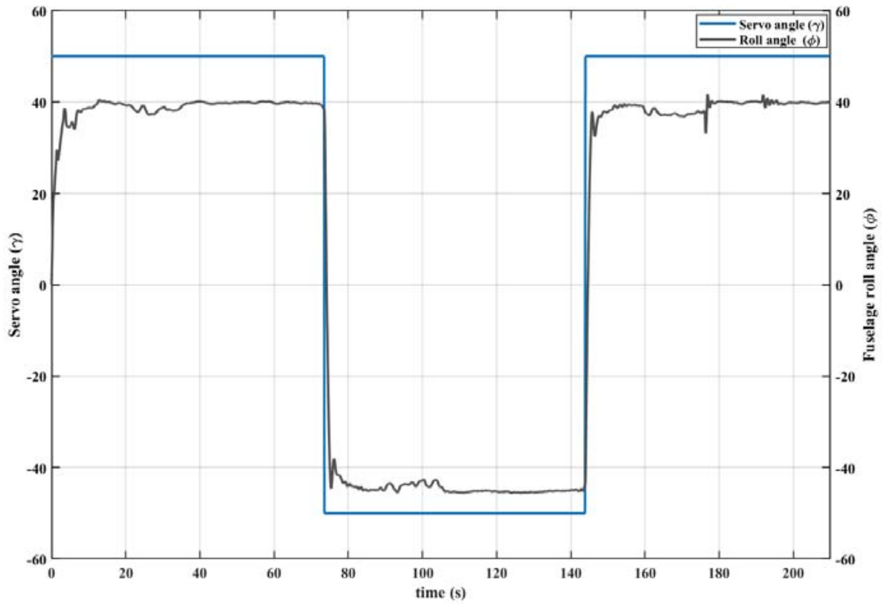

Figure 5.7: Comparison of internal roll γ and fuselage roll ϕ.

to study the changes on roll response. Figure 5.7 illustrates the roll difference. This difference is more obvious in larger roll angle. One interpretation could refer to physical roll limits of the vehicle due to internal configuration.

Heading control in confined area of swimming pool was not very promising due to denied GPS situation. Figure 5.8 illustrates vehicle position in x-y plane with respect to the inertia frame. Even though the feedback controller calculated the heading based on the sensory data received from IMU, the drift from the desired path specially on the wings-level flight was more than %10. Work on tuning the heading controller continues as open water season starts.

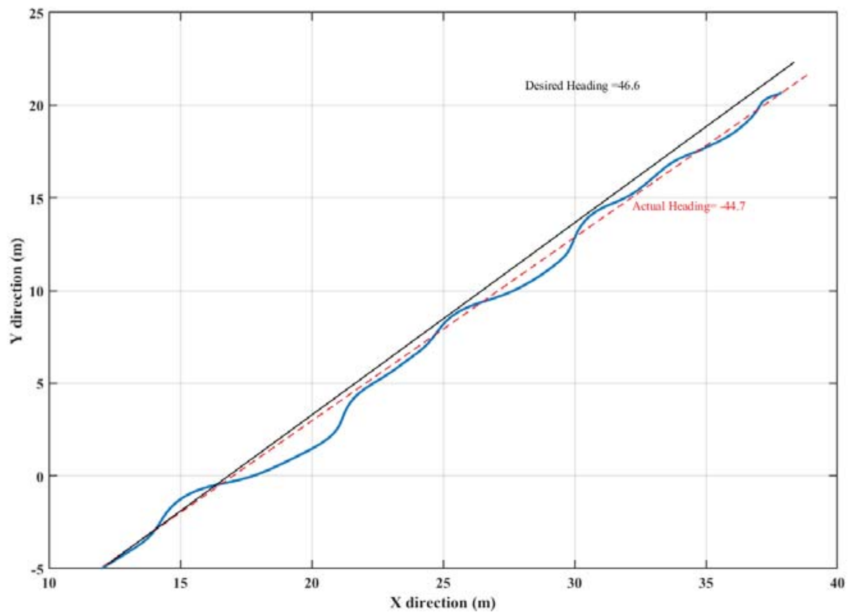

Figure 5.8: ROUGHIE heading remains along the desired path despite controller behaviour. The error can be compensated with actual GPS data.

5.2 Advanced Flights

To evaluate and verify the feasibility of the proposed advanced flights, a series of water tests have been conducted at the Michigan Technological University dive tank using our in-house underwater glider. The tests were conducted extensively to ensure that each flight pattern is repeatable following the characterization tables presented in Chapter 4. The experimental validation of five advanced maneuvers resulting from concatenation of wings-level and helical flights are presented following the two distinct families of flights that they belong to: 1) continues curvature heading consists of Circle, Oval-turn, and U-Turn maneuvers and 2) switching curvature heading comprise

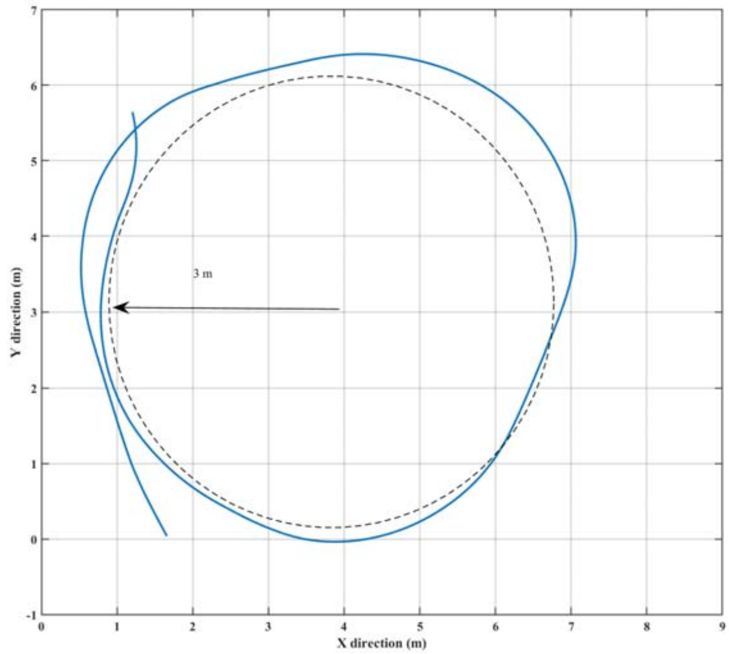

Figure 5.9: Top view of Experimental result of Circle Maneuver. The ROUGHIE achieves approximately 3 m radius circle in shallow depth of 4 m.

of S-Turn and Figure-8 maneuvers.

5.2.1 Circle, Oval Turn, and U-Turn Maneuvers

Circle, oval turn, and U-Turn are categorized in one group as family of concatenated turn that follow continuous curvature paths. The experimental result illustrated in Figure 5.9, shows the circle trajectory with approximately 3 m radius corresponding to a roll angle of 30°.

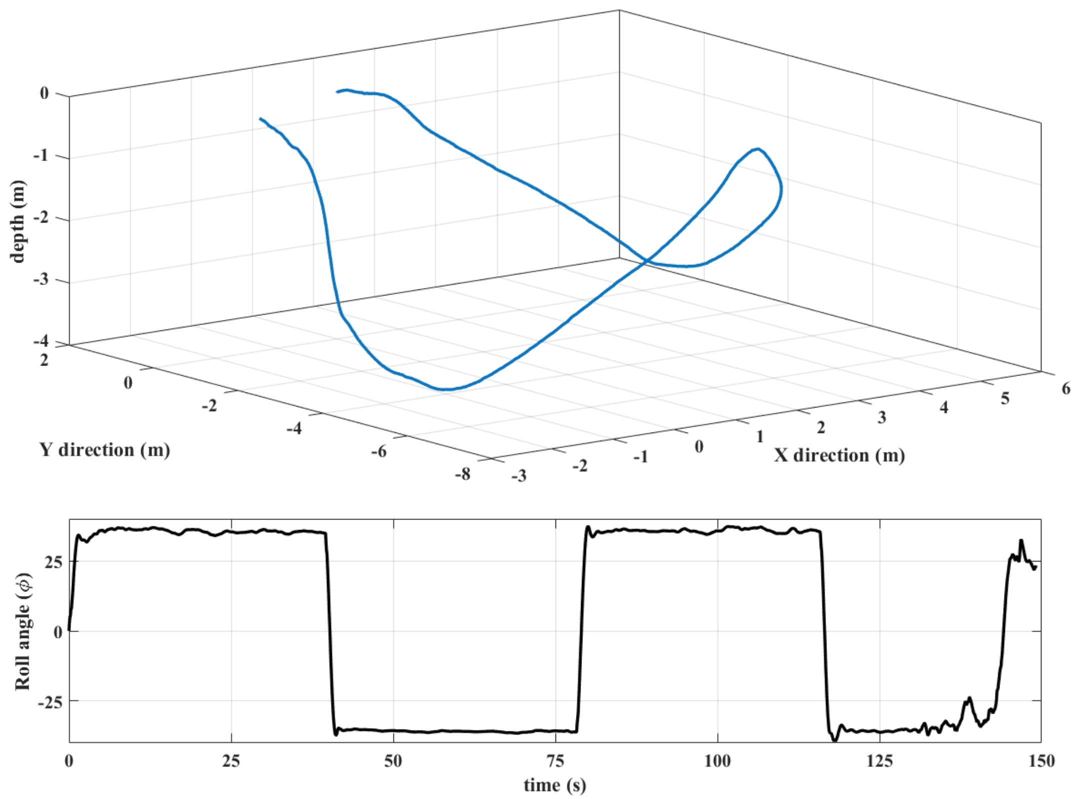

Figure 5.10: 3D view of a circular path with approximately 3 meter radius. he ROUGHIE completes a turn around a point maneuver by performing three concatenated motions (spiral down, neutrally buoyant, spiral up). The full circle is achieved in two glide cycles.

Figure 5.10 illustrates 3D view of circle maneuver. In this instance, vehicle performs a circle in two complete glide cycle while banked 30°, achieving a tight turn. To the best of our knowledge, the ROUGHIE is capable of performing the lowest reported turn radius among internally actuated underwater gliders by one order of magnitude. The ROUGHIE also showed good roll control in all tests that required a change in roll angle, the consistency of the achieved roll angle makes the ROUGHIE reliable to perform turning motion.

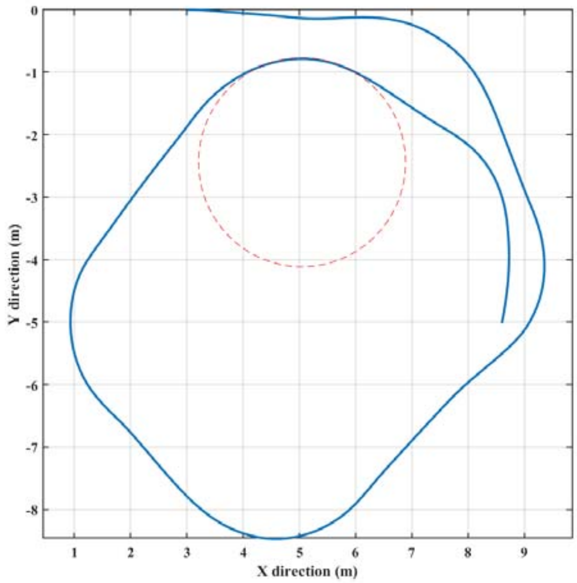

Figure 5.11: Experimental result for oval Turn with turn radius of 3m.

It is important to note that for every vehicle depending on the wing shape and location of the wing, the optimal roll angle to perform tightest radius may vary. For ROUGHIE to achieve the tightest circle the internal roll angle is set to $\gamma = 55$ which results in fuselage roll $\phi = 30$. In ROUGHIE larger roll angle results in side slip thus the vehicle does not generate larger horizontal component of lift force to decrease the turn radius. This maximum roll angle which in turn results in the lowest radius is a characterization factor and can be utilized in vehicle motion planning. These characters associate with the capabilities of the vehicle in performing circular maneuver or in general any maneuver that consists of a turn.

The rectangular or oval turn is similar to circle with the addition of straight flights between two half circles. Figure 5.11 illustrates the oval turn in experiment. U-Turn observed to be easy to achieve in experiments since the configuration of the flight had

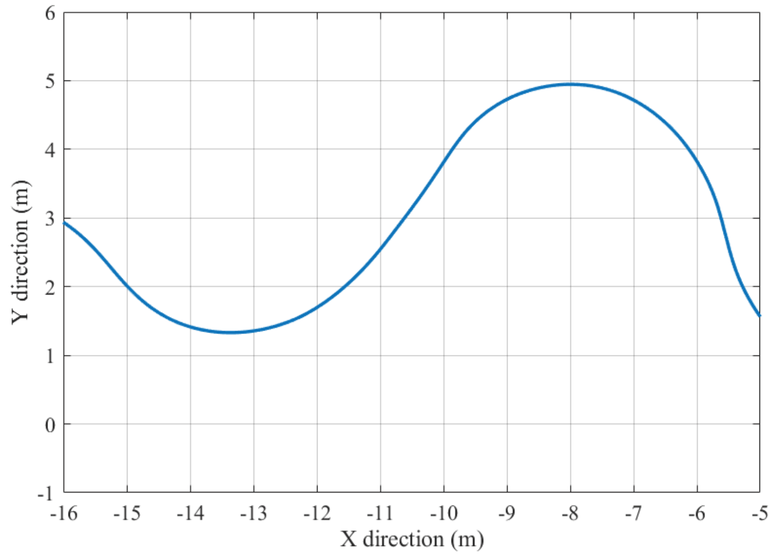

Figure 5.12: Experimental S-Turn

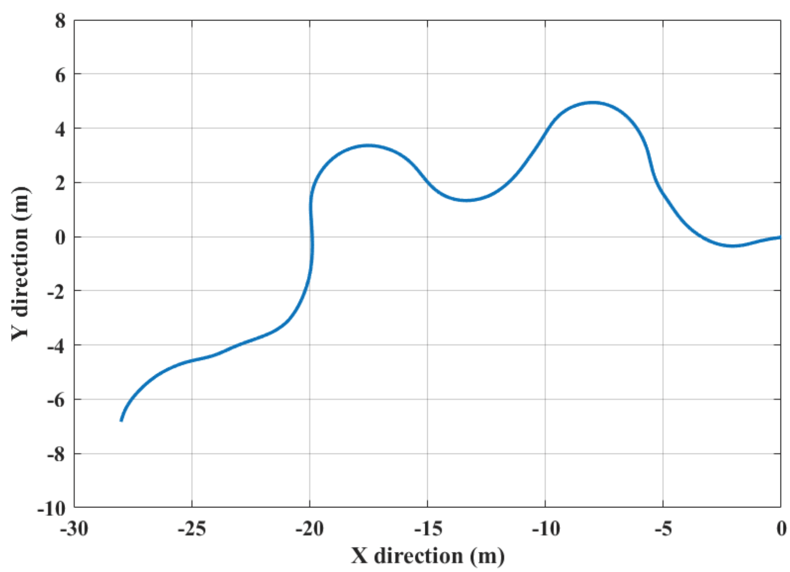

Figure 5.13: Multiple S-Turn

been practiced during circle and oval maneuver. The heading angle in U-turn may vary from 180° to any other desired angle to perform a turn around maneuver.

5.2.2 S-Turn Maneuver

Various experiments showed that turn radius is the dominant factor in performing S-Turn. The optimal roll angle to perform the S-Turn for ROUGHIE was recorded between $\phi = 20°$ to$\phi = 35°$ of fuselage roll angle. This optimality is related to the drag to lift ration of the wing and position of the wing on the vehicle. Figure 5.12 depicts the experimental result of continues S-Turn in the swimming pool. The snake shape of the S-Turn maneuver for multiple repetition is illustrated in Figure 5.13.

The symmetric S-Turn maneuver is illustrated in Figure 5.14, where the glider traverses across the dive tank. In this flight, the ROUGHIE initiated a left turn with a clockwise roll angle. The roll angle was set to 20°. The vehicle maintains a consistent turn radius in each segment, performing two consecutive S-Turns. The dashed circles illustrates the curvature of the flight.

In asymmetric S-Turns, the roll angle of the vehicle changes based on desired turn radius in each segment. For example in Figure 5.15 the roll angle varied between 20° and 30° resulting in two different turn radius. Thus, the curvature differs in each segment. During extensive pool testing, we observed the first segment of the S-Turn is less likely to agree with the desired turn radius. We relate this to vehicle's low momentum at the start of the flight.

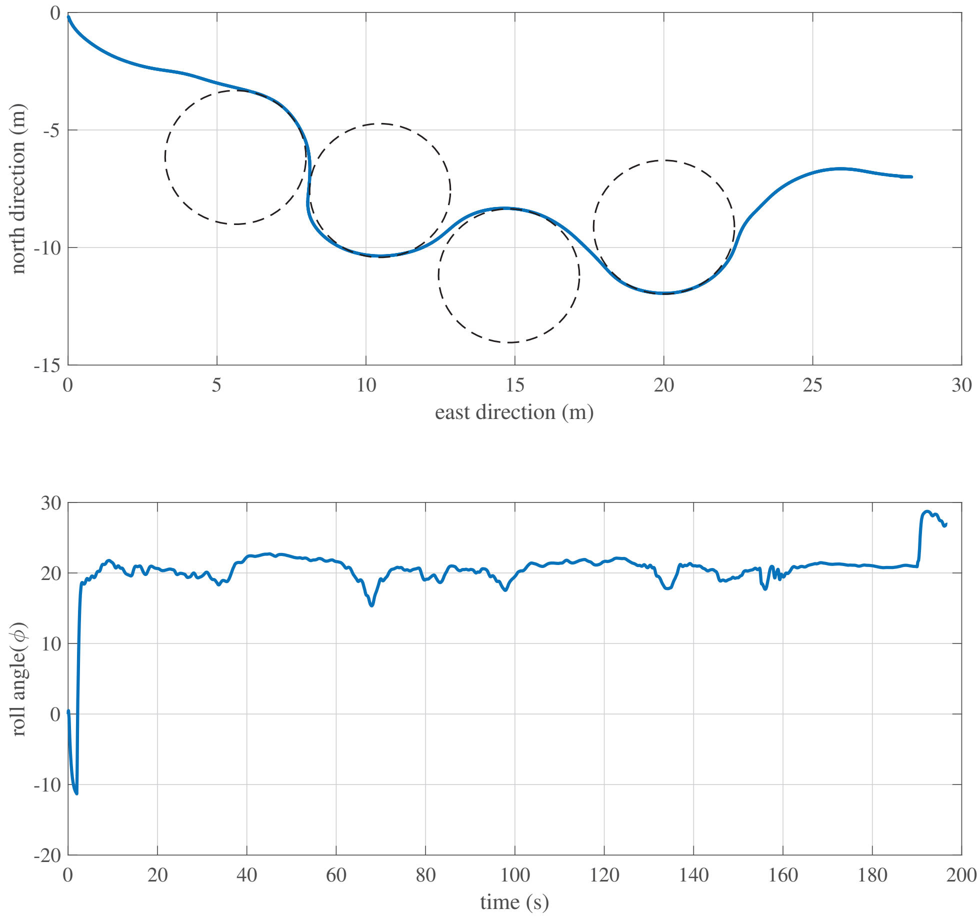

Figure 5.14: Symmetric S-turn maneuver with a 20° roll angle.

Visiting a point in 3D space with specific entrance/exit angle is a challenging task that can be computationally and operationally expensive for underwater gliders to perform. Using the S-Turn ability, the glider is able to perform an optimal trajectory completing a mission more efficiently.

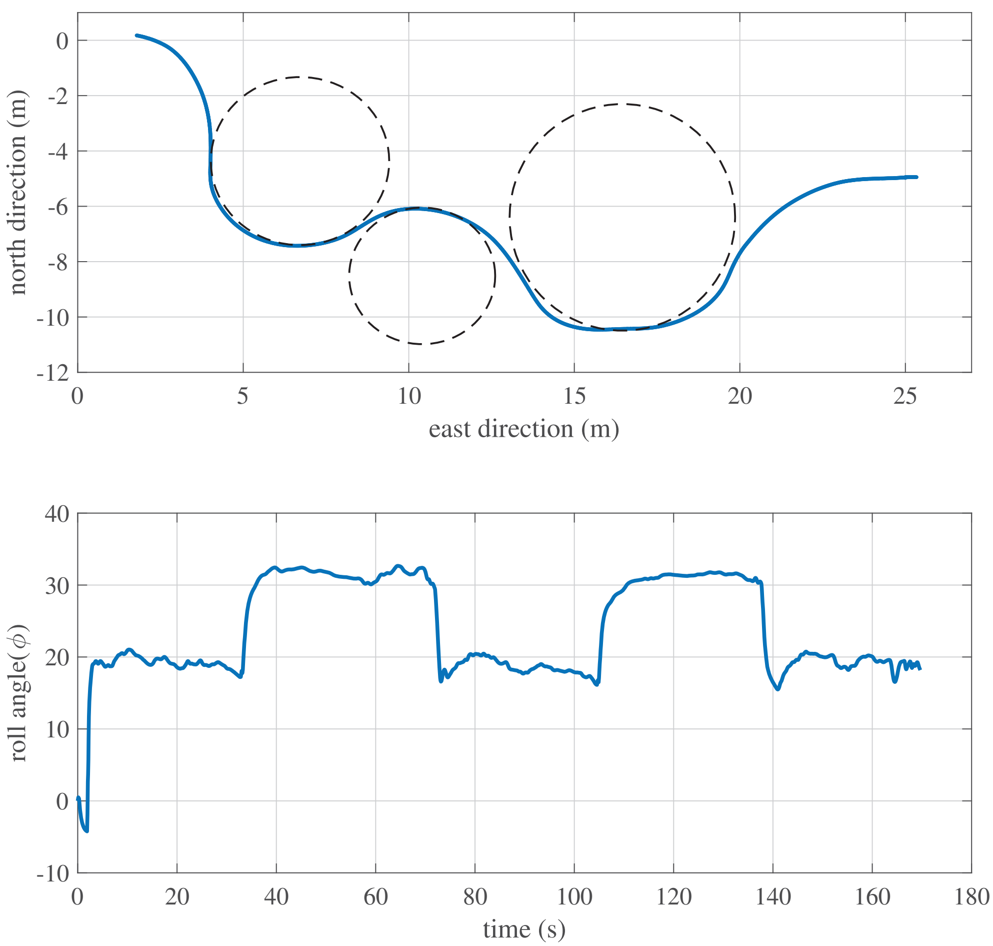

Figure 5.15: Asymmetric S-Turn

5.2.3 Figure-8 Maneuver

Figure-8 was the most challenging advanced maneuver to achieve in the swimming pool. The main reason was inaccessibility to GPS data indoors to assist the controller to achieve the desired pattern and to end the maneuver in the home position.

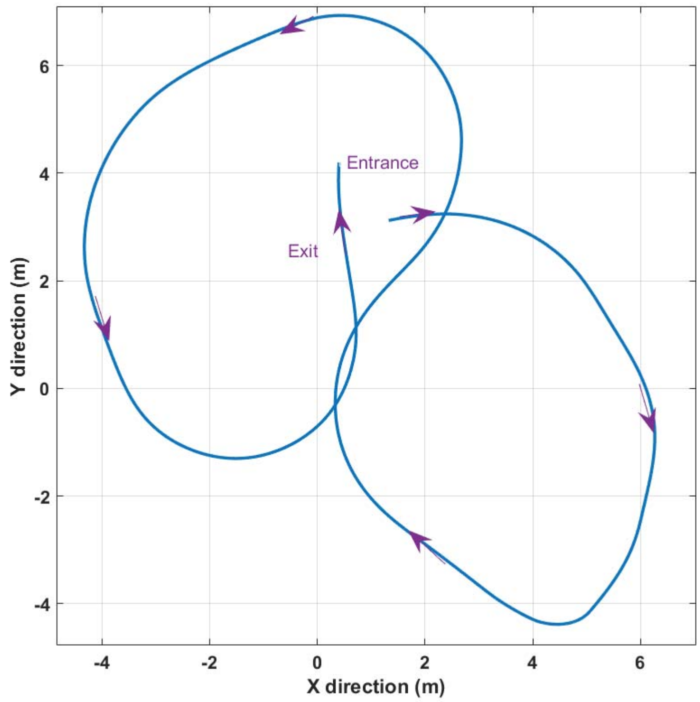

Figure 5.16: Experimental Figure-8

The objective in the experiment was to perform a pattern that resembles two interlocked circles. Since Figure-8 is composed of two S-Turn maneuvers the objective became to successfully close the trajectory and drive the vehicle as close as possible to the home position. To achieve this, two strategies were used simultaneously: first, the optimal turn radius of the ROUGHIE was utilized to assure the smallest turn radius is used thus the S-Turns produces small curves that can be closed with the lowest number of glide cycles. Second, glide cycle counting method was used to ensure that the vehicle completes an S-Turn with N glide cycles in both directions. The switching point between the two S-Turns occurs at surfacing point (right after gliding up) and the ROUGHIE turns around with the smallest turn radius.

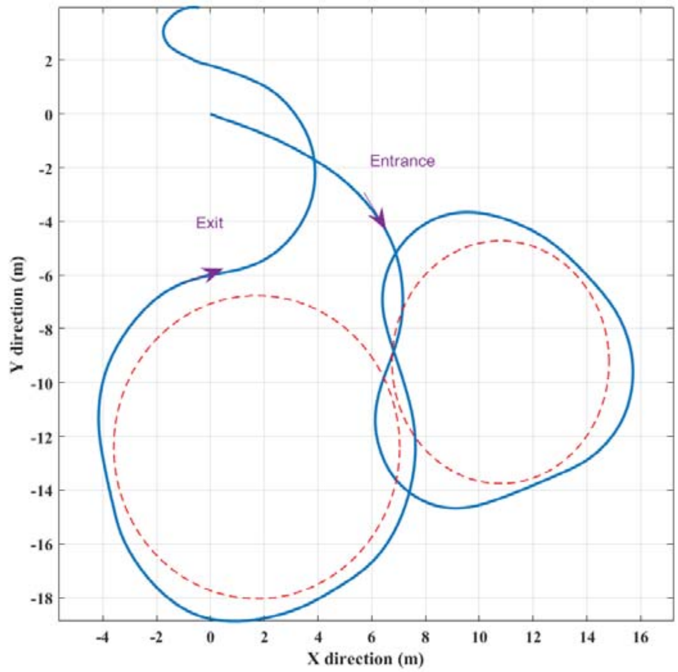

Figure 5.17: Vehicle enters in the first loop and exits the second loop while generating two interlocked circles.

Figure 5.16 and Figure 5.17 illustrate two instances of experimental result of the Figure-8. Number of glide cycles were limited to 6 and the optimal roll angle for successful Figure-8 maneuver was recorded at $\phi = 20°$.

5.3 Conclusion and Future Work

Concatenation of the basic steady motion flights enables underwater vehicles to track complex paths. During a mission the time history of the vehicle motion can be parsed in blocks that have similar flight characterization. Utilizing this technique and

substituting complex flight patterns, underwater vehicles are able to use a toolbox for path planning and path finding missions.

Two factors enable the completion of the special maneuvers: 1) a glider that is physically capable of tight helical motion and 2) a controller capable of supporting and controlling the transition stage between glide segments. For the purposes of this research, ROUGHIE, a low-cost underwater glider developed in-house was used, featuring a small minimum turn radius of 3 meters. The tight turn radius is enabled by a unique roll system that rotates the majority of the non-symmetric mass in the glider relative to the hull. To control the transition stages a feedforward-feedback switching controller was used that features a neutrally buoyant state enabling the vehicle to transit between different segments of the flight smoothly in presence of depth limitation.

In this work, five advanced maneuvers were verified. These five maneuvers belong to two distinct families of flights: 1) continues curvature heading consists of Circle, Oval-turn, and U-Turn maneuvers, and 2) switching curvature heading comprise of S-Turn and Figure-8 maneuvers. Circle and oval turn were presented as closed path trajectories for underwater gliders. In these maneuvers, the glider maintains a continues curvature heading through multiple glide cycles. S-Turn on the other hand traverse the glider in an "S" shape trajectory switching the curvature heading in every segment. Figure-8 consists of two S-Turns which resembles two intertwines circles.

In this maneuver the glider connects two S-Turn maneuvers.

Utilizing these five maneuvers in a motion control toolbox provides the opportunity for underwater vehicles to conduct maneuvers where complex path following is required. A motion planning algorithm enables the vehicle to select each advanced flight and incorporates it into the vehicle trajectory in real time during each mission.

Chapter 6

Part2: Utilizing Underwater Gliders for Engineering Education

Exploring undersea world plays an important role in protecting marine life and environment, discovering lakes and oceans, and resolving real-life oceanographic problems. Today, autonomous underwater vehicles (AUVs) are used for water quality monitoring and oceanographic data sampling. Underwater gliders (UGs) are a special type of AUVs that have long endurance and can help scientists and researchers to study lakes and oceans while contributing vastly in mapping ocean floors, underwater inspection, surveillance and underwater search and rescue missions.

Therefore, marine robots can be used in STEM programs to teach engineering design

process and science concepts through hands-on activities with marine engineering themes. There are few educational marine robotics kits available for STEM learning such as SeaPerch [58] a remotely operated vehicle (ROV), SeaGlide [59] an autonomous underwater vehicle, and Lego's waterbotic [60] a surface remotely operated vehicle. However, there are not many educational programs to promote marine robotics nationwide. One reason is that underwater vehicle development is challenging due to the physical design constraints and unforgiving environment, typical of many real-world engineering problems [28, 61]. The more challenging reason is the barrier to entry for beginners with no prior knowledge.

To provide a solution, an inexpensive, modular, easily duplicated marine robotic platform was developed by NASLab team at Michigan Tech. GUPPIE, a Glider for Underwater Problem-solving and Promotion of Interest in Engineering is an affordable platform with accessible components and ready-to-use hands-on curriculum integrated in a robotic educational program known as "Co-robots educational program" that can be used to inspire youth and motivate future workforce.

6.1 Introduction

Engineering is the ability of problem-solving using scientific knowledge through iterative design, optimization of material and technology, and building things or improving

the products. Engineering in K-12 STEM education can improve students performance and understanding of science and mathematics [62]. Mathematical analysis and modeling are essential to engineering design, similarly, scientific investigations are closely related to engineering design process to solve real-life problems [63]. Unfortunately different disciplines of STEM has been taught separately creating a gap between science, engineering, and technology in pre-college STEM curricula [64, 65].

To integrate engineering and technology with everyday classroom subjects, a transdisciplinary approach should be adopted where understanding and skills from two or more disciplines are applied to real-world problems with the aim of shaping the total learning experience [66, 67, 68, 69, 70, 71, 72]. Project-based Learning method is one of the popular transdisciplinary approaches in integrating engineering with STEM concepts. Many groups reported that using this approach they generated meaningful learning, increased effectiveness, and influenced student attitudes towards STEM career [73, 74, 75, 76, 77, 78]. Integrating all disciplines offers students the opportunity to make sense of the world in an authentic way[79].

Robotics combines engineering and technology concepts to enforce science and mathematics to solve real-world problems [65]. It provides an exceptional source of excitement that can be used to motivate students learning and personal development including cognitive, social skills, creative thinking, decision making, problem solving, communication, and team work [64, 80, 80, 81]. This energy can be funneled into

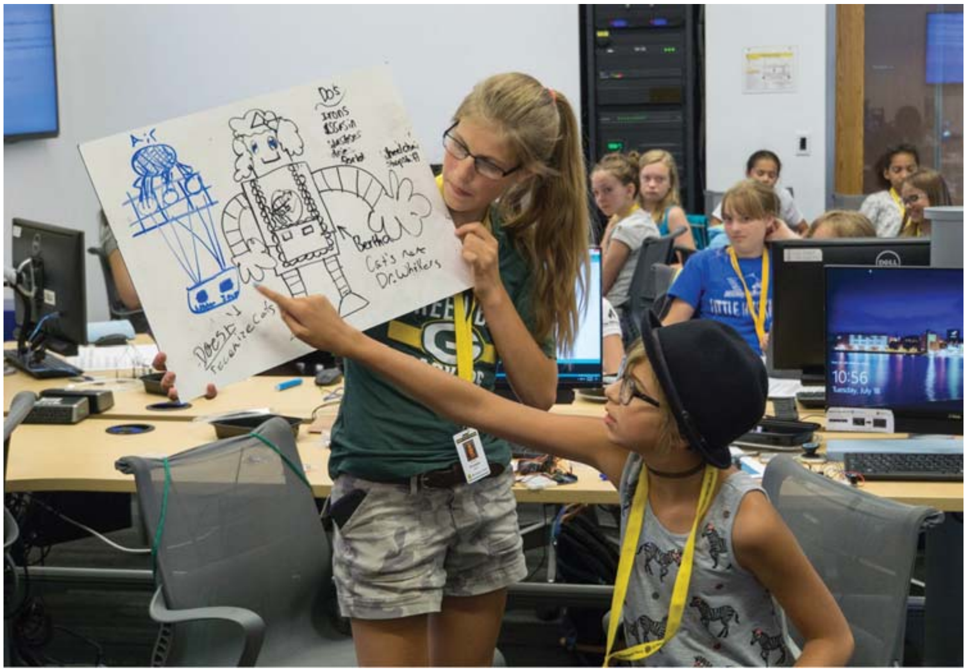

Figure 6.1: Students practice brainstorming and communication skills by discussing on ways robots can be used in daily life.

STEM learning while utilizing robots as educational tools to promote engineering and technology in STEM education [64, 82, 83].

So far, in educational robotic programs, platform-specific robotic curricula has been implemented for pre-college STEM education utilizing Lego Mindstorm robots [84, 85], STORMLab robotic kits [86], Parallex BoeBots [87], Art & Bots [88], and AERobot [89]. More affordable and free learning kits such as Arduino kits [90] and Electronikits [91] have also been employed with the goal of using mechatronics to improve robotics education. The vast majority of these robots are terrestrial or humanoid and they are not introducing the young learners to the wide spectrum of the robotics application in everyday life.

This work promotes the use of robots that help human's life in STEM education. The goal is to engage young students in engineering design process and habits of mind, practice identifying problems, brainstorming to find a possible solution, designing and building the solution, and testing and improving until achieving the satisfactory result. Figure 6.1 shows students brainstorming on ways robots can be useful in daily life.

In addition, this research studies the effect of meaningful context in increasing students awareness in early ages about role of engineering in protecting the environment and improving human life through multidisciplinary hand-on activities, use of collaborative robots or Co-robots was considered [92, 93].

6.2 GUPPIE

GUPPIE [94], a Glider for Underwater Problem-solving and Promotion of Interest in Engineering, was developed with three main traits: 1) it has great potential in engaging students with a wide range of interests [83]; 2) it is a theme-based robotics program that has real-life applications [61]; and 3) it presents autonomy in an underwater environment that introduces new but intriguing challenges.

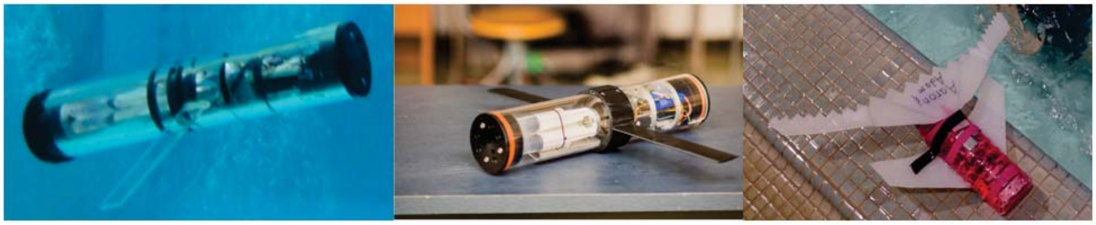

Figure 6.2: GUPPIE Evolution through 2013-2016

GUPPIE the co-explorer helps environmental observations and introduces future career options such as marine and ocean engineering to students. GUPPIE is an adaptable platform that can evolve with the age, needs, and prior knowledge of the students. This robot is made of low-cost and familiar objects such as syringes, plastic tubes, straw, plastic sealing rings, battery, and servo motor. An Arduino Uno is used in this robot to control the robot's motion and is programmed by students before deploying the GUPPIE in water.

For adequate use of GUPPIE for different age groups, the design has undergone an evolution process as depicted in Figure 6.2. The main required upgrade for 2013 model was user friendliness and electronic upgrades.

In 2014, the design of the GUPPIE was altered so that the structural components could be 3D printed. The fuselage encloses the mechanical components in a 22 cm poly-carbonate tube. A rail based mount was designed for ease of installing of the buoyancy drive and other sensors. A touch based remote access was added to the glider for ease of starting/stopping the glide without physically opening the vehicle.

Figure 6.3: Summer Youth Program 2015- scholar student is testing GUPPIE in the swimming pool

The main issue with this design was the trimming weight due to the large volume of the vehicle and replacement of aluminum structural parts with light 3D printed part. In the Summer Youth Program 2014 and 2015 only one GUPPIE was tested in the swimming pool as illustrated in Figure 6.3. This version of GUPPIE is suitable for high school and undergraduate students. A simulation software was developed for this model to be used during the undergraduate course curriculum as a hardware in the loop as illustrated in Figure 6.4 [95].

In 2016, the GUPPIE was redesigned to be more user friendly for middle school students. It was built using familiar components such as water bottle, syringe, and plastic sheets for wing design. The electronics consists of Arduino Nano, PCB, mechanical switch, push button, and continuous servo motor. This design is easy to trim

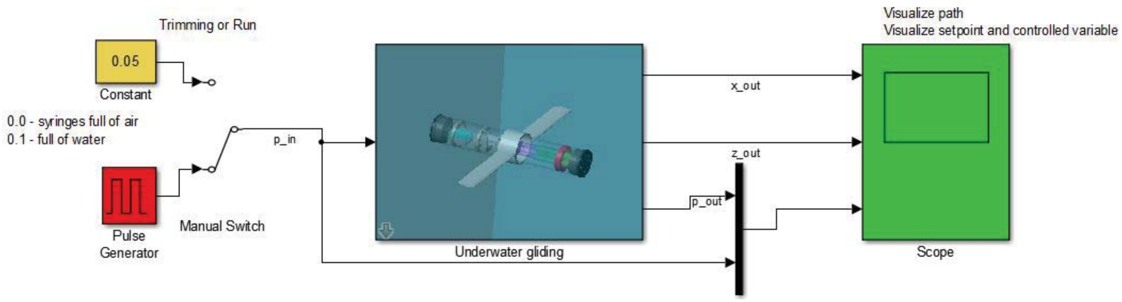

Figure 6.4: GUPPIE in simulation as a hardware in the loop platform

and assemble, although there was water leakage issue due to human error between the bottle and its cap. In the new version a different approach for sealing mechanism was employed to resolve this problem.

In 2017, the GUPPIE design was altered again to accommodate young students lack of experience in mechanical sealing methods and also lowered the cost of one platform to $50 making it affordable for most schools. Figure 6.5 depicts the recent GUPPIE platform.

6.3 Co-robots Educational Program

With collaboration of Nonlinear and Autonomous Systems Laboratory (NASLab) and Human-Interactive Robotics Lab (HIRoLab) at Michigan Technological university an educational program, Co-robots, was developed to integrate engineering process design in STEM education using robots that work with humans (Co-robots) to improve

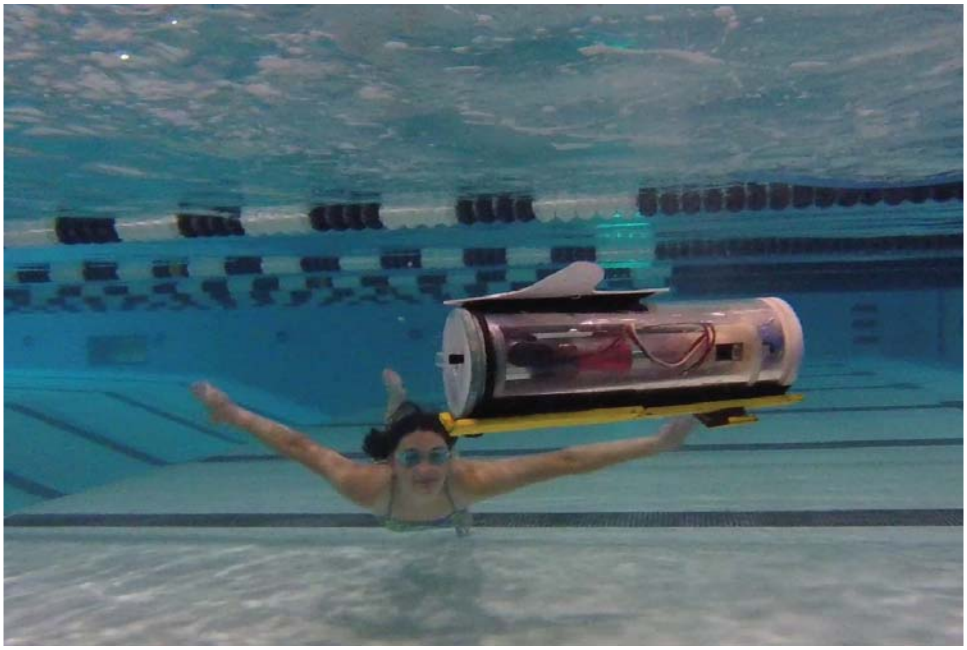

Figure 6.5: GUPPIE is an underwater glider that uses buoyancy to traverse through water.

quality of life.

The name of Co-robots was driven from the national robotic initiative call inviting scholars, agencies, and institutes to accelerate the development and use of robots in the United States that work cooperatively with people. Among the four groups of collaborative robots co-explorer and co-worker matched two of Michigan Tech's in-house outreach robotic platforms, GUPPIE and Neu-pulator. The uniqueness of these robots in STEM education helps awakening the curiosity of students to learn how engineering can result in creating technologies that helps human's life.

Co-robots educational program brings in five stages of engineering design cycle [96]

and Bloom's classification [97] such that students' knowledge, skill, and attitude towards engineering changes experiencing hands-on curricula. It breaks down complex robotic projects in its fundamental concepts, an scaffolding approach, to prevent intimidation towards technology and engineering and encourage students to face new challenges while build up their knowledge step-by-step with smaller tasks [98]. Co-robots is a combination of minds-on with hands-on activities [99], a pathway to learning and retaining concepts where there is no prior knowledge [100].

Co-robots educational program merges project-based, theme-based, and multidisciplinary STEM concepts that promotes engineering design process with creative and intriguing hands-on activities. It is an engineering-rich STEM model that has ready-to-teach materials, teacher professional training and student choice and voice that utilize both classroom and out-of-classroom projects as a solution to currant STEM education challenges [81, 101, 102].

The Co-robots program is divided into five fundamental elements: 1) engineering design, 2) electronics, 3) coding, 4) assembly and production, and 5) test and troubleshooting. These five factors with the addition of Co-robots platforms are the six pillars of the Co-robots model.

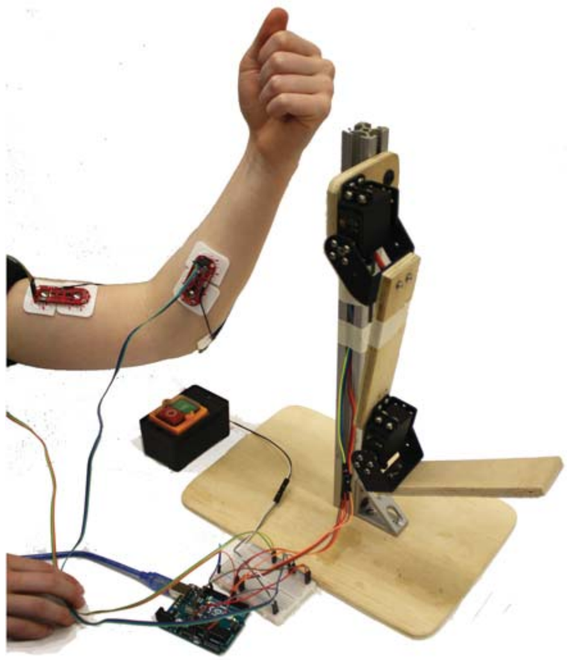

Figure 6.6: Neu-pulator uses Electromyography (EMG) signals to Neurally control a robotic arm to mimic human arm motion.

6.3.1 Robotic Platforms

Co-robot program started with the development of the GUPPIE to promote marine engineering in STEM education. Utilizing theme-based robots that helps humans and work alongside them intrigues use of technology and problem solving skills in young learners. This program has the potential to integrate multiple robots to provide variety to both students and educators.

In addition to GUPPIE the co-explorer, Neu-pulator a co-worker was utilized during

this program. Neu-pulator is a Neurally controlled manipulator that uses Electromyography (EMG) signals from muscle activities to move the robotic arm joints to mimic human's arm motion, illustrated in Figure 6.6.

The mechanical structure of the Neu-pulator resembles the elbow, shoulder, and torso of a human body [103]. This robot is made of wooden parts, brackets, battery, servo motors, and Arduino Nano processor. The Arduino can be programmed to calculate the required angle that each motor should move to, while the Neu-pulator is in motion. In addition, the Arduino program can be modified to make the motors move based on the sensory data, such as the signals received from muscle activation levels that helps it move as the user intended. Neu-pulator design undergone minor changes to increase the unfriendliness of this platform.

Both platforms utilize the basic components of robots such as battery, electronic components, servo motors, and micro processor. Considering the age of the participants (6th-8th grade), they have little to no knowledge about engineering design, electronics, and programming. What this age group has in common is their sense of curiosity and being engineers by nature. They enjoy building, revamping things, and then destroying them. They see this process as a game and fun activity. This "play and learn" method is the basis of hands-on activities in Co-robots model.

6.3.2 Engineering design

Engineers use Computer-aided design (CAD) software to model their design and perform analysis to ensure the device is suitable for the intended use. There are various CAD software suitable for young students such as Autodesk Inventor, Sketchup, Thinker, and 123D CAD. In Co-robots program Autodesk Inventor was utilized due to its user-friendliness and similarity to CAD software used by engineers.

When students became familiar with the software environment, they are instructed to sketch simple 2D shapes such as line, circle, and square to learn the software environment and familiarize themselves with different sketching options. Students use editing features to create 3D objects following step-by-step instructions presented to them by instructors. Figure 6.7 illustrates students using Inventor to model a mock up Neu-pulator. They learn how to change color and material of their objects learning about different substances.

After learning the basics of the design software students can design a real object from their surrounding. Utilizing a calipers they measure dimensions of a simple object such as a watch or ,more engineering related, a servo motor and sketch it in the design software.

The skill is put into practice by modeling a mock-up of a familiar object such as

Figure 6.7: Students practice modeling using engineering design software.

Figure 6.8: Technology is the hardest discipline to integrated in STEM education. Students learn how to use computer coding to program micro-controllers.

the Neu-pulator in Co-robot program depicted in Figure 7.6. In addition to practice modeling skills students observe how modeling can help visualization of the end product and examine the design to ensure it functions as expected. For example in the Neu-polator mock-up CAD design, students are asked to show the motion of the robotic arm by dragging the linkages. Designing proper joints guarantees the proper motion of the Neu-pulator.

6.3.3 Electronics and Coding

In Co-robots model, programming and electronics are closely related to one another. All the programming projects are integrated with electronics as hardware in the loop. In programming, students learn the basics of computational thinking, and programming syntax and logic such as variables, conditionals, loops, machine state, and debugging.

In this model students are encouraged to learn the basics of script or text-based coding through fun projects instead of graphical programming. Interacting with a coding software, dealing with the microprocessor, uploading the code through the software platform, debugging, and integration with the hardware gives students a taste of reality while accomplishing progress at each stage. Figure 6.8 shows students collaboration in debugging a code.

In Co-robots' electronic and programming projects, Arduino platform, a hubby level micro-controller with open source software and various form factors was chosen. We specifically chose Arduino Uno and Nano two examples of simplicity and small form factor to demonstrate how different microprocessors can be utilized in different projects. To connect to Arduino Uno (or any other microprocessor), students simply use Universal Serial Bus (USB) cable and set appropriate board model and port number on the software.

To learn how to program the microprocessor, students open one of the existing codes and run the code. Instructors describe the structure of the code to give students an idea on how algorithms work without going into details. Students manipulate the numbers and change the duration of blinking a built-in LED light on the Arduino board. This discovery sparks interests in students especially if they came to Co-robots program without prior experience in coding.

Scaffolding approach was utilized in building students knowledge in coding ability with various tasks complementing each other towards a more complex project. Each project requires building a circuit using breadboards, wires, and electronic components such as resistors, capacitors, and diodes. Starting from simple components such as LEDs students learn how to read simple schematics.

In coding stage they learn how to turn multiple LEDs on/off with different sequences. In next step adding a switch or button can help them to learn how to integrate human

Figure 6.9: Students practice their motor skill and ability to follow instruction to assemble robots.

interaction with the code during operation. Various projects along with the "fun projects" is designed to be utilized in Co-robots model. Using servo motors, ultrasonic sensors, LCD displays, buzzer, and etc. This real life sensation helps increasing students motivation towards previously perceived complex engineering concepts and improve their learning.

Fun projects are the flexible portion of the program and truly lets students to use their creativity to build devices they see around them and teach them a way of thinking to innovate new gadgets.

6.3.4 Assembly and Production

Previous robotic camp experience reported most students and especially girls showed high interest in “building things” [104]. Observing this trend, Co-robots model is populated with activities that include some type of building whenever possible. Building circuits, soldering, and utilizing tools helps students to use their hands as physical activity versus mental activity in coding and improve their motor skills, illustrated in Figure 6.9.

In Co-robots program students are divided in groups of two to three so that they can practice communication and teamwork. Working together helps them to learn from their peers and change their perspective about hands-on activities. Some students lack the motor skill and perceive it as complicated tasks with higher risk of failure while others are naturals. Some students are afraid of using electronics while others especially female students are not confident to use mechanical tools such as screw drivers.

On the other hand, using tools such as soldering irons or voltmeter which are considered more complex tools increases the confidence of pupils. Female students are excited to be able to use these tools and assemble different components together to shape a robot.

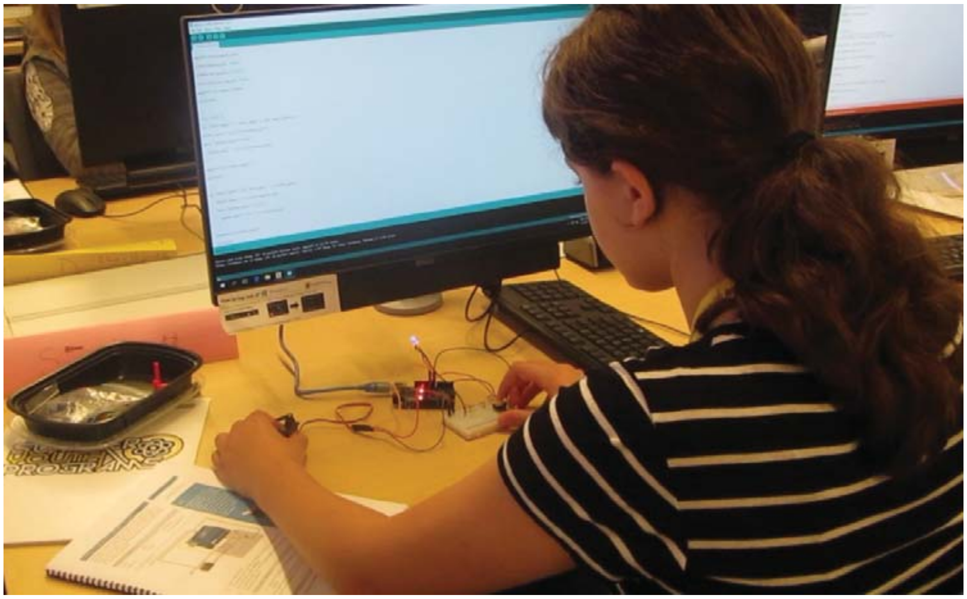

Figure 6.10: Troubleshooting and testing is the last component of engineering design process. Students learn how to find better solution by tracing the design process and identifying the problem.

6.3.5 Test and Troubleshooting

Engineering design process emphasized on re-iteration and optimization. Troubleshooting is the key element in engineering design process. Finding the problem, suggesting a solution, and revamping the design to resolve the issue.

In Co-robots model students constantly practice troubleshooting from building and assembly point of view or coding, depicted in Figure 6.10. They learn how and where to look for "bugs" that caused the problem in electronics or mechanical components as well as the algorithm and coding. As an example for assembly, if a circuit is not working as expected students are instructed to check the wiring if they are based on

the sketch or if there are loose wires. Paying attention to the polarity of components and making sure they built a closed circuit is another example. With regard to coding troubleshooting comes in different methods such as typos, wrong syntax, variable names, or missing functions. Computational thinking and algorithm troubleshooting in coding is the most difficult task for young learners.

Progressing through the Co-robots program students practice troubleshooting repeatedly. Students are encouraged to utilize available resources including teachers, peers, Internet, and instruction material to resolve any issue or problem. This approach improves students communication skills where they can explain to someone else what is the problem they have and what type of help they are seeking. At this stage student have a good understanding of engineering design process and are motivated to utilize multi-disciplinary concepts to accomplish task at hand. In Co-robots program instructors assists students without giving away the answers to the problem by directing them to the right path, preventing frustration while engaging students in finding solutions.

Chapter 7

Co-robots Program Implementation

Co-robots program practices engineering design process in electronics, programming, production, and testing for middle school students. The goal is to investigate the effect of meaningful hands-on activities, theme-based and project-based curricula in increasing motivation, interest, and change of attitude toward engineering in STEM education. This program specially focused on female students and provided scholarship and financial support to encourage participation.

The Co-robots program is designed to be an adaptable model thus it can be used in outreach, summer camp, after school hours programs, or in formal classroom set

up. Depending on the time or age of the students, one can modify the projects while keeping the overall structure consistent. The duration of the program can be extended, but a minimum of five days is recommended to ensure that new concepts such as programming is well-established.

Co-robots program was offered to middle and high school students at Michigan Technological University in 2014-17 through summer camps, attracting more than 200 students from across the country.

Implementing the co-robots program required preparing various hands-on activities and ready-to-use curricula, training teachers, and conducting assessments to guarantee continuous improvement and success of the program. The remaining of this chapter focuses on how these traits were implemented during week-long Co-robots programs: “Women in Robotics” and “Robotics 101” at Michigan Technological University.

7.1 Hands-on Activities

The Co-robots program started as a theme and project-based educational experience to broaden the audience of robotics programs. Two different types of hands-on activities are utilized in this program. First is the continuous trends of activities during

Figure 7.1: Students practice soldering to build circuits. Learning Hands-on skills are necessary to prepare future engineers.

every day learning process to increase students motor skills and engaging them in learning process. Figure 7.1 illustrates students learning soldering, in preparation of building the GUPPIE. These activities are flexible and can be adopted from various online projects with electronics and prototyping. This process helps students to learn hands-on skills to build two robotic platform at the end of the program.

The second group of hands-on activities are the games that students play at the end of each learning project. Students use their device or robots to play a game or solve a puzzle. Using servo motors and ultrasound sensor they build an obstacle detector which they use to estimate distance of a shark from a fish in a modeled ocean. They also use a UV (Ultra Violet) lighthouse to identify names of ships coming towards the land displayed on the modeled ocean wall. Figure 7.2 illustrates these role plays.

Figure 7.2: Fun projects motivates students to complete their tasks and play with their creation.

Figure 7.3: Playing games can motivate students to implement their knowledge in practice. Students playing "EMG Hero" trying to control the output signal with relaxing and contracting their muscles.

Figure 7.4: Playing with wooden stick gliders helps students to learn gravity and buoyancy interaction.

Figure 7.4 illustrates students playing with wooden glider made of wooden sticks and paper clips, a mock-up GUPPIE, to learn the effects of gravity and buoyancy in propelling the glider in the water.

At the end of the Co-robots program students use their robot to play a game, for example they use the Neu-pulator to play "EMG Hero" which is a game where players try to follow a path displayed on the screen by contracting and flexing their muscles, depicted in Figure 7.3. During this game students learn how electrical signals generated by their muscles are related to the contraction level of the muscles [103]. To measure the best signals, students learned how to appropriately place the sensor on the center of their muscle.

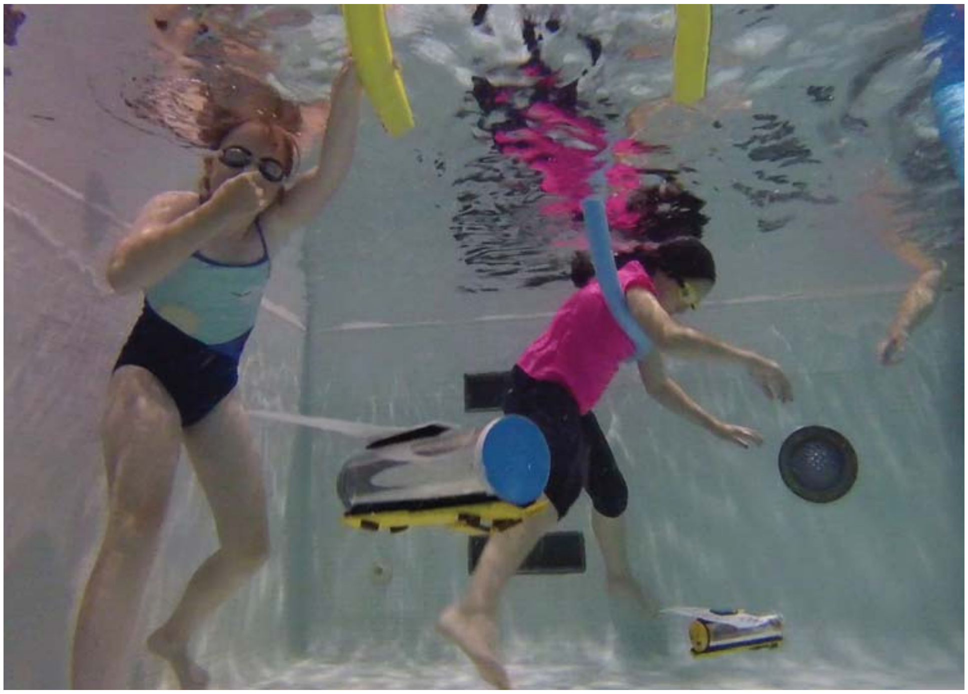

Figure 7.5: Students test GUPPIEs in swimming pool to observe which robots dive deeper and glides back to the surface.

Another example of playing with robots is when students swam with their GUPPIEs and race the robots against each other for deeper depth and farther distance travelled.Figure 7.5 depicts students involvement in a fun activity investigating the performance of their robot. Students learned how buoyancy and gravity work together to move their robot underwater. They learned adding extra weight to the vehicle makes it heavier and increases the gravity effects. They also learned moving the location of the wing and changing the lift force acting on their robot affects gliding performance. Students placed a camera on the GUPPIE to take "selfie" and group pictures realizing underwater vehicle's capability of recording underwater features when equipped with imagery sensors.

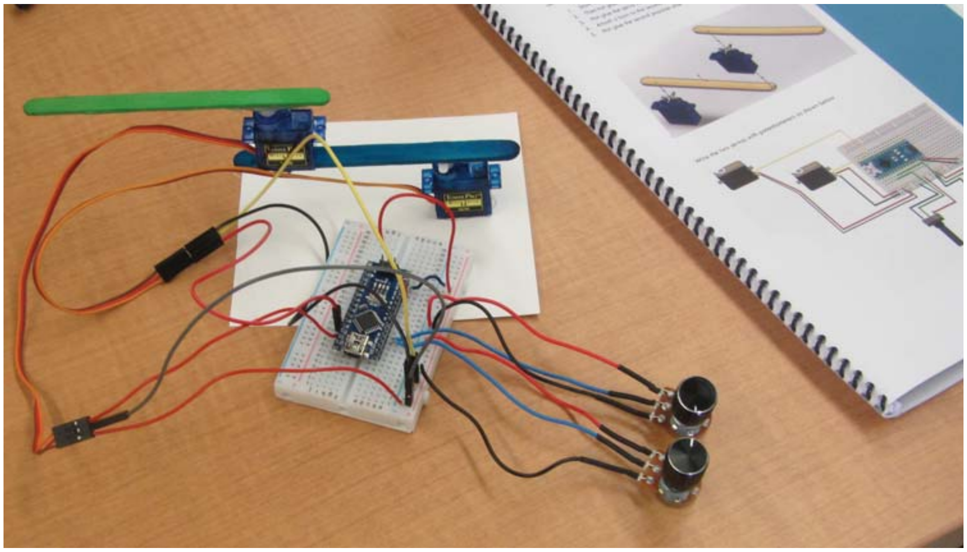

Figure 7.6: Students practice building mock-up model of their robot to understand the motion of different joints and linkages.

7.2 Curriculum

The framework of the curriculum in Co-robots program is aligned with Next Generation Science Standard (NGSS). The standard integrates three dimensions –science and engineering practices, disciplinary core ideas, and crosscutting concepts [105]. Utilizing this curriculum students practice identifying problems more accurately, utilize critical thinking to find better solutions, and optimize the final design.

Co-robots curriculum is a multi-layer instructional material which includes introduction to engineering and robotics, engineering design, coding, electronics, assembly, and production. At each layer students learn the basic and core idea of a particular concept. Then they practice that idea in projects largely involving hands-on

activities. Next layer progressively increases the level of learning in that concept.

For example, in engineering design lessons, modeling in engineering design software is divided in three levels: novice, beginner, and intermediate. At the novice level students learn the software environment, different tabs, and how to sketch simple geometry shapes and how to create new geometries using existing shapes. This stage involves play and learn utilizing small projects. In beginner level, they learn how to use editing options to create 3 dimensional objects and perform basic 3D editing such as merging, making holes, or rounding corners in multi-object designs. Intermediate level is designed for students that are willing to take their knowledge to the next level and design a complex model. This level is not mandatory for all the students is designed to provide opportunity for students with higher learning abilities. It also assists teachers in classroom management where students finish the projects ahead of the class.

Electrical design and coding is designed based on a fully hands-on and project-based approach to guarantee that students practice new concepts immediately and observe the outcome. This approach helps "clicking" and visualizing the application of each concepts in solving real world problems. Multiple cross-disciplinary projects are designed to integrate science and technology with engineering at this stage. Novice, beginner, and intermediate method is also utilized in coding and electronics to help students learning and teachers classroom management.

Figure 7.7: Production and robot assembly is designed as teamwork activities. Students learn how to help each other and work with peers with different skills and ability.

Production and assembly activities in curricula is conducted in groups thus students can share knowledge and practice selflearning through various resources. Instruction material for assembly is designed heavily with graphics. This approach helps students to visually identify assembly parts and materials, follow assembly sequence, and observe the final product. This portion of the lesson specifically concentrates on students ability to putting things together and building using their hands. Coding the robot motion control is also part of the production stage. Since coding from scratch could be intimidating for some students a partial code is provided to help students by filling in the blanks and complete the final code.

This curriculum evaluates students newly acquired knowledge at the end of each

lesson. The evaluation is divided into two categories, hands-on and regular questionnaire. Hands-on questions occurs during development of each skill and after acquiring the knowledge to ensure that students learning is continuously built upon positive experience. Hands-on tests are developed to help students to identify what concepts they did not grasped since they are not able to use it in practice. The regular paper based questionnaire examines students core knowledge regarding new concepts and skills they learned. The paper based test helps teachers to identify which core ideas requires more practice.

7.3 Teacher Training

One of the major issues with any engineering integrated curricula is lack of teachers with engineering knowledge. Utilizing engineering education experts, conducting teacher profession development training, and co-teaching are some of the suggested solutions in literature [96, 106, 107].

To address this issue, in Co-robots program we developed a systematic method to train teachers and instructors with different levels of engineering knowledge and experience. This method classifies trainees into two groups: 1) engineering students and alumni, 2) science and technology teachers. Former are current undergraduate or graduate students that are interested in participating in Co-robots program through university

to explore future career in education. Second group are school teachers that are interested in integrating engineering concepts in their classroom.

Graduate and undergraduate students and alumni training includes ways to integrate research with teaching and outreach to develop strong research, pedagogical, mentoring, and communication skills. Each undergraduate student is paired up with a graduate student which had already served as TAs and is trained through a Graduate Teaching Assistant Training course ED0510 through the Center for Teaching and Learning at Michigan Technological University. In addition to that every member of instructors team receives specific training through Michigan Tech's Center for Pre-College Outreach.

The training prepares the instructors team for students behavioral expectation, gender differences, various learning style, multiple intelligence, communication methods with younger students as well as classroom management for this particular age group. Each instructor receives the teaching material and is mentored on methods of teaching. They are required to practice all projects and hold practice teaching sessions to ensure the readiness for Co-robots program.

Science and technology teachers training program is more focused on educating engineering concept and engineering hands-on experience. Teachers receive the teaching material and are required to complete all projects. Since these teachers have limited knowledge of engineering, training starts from basics. While learning the concepts

and completing each project they are offered with troubleshooting methods in each concept.

For example in coding, there are several common mistake that students make during wiring the code. Teachers become familiar with those common mistakes and practice troubleshooting by correcting several examples. Same approach is taken in engineering design, electronics and circuitry, production, and testing.

During Co-robots program through 2015 to 2017 more than 20 undergraduate and graduate students were trained. In 2017 a teacher professional development workshop was piloted at Michigan Tech in conjunction with the Michigan Tech's department of Cognitive and Learning Center. Two local science teachers attended the workshop to improve their engineering knowledge in leading two middle school robotic team.

7.4 Assessment

It is important to determine what is being assessed and what kind of assessment method is more appropriate to answer research questions. Co-robots program and its participants were evaluated with infusion of quantitative and qualitative surveys, conversational discussions, and behavioral observation. Assessments were designed based on students voice and choice. Utilizing blend of assessments methods allows

investigation of boarder aspects of the program [108]. Pre and post surveys were used to quantitatively and qualitatively determine level of interest, confidence, attitude, and students understanding towards robotics and engineering concept in STEM. This assessment evaluates students learning outcome, interest, and motivation towards STEM as well as the Co-robots program performance and effectiveness.

The surveys were focused on the following factors that align with the Robotics Activities Attitudes Scale (RAAS) introduced by J. Cross et al [109]:

- Real-life value: Students perception of the relevance and value of the robots in everyday life.
- Social motivation: Students desire to use robots to help people and society.
- Interest/attitude: Students outlook on robotics technology and learning through robotics activities.
- Confidence: Students self-assurance in using tools, accomplishing tasks, and robotics project.

Quantitative survey included statements where students indicated their agreement or disagreement on a seven-point or five-point Likert scale. Students rated their interest in robotics, programming, electronics, building, and science and mathematics before and after the Co-robots program. Data gathered from these surveys helps

studying effects of Co-robots program on students interest in each engineering design disciplines as well as the effect of this program on students perception of science and mathematics application in real world. Although online survey forms were used to motivate students to fill the questionnaire, not all the surveys were turned in.

Co-robots program sessions were limited to 30 students to enable us trace each student individually throughout the program utilizing pre and post surveys, post activity checklists, and observe students learning curve and interest rate. Post activity checklists were used to determine students' learning, confidence, teamwork, and problem-solving at the end of each lesson.

Qualitative post program surveys were focused on investigating students' interest and confidence in each discipline and cross-disciplinary application of the activities. Topics such as design and modeling, programming, wiring, soldering, building circuits, and robot assembly were investigated. Students were asked about their opinion on application of components and sensors and if they find these knowledge useful. Some questions indirectly referred to students awareness and recognition of technology. Qualitative survey also reflected students opinion about the program content, instructors, variety of activities, learning environment, program scheduling, and time management from their prospective.

Interviews and conversational discussions were designed to qualitatively evaluate students experience and provide an opportunity to discuss the program content openly.

Students share their experience during the week-long program and had a chance to voice their fears and uncertainties experienced upon entering the program and compare it with the level of confidence and moments of excitement or frustration throughout the program. These interviews provided insight on how to improve the program.

To evaluate the program from an outsider perspective a third party observer monitored the classroom at all time without disturbing the flow of the class. Students and instructors interaction, students focus span, students attitude toward each other and teamwork trait, observable level of excitement and frustration in each lesson, instructors timely response to students inquiry and classroom management were factors that observe was requested to monitor. These information provides unbiased insight on program implementation and extensively improves the overall performance of the Co-robots program.

7.5 Week-long Co-robots Program Overview

The Co-robots summer program is a week-long adaption of the Co-robots model which takes place in 5 stages over 5 days and gradually builds up necessary skills.

7.5.1 Structure

In day one, students learn how to use an engineering design software, Autodesk Inventor [110]. They learned the basics of 3D design concepts such as opening a new file, saving files, recognizing different planes, exploring through 3D views, sketching simple shapes, measuring dimensions, creating 3D shapes, and a few advanced editing features.

An introduction to circuits and electronics is scheduled as part of day one to start students on technology aspects of the program. Students became familiar with different electronic components and microprocessors. They followed simple sketches to learn how electronic devices can connect to each other and complete a loop that is called a circuit. They learned about shorted and unconnected circuits, electronic component polarity, and parallel and series circuits.

On day two and three, students practiced coding and building circuits to complete five scaffolding projects. These projects integrate software and hardware, combining theoretical teaching with hands-on activities.

On day four, students were divided into two groups to build GUPPIEs and Neupulators in the morning and afternoon sessions. This grouping helped creating smaller class rooms were instructors can pay more attention to individual students. Students

Figure 7.8: "I thought it would be really boring, but instead I had like a ton of fun and it passed my expectations." 2016 middle school girl participant.

in each classroom were grouped into pairs to practice teamwork while building and coding the robots. In GUPPIE section, students learned about buoyancy, gravity, energy consumption, drag and lift – an advanced topic in underwater dynamics. Figure 7.8 shows students assembling their GUPPIEs. Students reviewed the science behind underwater glider locomotion based on change of buoyancy. They followed a simplified programming language method, pseudo code, to build a layout or algorithm for GUPPIE motion in a saw-tooth pattern. At this point, they realized that the mass and time are the two variables that they can *control*. To alleviate the technical activities on the fourth day, wing design and decoration was included as part of fun activities. Students learned about the effects of the wing on the vehicle motion and each team designed a wing.

Figure 7.9: Students working together to assemble the Neu-pulator.

In Neu-pulator section, students learned about the structural components of the Neu-pulator, such as the arm links, base, and fasteners. Specifically, they learned the differences between screws, bolts, nuts, and washers, and the appropriate tools and method to tighten and loosen them. Each team member would take turn in build the base frame for the arm and build the motor modules and connect the arm linkage, illustrated in Figure 7.9. Students experimented with the EMG sensors and, together with the servomotor wiring, completed the electrical circuit of the Neu-pulator. Students learned how small electrical signals generated by their muscles are related to the contraction level of the muscles.

On the four and in preparation of deploying the GUPPIE in the swimming pool, students tested the water-tightness of the glider to ensure that water did not penetrate

Figure 7.10: 2016 participants are trimming the GUPPIE: "I did learn a lot about the different capabilities of robots, such as the GUPPIE with its buoyancy control, I thought that was really interesting."

the hull casing. The GUPPIE is designed to be neutrally buoyant at the beginning of its flight underwater. Trimming of the robot was the next step before the final test. Weights were added to the vehicle after completion of the assembly for proper trim adjustment. Figure 7.10 depicts students while trimming their GUPPIE.

On day five, students tested both robots and rectified any problem using troubleshooting methods learned during the week. They deployed GUPPIEs in Michigan Tech's swimming pool and swam with it. Figure 7.11 illustrates an enthusiastic student watching her GUPPIE. Figure 7.12 shows middle school boys in 2016 after a fun day swimming with the GUPPIEs.

On day five, students also tested the functionality of Neu-pulator with two challenging

Figure 7.11: 2016 participant is swimming with the GUPPIE, “I don’t know what my expectations were, but they were blown out of the water!”

Figure 7.12: “It was a lot better [than the other course I took], more in depth in programming, we did more hands-on stuff. I liked more of the programming and building part.” 2016 middle school boy participant.

games: The Reaching Challenge and Balloon Volleyball. For the Reaching Challenge, students learned to control the Neu-pulator function with their muscles to try to move the robot to specific positions within the reach of another robot arm, illustrated in

Figure 7.13. The more positions that were successfully reached within a certain amount of time, the higher the students scored. For the Balloon Volleyball challenge,

Figure 7.13: Student working with instructor to control the motion of the Neu-pulator by flexing his muscle.

students designed a cardboard hand for the Neu-pulator and played against each other in a mini-volleyball tournament. The ball was a balloon, hanging from a string, and the net was made of paper. During this activity, students could modify their code to improve their volleyball performance, such as increasing the speed of the motor joints, or changing the direction of the joints to be able to spike the ball as they flexed their muscles.

7.5.2 Participants

The week-long Co-robots program has engaged pre-college students since 2014. Table 7.1 illustrates high school students participation in 2014-2016. Table 7.2 presents the number of each gender participated in Co-robots program in middle school in 2015-2017. The reason to select middle school age group for a more focused study was based on literature suggestion and the experience with high school students in previous camps [111, 112, 113, 114, 115, 116].

Although the experience was rewarding, we did not observe high impact in decision making toward STEM careers in high school level. Engaging students in younger age in engineering creates a foundation to build interest and motivation towards STEM career and sustain this interest in high school level. In 2016 and 2017, this program was offered in 2 weeks, one week of mixed-sex "Robotics 101" and one week of girls only " Women in Robotics".

Table 7.1
Co-robots program high school participant 2014-16.

	2014	2015	2016	Total
Girls	11	26	30	67
Boys	12	0	20	32

Table 7.2
Co-robots program middle school participant 2015-17.

	2015	2016	2017	Total
Girls	2	11	29	42
Boys	18	20	22	60

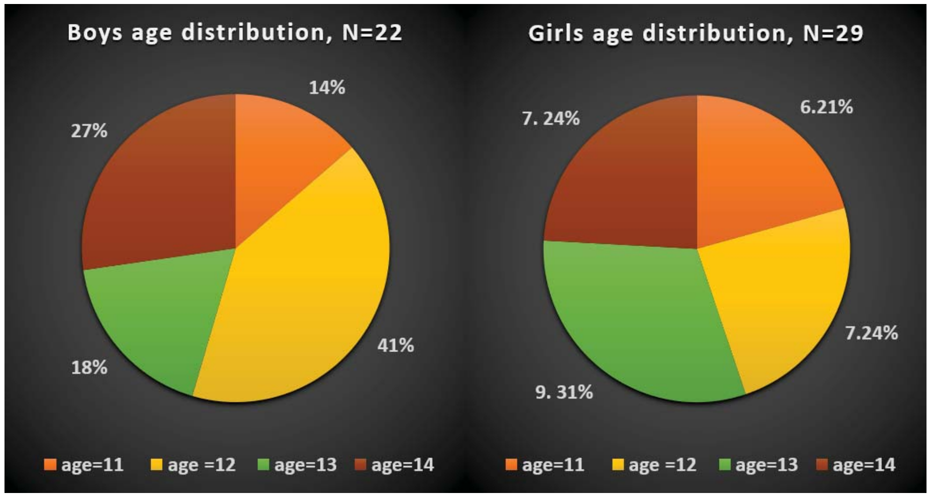

Figure 7.14: Age distribution based on gender in 2017.

As the data over the years shows number of girls increased exceptionally from 2 in pilot program in 2015 to 29 in 2017. This can be interpreted as tendency of middle school female students to participate in activities with similar gender due to sociocultural factors and family values in addition to cognitive behaviors [73, 117]. Offering the financial aid was also a key element to populate the program with higher number of female participants. Effects of peers on each other and word of mouth to spread the excitement that students experienced during Co-robots program attracted more students in coming years. Figure 7.14 illustrates age distribution for each gender.

In 2015 majority of students enrolled from states of Michigan and Wisconsin. In 2016 the ratio stayed the same. Figure 7.15 depicts demographic of participants in 2017. Main reasons for this distribution could refer to Alumni enrolling their children at a summer camp where Michigan Tech is a possible choice of University for future for the neighboring states. Students were asked during the interviews how they chose

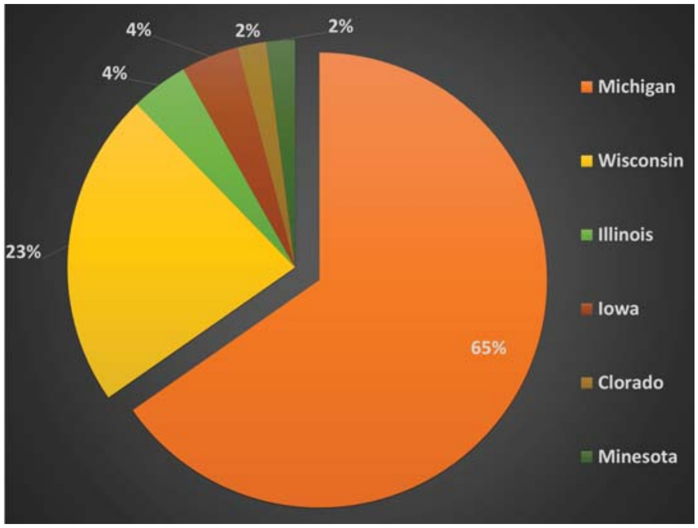

Figure 7.15: Co-robots program was offered to middle school students nationwide. Demographic shows that more that %80 of participants were from states of Michigan and Wisconsin in 2017.

this program and responses supported this reasoning.

Chapter 8

Co-robots Program Assessment and Conclusion

Mixed research assessment methods were used to answers the following research questions: 1) if meaningful hands-on activities had a positive effect on students; 2) if students' confidence level increased by accomplishing tasks that they have not done before; 3) and if the program influenced students' attitude towards robotics and STEM careers.

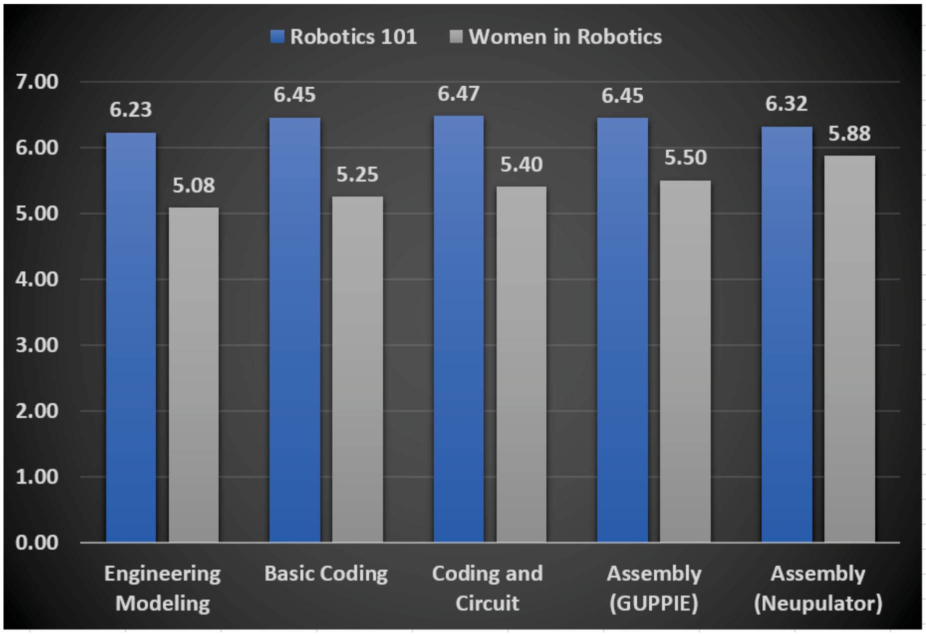

Figure 8.1: Students Average rating on each main activity in 2017

8.1 Quantitative Survey

To evaluate the likelihood of students high or low interest towards Co-robots activities in each day, series of questions were asked through pre and post activity surveys. Quantitative Likert scale surveys captured students level of agreement or disagreement with the fundamental research questions. Students rating on each trait of the program are depicted in Figure 8.1 and it demonstrates that Robotics 101 (mixed sex with majority of boys) had higher interest toward all the activities compare to girls. It is important to note that girls rated all the activities high score of 5 out of 7 in Likert rating which indicates high level of interest.

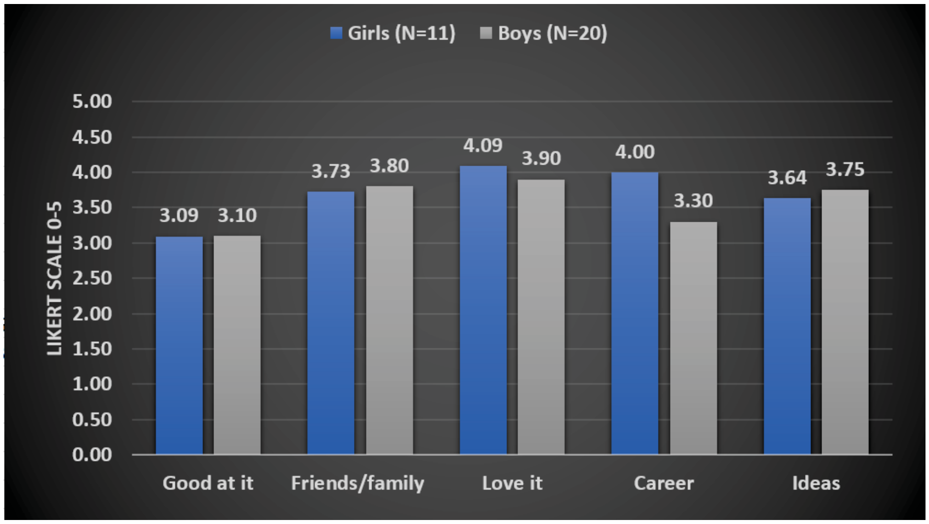

Figure 8.2: Boys and Girls interest in robotic based on Pre-survey in 2016, Likert scale of 5 (Strongly Agree) to 0 (Strongly Disagree)

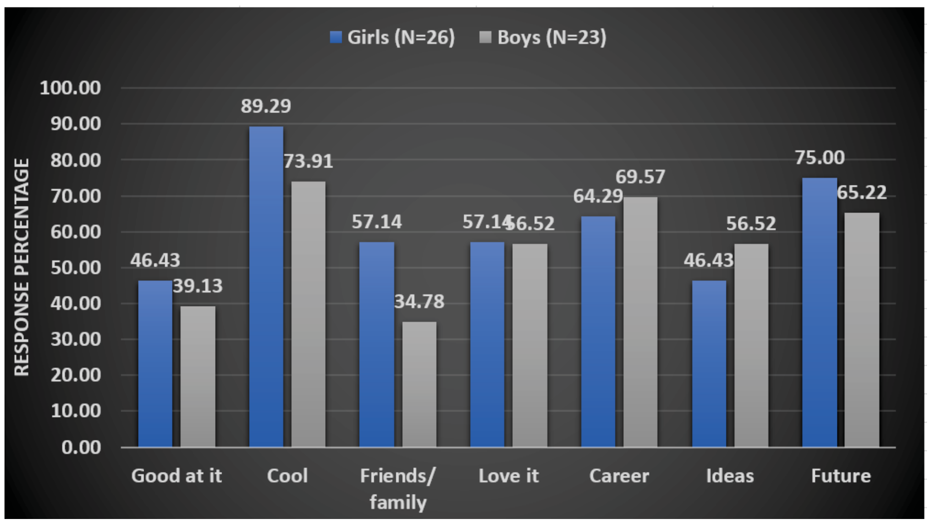

Figure 8.3: Boys and Girls interest in robotic based on Pre-survey in 2017, percentage of items checked from the list

In pre-survey students were asked “Why do you like robotics”. In 2016 Likert scale of 0-5 was chosen for the response method while in 2017 students could select a response without needing to rate them. Both years multiple choices were selected for response type and the topics were selected from following list:

- I am good at it.
- Because robotics is cool!
- My friends and family encourage my interest
- I love Robotics!
- Robotics is useful to my career goals
- It is the science of future
- I have lots of ideas for useful things to do with robots

Figure 8.2 and Figure 8.3 compares the response of boys and girls, respectively. “being cool” and “Love it” (enjoyment) received most rating among middle school students. Both girls and boys rated future and career options highly.

Students were asked about the reasoning why they liked or disliked an activity. Table 8.1 illustrates the positive reasoning and Table 8.2 shows the negative reasoning in 2017. Total positive and negative percentage is also reported in each table. Data suggests that students likely enjoyed the Co-robots program based on the total positive feedback compared to the negatives. “Not having background” and “being frustrated” was rated higher among negative reasoning. “fun”, “interesting”, “useful”, and “learning a lot” were among high rated reasoning for favorite activities.

Table 8.1
Positive reasoning for activity rating in 2017

Reasoning	Girls WIR	Girls Robo 101	Boys Robo 101
It was fun	84.24	62.50	85.71
It was interesting	87.50	83.33	94.28
It was useful	71.74	66.67	80.95
I learned a lot	79.89	54.17	79.89
I can do it with other people	57.06	33.33	50.47
I had experience in it	36.96	29.17	46.67
I am good at it	53.80	20.83	49.52
I have gotten a lot better at it	76.63	62.50	70.47
Total Positive	93.33	86.08	93.90

Table 8.2
Negative reasoning for activity rating in 2017

Reasoning	Girls WIR	Girls Robo101	Boys Robo101
It was boring	5.97	8.33	5.71
I didn't see the point	2.17	0.00	4.76
I didn't know what I was doing	7.06	25	3.80
I didn't have the background	7.06	12.50	7.06
It was frustrating	16.84	20.83	14.28
Total Negative	6.67	13.91	6.09

Tables 8.3 and 8.4 illustrate positive reasoning and negative reasoning for 2015-2016 middle school students. Students reported "lack of time", "difficulty of activities", and "lack of experience" major reasons of disliking an activity while "gaining experience", " hands-on", and "fun" was the reasons they liked an activity. It is interesting that lack of knowledge or experience has high rating in both positive and negative reasoning.

Based on the survey results, students can fall in three different categories depending on their attitudes towards engineering activities. The first group of students are

Table 8.3
Positive reasoning for activity rating , 2015-2016

Reason	SYP15	WIE15	WIE16	SPY16
Ability to do complicated tasks	0.00	0.00	10.52	15.38
Sense of accomplishment	0.00	5.88	5.26	11.53
Gaining/having experience	5.00	17.64	31.57	30.76
Satisfying	10.00	0.00	10.52	0.00
Challenging	10.00	5.88	0.00	0.00
Use in real life	5.00	5.88	10.52	0.00
Hands-on	40.00	47.05	5.26	15.38
Fun and cool	30.00	23.52	15.78	19.23

Table 8.4
Negative reasoning for activity rating, 2015-2016.

Reason	WIE15	SYP15	WIE16	SYP16
Not enough time	46.15	0	23.52	17.39
Complicated/difficult	23.07	27.77	35.29	26.08
Lack of experience	23.07	0.00	29.47	0.00
Not challenging enough	15.38	5.55	17.67	0
Lack of ability	7.69	0.00	5.88	17.39
Teamwork	0.00	11.11	0.00	0.00
Hard to follow instruction	0.00	0.00	11.76	4.34

interested in engineering and showed great enthusiasm for programming especially the hardware in the loop aspect of the Co-robots program. The second group of students are the ones that do not like engineering tasks such as programming although they can complete the challenges. They show high interest in other topics like building or testing and they make comments like "programming is not for me".

The third group, majority of the students, are the ones that need more time and guidance to learn the engineering topics and practice those skills in conjunction with the other related activities such as wiring and building circuits combined with coding. This group has the most potential to move from one end of the spectrum to the other

Table 8.5
Girls camp level of confidence- 2017

Activity	Ave. Rating	Pre survey	Post Survey
Engineering Modeling	5.08	3.92	5.00
Basic Coding	5.25	4.13	4.75
Coding and Circuitry	5.40	3.75	5.50
Assembly (GUPPIE)	5.50	4.00	5.25
Assembly (Neu-pulator)	5.88	4.75	5.75

Table 8.6
Robotics 101 camp level of confidence - 2017

Activity	Ave. Rating	Pre survey	Post Survey
Engineering Modeling	6.23	5.14	6.27
Basic Coding	6.45	5.32	6.32
Coding and Circuitry	6.47	5.60	6.13
Assembly (GUPPIE)	6.45	5.75	6.10
Assembly (Neu-pulator)	6.32	6.00	6.52

and change their attitude towards robotics and other STEM related activities. The lesson plans in the Co-robots program is designed to focus on this group of students.

Confidence plays major role on students attitude and perception toward learning. To evaluate Co-robots effects on students confidence a series of question were implanted in pre and post quantitative surveys. Table 8.5 and Table 8.6 shows both WIR and Robotics 101 students confidence before and after attending each group of activities. Average rating for each activity group is depicted to highlight rating in pre and post surveys. Table 8.7 shows students confidence in 2015 and 2016. The results are shown separately due to minor change in survey questions. Overall students feedback shows that Co-robots program had positive effect on their confidence in engineering and technology aspects of STEM concepts.

Table 8.7
Students confidence level in daily activities, 2015-2016.

Activity	Pre 2015	Post 2015	Pre 2016	Post 2016
Engineering Modeling	3.9	4.5	4	6
Basic Coding	4.6	5.9	4	6
Coding and Circuitry	4.1	5.6	4	6
Robot programming	5.1	5.8	4	6
Robot Assembly	5.1	6	5	6

Table 8.8
Average rating for level of interest in three main traits of Co-robots program in 2016.

	Pre/boys	Post/boys	Pre/girls	Post/girls
Building	6	5.9	6.55	7
Programming	4.7	5.1	5.4	5.5
Robotics	5.65	6	5.55	6.5

Both girls and boys reported higher confidence after attending the camp in different disciplines. Chief among the boosted confidence traits was "Engineering Modeling" and "Coding and circuits" for girls. Data suggests that hands-on activities improves learning and interests in new and challenging STEM concepts.

In pre and post survey students were asked what type of things robots are most useful to evaluate if theme-base curriculum changes students attitudes towards robots. Responses were grouped into four categories: 1) capability such as physical labor and spying, 2) research/exploration for example travel in space, 3) helping people such as medical and service help, and 4) helping me referring chores. Some responses fits multiple category for example " doing the jobs that are too dangerous for humans" fits in capability, exploration, and helping human.

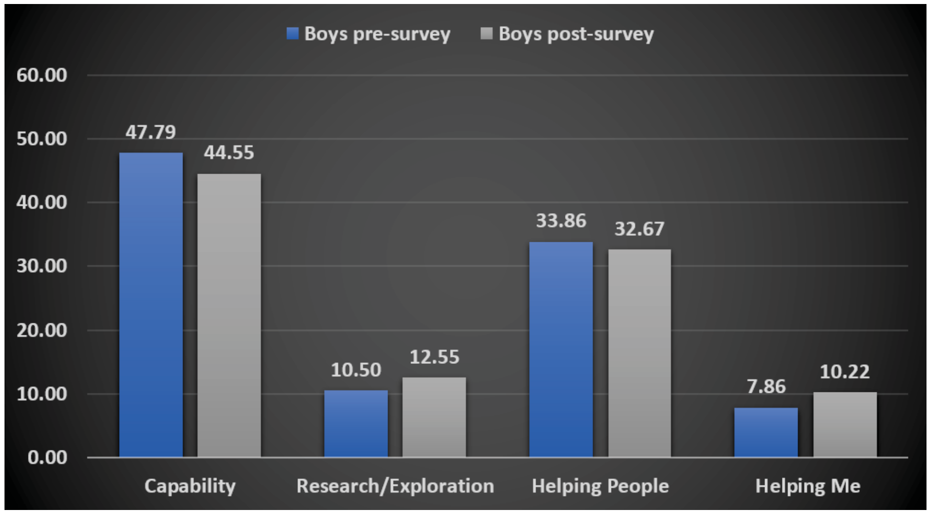

Figure 8.4: Comparison of categories in boys response to: "List things that you think a robot is most useful for", Cumulative result 2015-2017

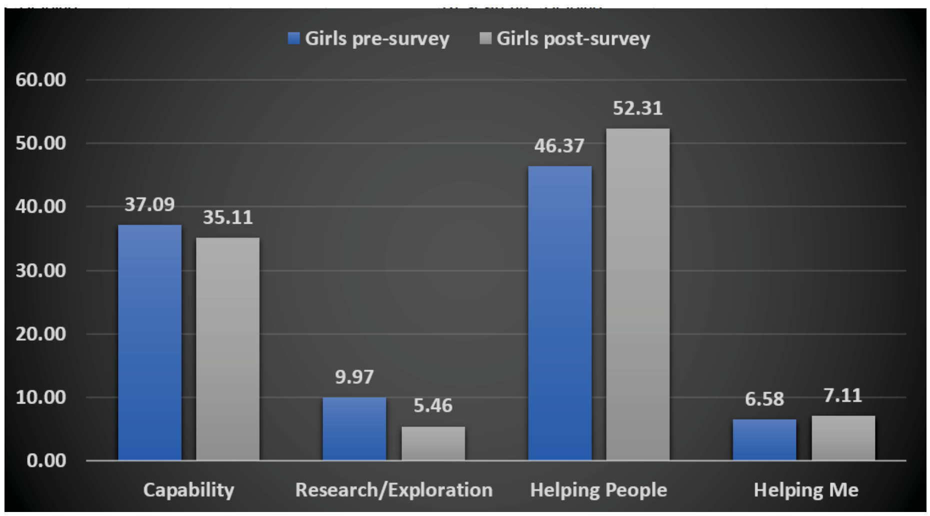

Figure 8.5: Comparison of categories in girls response to: "List things that you think a robot is most useful for", Cumulative result 2015-2017

Figures 8.4 and 8.5 shows boys and girls cumulative response during 2015 to 2017. Girls showed more interest in "helping people" and "helping me" while boys reported "research and exploration" in addition to "helping people" of use of robots.

In 2017 the Co-robots program was modified based on the feedback of the program

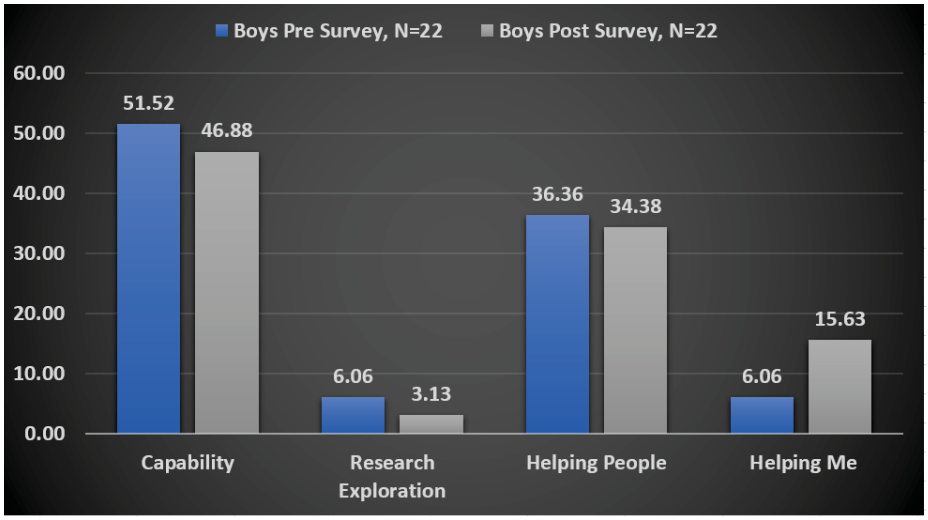

Figure 8.6: Comparison of categories in girls response to: "List things that you think a robot is most useful for", 2017

in 2015 and 2016, thus survey results of 2017 are depicted separately throughout this work to illustrate the outcome of the program. Figures 8.6 and 8.7 illustrate students responses in pre and post survey for boys and girls respectively. Boys in general rated capability more that girls. Helping people received higher rating from girls in post survey. This finding supports the idea of adding meaningful concept to robots to increase interest in female students.

Students were also asked about their experience with instructors. Both girls and boys rated instructors extremely and very encouraging to ask question, friendly, positive, and enthusiastic during their experience at the summer camp. When they were asked "How helpful was your instructor in explaining the material?", girls rated with % 54.55 extremely and % 40.91 very helpful while boys rated % 70.37 extremely helpful and % 18.52 very helpful. %11.11 of boys found the instruction moderate. In respond

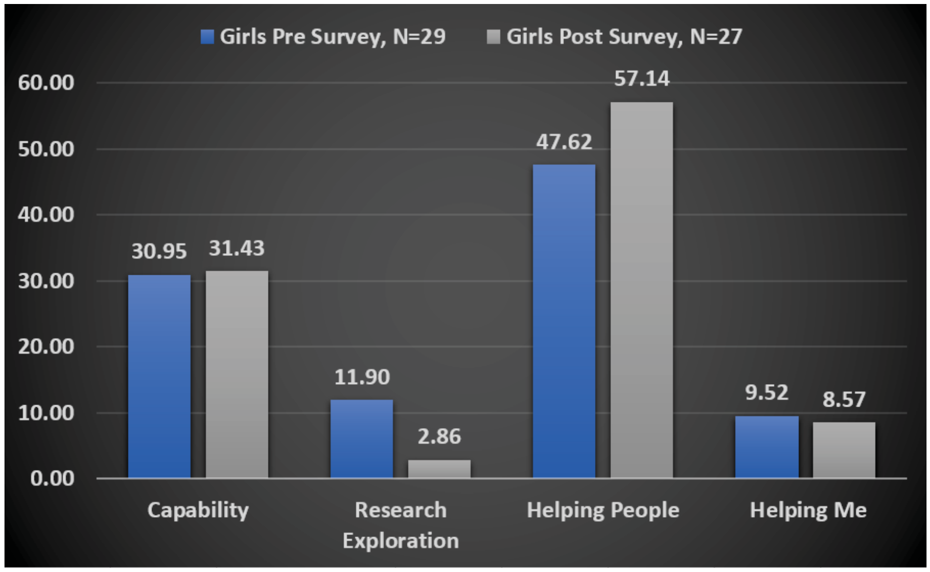

Figure 8.7: Comparison of categories in boys response to:"List things that you think a robot is most useful for", 2017

to "How creative was your instructor/were they able to keep class interesting?" girls expressed % 90.91 success rate while boys rated it % 81.48.

8.2 Qualitative Survey

Qualitative survey helped to gather more information about students attitude towards engineering and robotics. In pre and post survey students were asked " if they were to build a robot, what would the robot do" in support of the quantitative question on " list things that robots are useful for".

In 2017, % 34 of girls mentioned "Fill and empty the dishwasher for me, clean my room, help with school homework, and hold things", although most of them mentioned

they will build robots that helps human in one way or another. These responses are inspired by watching videos during course introduction, NasLab and HIROLab tours, and brainstorming in class projects illustrating effects of Co-robots camp on students understanding and attitude towards robotics application listed here:

– I would love to see a robot climb a wall or jump.

– I am interested in the medical field so I would either advance robotic working prosthetic limbs or build robotic medical assistants for nurses and doctors.

– I would want my robot to help doctors and nurses in their jobs.

– I would like to build something that can help clean our oceans.

– I want it to be an alarm clock that dispenses pills and a cup of water at a certain time, by a persons fingerprint.

– I would want it to help people like making prosthetic, heart monitors, etc.

– I would want my robot to help rescue homeless animals in danger.

– would want it to be like a friend.

– My robot would help people get from place to place easier but clean for the environment.

To evaluate students learning in engineering and technology a series of question regarding the use of various component in Co-robots camp was implemented in post survey such as:

- Did the camp help you learn how to program an Arduino?
- Did the camp help you learn how to build a robot?
- Did this camp help you to learn about building a circuit?

Students responded unanimously that they learned a lot especially that they never had experience with any of these activities.

Students were asked "If their exploration experience helped them to discover new careers". % 72.7 of girls expressed they learned about new fields of engineering such as mechanical engineering, prosthesis engineering, underwater and marine engineering, programmer, architecture, bio-medical engineering, robotics, use of robotics in other careers specially medical field. Boys had broader knowledge about engineering before attending the camp with % 40.74 of them discovering new fields of engineering such as robotics, mechanical and electrical engineering, programming, robot coder, and game producer. This outcome shows that engineering integrated STEM classrooms, informal or formal, helps female students to explore and recognize more career choices specifically in engineering field.

The goal of the Co-robots is to help students to facilitate integration of robots in every day life as it prepares next generation of professionals with good background and understanding of the technology.

8.3 Observations

An observer monitored Co-robots classroom throughout the program and highlighted the strength of the program and ways to improve the overall quality of teaching experience and class management. Observer reported the ice-breaker activities were effective and helped everyone feel more comfortable early on. Teachers were successful in engaging students with lectures, videos, missions, and challenges. Previewing the Neu-pulator and GUPPIE robot at introduction session built excitement and interest. Mini-research projects such as looking up gliders, and having discussions and brainstorming about it afterward gave students a bigger picture about robotics.

Based on observation, girls worked well together, more collaboration than with boys. Students were satisfied with who they were paired up with where both partners had necessary skills such as coding, wiring, and building to overcome challenges in group activities. Observation indicates that students enjoyed being able to learn by themselves at their own pace. They also felt comfortable asking questions, hands were up all the time from not being shy to ask a question. Strategical break times helped

students to relax and regroup after technically plentiful projects.

The observer suggested that common problems should be addressed to the whole class which saves time. Emphasis on facts such as hardware/software issues are not students fault and that building, soldering, and coding are complex activities and students will perform better with more practice. The group of students in the camp were generally all very bright, well behaved kids that were already in some way engaged in STEM. The outcome of the camp would probably look different with average middle school classroom.

- Pairing experienced students with students with no previous robotics experience has positive impact in creating team work and improving engagement.

- TAs need to be aware of students who frequently lose focus and intervene as needed.

- Make sure to scan the room frequently. Many students are comfortable asking for help and demanding attention while some students struggle more quietly.

- Allow some struggles before assisting students will give them the opportunity to think and learn on their own, but also consider the time constraint of the daily activities.

- Girls are interested in the “helping people” aspect of robotics.

Observer reported some of the “aha” moments of students during the Co-robots activities as encouraging testimonies.

– Well now we know how GUPPIE works if the wings are in the back, it will go down better.

– Leaving for lunch: I do not want to leave!

– I want to do more programming rather than hardware.

– I wanna work at DARPA!

– I am so excited, it works!

– Got my game face on! – A girl gets ready to code.

– This is hard, but I’m over halfway through my code!

8.4 Interviews and Group Discussion

To evoke more detailed responses in “students voice and choice manner”, group interviews (groups of 3-6 students) were conducted at the end of the program. Students expressed their excitements, frustration, likes, and dislikes in a conversational manner. Encouraging testimonies and productive criticisms were the outcomes.

Students suggested ways to make the program better and more effective such as changes in instruction book, adding the break time when projects are more complicated, adding more projects, extending the duration of program, and offering advance level after this program. They enjoyed building the robot rather than using an off-the-shelf robot.

Some students mentioned that this camp was different from other STEM programs they attended previously in terms of methods of teaching and the material. They expected less coding and more just playing with the robots. The majority of boys were interested in robotics and computer science and it was the main reason to attend this program. They enjoyed the extent of hands-on activities with Arduino and servo motors and the integration of hardware and software.

Female students expressed their surprise finding out the number of girls that are interested in engineering, robotics, and coding. They also mentioned teachers felt like actual people and could explain things to their level of understanding.

Students were asked in interviews "if the program fulfilled their expectation" and "what can we do to do to make the program better". We observed that girls and boys express their opinions about the activities differently. Girls showed more care about usefulness and the rewarding nature of the activities while boys enjoyed it because it was cool and fun. A selection of the testimonials are listed here.

∗ Boys

- It was a lot better [than the other course he took], more in depth in programming, we did more hands on stuff. I liked more of the programming and building part.
- It changed the way I thought about robotics, the things I knew.
- Most of it met my expectations, I didn't know we were going to be doing programming, so I was happy about that.
- I did learn a lot about the different capabilities of robots, such as the GUPPIE with its buoyancy control, I thought that was really interesting.
- I programmed one from scratch instead of using the example, that was probably the moment I'll remember.
- When we learned about the autonomous lab, the nonlinear and autonomous lab, that really interests me now, autonomous systems. That's something I'm more interested in after camp.
- I learned I'm not good at making robots, I don't really know how to do programming and wiring stuff.
- We should have another class for people coming back, more in depth class, so here's your supplies and at the end of the week you're battling, or more of a challenge.
- Give us more projects with servo, switch, and Arduino.

- Let us take the robots home.
- Add competition of the bottle-bots.

* Girls

  - I don't know what my expectations were, but they were blown out of the water!
  - I learned how to program, and I thought programming would be really hard and confusing and that it would take loads of effort to do it, but it was actually kind of easy once you learned how to read it.
  - I thought that robots were just to like play with and stuff, like toys, but now they're helping, where people can't go, they're like searching, deep in the ocean... lives.
  - I always wanted to be an engineer, I think actually knowing more about it now makes me more sure of my choice.
  - Make the program longer.
  - Teach more programming.

Students were asked how their opinion about robotics changed. Boys were mostly familiar with application of robotics but they enjoyed that they could observe the robots more closely and it was "cool" especially when they visited ROUGHIE and foot prosthesis at NASLab and HIROLab the two real life application of these robots.

Figure 8.8: Co-robots program engaged 29 female students in summer of 2017 and received positive reviews based on post program evaluation.

Group discussion revealed that a major reason for students to like or dislike an activity was correlated to the amount of time spent on each activities. Most of the students did not have previous experience with programming, wiring a circuit, or using CAD software before attending the program. Thus, they needed more time to learn the topics in more detail. The goal of this program was to familiarize students with those concepts and increase the awareness in necessity of learning these topics. Students with prior robotics camp experience had a better grasp of the task at hand and faced the challenges with higher interest and confidence.

Overall students expressed that attending these camps helps them to focus on STEM specially with schools that invest less on STEM or are not equipped with hands-on laboratory. Most of the students mentioned finding friends and working in the group was motivating and made the camp more fun.

8.5 Conclusion and Future Work

Co-robots educational model promotes engineering design practice in K-12 STEM pedagogy. It integrates hands-on activities with theoretical lectures to improve students learning in young learners with limited knowledge of engineering and robotics. Co-robots combines technology and engineering to utilize science and mathematics using a project-based approach where projects are broken down to tasks to build up students knowledge with scaffolding methods.

Co-robots model is divided in five fundamental disciplines: 1) engineering modeling and design, 2) electronics and circuitry, 3) Coding, 4) assembly and production, and 5) testing and troubleshooting. Students practice the engineering design process throughout the program with each hands-on activity. To implement a class or summer camp based on Co-robots model four factors play vital role: 1) Hands-on activities, 2) Curriculum, 3) teacher training, and 4) Assessment. Each factor has to be tailored with the age and size of the group.

Co-robots model was implemented through 2015 to 2017 at Michigan Technological University in collaboration with Western Upper Peninsulas Center for Science, Mathematics, and Environmental Education (WUPC) and Michigan Tech's Center for Pre-College Outreach and Summer Youth Program (SYP). Co-robots program

was offered to more than 100 middle school students. In 2017, 29 girls participated in Co-robots program. “ Women in Robotics” was girls only camp and attracted 23 female students (Figure 8.8). “Robotic 101” was offered to both girls and boys which attracted 28 students out of which 6 were girls.

This robotic platform was also used in several outreach programs and water festivals in the Upper Peninsula of Michigan through 2013 to present time, engaging over 1000 local students to STEM concepts. As part of the contribution of this work three community college students were mentored using this platform through MiCUP program during summer 2015-17.

The goal of these programs was to investigate students attitude, motivation, and interests towards engineering and robotics using hands-on activities. Mixed survey methods were utilized to assess the outcome of the program. Evaluation suggests that Co-robots program had positive effect on students attitude and understanding of engineering and robotics. Students learned how to integrate software with hardware and assemble an electro-mechanical system and is able to perform tasks autonomously.

A teacher training professional development program is under development to assist teachers to bring engineering to classroom and implement Co-robots model to practice STEM concept with hands-on activity with ready-to-use material and projects. A pilot workshop was held at Michigan Tech with two local teachers in summer of 2017 to receive feedback on program set up and content.

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