OPTIMIZATION OF BIOMIMETIC PROPULSION IN A FISH LIKE ROBOT

BY

STEVE KAMADULSKI

THESIS

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Adviser:

Professor Joseph Bentsman

ABSTRACT

The study of biomimetics is largely driven by the desire to integrate design advantages found in the natural world to experimental devices and, ultimately, practical machines.

The work contained herein consisted of the construction of a biomimetic carangiform robotic fish as a functional experimental apparatus, the prediction of propulsive forces based on mechanical fish tail linkage kinematics using a lift based theory, an experimental process to obtain fish swimming velocity data for a number of different swim profiles, and the comparison of theoretical to experimental results.

The robot constructed possesses a propulsive section with five short links capable of fitting the sinusoids produced by Lighthill's model of fish tail motion accurately.

A lift based model was developed and estimated the net propulsive force generated per square foot of foil to be 6.53 lbf/ft^2 of foil, 7.78 lbf/ft^2, and 7.95 lbf/ft^2 for the three cases evaluated theoretically.

The trends in the experimental fish swimming velocity data point to convergence at 0.375 ft/s, 0.40 ft/s, and 0.42 ft/s in the three varied C-term wave envelope coefficients tests corresponding to the force estimates above.

The experimental data points to validation of the theoretical model, and it has the potential to be a useful tool in planning fish tail kinematics in future work.

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CHAPTER 1
INTRODUCTION

1.1 Motivations

As the field of robotics progresses, many scientists are looking to the natural world for design inspiration, reasoning that if nature has spent thousands of years refining a given design, it will be an appropriate performance benchmark. Enough scientists and engineers have turned to this method of synthesis that it has taken on its own moniker, that of “biomimetics”. One application where biomimetics has generated a substantial body of work is that of undersea propulsion, using various undersea creatures, from undulating eels and ray fish to purely oscillating tunas, as starting points for mechanical designs. The motivation for these studies vary from simply seeing if a given form could be reproduced and function, to form mimicry for the purpose of measuring performance, to building a form true to life to measure the hydrodynamic effects going on around the machine as it swims. The study performed herein seeks to broach into the realm of optimization, that is, to see if it possible to take a mathematical model of fish-like motion and vary the parameters in the model to determine which settings can be exploited to produce a more advantageous result.

Recently there has been a societal trend towards improving efficiency in devices that consume large amounts of energy. Hybrid electric-gasoline powered and electric powered automobiles have been taking market share away from conventional gasoline powered autos. Cold cathode fluorescent lamps (CCFL) and light emitting diode (LED) light bulbs are replacing incandescent lighting. LED backlights have begun replacing

CCFL backlighting in television sets. New commercial passenger airliner designs now use carbon fiber to decrease weight and improve fuel consumption. Little, though, has been done to address the large amounts of energy used by over-the-sea container ships used to haul goods between the major economies of the globe. Commercial sea transport is one area where the propulsion efficiency advantages held by oscillating foils over rotating propellers may be applied. Deep sea diving submersibles, whether robotic or manned, is another potential application for this technology. Increases in propulsion efficiency would allow greater operational run-times on equipment that have fixed battery or fuel reserves.

1.2 How Fish Swim

A great deal of study has been conducted on the manner and modes of swimming marine creatures from both a life sciences point of view as well as an engineering perspective. Fish, in general, swim one of two ways; thrust is either generated by periodic movement of some portion of the creature's main body, or by any of a number of mechanisms involving the creature's median and pectoral fins [60]. The former method of propulsion, termed body and caudal fin locomotion, is utilized by an estimated 85% of fish families and will be the focus of this study because of its use by fast and efficient swimming fish species. Median and pectoral fin swimming is favored by species that swim slowly and are required to be highly maneuverable. There are four modes of swimming that fall under the method of body and caudal fin locomotion; anguilliform – whole body undulation, subcarangiform – undulations confined to final half of body, carangiform – undulations confined to final third of body, and thunniform – undulations confined to the caudal fin and peduncle only [11]. Scientists have identified two primary phenomena at work during fish swimming that are responsible for propulsive thrust. The first is an added-mass effect whereby the fish body imparts momentum to the water directed backward and an equal opposing force is exerted on the fish propelling it forward. The second is a vorticity effect whereby the vortices in the fish body's own wake impart a propulsive force, as the vortices in the fish's wake have a rotation and effect opposite that of a classical drag inducing Karman vortex street [60]. Added-mass effects are associated primarily with anguilliform swimming, while vorticity effects are associated primarily with thunniform swimming; subcarangiform and carangiform swimming utilize both phenomena.

Colgate and Lynch summarize the work of Dickinson on unsteady hydrodynamic mechanisms present in energy recovery in the reverse Karman vortex street in a fish's swimming wake. The swimming motion of the fish is made more efficient because of a lift effect each trailing vortex imparts as it is shed from the edge of the oscillating foil. The oscillating foil, a caudal fin or otherwise, sheds a starting vortex as it begins movement which aids the movement of the foil until it must stop to change directions. Upon stopping, the foil sheds a stopping vortex in equal an opposite force to the starting vortex [11]. Kelvin's Law states that net circulation in the fluid system is constant; the shedding of starting and stopping vortices is how net circulation is held constant in a fluid field that is initially still.

F.E. Fish conducted a study on bottlenose dolphins that sought to establish relationships between various parameters and effective power output and propulsive efficiency. The morphology of bottlenose dolphins is that of a subcarangiform with a lunate (crescent-shaped) tail, which implies that they rely on both added-mass effects and vortex energy recovery. Two trends were established in Fish's study; the first was that the angle of attack of the tail fin is reduced, the velocity of the swimmer is increased, and the second is that as the frequency of the tail beat is increased the velocity of the swimmer increases [14]. The second result is intuitive but the first is not. In Fish's study the regression line is formed from data with a high spread. P.R. Bandyopadhyay's analysis on foil angle of attack vs. lift coefficient indicates that as angle is increased, lift coefficient, and therefore potential propulsive speed, increases, but only to a point, after which, lift coefficient begins to fall [6]. The effects these parameters have on propulsive efficiency are important to prove out definitively through experimentation, and the clear effect they have indicates that they are important design parameters.

The simplest body movement that will effectively generate forward thrust is that of a sinusoid. This concept was given a treatment by MacIver *et al.* where a simple sinusoid was applied to a simulated anguilliform body to generate sufficient thrust to move the body through a flow tank [44].

Fish swimming is affected by many hydrodynamic phenomena that are not yet fully understood. "Gray's paradox" is one example of gaps in our understanding. In 1936, the British zoologist James Gray conducted a study on the propulsive output of dolphins and discovered that they were deficient in output by an approximate factor of seven to achieve their maximum swimming speed when compared to a rigid fluids model [71]. Indeed, in the time since, much work as been dedicated to characterizing these phenomena. In a trial performed by Gopalkrishnan and others, a flat plate was placed in a cylinder's wake to determine what effect oscillating the plate would have on incoming vortices shed by the cylinder. When the flow was started three different conditions were observed, destructive interference between the plate’s vortices and the cylinder’s which increased the plate’s thrust, constructive interference between vortices that reduced the plate’s thrust to a minimum, and an in-between condition that created unsteady interactions between vortices and increased the width of the plate’s wake [18]. Control of the propulsive foil’s wake has been proven experimentally to be the primary driver in whether or not said foil generates effective thrust. The goal as stated by Triantafyllou *et al*. is that the flow should not separate from the foil to generate harmful pressure losses and that body motion should be synchronized to prevent uncontrolled flow separation and vortex shedding [70]. Studies on dolphins have calculated their tail fins to operate with efficiencies in the 75% to 90% range and that the flexibility of the fin helps contribute to this [13], indicating that a rigid flow model of foils may be adequate only as an approximation. Other studies indicate that fineness ratio, the ratio of body length to maximum thickness, affects swimming efficiency by reducing drag, with fineness ratios of three to seven appearing to be optimal [15].

1.3 Need for Higher Performance Sub-sea Propulsion Systems

Propulsion efficiency is one major benefit to oscillating foil locomotion. Propellers used to drive sub-sea craft are generally not more than 40% efficient, while testing conducted in 1995 by M.I.T. on oscillating foils demonstrated that efficiencies upwards of 80% are possible, and was theorized that if locomotion in a constant street of reverse Karman vortices was possible, efficiencies over 100% could be achieved [71]. Follow on testing by Anderson *et al*. measured the effects heave (lateral displacement), foil length, angle of attack, and phase angle between heave and foil pitch have on efficiency. Eight test cases were devised and efficiencies between 6% and 87% were achieved [3].

Another study by Hover *et* al. demonstrated the effect various angle of attack profiles have on propulsive efficiency and thrust coefficient. Harmonic motion, square wave, sawtooth wave, and sinusoid were compared, and it was found that sinusoid proved efficiency on par with harmonic motion while providing a much higher thrust coefficient [22]. These studies are significant because they show optimization is possible, at least in the single foil steady flow case, and point to future work involving a complete oscillating drive. Other work has been done computationally showing the profound effect Strouhal number has on efficiency for the single foil case [53]. The body of work showing the promise of oscillating foil propulsion is growing, but more work needs to be done on complete drives with lessons learned from single foil analysis applied.

Another benefit to the development of oscillating foil propulsion is that new, novel designs for craft are becoming possible. In some cases, new more efficient propulsion designs are driven by the need of innovative craft, in others, efficient designs spur the development of innovative craft. Edd et al. used the swimming motion of a synthetic flagellum to simulate the effectiveness of a micro robot in use in surgical procedures [12]. Zhang et al. utilized oscillating foils for propulsion in the development of their fish-like microrobot when ionic conducting polymer film propulsion surfaces were not alone sufficient [81]. These cases illustrate one advantage of more efficient propulsion; the need to carry less energy, whether in fuel tanks or batteries, making the craft smaller. Another way this advantage is applied is by maintaining the same onboard energy reserves and making use of the longer operational time that is now possible. In the future many applications may take advantage of this, from radio controlled toys to deep sea diving research craft.

1.4 Vortex Shedding Theory

The shedding of vortices from the fish's main body and tail is believed to be the primary reason that fish swimming is as effective as it is. This idea is spurring ongoing research, with much of the scientific findings supporting the theory's credibility. Vortex shedding theory, as it relates to fish-like locomotion, states that a oscillating foil in a fluid will generate two columns of vortices behind it that, if conditions are right, will be organized in a manner consistent with a jet, and thus positive thrust will be produced. The character of the vortices produced determines the power required to create the jet, as well as the velocity of the jet produced.

Work has been conducted on discovering the nature of the vortex structures produced behind oscillating foils through use of a soap film [59]. In these tests it becomes apparent that the vortices tend to organize in two distinct columns. Schnipper et al. developed a number of different vortex structures behind an oscillating foil by altering various experimental parameters. Two of the more basic structures were the Kármán street and the reverse Kármán street shown in Figure 1.1. It was discovered that the relatively small amplitudes, the oscillating foil will produce a Kármán street, and for relatively larger amplitudes, the oscillating foil will produce a reverse Kármán street.

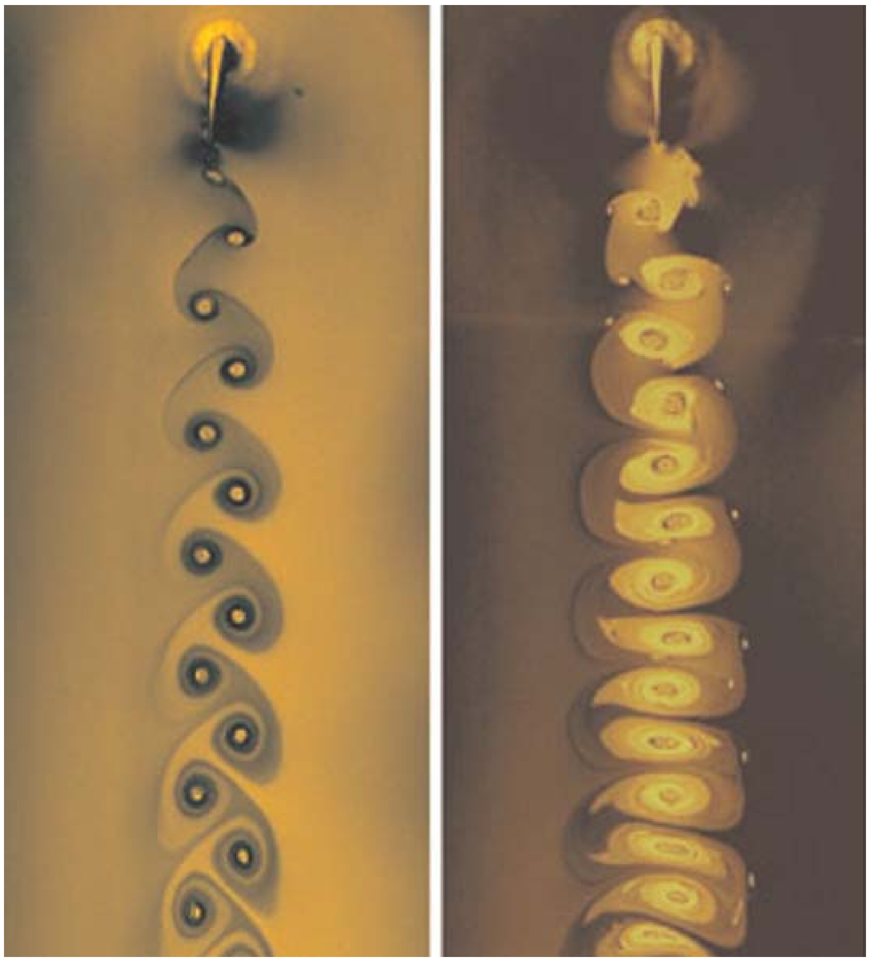


Figure 1.1 – Oscillating foils in soap film, Kármán street left, reverse Kármán street right [adapted from (Schnipper *et al*. 2009)]

In a Kármán street, two vortices of opposite rotation are created per oscillation. The reverse Kármán street is similar to this, but the opposing vortices created have the reverse sign.

A review of the literature on oscillating foils has shown the reverse Kármán street as the vortex formation with the most evidence for optimality [69]. The jet following the oscillating foil can take many forms, from the Kármán streets already discussed, to formations with more than two vortices per oscillation. These extra vortices lend only dynamic instability to the fluid flows resulting in a reduction in thrust, and in some cases increase drag on the foil. The parameters that affect the nature of the jet produced by an oscillating foil are the frequency of oscillation, the amplitude of sweep, and the jet velocity. These parameters determine the non-dimensional frequency of the jet profile, and it has been shown the optimal non-dimensional frequency lies between 0.25 and 0.35, resulting in a reverse Kármán street that, for a given thrust, requires the least energy [69]. A further treatment of the non-dimensional frequency will be given in chapter 2.

It has been shown that fish are adept at taking advantage of their surroundings to reduce their swimming effort. Observations on rainbow trout have shown that fish are willing to alter their swim path in order to synchronize themselves with vortices being shed from upstream objects. This nearly slaloming motion allows them to lower their tail beat frequency but maintain their swim speed. This is taken as further evidence that fish can recover energy from nearby vortices. The study of rainbow trout revealed that trout lower their tail beat frequency to match that of the vortices being shed from upstream objects [36]. The fish also elongate their wavelength during these maneuvers, and the slaloming becomes more pronounced the larger the upstream object.

Swimming effort also determines the top speed of the fish. Shukla and Eldredge studied the effect swimming effort has on the speed of a fish and found that as long as the speed of wave propagation down the tail is greater than the swimming speed of the fish, thrust is produced [62]. Free swimming bodies in Reynolds flow of sufficiently high number to ignore viscous drag continue to accelerate until the wave speed divided by the swimming speed increases to unity. Conversely, deceleration occurs until the wave speed divided by the swimming speed decreases to unity. In reality, at ultimate swimming speed, the tail wave speed is greater than the speed of the flow around the fish as the forces on the body are balance by drag.

Zhu *et al.* demonstrated that energy recovery from nearby vortices is possible through manipulation of the vortex street behind the foil. In trials using numerical computer simulation, the team encountered two reverse Kármán street scenarios with interesting properties. The first scenario involved constructive interference between oncoming vortices and the vortices shed by the foil; this situation resulted in forces that tended to increase the amplitude of the foil, as well as increase thrust and power consumption. The second scenario involved destructive interference between oncoming vortices and vortices shed by the foil; this situation resulted in forces that tended to decrease the amplitude of the foil, as well as increase thrust slightly while reducing power consumption. These interactions indicate that the foil may be recovering energy from the oncoming vortices in the second scenario [82].

The interactions of vortices to increase the efficiency of an oscillating foil raises some interesting questions as to whether or not a design could take advantage of vortices inherent in the flow to create propulsor with exceptional efficiency. Melli and Rowley attempted this with a mechanical swimmer made up of a lead foil, a trailing foil, and a phase-locked loop controller. The two NACA 0012 hydrofoils were spaced 2.5 chord lengths apart, and the feedback controller was configured such that the angle of attack and the stagnation point of the trailing foil were in phase. A comparison was made between the swimmer with feedback control and without, and the data showed that the controller resulted in more thrust, less power consumption, and a greater overall efficiency [48].

The case of schooling fish is considered. In schooling fish, it is theorized that the lead fish sheds vortices that are used by trailing fish to aid their swimming. The interaction of schools has been studied by Kelly and Xiong through the use of a swimming frame with three electrically powered hydrofoils. The hydrofoil array was organized in an equilateral triangle formation and used to mimic cooperative swimming, as the hydrofoils were constrained to move as a group. Spacing of the hydrofoils along the streamline direction as well as the lateral direction was first optimized; then the effects of foil phasing were studied. The foil array was tasked to swim straight for a fixed amount of time, and the distance traveled was measured. In this study, as in earlier studies, the data suggests that when vortices destructively interfere with each other in the jet area of the foil, the efficiency of the foil is maximized locally [31]. The experimental data clearly showed improvement in the distance traveled in the given time interval as the phase angles of the two trailing foils were adjusted relative to the lead foil.

1.5 Tail Motion Modeling

Before a mechanical design for an oscillating foil propulsor can be synthesized, first a basis for motion modeling and control of the propulsor elements must be established to ensure the propulsor will be feasible to build as well as effective. In 1960 M.J. Lighthill published an influential paper that proposed a mathematical model for fish tail motion based on his observations on slender fish. The equation he proposed was:

$$y = f_B(x, t) = (c_1x + c_2x^2) \sin(kx + \omega t) \tag{1}$$

where y equals the lateral displacement of the tail from the undulation center, c_1 and c_2 are unknown coefficients, x is the location on the tail, k is the body wave number which equals two times pi divided by the tail length, ω is the tail beat frequency, and t is the time elapsed [38]. This equation has been one of the foundation stones for much of the work conducted on fish-like locomotion since. The model Lighthill proposes is sinusoidal, and given that it varies by time, it takes the form of a traveling wave, growing in amplitude, as time elapses.

Fish are vertebrates with a spinal column made up of many small bone segments and connective tissue. Mimicking this with an artificial mechanism is problematic; the mechanical links are almost sure to be longer than the individual fish vertebrae, so the mechanical fish tail inherently lacks the flexibility of an actual fish. In the construction of an artificial fish tail, the minimizing of tail link size and the use of numerous links will allow the artificial fish tail to better fit the sinusoidal curves of actual fish motion. By virtue of having to approximate the theoretical fish motion curve with mechanical equipment, researchers have begun to tackle the question of how to best fit the curve.

Guo and Peng describe the traditional method of fitting Lighthill's fish tail motion equation as the Joint Location Method, wherein the researcher fits each endpoint of each link directly on the sinusoidal curve developed. They identify the drawback of this method – that the link will inevitably end up completely on one side of the curve or the other, and propose that error might be diminished with a best fitting method using the entire length of the link. They describe their own fitting method, called Simulation Fitting Method, where the tail links are forced into fitting the curve by elastic members attached between the curve and the tail at equal intervals; a mathematical model is constructed to simulate this [19]. The method shows graphical promise and demonstrates the reduction in average error mathematically, although no experiment is made to prove its efficacy.

In addition to straight ahead swimming, research has been conducted on swimming while maneuvering. In Lighthill's equation, the fish body is treated as the center of tail undulation, and when fitting mechanical links to the motion sinusoid, the fish body is effectively the first point on link one, and is stationary. Liu and Hu created motion equations simulating turning fish by tracing out the curve this center of undulation creates as the fish turns and modifying Lighthill's equation as needed [40]. In this way they were able to allow their fish robot turn quickly. Such work points the direction for future robot design, as well as helps validate Lighthill's original findings.

CHAPTER 2
LITERATURE REVIEW

2.1 Scope

Literature reviewed in preparation of completing this project was drawn primarily from three tracks of research; investigations centering on mechanical oscillating foils for use as a propulsor; analyses studying fish motion, whether organic or mechanical, and its effects on the nearby flow field; and previous mechatronic design studies conducted on the robot fish concept. The analyses conducted on fish motion can be further divided into those involving experimental approaches, those involving numerical models, and those involving computational flow dynamics simulations.

2.2 Investigations in Oscillating Foil Propulsion

There exists and extensive body of work on the subject of foils in moving flow fields as well as oscillating foils in both zero upstream velocity and moving flow. The study of these objects have borrowed much of the common terminology from the study of bluff bodies, that is, the study of broad geometry or foils in a viscous fluid. One of the more prevalent quantities used in both fields is the Strouhal number. The dimensionless Strouhal number was developed to characterize the flow fields behind bluffs in moving water, but it has been adapted to describe the jets created by oscillating foils. It is equivalent to the non-dimensional frequency of the produced jet mentioned in section 1.4

$$St = f * A / U \tag{2}$$

where f is the tail beat frequency in Hz, A is the width of the wake, and U is the speed of the jet. For the study of fish like locomotion, A is commonly taken as the peak to peak amplitude of tail motion, and U is commonly taken as the forward swimming speed as the jet velocity is often difficult to measure directly [70]. With these measures taken, M.S. Triantafyllou and G.S. Triantafyllou investigated a large amount of swimming data on fish and found that, for all manners of fish, fish swimming motion produces a Strouhal number between 0.25 and 0.35 [71]. They then investigated oscillating foils in the laboratory, and again found that the thrust producing jet behind the foil is formed most efficiently when the Strouhal number is between 0.25 and 0.35 [71]. Using Strouhal number as a design parameter, they were able to achieve propulsion efficiencies in the laboratory of beyond 86 percent.

Rohr and Fish analyzed swimming data on dolphins to draw a comparison between dolphin swimming Strouhal data to that of fish [55]. Dolphins have a slightly different swimming structure than fish, in that they oscillate their caudal fins up and down rather than side to side. Rohr and Fish found that dolphins favor a Strouhal number range similar to that of fish, but use a slightly lower range of St – from 0.20 to 0.30. They discovered the majority of the dolphin data points fell into the lower bound of fish, with 44% of St data points falling into the range of 0.225 and 0.275.

Wen *et al*. measured their own robot fish construct's performance against the performance of an actual Saithe fish [75]. The team's robot developed swim characteristics with St varying between 0.41 and 0.426. The Saithe fish used for comparison developed swim characteristics producing a St of 0.34 and produced a swimming speed per unit body length twice that of the robot, despite using approximately half the tail end amplitude and approximately the same tail frequency. The data lends further support to the notion that swimming efficiency decreases with increasing Strouhal number.

Barrett *et al.* retrieved data on a towed rigid fish to attempt to quantify how much drag reduction, if any, a swimming fish is experiencing compared to a rigid viscous model [7]. The St derived for the team's swimming fish robot was 0.25 and power consumption under full load was 1.83 W. The team found that to drag the fish through the same pool with a tow required 2.37 W to achieve the same speed. The team also calculated coefficient of drag for both the swimming case and the towed case. They found the coefficient of drag during swimming to be 0.0058, while the rigid-body produced a drag coefficient of 0.009, a reduction of 35%.

Kodati *et al.* investigated the effect Strouhal number has on propulsion efficiency for a variety of foil shapes and materials [34]. The materials used were left uncoated, so as to test the effect surface profile has on foil efficiency. The tests involved focused on Strouhal numbers over 0.5. Their data showed that propulsion efficiency for St > 0.5 are erratic, and greatly influenced by factors outside those parameters often closely controlled during robot swim tests. The team found that polyethylene fins had a higher drag coefficient than that of delrin or polyimide. This was attributed to polyethylene's rough finish. The drag coefficient tests indicate that there is some sideways transfer of momentum to the fluid.

Massey varied tail beat frequency for a robot fish and measured the effect on swim speed. As frequency was increased, swim speed increased, but the effect was not proportional [46]. A baseline of 0.955 Hz was taken, resulting in a swim speed of 9.3 in/s and a St of 0.51, as the frequency was increased to 1.273 Hz and 1.592 Hz, the swim speed increased to 13.0 in/s and 14.3 in/s respectively, and St varied to 0.49 and 0.56 respectively. Since the increase in swim speed was not proportional, St initially fell for case two, but rose again for case 3. This highlights the difficulty in tuning for an optimal Strouhal number; St is affected by swim speed which is an experimental parameter, not a variable that the designer can change. To lower or raise Strouhal number, tail beat frequency can be lowered or raised, but swim speed will change in kind, but perhaps not to the same proportion. Tail sweep amplitude can be altered, but swim speed will be surely altered as well.

2.3 Experimental Approaches

Experimental approaches to studying fish motion usually involve either attempts to replicate the pliability and swim motion of actual fish, observations on an oscillating foil, or observations on some manner of fish robot. In some cases, careful measurements are taken using sophisticated measuring equipment such as lasers or Digital Particle Image Velocimetry to collect flow velocity data directly; in others, visualization of the flow is all that is required. Measurement of the forces on oscillating foils has also been demonstrated.

Digital Particle Image Velocimetry (DPIV) can be used to measure flow velocity and to visualize flow interactions. DPIV is a process that takes two images of the flow field separated by a small time interval, and compares small interrogation window samples of the overall image using a cross correlation function. Where the interrogation windows are deemed a match by the algorithm, a peak is marked in the frame – the difference in peak mark orientation between time intervals allows the flow to be visualized. Wolfgang *et al*. used DPIV to study the velocity of the jet behind their robotic fish [77]. Using DPIV they were able to observe an 8 cm/s flow velocity, as well as visualize the vortex street forming the jet. In another case of using DPIV to measure flow, Triantafyllou *et al*. took DPIV data along the side of their flapping plate water tunnel [70]. The water tunnel was equipped with a variable plate whose profile was controlled by eight pistons impinging on a flexible surface. Through the use of DPIV the team was able to search for flow separation and observe turbulence along the plate as the profile changed dynamically. They found that for a plate traveling wave speed to flow speed ratio of 1.2, turbulence was locally minimized. Techet *et al*. used DPIV to observe the fluid boundary layer surrounding their fish robot under swimming condition and under towing condition [67]. An underwater camera looking down at the robot with a pulse laser creating a sheet of light at the fish's vertical centerline was used to generate data. Using this experimental set-up the team was able to observe a lack of flow separation for the swimming fish, while the rigidly towed fish exhibited a turbulent flow profile.

Another approach to data sampling is the use of a high-speed camera. The camera can be used to take piece-wise images of the experiment in progress and the images can be post processed to extract the data. Yan *et al*. took this approach to measure the swim velocity of their robotic fish [78]. Data was collected at 30 frames per second and images were rectified using a custom program to extract information on velocity vs. tail beat frequency, maximum tail amplitude, body wave length, phase difference, and linear coefficient of tail movement.

Gopalkrishnan *et al*. used the commercially available Kalliroscope fluid to visualize the interaction of vortices shed from a bluff body with the vortices shed from an oscillating foil [18]. Kalliroscope fluid is a colloidal fluid with organic flakes suspended in it that aids in the visualization of flow fields.

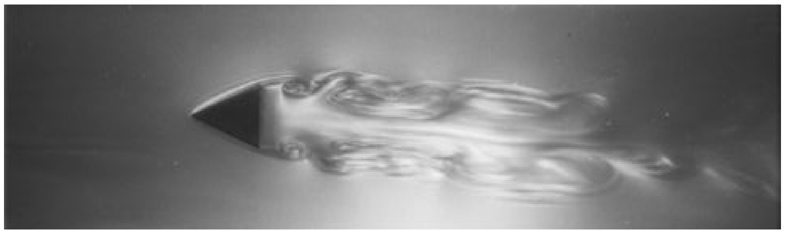


Figure 2.1 – Visualization of Kalliroscope fluid flow field in vicinity of triangle cross section (photograph courtesy of Kalliroscope.com, 2012)]

The oscillating foil was positioned behind a d-shaped cylinder and three modes of interaction were observed. The first mode consisted of the paring of foil vortices with counter-rotating cylinder vortices to form a street roughly four vortices wide resulting in foil wake expansion. The second mode involved the destructive interaction between cylinder vortices and foil vortices. The third mode involved the constructive interaction between cylinder vortices and foil vortices. These experiments found that the foil must have a sweep approximately the same as the spacing between cylinder vortices for the modal interactions to take place.

Another much simpler, but still effective, method of visualizing the flow field is the use of dye flow into water. This method is very similar to the method of using smoke in a wind tunnel to observe aerodynamic phenomenon, which is a technique widely used in industry. In dye flow visualization, dye is injected in the free stream some distance in front of the object being studied, the momentum of the water will prevent much of the dye's diffusion and hydrodynamic interactions will be apparent when the dye collides with the object. Srigrarom *et al*. used dye flow visualization to study an oscillating flow in a water tunnel at Reynolds number of 13,000 to 16,000 [64]. The visualization was used to confirm vortical phenomenon during data sampling to measure propulsive efficiency. Using this method the Kármán street, the reverse Kármán street, and a transitional wake formation between the two with paired vortices were visualized.

Read *et al*. experimented with a carriage mounted foil in a moving flow to determine the forces exerted on the foil during maneuvering [54]. The experimental set-up consisted of a NACA 0012 hydrofoil with a smooth surface profile, constructed of wood and fiberglass, riding on stainless steel axles supported by bearing assemblies at each end. The foil was mounted horizontally with an arm at each end running to a pitch servomotor mounted in the carriage. The carriage remained above the waterline and the foil below. The foil's angle of attack was also variable. Piezoelectric load cells were installed in the bearing assemblies and oriented to measure forces in the vertical direction (lift, the maneuvering force) and parallel to the flow stream (thrust), horizontal forces perpendicular to the flow stream were not measured. The team discovered that the highest lift coefficient generated by the foil resulted when the phase angle between pitch and heave was 100 degrees and the foil angle of attack was 30 degrees. Simpson *et al*. also used load transducers to study a flapping foil's ability to extract energy from a fluid, for the purpose of power generation [63]. In their experiments they used load transducers to measure lift and torque on the foil by a flowing fluid, and relate this to power by taking the dot product of lift with the fluid stream velocity and the dot product of torque with the angular velocity of the tail. With power imparted to the foil calculated, they calculated the power in the flow and derive a measure of foil energy extraction efficiency. Trials were run for various aspect ration foils at a constant Strouhal number of 0.4. The team found the greatest energy extraction efficiency of 43% with a foil of aspect ratio 7.9.

2.4 Numerical Modeling

Numerical modeling presents a powerful tool for studies into fish like locomotion because it allows the investigator to simulate relatively easily in the theoretical domain what would take hundreds or thousands of man-hours of fabrication to replicate in the lab. Numerical modeling has been used for characterizing fish swimming, the transition between fish swimming modes, robot design, and to simulate hydrodynamic phenomena.

Motion modeling of fish swimming motion is a natural application of numerical techniques, since the motivation behind the use of fish like motion is often efficiency. Mason and Burdick created a numerical model based on the swim behavior of carangiform fish, assuming three mechanical links [45]. The model ignores added mass effects, vorticity of the body and links, and turbulence around the tail fin. The model also ignores three dimensional effects. Using these simplifications, the team devised a system of equations that resolved the velocity vector at the quarter-chord point of the tail fin, and used the Kutta-Joukowski theorem to resolve the lift force on the tail fin. When lift was tested for experimentally, they found that their numerical model closely matched their experimental data for approximately the first meter of swimming. A general solution to the numerical treatment of fish swimming was considered by Kanso *et al*. [30]. The team used numerical methods to characterize the dynamics of an N number of articulating solid bodies in a perfect fluid. They used assumptions that the flow dynamics are symmetrical and that the dynamics of the systems do not vary, i.e. that the total momentum of the system is conserved, to create a matrix that is the shape space of the system. The constraint that the articulating bodies are attached, whether by hinge or ball and socket joints is applied to the state space. This constraint allows the shape space to derive the relative link motions. Kanso and Marsden use this model later, taking an optimal control approach, to describe fish tail motion for a desired net movement [29]. Other motion models include the treatment of pitch, roll, and yaw by Giguere *et al*. for a underwater robot using six propulsive foils simultaneously [17], a treatment of steady turning by Hu *et al*. [23], and the use of modified doublet lattice method to determine the suction force created by an oscillating foil by Shimizu *et al*. [61].

The transitions between fish swimming modes have also been addressed with numerical techniques. Saimek and Li created a state space based on two-dimensional, inviscid, incompressible, and irrotational flow to assist with the non-minimum phase nature of fish swimming and the transition between swimming modes [58]. They defined three swimming modes, which they termed motion primitives; fish at rest, cruising speed one, and cruising speed two, and defined a state space for each off-line, so that the states could be used later in experiments involving a two link fish tail on a moving carriage. The experiments utilized a cascade controller consisting of a finite-time linear quadratic regulator and on-line feedback linearization to transition between states. Morgansen *et al*. built upon the work done by Mason and Burdick in [45] by developing a three degree of freedom velocity model for their carriage mounted oscillating foil, and simulating non-linear control of forward motion and turning [50]. The team compared time response graphs of the simulations versus time response graphs derived from experimental measurements and found they were similar. This work was expanded to include feedback control to improve trajectory tracking [51].

A potential use for numerical modeling is in the mechatronic design of robots, with its use in the area of kinematics and event planning. Low and Willy took this approach to verify their design for their ray finned robot [42]. Their ray fin design consisted of servo motors and crank mechanisms to undulate a flexible membrane. Using a numerical model of the movement of these elements, they were able to track the position of each link for all angular positions to verify the design would be successful in operating without mechanical difficulty. Yu *et al*. also demonstrated the development of a numerical method to define link movement, this time in carangiform motion [80]. Unlike Kanso *et al*. which rigorously used hydrodynamic effects to define a shape space, Yu *et al*. used Lighthill's equation, treated in this paper as equation 1, on fish motion to define a shape space of relative position using a link fitting method. In this model, the length of the tail section of the fish robot is defined as R, with the endpoint of the tail defined as two pi times R. In this way, the endpoint of the tail link is positioned at the two pi position of the sinusoid obtained from Lighthill's equation, and intermediate links are then fitted to the curve. The team then organizes tail link angle positions into matrix form, with the change in time resulting in a system of tail link angle matrices. Guo and Peng also used Lighthill's equation to define fish tail motion, but sought to reduce error in overall link location, as discussed in paragraph 1.5, using a numerical fitting technique [19]. Using what the team called simulation fitting method (SFM), systems of equations derived from Newtonian physics are employed to evenly distribute the discrete link length on both sides of the sinusoidal curve given by Lighthill's equation. This numerical fitting technique demonstrated reduced error when compared to fitting end points on the sinusoid for the 24 discreet time points used in the study.

In previous studies, numerical modeling has been applied to oscillating foils to characterize phenomenon in the areas local to foil surfaces. Triantafyllou *et al*. observed that numerical analyses showed that the performance of three dimensional foils were significantly affected by Strouhal number versus an idealized two dimensional foil, due to foil geometry and the introduction of an aspect ratio [68]. Young *et al*. developed a numerical model based on solving a system of Navier Stokes equations to resolve thrust produced by a foil and foil efficiency [79]. The team was able to estimate foil efficiency for turbulent and laminar flow for a variety of Strouhal numbers.

Commercial tools are available to be adapted to the study of fish like locomotion. Anderson and Chhabra used Submarine Hydrodynamic Analysis Tool (SUBHAT) by the Boeing Computer Services Company, and Hydrodynamic Analysis Techniques (HYDAT) by the Naval Coastal Systems Center to numerically analyze the geometry of their Vorticity Control Unmanned Undersea Vehicle [2]. These software packages were developed to characterize conventional marine vessels, but were employed to derive various hydrodynamic coefficients such as lift, drag, pitch moment, and a coefficient that contributes to Munk's moment, a force that destabilizes vessels undergoing a turning motion.

2.5 Computational Flow Dynamics

Computational flow dynamics (CFD) has been used to study both the interactions of oscillating foils with its surrounding flow, as well as the flows constituting the jet behind the foil. CFD analysis usually relies on a commercially available software package to model the physical nature of that which is to be tested, and a powerful computer to simulate the results.

Akhtar and Mittal used CFD to simulate flows past a lead foil and a trailing foil on a Cartesian grid. Their purpose was to observe vortex shedding from the upstream dorsal fin and the vertical interactions with the trailing tail fin to observe if thrust was increased [1]. CFD allowed the visualization of vortex formation, and by stepping the simulation through a set time interval, complete vortical interactions, from lead foil vortex formation to that particular vortex leaving the rear edge of the trailing foil, could be observed. They found coefficient of thrust conclusively increased with leading foil vs. a single foil, and that their results support the hypothesis that fish dorsal fins increase the thrust of their tails fins.

Wolfgang *et al*. created a CFD model of their giant danio robotic fish to predict the velocity flow field for comparison to their experimental data [77]. The CFD simulation closely matched the DPIV data for localized velocity, but the CFD revealed vorticity behavior in the area of the mid-body that is not readily apparent from the DPIV images. Mohammadshahi *et al*. similarly used CFD to model their robotic fish; the team's purpose was to use CFD simulations to evaluate hydrodynamic forces around the fish body [49]. The CFD mesh constructed resolved velocity, pressure, and vorticity around the fish as it swam in a 75 cm/s upstream flow. The simulation also allowed the determination of time dependant drag coefficient. Similarly, pressure fluctuations in the locality of a two dimensional representation of an oscillating NACA 0009 hydrofoil were simulated by Ausoni *et al*. using a commercially available ANSYS package [5].

Flow simulation can also allow for the creation of a virtual environment in which fish control strategies can be studied, as evidenced by Hu and Liu with the OpenGL model of their robot fish [24]. Each individual exterior part of the fish was meshed piece-wise, while sensors and sonar were implemented in the virtual domain so that the fish could swim autonomously. Hu and Liu used the simulation to test the interaction of their autonomous fish with a column obstacle, as well as to comparison of tail-beat frequency vs. swim velocity test data with the simulator, with their simulation achieving realistic results.

2.6 Mechatronic Design

Mechatronics is an extremely rich and diverse field encompassing all manner of mobile robots, and many of the technologies developed for land robotics can be adapted for use in simulating marine life. The state of the art in biomimetic undersea locomotion is encompassed by thunniform and ostraciiform propulsion, carangiform propulsion, anguilliform propulsion, design of ray like propulsion, approaches to sharp maneuvering, pectoral fin propulsion, use of advanced materials in actuators, and design innovation for specific tasks.

Thunniform and ostraciiform propulsion are the simplest approaches to fish like locomotion. Both forms involve little in the way of complex mechanical design, being characterized by movements of only the extreme rear of the robot. A signature of these designs is the presence of a single moving link, the tail fin; they represent the implementation of the classical oscillatory foil for propulsion. Tzeranis *et al*. proposed a design for an autonomous thunniform, detailing its control scheme [73]. Papadopoulos *et al*. later followed up this work with the actual implementation, focusing on the advantages of the low cost and small size of the design [52]. The robot used a single DC gear motor and was able to achieve speeds of 0.157 m/s. While the Tzeranis-Papadopoulos design was teleoperated, the ostraciiform design synthesized by Hur *et al*. employed a third order model for control and operated in closed loop during swimming

[28]. In experimental studies, their H-infinity methodology controller proved to be robust, accurately tracking a reference input for yaw angle.

Carangiform propulsion is one of the more popular design choices when new robotic fish are in the planning phase. This is because carangiform motion is associated with fast and efficient long distance swimmers, such as the bluefin tuna. Carangiform swimmers are characterized by having usually three or more links because to accurately reproduce the natural motion, the tail mechanism must be approximately one third the robot length and have ample articulation ability. Hirata developed a carangiform fish of three links, using a clever mechanical linkage to actuate the three links with only two servomotors [21]. The robot was used to study the effect phase angle between link two and link three would have on swimming speed. Yu *et al*. constructed a four link carangiform swimmer for use in the team's study of teleoperated control strategies [80]. In this robot, the tail links are each direct driven by a servo motor mounted to the link. Watts *et al*. constructed a carangiform swimmer with a similar actuation scheme to Yu *et al*. in that each link is driven by a DC motor with feedback, but in Watts team's robot, each motor uses an external bevel gear-set to drive the link following the one it is mounted to [74]. The tail mechanism of this robot was comprised of five links, and the robot was designed and built for use in competition in Europe's Student Autonomous Underwater Challenge, wherein underwater robots are timed in their completion of various autonomous tasks. Anderson and Kerrebrock developed the Vorticity Control Unmanned Undersea Vehicle (VCUUV), which is a large, 300 lb, carangiform type fish robot of three links [3]. The VCUUV uses an electrically driven hydraulic power unit for supply pressure to actuate its links. The VCUUV is particularly noteworthy because of its high development state; it has the ability to dive up to 10 meters, can swim 1.25 m/s, and possesses turning rates of up to 75 deg/s.

Robots using anguilliform propulsion are being developed because of the advantages pure undulatory motion offers the designer. The use of the whole robot body in propulsion means that the robot can be made shorter, and if coupled with a disciplined approach to the kinematic design regarding motion amplitude, the robot can be enabled to fit into and explore areas few other types of undersea vessels can. Knutsen constructed an anguilliform swimmer based on a design with five links [32]. The tail was comprised of five direct acting servomotors which doubled as the hinge connections between links. Knutsen describes the implementation of an open loop control scheme, and was able to demonstrate four unique swimming gaits using the robot.

The motion of rays, such as the manta, has also been the subject of interest by researchers. Design studies into ray like motion include Low's design and modeling of a ray fin. Low's fin uses a series of servo motors equipped with cranks to manipulate the surface of a flexible membrane to produce the biomimetic motion [43]. The physical implementation of Low's design consisted of eight servomotors and was able to swim straight at a speed of approximately 20 cm/s. Khorrami *et al*. sought to reproduce a tail similar to that of an electric ray [33]. The team used two PVC plates linked together and a rack and pinion actuator hard mounted on the ray body and extending into the tail to drive the tail oscillations; this design achieved a top speed of 0.16 cm/s. Hu *et al*. reproduced ray fin motion similar to Low, but the team's design contrasted in that the servomotors actuating the flexible membrane manipulated it directly via long members that were embedded in the membrane and connected to each servo horn [27]. Hu *et al*. were able to demonstrate a maximum propulsive speed of 0.34 m/s with their design.

An obvious area of concern in underwater maneuvering is turning, as a long turning radius could prevent tracking of the desired reference in an autonomous robot and destabilize its control system. One of the more famous studies into fish like maneuvering is in the case of the University of Essex's G9 fish. The G9 was designed to reproduce the sharp turning abilities present in actual fish. Work on optimizing sharp turning behavior in robotic fish started with the G9's predecessor, the G8. Liu and Hu defined a state space for sharp turning behavior in the four link carangiform G8 [41]. In experimental testing, Liu and Hu were able to achieve a turn angle of approximately 60 degrees in just under two seconds. The mechatronic design and control of fish robots at Essex was further refined with the development of the MT1 [39]. With the development of the high speed actuated, three link G9, Hu *et al*. demonstrated that turning rates for robotic fish could approach those for actual fish, with a turning rate of 105 degrees in two seconds achieved [26, 23, 25]. The state space developed for the G8 was expanded for the G9 to encompass four distinct swimming modes; cruise-straight, cruise-in-turn, sharp-turn, and ascent-decent; with the first two modes being more prosaic steady swimming and small angle turning modes respectively, and the last used to change the elevation of the fish.

While it has not been the focus of study for efficient propulsion, pectoral fin propulsion has gained interest for use in efficient maneuvering. Geder *et al*. designed and constructed a swimmer with controlled curvature pectoral fins for the purpose of implementing PID control on the system [16]. The team's aim was to characterize the propulsive nature of the fins, and they found that they were capable of three modes of locomotion; positive lift and negative lift in addition to forward thrust, indicating the possible usefulness of pectoral motion in ascent/descent. Lauder *et al*. developed a pectoral fin propulsor that simulated the cupping and sweeping motion of the sunfish [35]. The propulsor consisted of five nylon tendons, each actuated by a servomotor, that manipulate structural members in a urethane webbing material. Using this experimental set-up, the team was able to prove that cupping and sweeping motion of the pectoral fin was superior to a simple sweep from a drag/thrust standpoint, which indicates the sweeping motion's potential use to slow a vessel down. Westneat and Walker collected data on actual pectoral swimming fish and found that fish that oscillated their pectoral fins tended to swim faster than those fish that "rowed", which shows the promise of a pectoral fin as an oscillatory propulsor [76]. The promise of using lateral oscillations of pectoral fins for lateral movements in a fish robot has yet to be explored.

Advanced materials that can be elastically manipulated when an electrical field is applied are finding use as actuators in fish robots. Ionic polymer-metal composites (IPMC) are one such class of materials. IPMCs are materials made from an outer sheath of conducting material with an ion exchange membrane in between; these materials deform elastically when a voltage is applied because of static interactions inside the material itself. Chen *et al*. developed a thunniform swimmer to test the performance of an IPMC actuator made from two gold conductors over a pair of articles [10, 47]. The team modeled all the dynamics of the system in order to have simulation data with which to compare their experimental results. Experimentally the largest velocity that was achieved was approximately 0.02 m/s, while the simulation correlated well. Tan *et al*. constructed a similar thunniform swimmer, in this team's case the focus was on mobile sensing, with the maximum velocity achieved being approximately 6 mm/s [66]. Shape memory alloys (SMA) are another class of materials that can be manipulated through the use of an applied voltage. Unlike IPMCs, SMAs elastically deform when subjected to a voltage because of resistive heating reversibly changing the material's crystal structure. Rossi *et al*. tested a SMA composed of nickel and titanium for use in their fish robot [56]. The NiTi was used as an actuator to elicit a bending moment in a piece of polycarbonate plastic. The NiTi was attached to each end of the polycarbonate and a voltage applied; total reduction in length of the NiTi wire was 0.34 cm, while the lateral displacement of the polycarbonate was 1.02 cm. Rossi *et al*. built upon this work in the realization of actual swim tests involving their SMA actuator [57]. Six replica actuators were employed in the aft section of a carangiform swimmer made of a skeleton of polycarbonate and PVC. Maximum speed achieved was 0.033 body lengths per second, while the maximum amplitude of the tail was 8 cm.

The design of fish robots are usually focused on achieving similarity with a natural model, but occasionally the design is driven by a desire to perform a specific task or to push the performance envelope in a certain area, which can result in designs that look quite unlike those found in nature. Behkam and Sitti constructed a swimming robot using a flagellar motion for propulsion [8]. Flagellar swimming motion is derived from a three dimensional helical wave propagating down the tail; in some ways it can be though of a hybrid between fish like motion and the motion of a propeller. The robot was constructed from a stepper motor, a flagella made from steel wire, and a delrin coupler to connect the two. The team gathered experimental swim data for a number of motor frequencies and demonstrated that their design is capable of 13 mN of thrust when swimming at a frequency of 8 Hz in a silicone based oil. Licht *et al*. demonstrated how the fish like propulsion concept can be scaled upward with their free swimming autonomous underwater vehicle (AUV) [37]. The goal was to design a vehicle that would be highly maneuverable, so that its control would be precise enough to conduct undersea science. The vehicle was designed to be modular, with numerous areas where close coupled oscillating foil and driver assemblies could be installed. The team's initial analysis involved four servomotor modules, one at each corner of the craft, with an estimation of swimming speed and drag coefficient resulting in 2 m/s and 0.1 respectively.

CHAPTER 3
EXPERIMENTAL METHODOLOGY

3.1 Research Question

Approaches to the optimization of fish like swimming in robots have taken a number of different approaches, including tuning the robot's swim characteristics for a particular Strouhal number, designing extensive surfaces on the fish body to act as a passive lead foils whose vortices can be exploited by the tail foil, and the use of models to mimic a natural fish's motion with increased fidelity. The novel approach to optimization taken in this study is the manipulation of the C-term wave envelope coefficients in Lighthill's equation to measure their effect on propulsion in a five link mobile swimming fish robot. Referring back to equation 1, we see two C-terms, the first affecting the linear portion of the wave envelope and the second affecting the quadratic portion of the wave envelope. Clearly these coefficients have a large impact on the swim profile, and require in-depth study.

The body of work on optimizing fish like swimming is continuously maturing, with an extensive volume in existence today. The approaches vary, including studies into the natural world as in [14], Strouhal number and jet profile as in [71, 4, 75, 34], numerical models as in [53], foil angle of attack as in [22], and the effect of tail beat frequency as in [46]. The wave envelope coefficients in the Lighthill equation have not yet received sole focus in an extensive experimental trial. The linear C-term coefficient received a short treatment in [78], but the experimental data was not extensive enough to show an obvious effect.

The characterization of the effects each C-term has on the propulsion efficiency derived is important for two reasons; first is that it defines a new area in fish like swimming to be investigated for efficiency gains, second is that if a clear efficiency choice is obtained among the trials attempted then the data will point the way for future work suggested in the former. The ultimate goal of this study, like similar studies into the efficiency of fish like swimming, is to enhance the body of knowledge so that the advantages of this type of locomotion can be exploited in applications of transportation, undersea exploration, defense, and possibly even medicine.

3.2 Experimental Program

The characterization of C-term effects requires an experimental approach in order to gather real world data on propulsion efficiency. For the experimental program to be executed, a free swimming biomimetic fish robot must be developed consisting of a hull, actuated fish tail, control surfaces, electronics and software. The purpose of the hull is to provide a water tight vessel to for the electronics package and act as the major structural element tying the other machine elements together. The actuated fish tail provides the propulsive force driving the robot. The control surfaces enable directional control of the fish. The electronics package consists of a controller, batteries, and radio control receiver and handles the time varying location of the tail links and the communication with the land based radio transmitter. The robot software will act as operating system on the controller and set the states of the various tail link actuators and the control surface actuators. A testing location with adequate height, width, a depth of water must also be secured to avoid any edge, boundary layer, or other effects from contaminating the experimental data. The test location must be equipped with data recording equipment to allow post processing of lab measurements into useful data.

After the laboratory infrastructure is in place, the experiment itself must be designed. The experimental strategy used in this study is straightforward. The fish will be set at a start position inside the frame being recorded by image capture equipment, then the fish will be set to move forward using the full running amperage of its tail actuators while its image is being captured, finally the image data will post processed to derive the maximum velocity achieved by the fish. The maximum propulsive velocity of the fish is analogous to propulsion efficiency because the amount of energy being placed into the system will not change and is a known quantity. As part of the experimental program, bus voltage must be checked between tests and restored as necessary to ensure a little variation between running current as possible.

3.3 Foil Control Function

The tail modeling function given by Lighthill gives the scientist a basis for which the control system can be designed around. The requirement still exists, though, to condition the results of the equation into a form that can be used by the controller hardware. The conditioning approach taken here to achieve OscData is that which is presented in [65], in which the time dependant portion of the model is removed and the characterization of fish motion is decomposed into time independent matrix. The decomposition is into M number of time periods separated by time interval I, as 2π/M replaces the time dependant frequency f.

$$y_{body}(x,i) = (c_1 x + c_2 x^2)[\sin(kx + \frac{2\pi}{M} i) \qquad (3)$$

The constraints applied are that the corresponding end link coordinates must result in the actual link length l, and that the j-th tail link must fit the curve. The result is a system of equations.

$$(x_{i,j} - x_{i,j-1})^2 + (y_{i,j} - y_{i,j-1})^2 = l_j'^2 \tag{4}$$

$$y_{i,j} = (c_1 x_{ij} + c_2 x_{ij}^2)\sin(kx_{ij} + \frac{2\pi}{M} i) \tag{5}$$

In this system, l_j' is the normalized length of the j-th link. Using an iterative process to resolve the tail geometry for each time step, a rectangular matrix is created for tail link angles, which the derivative is the tail link angle change with respect to time.

$$OscData[M][N] = \begin{pmatrix} \phi_{01} & \phi_{02} & \cdots & \phi_{0N} \\ \phi_{11} & \phi_{12} & \cdots & \phi_{1N} \\ \cdots & \cdots & \cdots & \cdots \\ \phi_{M-1,1} & \phi_{M-1,2} & \cdots & \phi_{M-1,N} \end{pmatrix} \tag{6}$$

$$OscData'[M][N] = \begin{pmatrix} \phi_{01} + \Delta\phi_1 & \phi_{02} + \Delta\phi_2 & \cdots & \phi_{0N} + \Delta\phi_N \\ \phi_{11} + \Delta\phi_1 & \phi_{12} + \Delta\phi_2 & \cdots & \phi_{1N} + \Delta\phi_N \\ \cdots & \cdots & \cdots & \cdots \\ \phi_{M-1,1} + \Delta\phi_1 & \phi_{M-1,2} + \Delta\phi_2 & \cdots & \phi_{M-1,N} + \Delta\phi_N \end{pmatrix} \tag{7}$$

In this system N represents the order of the link pin connection, starting numbering at zero with the connection to the body, and M, as in equation 3, is the time step. The final operation to convert the model into a state space for the controller is to transform the angular information into servomotor states. This is done by scaling the angle to a servomotor articulation that ranges from -ξ degrees to +ξ degrees. The angle is divided by ξ degrees, multiplied by 127, the common neutral state of a servomotor when using proportional control, then added to 127. Thus, for an angle of -ξ degrees the state is 0, for an angle of +ξ degrees the state is 254, and for an angle of 0 degrees the state is 127.

$$[\Gamma] = \frac{OscData[M][N]}{\xi^{o}} \bullet 127 + 127 = \begin{pmatrix} \Gamma_{01} & \Gamma_{02} & \cdots & \Gamma_{0N} \\ \Gamma_{11} & \Gamma_{12} & \cdots & \Gamma_{1N} \\ \cdots & \cdots & \cdots & \cdots \\ \Gamma_{M-1,1} & \Gamma_{M-1,2} & \cdots & \Gamma_{M-1,N} \end{pmatrix} \tag{8}$$

Finally the controller interprets the servomotor state space and generates a pulse width modulated (PWM) signal for each servomotor. The most common PWM signal for neutral position in servomotors is 1.5 ms, with the sweep ranging from 1.0 ms to 2.0 ms.

$$F([\Gamma]) = \begin{pmatrix} \Psi_{01} & \Psi_{02} & \cdots & \Psi_{0N} \\ \Psi_{11} & \Psi_{12} & \cdots & \Psi_{1N} \\ \cdots & \cdots & \cdots & \cdots \\ \Psi_{M-1,1} & \Psi_{M-1,2} & \cdots & \Psi_{M-1,N} \end{pmatrix} \tag{9}$$

Three cases are tested in this study, the first using a linear coefficient C-term of 0.1 and a quadratic coefficient C-term of 0.05, the second using a linear coefficient C-term of 0.5 and a quadratic coefficient C-term of 0.05, and the third using a linear coefficient C-term of 0.1 and a quadratic coefficient C-term of 0.50. The methodology and results of the iterative process and its results are shown in appendix A for each case tested. Figures 3.1, 3.3, and 3.5 illustrate the continuous sinusoids given by Lighthill's equation for each time step. Figure 3.2, 3.4, and 3.6 show the results of the tail link fitting operation. For all cases, a tail oscillation frequency of 1 Hz was used to ensure that the servomotors were within their maximum operating speed with safety margin during testing, to avoid having experimental data contaminated by servomotors not keeping proper time. The sampling frequency used was 20 Hz; this frequency was chosen because it yielded a time step interval that was slightly greater than the response time of the servomotors, therefore increasing sampling frequency above 20 Hz would not increase state space resolution with this hardware and would not improve fidelity.

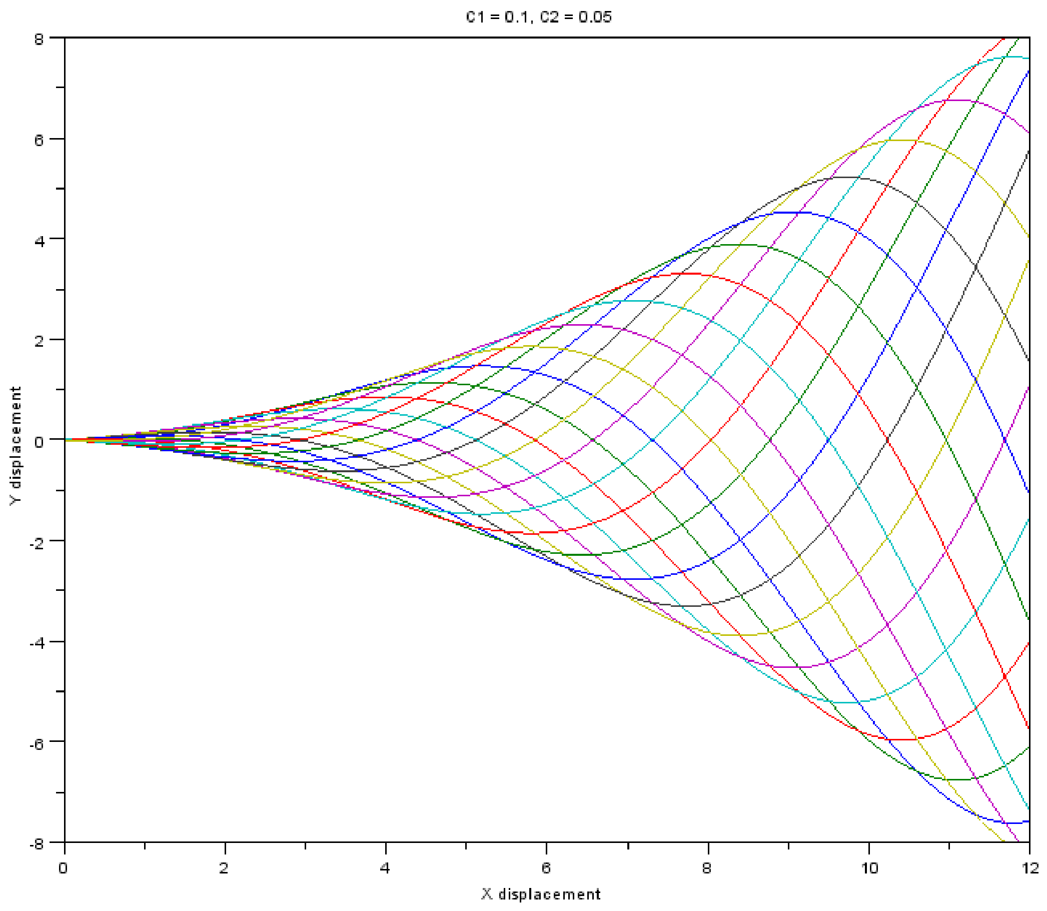


Figure 3.1 – Tail y displacement with change in x, evaluated every 0.05 seconds at a frequency of 1 Hz, case 1

Figure 3.1 shows the baseline time-stepped sinusoids for case 1. This case is characterized by a gradual increase in amplitude, resulting in a small angle of attack for the tail fin. Compared to the other two cases, it might be said that this swim profile more resembles an anguilliform or subcarangiform swimming style in behavior, but not in ratio of oscillatory body portion to overall body length.

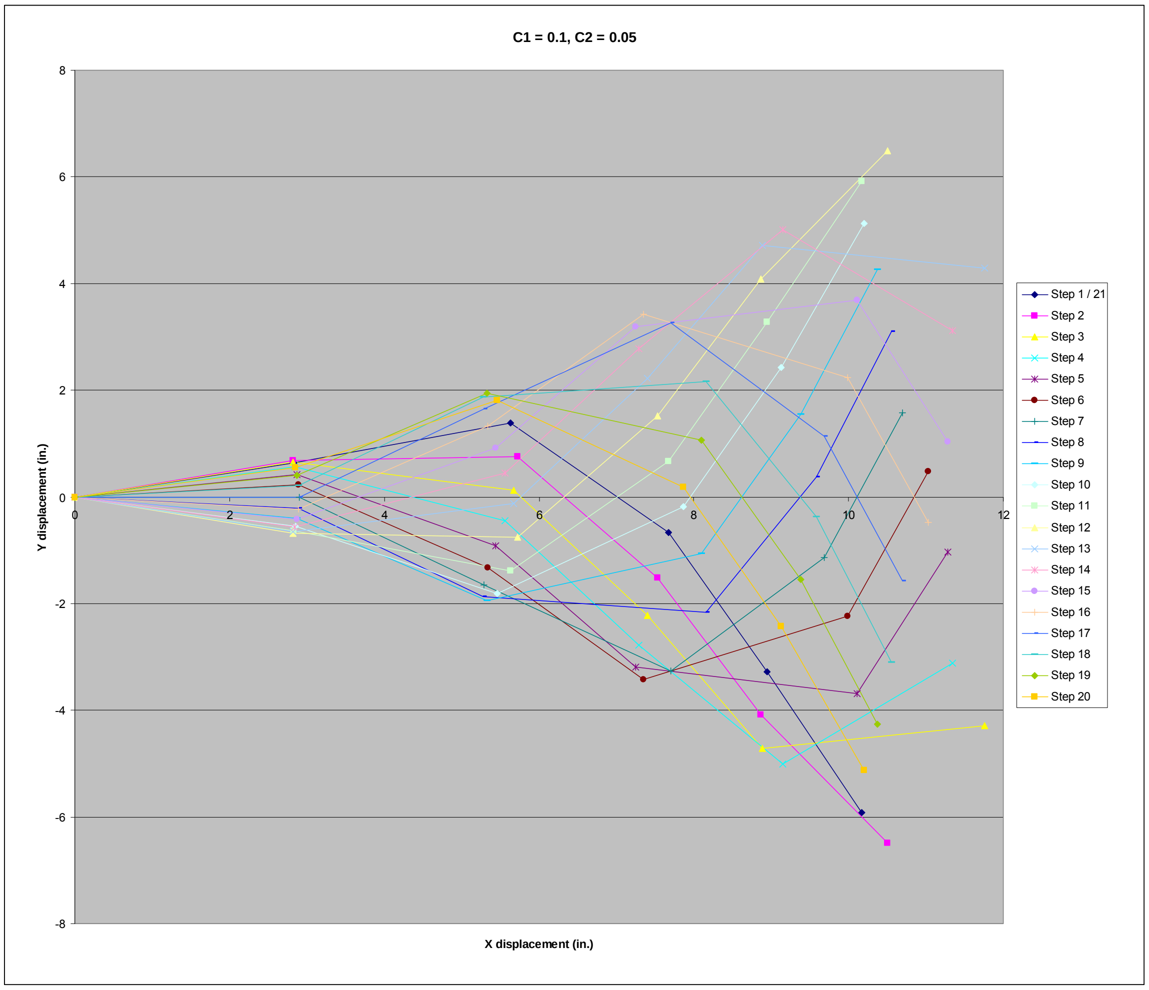


Figure 3.2 – Tail link curve fitting, case 1

Figure 3.2 shows the baseline time-stepped tail link curve fitting for case 1. This swim profile is observed to be very “snaking” in appearance when compared to the other two cases. The gradual increase in amplitude is the easiest for the discrete sized tail links to track, resulting in a minimum of error in curve fitting.

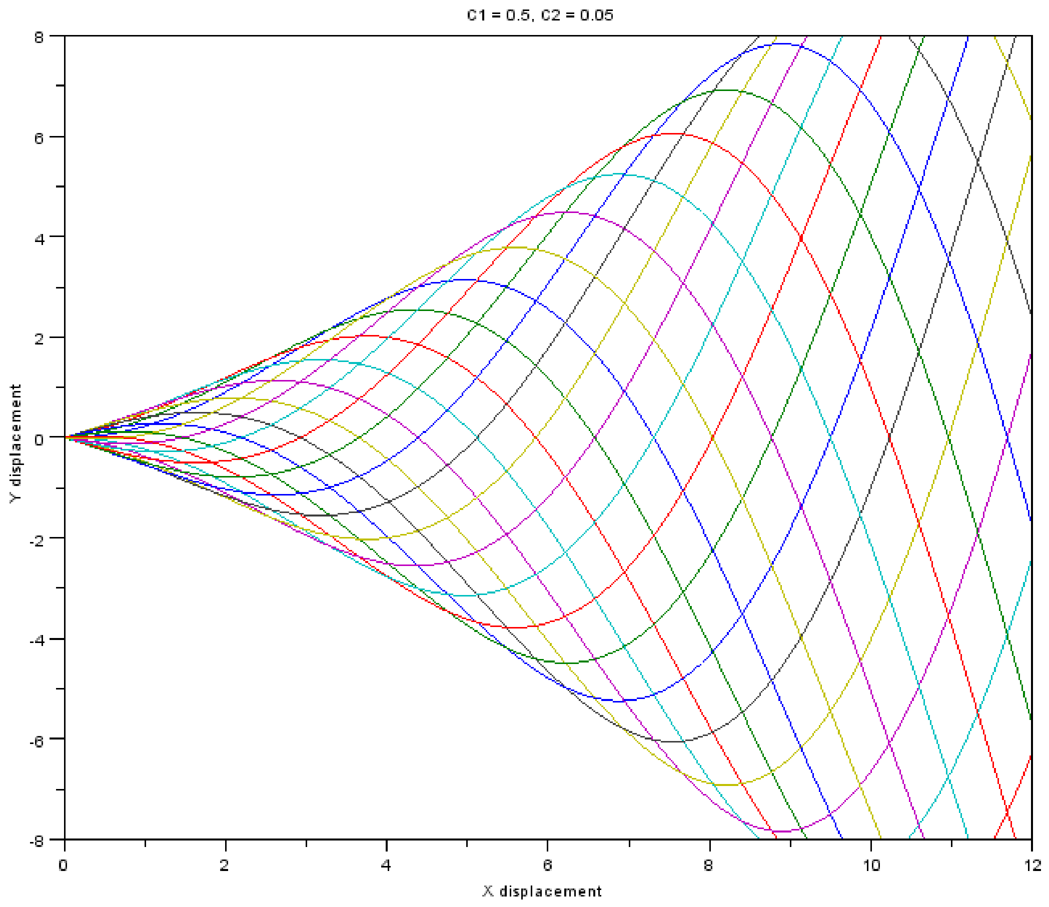


Figure 3.3 – Tail y displacement with change in x, evaluated every 0.05 seconds at a frequency of 1 Hz, case 2

Figure 3.3 shows the increased linear C-term time-stepped sinusoids for case 2. This case is characterized by an accelerated increase in amplitude as the wave travels down the fish tail when compared with case 1, resulting in a larger angle of attack for the tail fin. Compared to the other two cases, it might be said that this swim profile more resembles a carangiform swimming style.

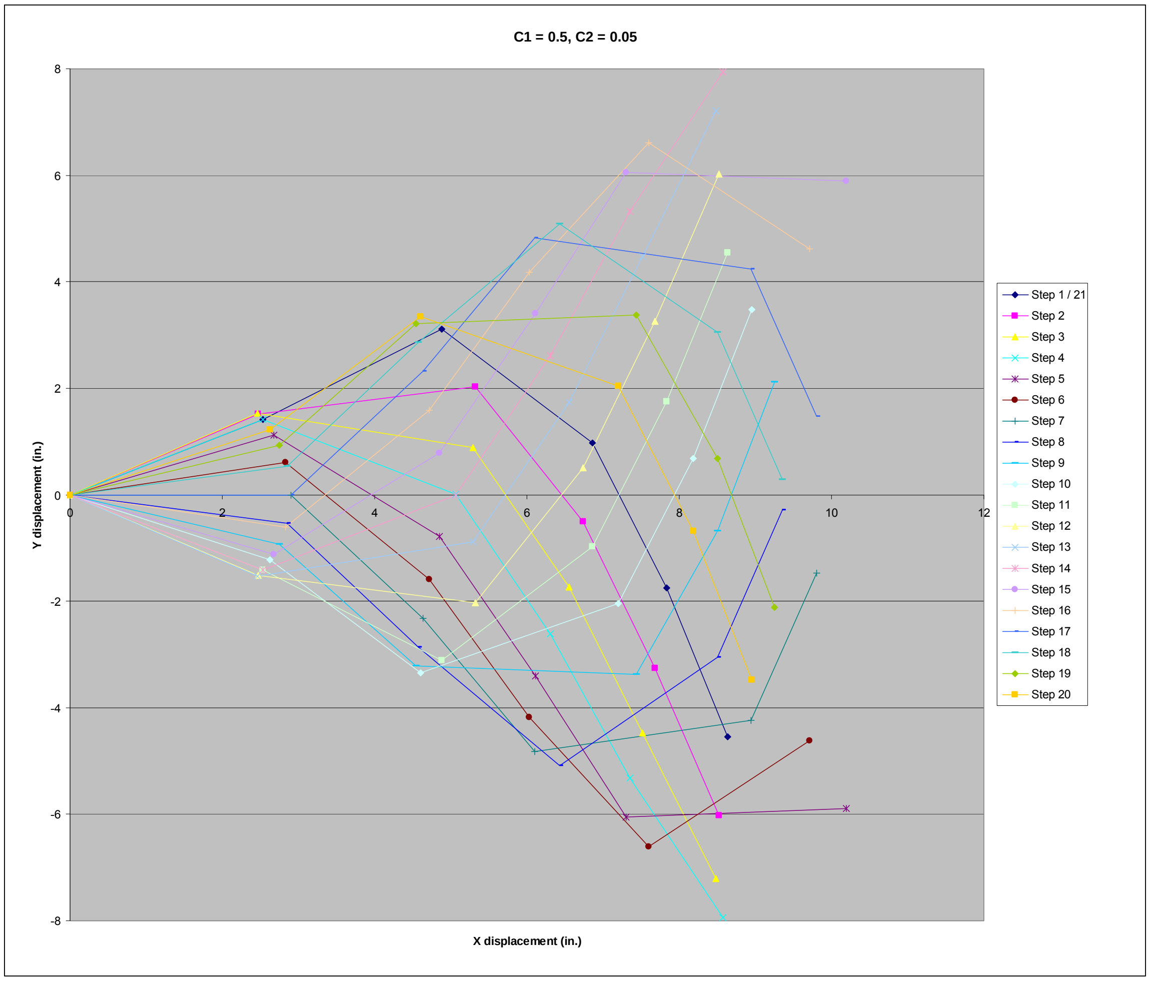


Figure 3.4 – Tail link curve fitting, case 2

Figure 3.4 shows the increased linear C-term tail link curve fitting for case 2. This swim profile is observed to have a moderate motion when compared to the other two cases. The increase in amplitude in this case still provides a curve that the discrete sized tail links can track well, resulting in an error that is still within acceptable limits.

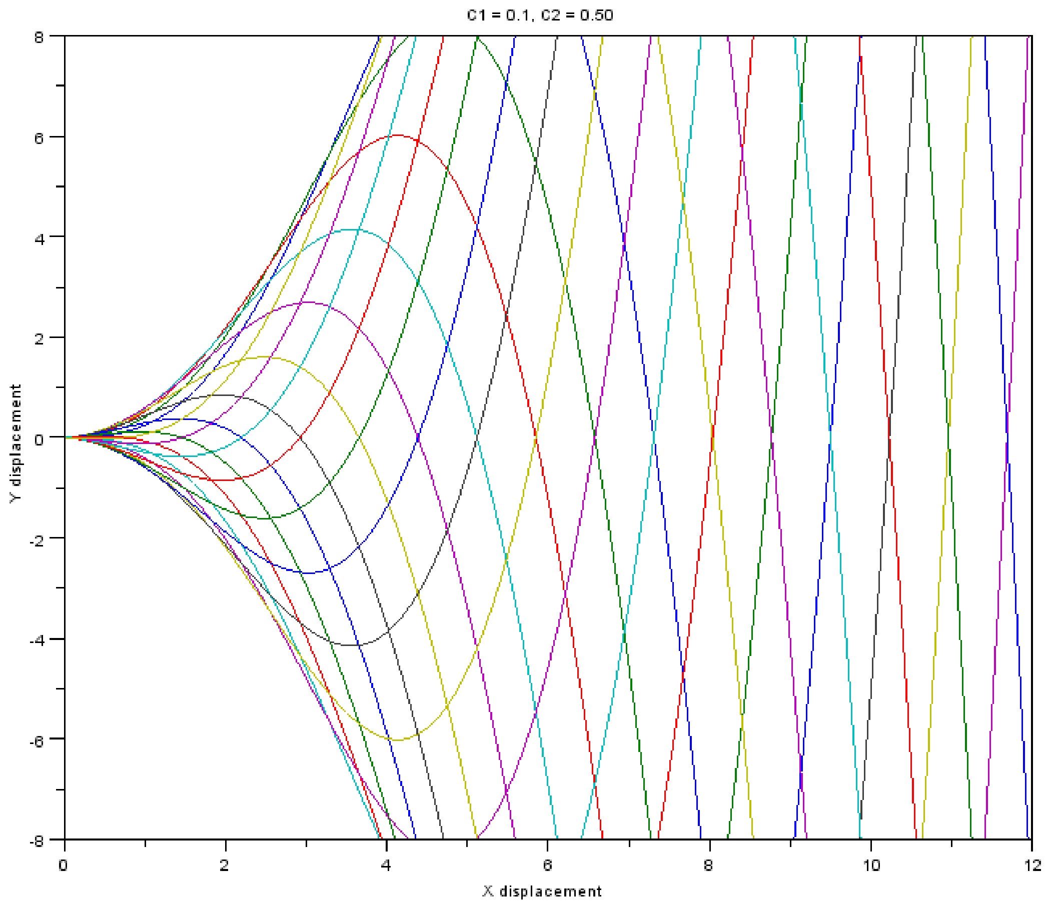


Figure 3.5 – Tail y displacement with change in x, evaluated every 0.05 seconds at a frequency of 1 Hz, case 3

Figure 3.5 shows the increased quadratic C-term time-stepped sinusoids for case 3. This case is characterized by the least gradual increase in amplitude as the wave travels down the fish tail when compared with cases 1 and 2, resulting in a largest tail fin angle of attack. Compared to the other two cases, it might be said that this swim profile more resembles a thunniform swimming style in behavior, but not in ratio of oscillatory body portion to overall body length.

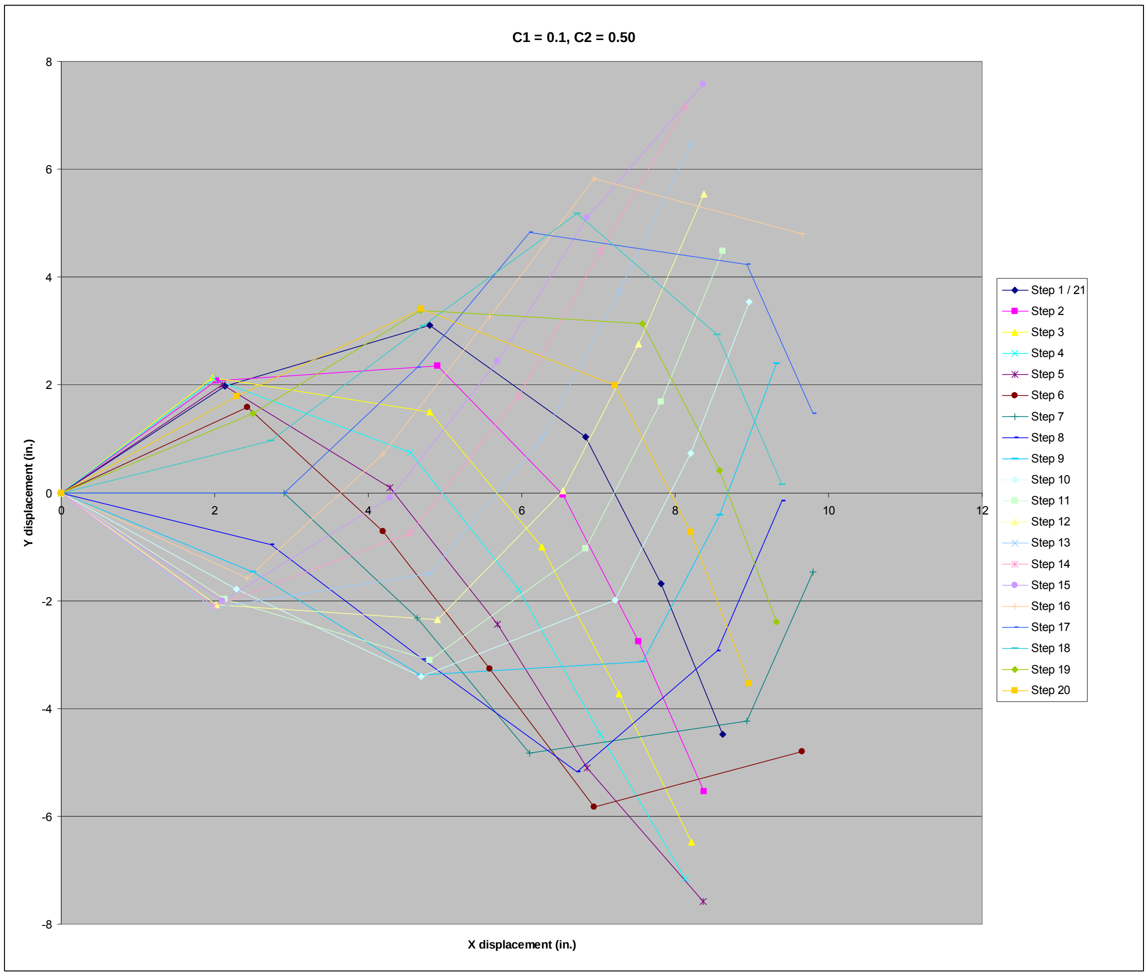


Figure 3.6 – Tail link curve fitting, case 3

Figure 3.6 shows the increased quadratic C-term tail link curve fitting for case 3. This swim profile is observed to have a pronounced “tail whipping” appearance when compared to the other two cases. The sharply increasing amplitude in this case is approaching the practical limit that the discrete sized tail links used in this robot can track with acceptable error.

3.4 Bio-mimetic Drive

As demonstrated in paragraph 3.3, the robot's tail must be constructed with as many links as practical so that the continuous curve produced by Lighthill's equation can be adhered to with a minimum of error. The tail constructed used PVC as the structural material and five direct acting standard sized hobby servomotors for actuation, one servomotor for each link. Each link is formed of two pieces, an upper and a lower half, that are screwed together with stainless steel bolts. When the two halves are disassembled, access to the servomotor pocket is allowed. Each servomotor is attached to its link using four stainless steel screws. Each link is driven by the particular servomotor on board it, with the mounting bracket that attaches the tail to the hull being devoid of a servomotor. Each link is 2.9 in long. The servomotors, as mentioned before, direct drive the tail links, with a 3/8 in driveshaft installed on the horn of each servomotor running upward through the upper half of its tail link into space. Each driveshaft is connected to the link in front of it via a clamping shaft collar fixed to the forward link with four stainless steel screws. The driveshaft and clamping shaft collar form the upper portion of a hinge joint. The lower portion of the hinge joint is comprised of a 3/8 in stainless steel screw embedded in the link's PVC structure along the same centerline as the driveshaft; the shank of this screw rides inside a similarly sized hole in a structural member that cantilevers off the forward link.

The final link is unique in that it has the tail hydrofoil integrated into it. The hydrofoil is a NACA 0012 section that tapers down to a NACA 0008 section at the top, with a slight aft taper angle. The NACA 0012 section was chosen for the base of the foil because it provided the most advantageous thickness (a maximum thickness of 12% of the chord length) to lift coefficient ratio, as well as the reason it is dimensionally similar to propulsors used by some aquatic animals [35]. The NACA 0008 section was chosen for the top of the foil because of its slenderness (a maximum thickness of 6% of the chord length) and that it has an incrementally reduced coefficient of lift compared to the 0012 that equalizes out the truncation of the hydrofoil near the bottom. The NACA 0008 is angled back from the base in a further attempt to reduce viscous drag. The NACA 0012 has been a popular choice in oscillating foil studies [4, 7, 35, 48, 53, 54, 63] and its use here is appropriate.

The servomotors are standard sized, high torque, quick response drivers. They were not originally intended for submersible use; each servomotor has been packed with dielectric grease to harden it against water intrusion. Figure 3.7 shows the robot fish tail fully assembled and ready to be installed to the forward section of the vessel. The large inertial qualities of the tail and the powerful servomotors are likely to cause a recoiling action in the forward section, this has been mitigated by employing techniques defined by Lighthill and summarized in [60]. Firstly, the depth of the tail tapers as it moves aft, and the tail fin is truncated somewhat to reduce its depth. Secondly, the mass of the robot is concentrated in the forward section, owing to the weight of the outer hull bull-noses and the center chassis plate. In experimental use, the fish operates with little recoil; unsteady field effects and existing eddies in the test tank displayed dominating effects on course error during testing. Trials subjected to these errors were obviously erroneous and were screened out of the data collected.

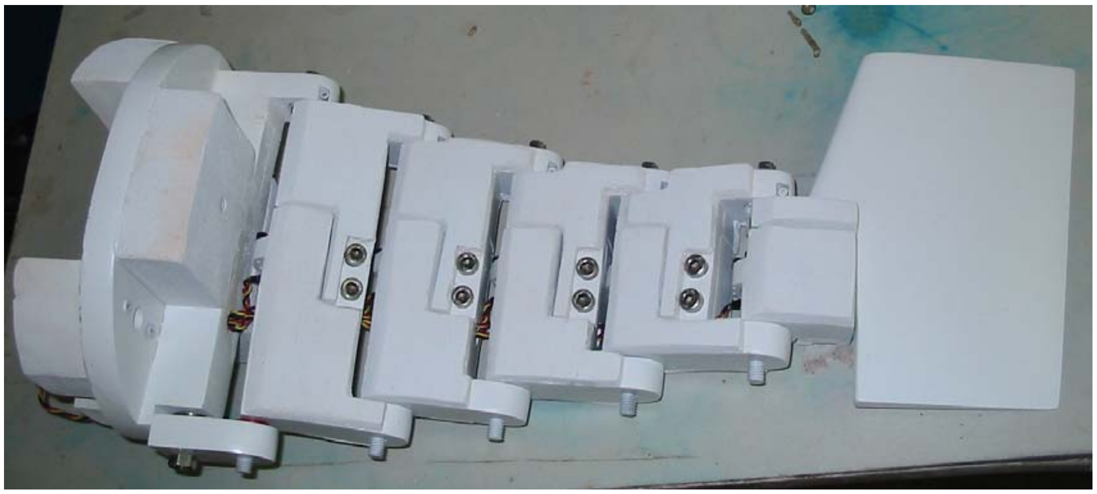


Figure 3.7 – Robot fish tail, fully assembled

For use as a comparison to the experimental data, a numerical model of propulsive force will be employed to verify the validity of experimental results. Kodati *et al.* describe in [34] the method that the model here is based on. Observe the forces and coordinate systems in Figure 3.8.

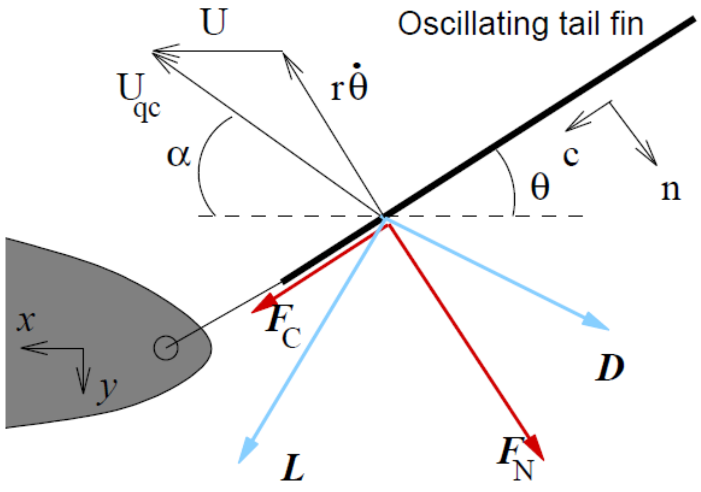


Figure 3.8 – Forces on oscillating foil and coordinate systems [adapted from (Kodati *et al*. 2007)]

In this model X and Y directions are the X and Y directions associated with the plane of the fish robot, while C is the chord direction of the foil and N is the normal direction of the foil. The model accounts for U, the swim velocity of the fish in the X direction, L, the lift force generated by the foil, D, the drag force generated by the foil, θ, the angle between the foil and the X direction, and α, the foil angle of attack. Foil angle and time relative foil angle change were derived from the tables in appendix A used for link fitting. The instantaneous total velocity vector is determined using equation 10.

$$U_{qc} = \sqrt{r^2\dot{\theta}^2 + U^2} \tag{10}$$

The foil's instantaneous angle of attack is determined using equation 11.

$$\alpha = \arctan(\frac{r\dot{\theta}\cos\theta}{U + r\dot{\theta}\sin\theta}) \tag{11}$$

The time derivative of α is determined using equation 12.

$$\dot{\alpha} = \frac{-r^2\dot{\theta}^3 + Ur(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta)}{U^2 + (r\dot{\theta})^2 + 2Ur\dot{\theta}\sin\theta} \tag{12}$$

In the case of fish propulsion, we are primarily interested in the forces in the X direction. To obtain these, first we must obtain the chordwise forces, which are lift, added mass, and drag.

$$F_C = F_C^L + F_C^{am} + F_C^D \tag{13}$$

$$F_C^L = (C_L \sin\alpha)\rho A U_{qc}^2 \sin(\alpha + \theta) \tag{14}$$

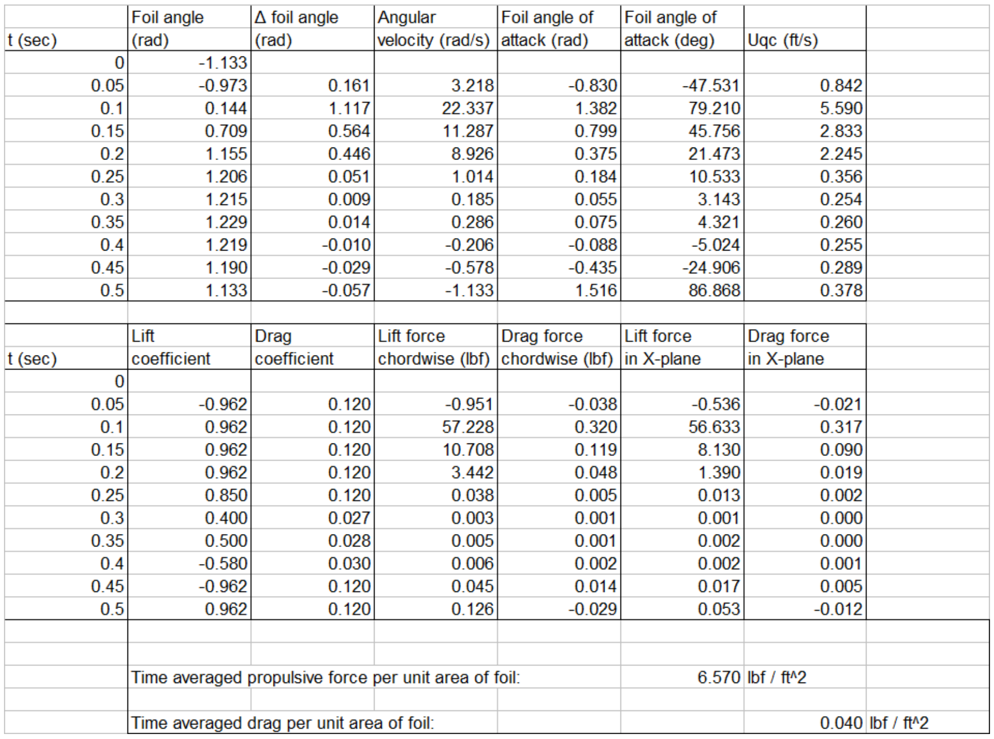
$$F_C^{am} = -\mu_C\dot{U}_C - \mu_{NC}\dot{U}_N - \mu_{C\omega}\ddot{\theta} + \dot{\theta}(\mu_{NC}U_C + \mu_N U_N + \mu_{N\omega}\dot{\theta}) \tag{15}$$

$$\dot{U}_N = \frac{1}{U_{qc}} r^2\dot{\theta}\ddot{\theta}\cos(\alpha + \theta) - U_{qc}(\dot{\alpha} + \dot{\theta})\sin(\alpha + \theta) \tag{16}$$

$$\dot{U}_C = -\frac{1}{U_{qc}} r^2\dot{\theta}\ddot{\theta}\sin(\alpha + \theta) - U_{qc}(\dot{\alpha} + \dot{\theta})\cos(\alpha + \theta) \tag{17}$$

$$F_C^D = C_D\rho A U_{qc}\cos(\alpha + \theta) \tag{18}$$

In the model used here, we ignore added mass, as the primary propulsion phenomenon used by carangiform and thunniform swimmers is lift caused by vorticity [60]. The foil area term is dropped from equations 14 and 18 because it is desired to derive force in terms of unit foil area. Tables 3.1, 3.2, and 3.3 show the estimation of propulsive force for each of the experimental cases given by the model. Lift and drag coefficients were obtained from readily available information sources on NACA foils.



t (sec)	Foil angle (rad)	Δ foil angle (rad)	Angular velocity (rad/s)	Foil angle of attack (rad)	Foil angle of attack (deg)	Uqc (ft/s)
0	-1.133					
0.05	-0.973	0.161	3.218	-0.830	-47.531	0.842
0.1	0.144	1.117	22.337	1.382	79.210	5.590
0.15	0.709	0.564	11.287	0.799	45.756	2.833
0.2	1.155	0.446	8.926	0.375	21.473	2.245
0.25	1.206	0.051	1.014	0.184	10.533	0.356
0.3	1.215	0.009	0.185	0.055	3.143	0.254
0.35	1.229	0.014	0.286	0.075	4.321	0.260
0.4	1.219	-0.010	-0.206	-0.088	-5.024	0.255
0.45	1.190	-0.029	-0.578	-0.435	-24.906	0.289
0.5	1.133	-0.057	-1.133	1.516	86.868	0.378

t (sec)	Lift coefficient	Drag coefficient	Lift force chordwise (lbf)	Drag force chordwise (lbf)	Lift force in X-plane	Drag force in X-plane
0						
0.05	-0.962	0.120	-0.951	-0.038	-0.536	-0.021
0.1	0.962	0.120	57.228	0.320	56.633	0.317
0.15	0.962	0.120	10.708	0.119	8.130	0.090
0.2	0.962	0.120	3.442	0.048	1.390	0.019
0.25	0.850	0.120	0.038	0.005	0.013	0.002
0.3	0.400	0.027	0.003	0.001	0.001	0.000
0.35	0.500	0.028	0.005	0.001	0.002	0.000
0.4	-0.580	0.030	0.006	0.002	0.002	0.001
0.45	-0.962	0.120	0.045	0.014	0.017	0.005
0.5	0.962	0.120	0.126	-0.029	0.053	-0.012

Time averaged propulsive force per unit area of foil:	6.570	lbf / ft^2
Time averaged drag per unit area of foil:	0.040	lbf / ft^2

Table 3.1 – Propulsion force estimate, case 1, c1 = 0.1, c2 = 0.05

t (sec)	Foil angle (rad)	Δ foil angle (rad)	Angular velocity (rad/s)	Foil angle of attack (rad)	Foil angle of attack (deg)	Uqc (ft/s)
0	-1.292					
0.05	-1.274	0.018	0.359	0.159	9.104	0.266
0.1	-1.231	0.042	0.848	0.953	54.618	0.328
0.15	-1.136	0.095	1.905	-0.834	-47.790	0.538
0.2	0.055	1.191	23.819	1.474	84.462	5.960
0.25	0.758	0.703	14.055	0.764	43.772	3.523
0.3	1.270	0.513	10.250	0.274	15.714	2.575
0.35	1.274	0.004	0.076	0.021	1.185	0.251
0.4	1.308	0.034	0.676	0.106	6.070	0.302
0.45	1.304	-0.003	-0.068	-0.019	-1.105	0.251
0.5	1.292	-0.013	-0.251	-0.091	-5.209	0.258

t (sec)	Lift coefficient	Drag coefficient	Lift force chordwise (lbf)	Drag force chordwise (lbf)	Lift force in x-plane	Drag force in x-plane
0						
0.05	0.650	0.070	-0.013	0.004	-0.004	0.001
0.1	0.962	0.120	-0.045	0.024	-0.015	0.008
0.15	-0.962	0.120	-0.368	-0.026	-0.155	-0.011
0.2	0.962	0.120	65.926	0.346	65.827	0.345
0.25	0.962	0.120	16.001	0.142	11.625	0.103
0.3	0.940	0.120	3.273	0.041	0.969	0.012
0.35	0.100	0.025	0.000	0.001	0.000	0.000
0.4	0.400	0.030	0.007	0.001	0.002	0.000
0.45	-0.100	0.025	0.000	0.001	0.000	0.000
0.5	0.580	0.029	-0.006	0.001	-0.002	0.000

Time averaged propulsive force per unit area of foil: 7.825 lbf / ft^2

Time averaged drag per unit area of foil: 0.046 lbf / ft^2

Table 3.2 – Propulsion force estimate, case 2, c1 = 0.5, c2 = 0.05

t (sec)	Foil angle (rad)	Δ foil angle (rad)	Angular velocity (rad/s)	Foil angle of attack (rad)	Foil angle of attack (deg)	Uqc (ft/s)
0	-1.291					
0.05	-1.272	0.019	0.380	0.174	9.974	0.267
0.1	-1.239	0.033	0.660	0.520	29.791	0.300
0.15	-1.179	0.061	1.210	-1.321	-75.662	0.392
0.2	-1.020	0.158	3.164	-0.773	-44.291	0.830
0.25	0.365	1.385	27.709	1.172	67.172	6.932
0.3	1.270	0.905	18.094	0.285	16.350	4.530
0.35	1.279	0.009	0.183	0.045	2.561	0.254
0.4	1.313	0.034	0.678	0.104	5.962	0.302
0.45	1.305	-0.008	-0.157	-0.049	-2.785	0.253
0.5	1.291	-0.014	-0.280	-0.105	-6.044	0.260

t (sec)	Lift coefficient	Drag coefficient	Lift force chordwise (lbf)	Drag force chordwise (lbf)	Lift force in x-plane	Drag force in x-plane
0						
0.05	0.650	0.068	-0.014	0.004	-0.004	0.001
0.1	0.962	0.120	-0.055	0.016	-0.018	0.005
0.15	-0.962	0.120	-0.167	-0.029	-0.064	-0.011
0.2	-0.962	0.120	-0.875	-0.035	-0.458	-0.018
0.25	0.962	0.120	82.603	0.372	77.157	0.348
0.3	0.962	0.120	10.782	0.074	3.196	0.022
0.35	0.250	0.026	0.001	0.001	0.000	0.000
0.4	0.400	0.030	0.007	0.001	0.002	0.000
0.45	-0.250	0.026	0.001	0.001	0.000	0.000
0.5	-0.400	0.030	0.005	0.001	0.001	0.000

Time averaged propulsive force per unit area of foil: 7.981 lbf / ft^2

Time averaged drag per unit area of foil: 0.035 lbf / ft^2

Table 3.3 – Propulsion force estimate, case 3, c1 = 0.1, c2 = 0.50

3.5 Control Surfaces

Like the tail fin, the side control surfaces are NACA 0012 sections that taper down to a NACA 0008 section, with a slight rearward taper angle. These hydrofoils are approximately seven inches in length, and provide the robot with pitch and roll control, as well as flexibility for use in turning control.

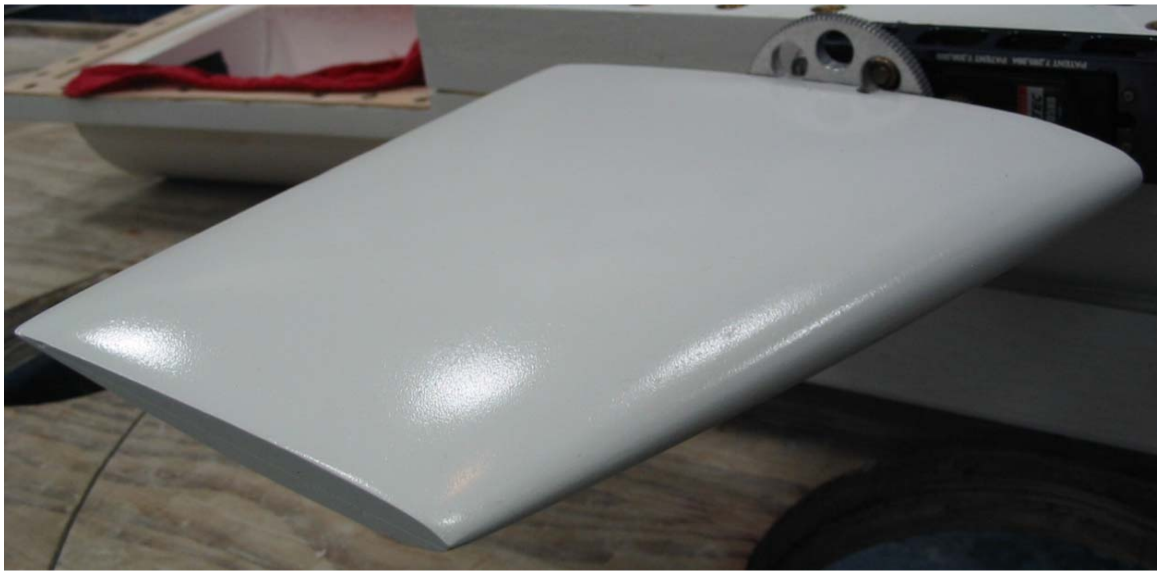


Figure 3.9 – Robot pectoral fin control surface

The control surface actuators are 1260 degree turn, high torque, winch servomotors driving a 5:1 ratio gear set. A driven gear is attached to each hydrofoil with four stainless steel screws. The winch servomotor screws into an aluminum frame which is attached to the fish robot's center chassis plate with four stainless steel studs and nuts. The aluminum frame houses a ball bearing that the driven gear shaft is held into by a c-clip; it is this shaft that the driven gear is clamped to via a shaft collar and set screw assembly.

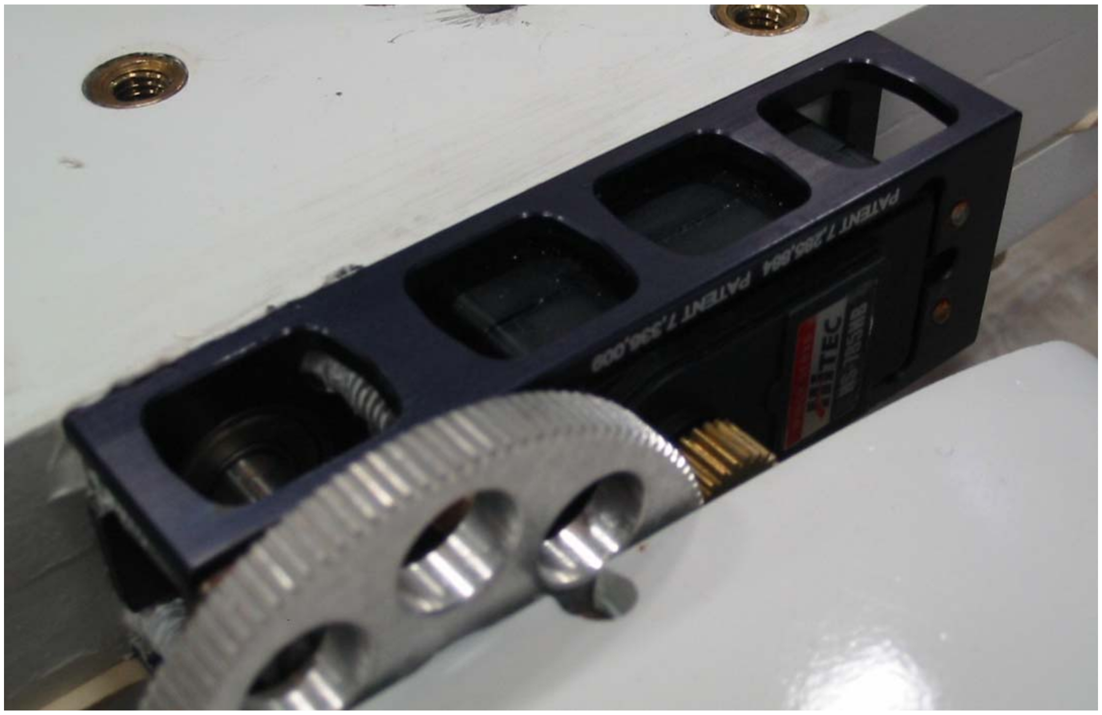


Figure 3.10 – Robot pectoral fin control surface actuator

3.6 Control Hardware

The robot's control system should be sophisticated enough to accurately model fish swimming as defined by the state matrices. For this purpose, a microcontroller of sufficient processing speed must be chosen and it must have associated with it enough memory capacity to contain the program modules required to set all the various servomotor states. In addition, the robot must either operate autonomously or be teleoperated, and have enough on-board energy storage to complete the prescribed testing regime.

The controller selected for the project is an Innovation First Robot Controller (IFRC). It encompasses a Microchip PICmicro® 18F8520 microcontroller and 32 kb of memory. The 18F8520 microcontroller is capable of 10 million instructions per second, which exceeds project requirements. The IFRC is equipped with eight PWM outputs, and since the construction of the robot requires seven, it is suitable for use.

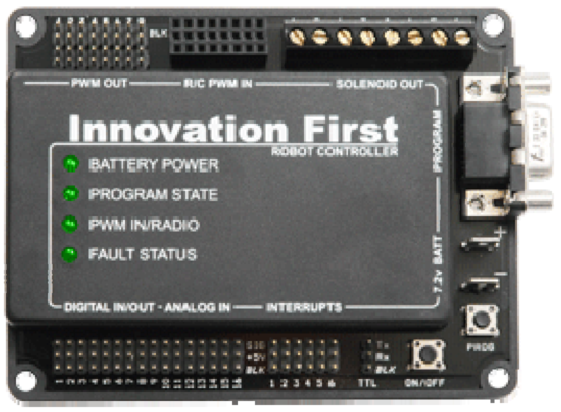


Figure 3.11 – Innovation First Robot Controller (photograph courtesy of Innovation First®, 2012)]

The IFRC is programmable in C coding language, and programs are uploaded via a RS232 port.

Communication with the robot is also a requirement of the project, as the fish will not be autonomous because the data collection strategy requires it to complete a very specific task. Autonomous control is an option for the future, but for these experiments the robot will be teleoperated from land using a 75 MHz radio transmitter and receiver. The radio transmitter and receiver are off the shelf commercially available items, and the receiver will be powered from the IFRC through its connection to the IFRC's PWM ports. The selection of radio transmitter is of particular concern due to the attenuation of radio waves in liquid medium. A technical hurdle in teleoperated underwater robotics is the rapid radio wave signal reduction after the point in which the waves enter the water. Butler details the problem thoroughly in [9] and describes the method to calculate end signal strength. The first step in calculating the end signal strength is to determine the attenuation over distance.

$$\alpha = 0.0173\sqrt{f\sigma} \tag{10}$$

In this equation α is the attenuation in dB per meter, f is the radio wave frequency in Hz (in this case 75(10^6) Hz), and σ is the conductivity of the medium in Siemens per meter. The average conductivity of freshwater is less than 0.1 S/m; 0.075 S/m is used as an estimate here. Attenuation over distance is calculated to be 41.03 dB/m. The next step is to calculate refraction loss at the water's surface.

$$RL = -20\log(7.4586(10\wedge-6)\sqrt{\frac{f}{\sigma}}) \tag{11}$$

In this case, the refraction loss is 28.89 dB. A radio wave signal is only apparent when it is some amount more powerful than the background thermal noise. Thermal noise is calculated using the signal bandwidth Δf, in this case 3(10^3) Hz.

$$P_{dBm} = -174 + 10\log(\Delta f) \tag{12}$$

Equation 12 results in a thermal noise of -93.94 dB relative to 1 milliwatt, and the minimum discernable receive level is 10 dB above this, -83.94 dB. Using equation 13 we are able to calculate the maximum distance D to signal loss.

$$-\alpha D - RL = P_{dBm} \tag{13}$$

The end result is a distance of 1.342 m or 4.402 ft in water. This represents the robot's maximum diving depth before loss of communication.

All systems and subsystems of the robot fish are electrically powered which necessitates on-board storage of electricity. The robot is equipped with two battery packs, a 7.2 volt 2450 mAh bus to power the robot controller and radio receiver, and a 7.2 volt 12000 mAh bus to power the servo motors. The creation of a second voltage bus was a project requirement because the robot controller selected has a four amp breaker designed to protect the controller circuitry from excessive current draws on its PWM out ports.

3.7 Control Software

The software operating the robot has a multitude of responsibilities, it must allow for the scalar mapping of various radio transmitter control stick positions, resolution of receiver channel input into software variables, tracking the passage of time, and time dependant determination of servomotor states. Item three is handled by subroutine clock, while items one, two, and four are handled by subroutine user_routines.

The controller software tracks the passage of time in a relative sense using the subroutine clock. Subroutine clock runs continuously in the background of the control scheme; it exploits the microcontroller's timer 2 register to generate an interrupt in the program every millisecond, with each interrupt increasing the clock count one. As currently configured, the clock will reset itself every 1000 ms, as keeping time beyond this point only complicates other aspects of the control scheme because the tail oscillation frequency is set to 1 Hz. The time stepped servomotor states are established in user_routines in what could be termed a look up table, using an extended if-else if-else command.

The operating software subroutine user_routines resolves the block diagram shown in Figure 3.12 while serving to function as the "servomotor state implementation". This subroutine is responsible for obtaining scalar PWM_in information from the radio receiver.

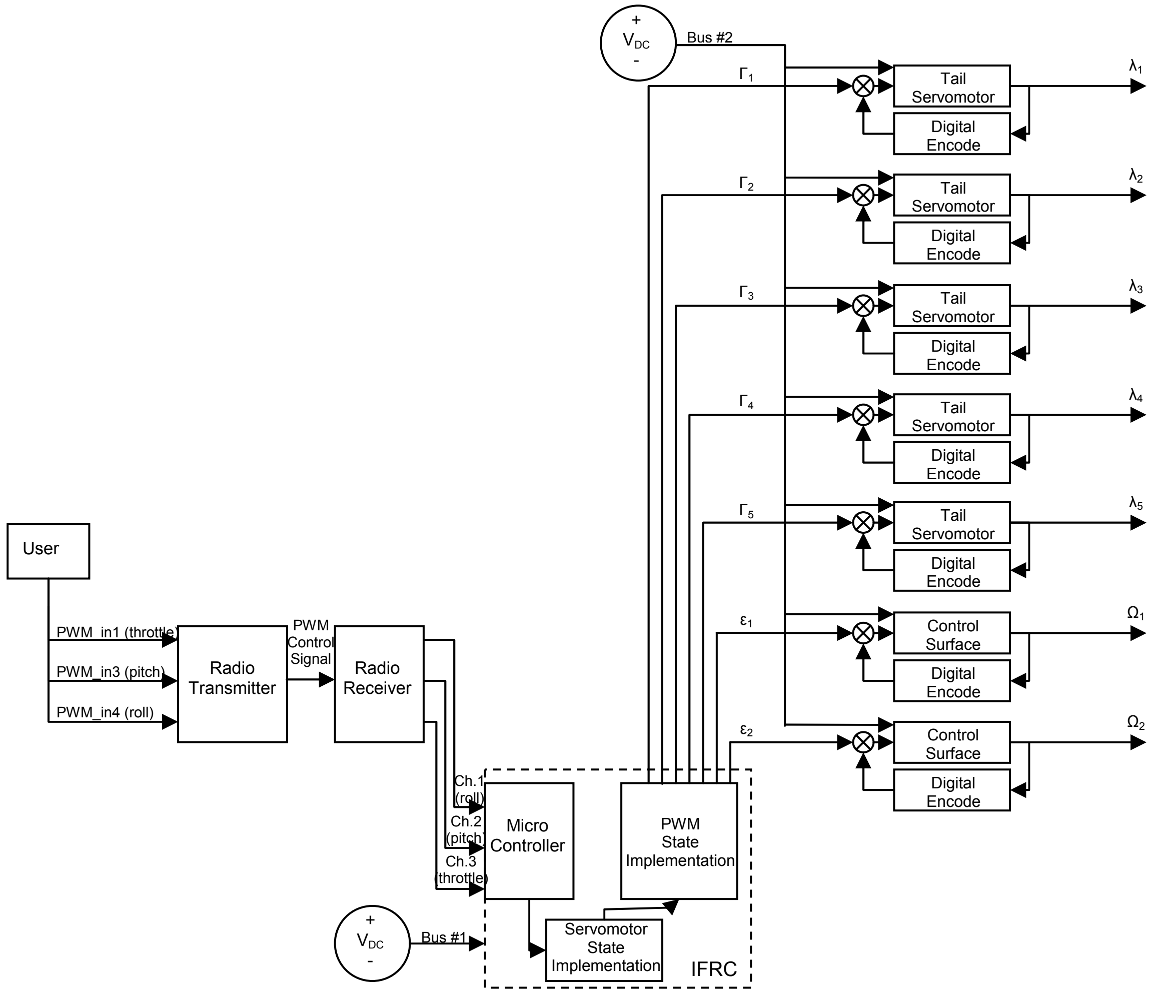


Figure 3.12 – Control scheme block diagram

Setting the tail link servomotor states as described above, the subroutine user_routines also sets the servomotor states for the control surfaces by taking information on right control stick position, which controls pitch on the up and down and roll on the left and right, from the radio receiver and transforming it into scalar information that is then used in a mixing function to set the control surface angles via superposition.

CHAPTER 4

EXPERIMENTAL EXECUTION

4.1 Laboratory Set-up

The experiments were held at University of Illinois Urbana-Champaign's own Ven Te Chow Hydrosystems Laboratory. The laboratory houses many different water tanks and flumes; the tank used in these experiments was the 24.25 ft long, 9 ft wide, and 7.5 ft deep MARGINS tank. This tank was originally constructed to study sediment deposition on the continental shelf, but it was configured for use in these experiments. The floor of the tank and water level were set such that an effective depth of approximately twenty inches was achieved. This allowed for access inside the tank in order for the test trials to be facilitated.

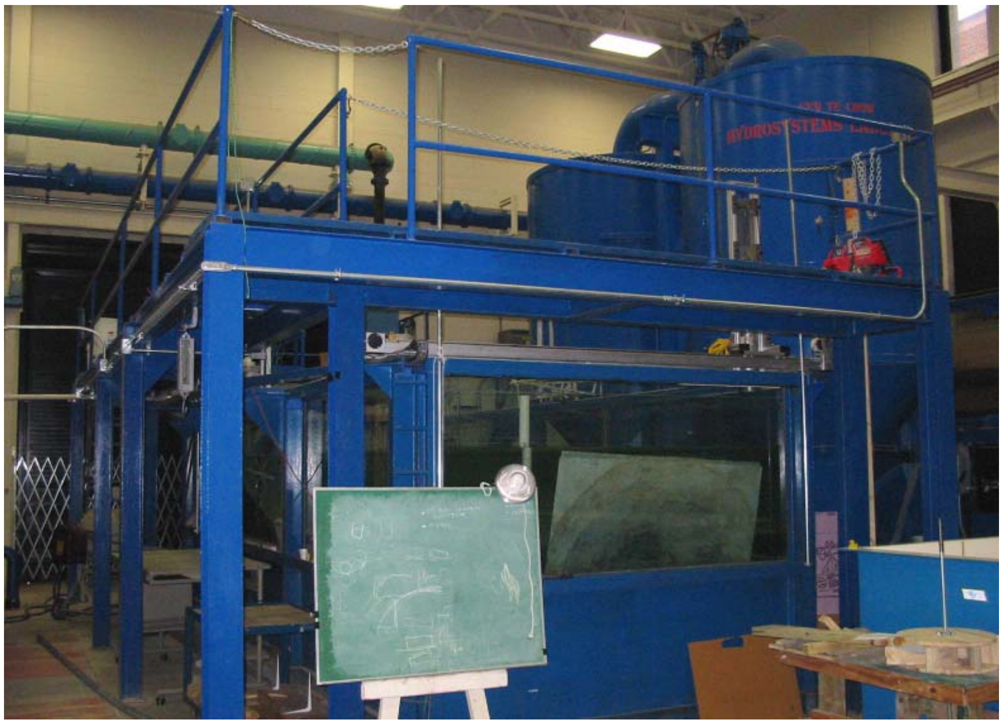


Figure 4.1 – MARGINS tank, front

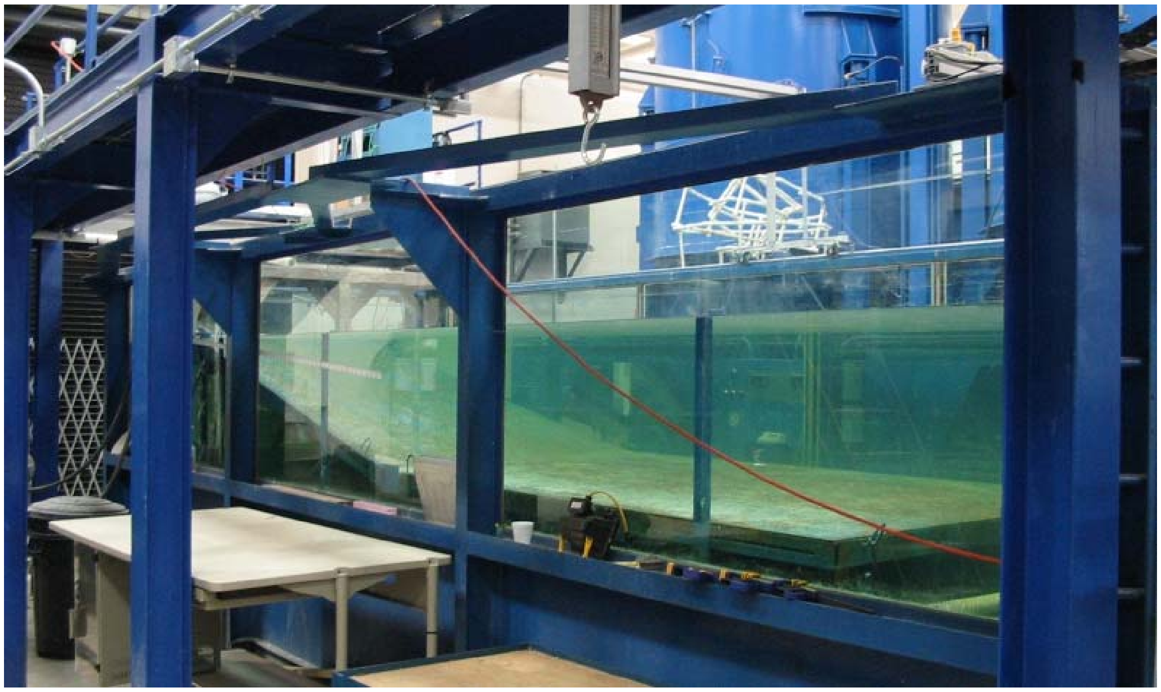


Figure 4.2 – MARGINS tank, side

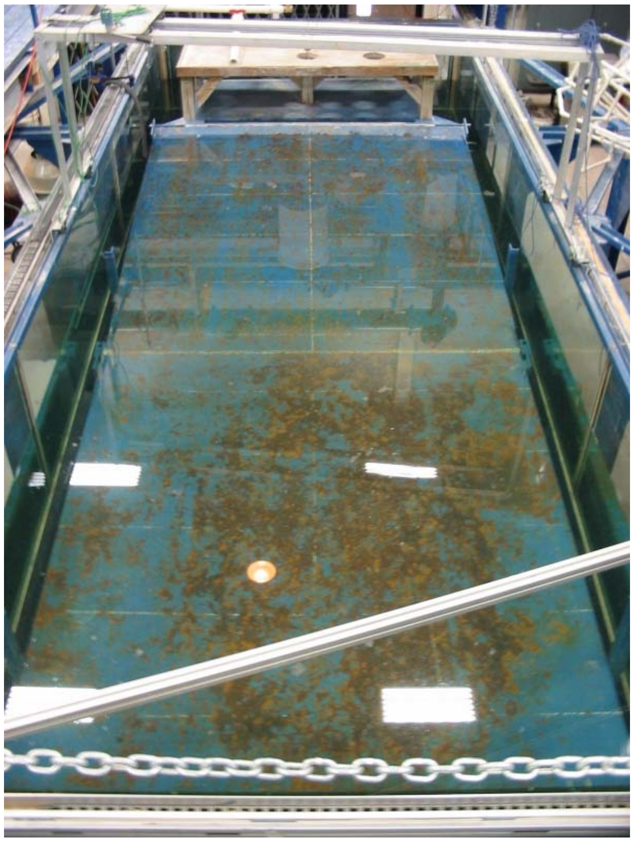


Figure 4.3 – MARGINS tank, top

The MARGINS tank's wetted area is approximately 15 ft long by 9 ft wide, with the first approximately 6 ft of length dedicated to a sloped section required by its original purposing. The sloped section reduces the tank's effective dimensions to 9 ft long by 9 ft wide, which is more than adequate for the tests conducted. The main considerations for tank dimensions are that they be sizable enough to avoid causing boundary layer effects on the robot, inducing viscous drag, or causing eddies as the robot swims by.

The robot used in these tests was the Aquatic High-fidelity Actuation Biomimic fish robot (AHAB), designed and fabricated by the author. AHAB is 42 inches long, 30 inches wide from pectoral fin tip to pectoral fin tip, and 17 inches tall from lowest point to top of the highest point of the top hull. The robot is very close to neutrally buoyant, having a very slow rise to the surface. This facilitated testing, as the robot would remain at the water surface with approximately 1/16 inch of the top buoyancy compensator assembly protruding into atmosphere and the tail fin well submerged. The buoyancy compensator assembly is part of the robot's structural design and assists with counter-acting the presence of heavier hardware such as batteries, fasteners, and such. The buoyancy compensator also mitigates some of the non-minimum phase behaviors that might otherwise be present during operation, such as uncontrolled rolling and un-counteracted moments about the robot's center of gravity. Many of the details of AHAB's construction are given in chapter 3.

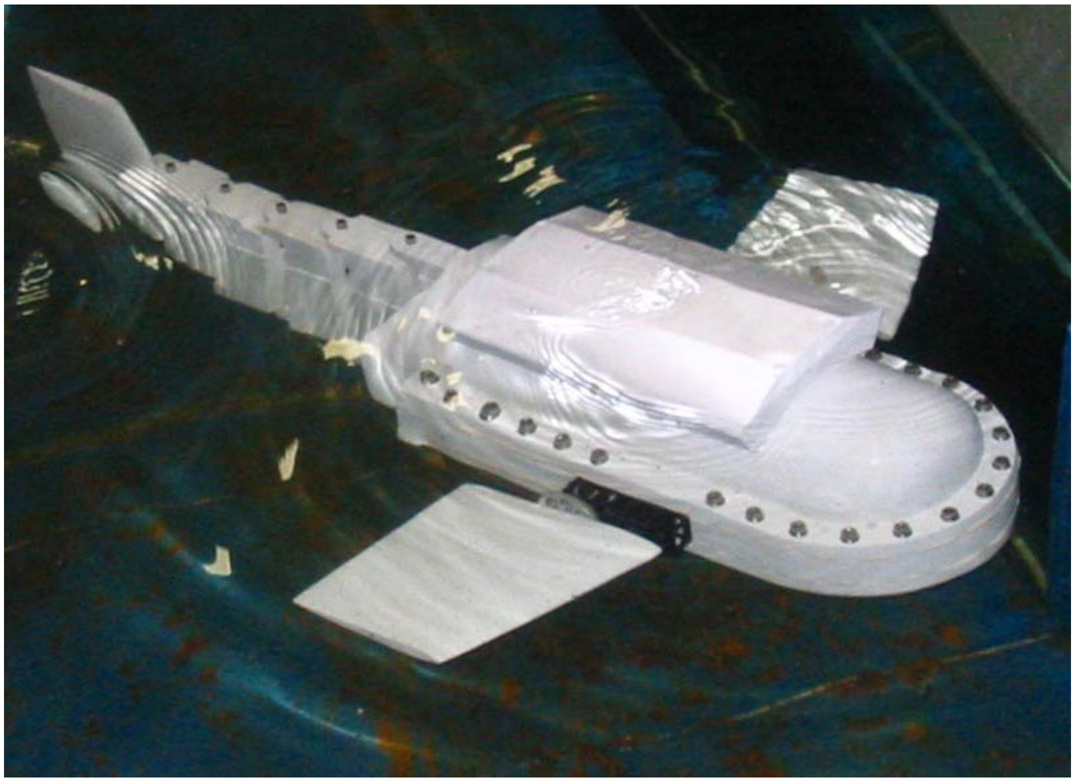


Figure 4.4 – University of Illinois's AHAB fish robot

The lab apparatus was configured with two DSLR cameras for use as data collection devices. The first camera was configured to record video and was mounted to a cross member running between two a-frames that straddled the tank. This camera was pointed straight down on the test area at a height of approximately 4 ft above the water level and operated at 30 Hz. The second camera was configured to record high resolution still images of the test area from an elevated position on the tank catwalk. Images taken by this camera were time stamped to an accuracy of a millisecond, and images were collected at 1 Hz. The view from camera #1 can be seen in Figure 4.5 and the view from camera #2 can be seen in Figure 4.6.

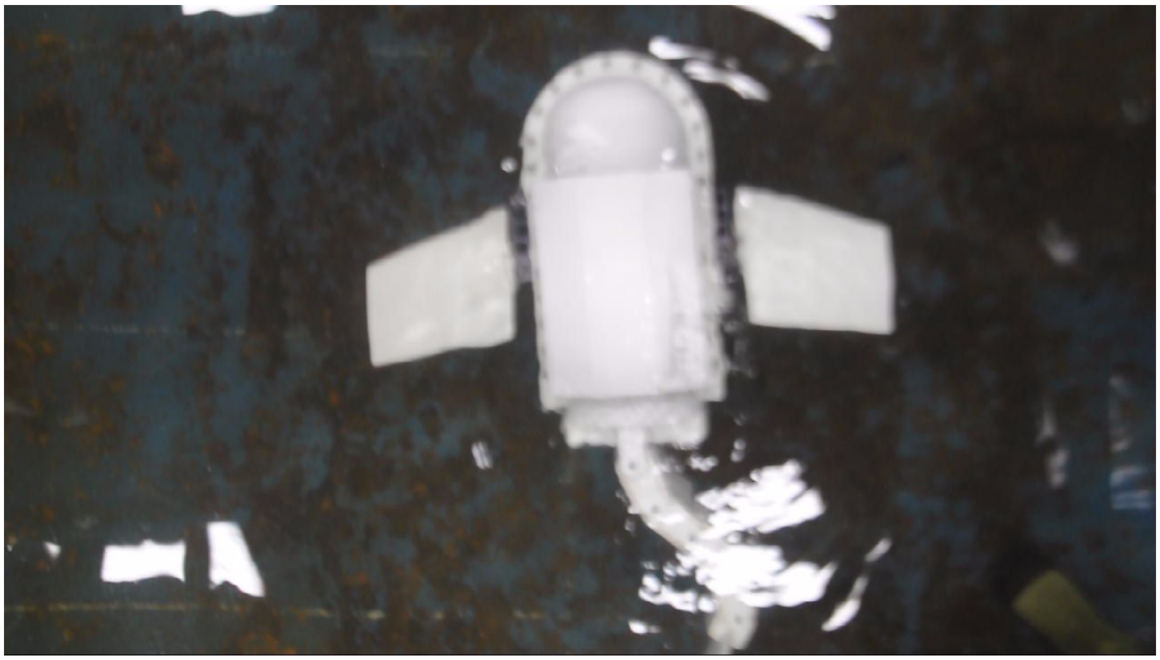


Figure 4.5 – Extracted frame from video recording of experiment test area, camera #1

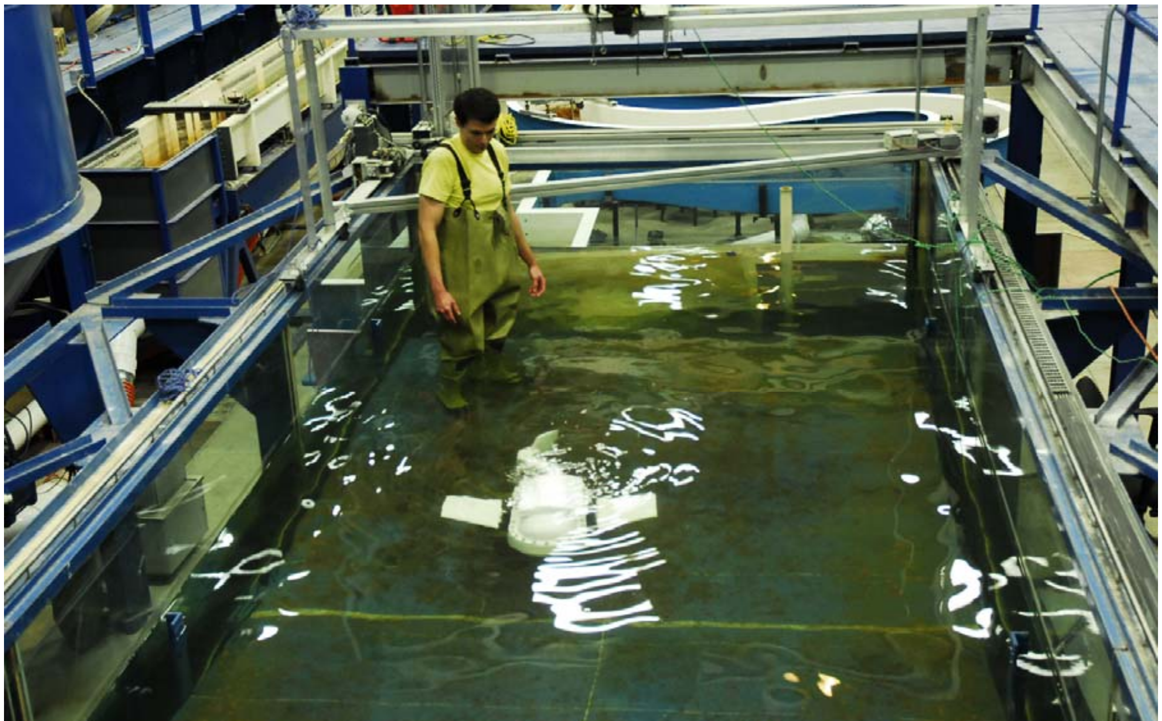


Figure 4.6 – Still image capture of experiment test area, camera #2

A sketch of the data collection set-up is shown in Figure 4.7. The purpose of taking two sets of experimental data was to allow one to verify the results of the other, as camera #1 had a superior frame rate but lower resolution, and camera #2 had a superior resolution but lower frame rate. The still images taken by camera #2 require rectification by Matlab or similar package prior for use in comparison with the data from camera #1. The rectification points used were four spud points on the tank that had precise locations. They can be seen in Figure 4.6 as the four blue structural angles protruding through the water line, one at each corner of the horizontal tank floor section.

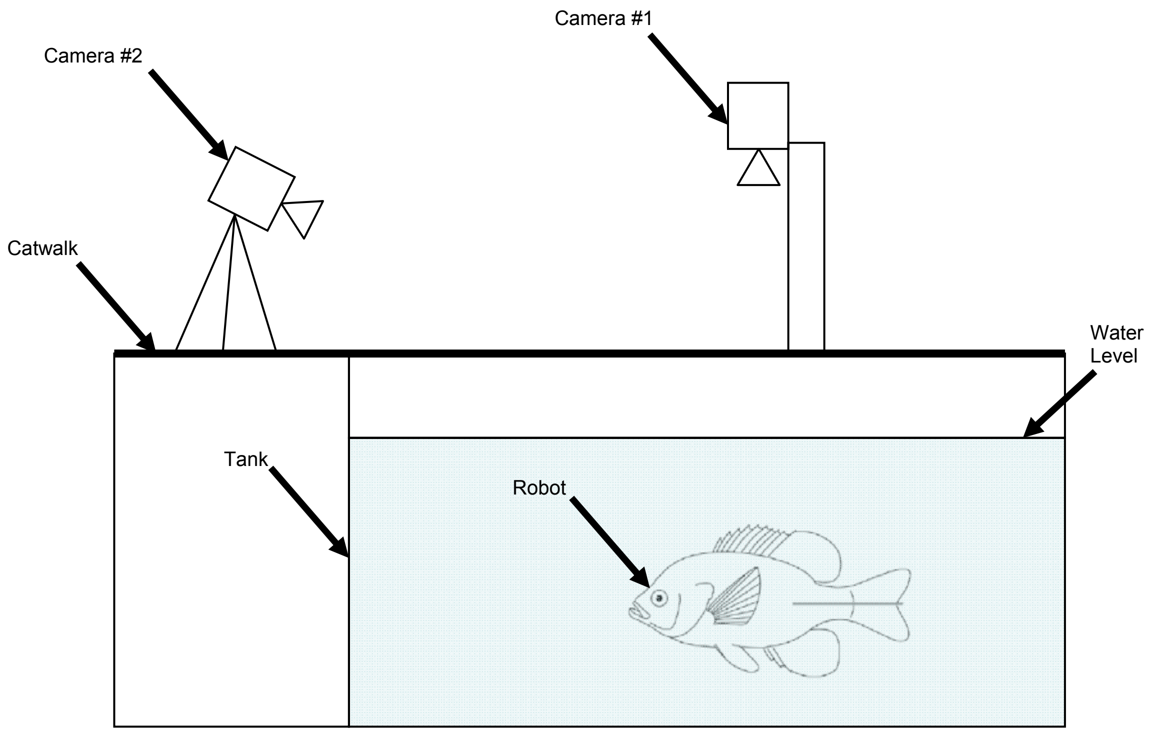


Figure 4.7 – Sketch of experimental data collection strategy

4.2 Test Regime

Since the purpose of the testing was to characterize three different swim profiles, the tests were structured in three phases. The program containing case 1 was loaded into the controller memory, the controller and servomotor voltage buses verified to be fully charged, and the robot assembled. The robot was taken into the tank and trials were accumulated until three quality runs were obtained. Quality was determined based on the lack of any outside induced moments on the robot, RF interference with the teleoperation system, or issues with the data collection equipment. Once data had been taken on the first case, the robot was partially disassembled to access the controller and the program changed to case 2. The bus voltages were verified to be unchanged within measuring equipment accuracy. The large storage capacity of the servomotor voltage bus and the small draw by the robot controller on its voltage bus resulted in very little variation in voltage throughout testing, ranging from a high of 7.64 V to a low of 7.56 V on the servomotor bus and no measurable change in the controller bus. With the program changed and robot voltages verified, the experimental process was repeated for case 2. The overall procedure was repeated again for case 3.

Activities in the tank consisted of a person maneuvering the robot to the rear of the tank where the depth is consistent, positioning it near the limit of the test area being recorded by camera #1, steadying it while perturbations in the water subside, then releasing it carefully so as to not enact an impulse upon it. Very shortly after release, the operator triggers the controller to swim forward. Successful trials swim almost entirely straight, some recoil induced in the forward section by the tail motion causes the swimming to meander small amounts.

As mentioned earlier, the data collected by camera #2 requires rectification prior to use. This process consisted of correcting the still images for the barrel distortion of the camera then applying a rectification algorithm contained in Matlab to the images. The rectification required selecting points of known location in the image to use as reference for the algorithm. Once the algorithm was given frame correction for X and Y scales, the script developed for the post processing of the experimental data was given a particular point on the robot to track. As the script advanced through the time stamped frames, it was able to develop X location, Y location, and time elapsed information, and was able to calculate point velocity. Typical visual output from the script is shown in Figure 4.8.

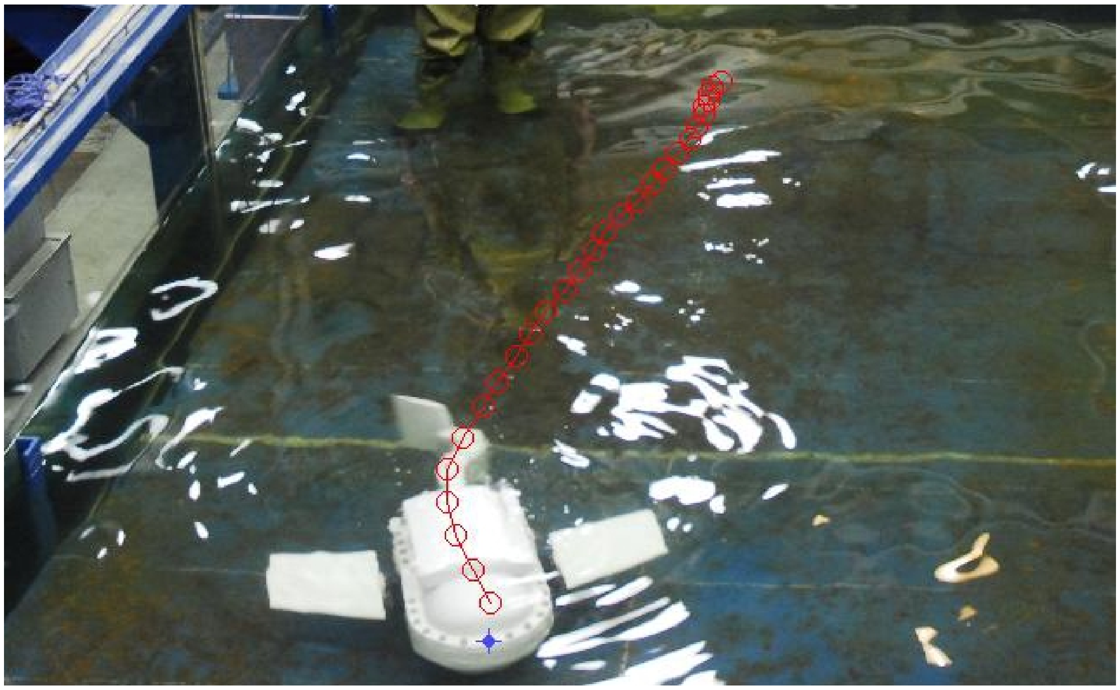


Figure 4.8 – Particle tracking trajectory obtained from Matlab rectifying script

4.3 Observations

Observations taken during testing were primarily to obtain data on swim velocity to determine the effect C-term wave envelope coefficients have on the propulsion efficiency of the robot. The rectified velocities and other data gathered are presented here in their raw form in Tables 4.1 through 4.9. Two items are of note, firstly some of the raw data collected has been truncated in the interest of ensuring experimental accuracy, and secondly, the time elapsed in each experimental run varied from trial to trial resulting in data tables of differing length. The first consideration is for the purpose of obtaining valid results; there exists some concerns on how well the rectification algorithm evaluates velocity at distances very close to the camera. Additive to this issue is the fact that the tank floor slopes upward as the robot comes close to the camera, resulting in the introduction of boundary layer effects and other hydrodynamic phenomenon on the acting on the robot. Since the numerical model estimating propulsive force is absent these effects, runs have been shortened to eliminate them. The second consideration is of little consequence, as the data will show, apparent plateaus appear in the velocity data indicating that trials were long enough to gain an experimental outcome.

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	3.73292	6.3786	0	0	0
1.62	3.63579	6.02024	0.37129	1.62	0.229191
2.62	3.54346	5.77236	0.264515	1	0.264515
3.62	3.40909	5.47013	0.330753	1	0.330753
4.67	3.31863	5.06841	0.411779	1.05	0.392171
5.76	3.17029	4.73427	0.36559	1.09	0.335404
7.09	2.88359	4.28876	0.529787	1.33	0.398336
8.53	2.7174	3.72172	0.590893	1.44	0.410342
10.02	2.62884	3.19531	0.533813	1.49	0.358264
11.45	2.47969	2.64227	0.57279	1.43	0.400553
12.83	2.63872	2.08902	0.575652	1.38	0.417139
14.18	2.68128	1.65796	0.433155	1.35	0.320856
15.53	2.88729	1.14484	0.552934	1.35	0.40958
17.1	3.21178	0.649655	0.592031	1.57	0.37709
18.53	3.54489	0.24911	0.52096	1.43	0.364308

Table 4.1 – Robot swim velocity data, case 1, C_1=0.1, C_2=0.05, trial 1

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	4.24635	6.15375	0	0	0
1.32	4.14606	5.94527	0.231349	1.32	0.175264
2.64	4.04461	5.5746	0.384296	1.32	0.291134
4	4.12632	5.26695	0.318322	1.36	0.23406
5.39	3.96214	4.83911	0.458263	1.39	0.329686
6.79	3.85529	4.42189	0.430683	1.4	0.307631
8.08	3.99869	4.00839	0.437659	1.29	0.33927
9.41	3.84235	3.55209	0.482339	1.33	0.362661
10.73	3.83135	3.07775	0.474468	1.32	0.359446
12.08	3.99412	2.6105	0.494789	1.35	0.36651
13.65	3.98016	2.10142	0.509277	1.57	0.32438
14.9	4.1864	1.61248	0.530654	1.25	0.424523
16.31	4.33157	1.14351	0.490925	1.41	0.348174
17.64	4.32608	0.604702	0.538837	1.33	0.405141
18.9	4.48788	0.161901	0.471433	1.26	0.374153
20.16	4.6194	-0.296795	0.477179	1.26	0.378713

Table 4.2 – Robot swim velocity data, case 1, C_1=0.1, C_2=0.05, trial 2

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	4.08304	6.38024	0	0	0
1.1	4.06533	6.34619	0.03838	1.1	0.0348909
2.05	4.0384	6.15395	0.19412	0.95	0.204337
3.26	4.0515	5.81777	0.336427	1.21	0.278038
4.26	4.01068	5.59923	0.222322	1	0.222322
5.42	3.96486	5.32832	0.274759	1.16	0.236861
6.57	3.93218	4.98195	0.347906	1.15	0.302527
7.73	3.57656	4.7882	0.404983	1.16	0.349124
8.76	3.47425	4.47655	0.328013	1.03	0.318459
9.89	3.41966	4.16428	0.317006	1.13	0.280536
11.01	3.39475	3.81729	0.347884	1.12	0.310611
12.1	3.26808	3.50706	0.335088	1.09	0.30742
13.1	3.16217	3.19673	0.327912	1	0.327912
14.26	3.05888	2.81918	0.391414	1.16	0.337426
15.26	2.93195	2.49283	0.350169	1	0.350169
16.34	2.79529	2.12183	0.395374	1.08	0.366087
17.42	2.62317	1.73846	0.420237	1.08	0.389108

Table 4.3 – Robot swim velocity data, case 1, C_1=0.1, C_2=0.05, trial 3

The trial 1 and trial 3 data for case one shows some evidence of a meandering swim behavior, but this had little apparent effect on the instantaneous magnitude of velocity data, as evidenced by trial 2 having the least consistent acceleration of the three trials.

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	4.25951	6.46953	0	0	0
1	4.34611	6.35361	0.144697	1	0.144697
2.31	4.4135	6.12719	0.236235	1.31	0.180332
3.41	4.42953	5.92035	0.207456	1.1	0.188596
4.84	4.32469	5.5587	0.376546	1.43	0.263319
6.16	4.22764	5.14957	0.420485	1.32	0.318549
7.64	4.29468	4.75274	0.402452	1.48	0.271927
9	4.08358	4.31529	0.485721	1.36	0.357148
10.38	4.12111	3.9167	0.40035	1.38	0.290109
11.74	4.08826	3.43997	0.47786	1.36	0.351368
13.08	4.00089	2.95917	0.488671	1.34	0.36468
14.3	4.0867	2.57311	0.395481	1.22	0.324165
15.66	4.2373	2.14269	0.456011	1.36	0.335302
16.92	4.25583	1.73091	0.412195	1.26	0.327139
18.16	4.27414	1.2805	0.450777	1.24	0.36353
19.55	4.49623	0.818923	0.512234	1.39	0.368514
20.84	4.56166	0.357826	0.465716	1.29	0.36102
22.16	4.53826	-0.111248	0.469658	1.32	0.355801
23.38	4.74191	-0.589754	0.52004	1.22	0.426262

Table 4.4 – Robot swim velocity data, case 2, C_1=0.5, C_2=0.05, trial 1

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	3.9168	5.54642	0	0	0
2.03	3.69699	5.15325	0.450441	2.03	0.221892
3.27	3.56998	4.85512	0.324057	1.24	0.261336
4.44	3.33901	4.58723	0.353712	1.17	0.302318
5.71	3.03243	4.24603	0.458705	1.27	0.361185
6.87	2.8409	3.93529	0.365022	1.16	0.314674
8.03	2.70492	3.62029	0.3431	1.16	0.295776
9.2	2.61261	3.29299	0.340073	1.17	0.290661
10.36	2.44334	2.92629	0.403876	1.16	0.348169
11.71	2.21558	2.52052	0.465325	1.35	0.344685
12.87	2.13082	2.17346	0.357261	1.16	0.307983
13.95	2.10228	1.80547	0.369091	1.08	0.341751
15.04	2.10367	1.4228	0.382672	1.09	0.351075
16.17	2.1033	1.0552	0.367599	1.13	0.325308
17.29	2.12947	0.635572	0.420447	1.12	0.375399
18.51	2.05188	0.195439	0.446919	1.22	0.366327
19.63	2.02237	-0.188432	0.385003	1.12	0.343753
20.79	1.95945	-0.618703	0.434847	1.16	0.374869
21.87	1.96433	-1.11289	0.494211	1.08	0.457603

Table 4.5 – Robot swim velocity data, case 2, C_1=0.5, C_2=0.05, trial 2

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	4.56466	6.45292	0	0	0
1	4.59941	6.28643	0.170079	1	0.170079
2	4.61159	6.192	0.0952097	1	0.0952097
3.08	4.60599	5.96001	0.232059	1.08	0.214869
4.08	4.56235	5.72796	0.236121	1	0.236121
5.16	4.50811	5.41	0.322548	1.08	0.298656
6.08	4.4422	5.13236	0.285355	0.92	0.310168
7.16	4.39341	4.77635	0.359337	1.08	0.332719
8.31	4.29201	4.44542	0.346122	1.15	0.300976
9.31	4.23205	4.12855	0.322491	1	0.322491
10.4	4.12718	3.74924	0.39354	1.09	0.361046
11.46	4.0897	3.38119	0.369951	1.06	0.34901
12.92	4.1506	2.89878	0.486239	1.46	0.33304
13.92	4.22301	2.50758	0.397848	1	0.397848
15	4.38563	2.18273	0.363277	1.08	0.336368
16.16	4.52819	1.8142	0.395142	1.16	0.340639
17.33	4.6212	1.40388	0.420739	1.17	0.359606
18.41	4.92786	1.13367	0.408718	1.08	0.378442
19.47	5.16924	0.819211	0.396419	1.06	0.37398
20.57	5.37103	0.444467	0.425621	1.1	0.386928
21.74	5.63526	0.0595087	0.466914	1.17	0.399072
23	6.02586	-0.264884	0.507736	1.26	0.402965

Table 4.6 – Robot swim velocity data, case 2, C_1=0.5, C_2=0.05, trial 3

The instantaneous magnitude of velocity data for the case 2 data is very consistent from trial to trial. This maybe attributable to this swim profile's "smooth" gait and the lack of recoil forces causing jerk. Conversely, trials for case 3 tended to slalom, or have a back and forth gait. This might have to do with the large changes in foil effective angle of attack during its cycle.

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	4.15531	6.64033	0	0	0
0.76	4.21661	6.52476	0.130825	0.76	0.172138
1.78	4.13051	6.51785	0.0863794	1.02	0.0846857
2.54	4.06881	6.37817	0.152705	0.76	0.200927
3.33	3.92228	6.20346	0.228017	0.79	0.28863
4.29	3.87119	6.00497	0.20496	0.96	0.2135
5.23	3.82311	5.80213	0.208465	0.94	0.221772
6.19	3.76831	5.47571	0.330984	0.96	0.344775
7.26	3.7316	5.1622	0.31565	1.07	0.295
8.21	3.66993	4.96966	0.202179	0.95	0.21282
9.23	3.65883	4.63229	0.337551	1.02	0.330932
10	3.66893	4.37585	0.256639	0.77	0.333297
10.87	3.69471	4.11599	0.261139	0.87	0.30016
11.95	3.63465	3.79022	0.331262	1.08	0.306724
12.78	3.65156	3.55034	0.240467	0.83	0.289719
13.62	3.63403	3.21842	0.332385	0.84	0.395696
14.48	3.55185	2.89795	0.330845	0.86	0.384704
15.62	3.58822	2.57386	0.326119	1.14	0.286069
16.41	3.50311	2.27269	0.312963	0.79	0.396156
17.23	3.52286	1.96268	0.310642	0.82	0.378832
18.19	3.56641	1.68655	0.279538	0.96	0.291185
19.08	3.64255	1.33046	0.364142	0.89	0.409148
20	3.72705	1.0171	0.324551	0.92	0.352773
21.08	3.76677	0.660098	0.359208	1.08	0.3326
21.92	3.89188	0.358529	0.326488	0.84	0.388676
22.84	3.97098	0.0232258	0.344508	0.92	0.374465
23.7	4.02963	-0.242404	0.272027	0.86	0.316311
24.54	4.041	-0.594892	0.352671	0.84	0.419846
25.43	4.10041	-0.909447	0.320117	0.89	0.359682
26.17	4.26729	-1.20416	0.338683	0.74	0.45768

Table 4.7 – Robot swim velocity data, case 3, C_1=0.1, C_2=0.50, trial 1

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	4.11403	6.47716	0	0	0
0.85	3.92518	6.34402	0.231069	0.85	0.271846
1.65	3.86891	6.13024	0.221061	0.8	0.276326
2.48	3.81518	6.04069	0.104435	0.83	0.125825
3.32	3.72726	5.95569	0.122291	0.84	0.145584
4.24	3.58476	5.71796	0.27717	0.92	0.301272
5	3.39008	5.52947	0.27097	0.76	0.35654
5.93	3.18732	5.42959	0.22603	0.93	0.243043
6.8	3.00809	5.22494	0.272042	0.87	0.312692
7.63	2.90543	5.00484	0.242857	0.83	0.292598
8.55	2.84294	4.71954	0.292069	0.92	0.317466
9.49	2.74456	4.53534	0.208824	0.94	0.222153
10.41	2.63606	4.30142	0.257861	0.92	0.280284
11.16	2.48517	4.07486	0.272209	0.75	0.362945
12	2.33778	3.84902	0.269684	0.84	0.321053
12.83	2.23933	3.6532	0.219169	0.83	0.264059
13.66	2.30188	3.45782	0.205155	0.83	0.247175
14.54	2.40398	3.18635	0.290031	0.88	0.32958
15.41	2.45066	2.96671	0.224546	0.87	0.258099
16.3	2.46876	2.73824	0.229185	0.89	0.257511
17	2.39907	2.50602	0.242454	0.7	0.346362
17.85	2.42469	2.26351	0.243859	0.85	0.286892
18.8	2.52696	2.04149	0.244438	0.95	0.257303
19.66	2.65724	1.77637	0.295407	0.86	0.343496
20.56	2.78865	1.49096	0.314203	0.9	0.349115
21.46	2.91666	1.22552	0.294698	0.9	0.327442
22.33	3.0375	0.941441	0.308714	0.87	0.354843
23.21	3.13084	0.640007	0.315557	0.88	0.358587
24.32	3.3233	0.260083	0.425891	1.11	0.383685
25.24	3.45693	-0.0347417	0.323694	0.92	0.351842
26.32	3.63691	-0.359743	0.371508	1.08	0.343989
27.24	3.80965	-0.697639	0.379492	0.92	0.412491
28.24	4.01162	-1.05036	0.406449	1	0.406449
29	4.16478	-1.3514	0.337766	0.76	0.444428

Table 4.8 – Robot swim velocity data, case 3, C_1=0.1, C_2=0.50, trial 2

Elapsed Time [sec]	X [ft]	Y [ft]	dr [ft]	dt [sec]	dV [ft/sec]
0	4.19874	6.71582	0	0	0
0.92	4.12278	6.59952	0.138914	0.92	0.150994
2	4.102	6.40429	0.196336	1.08	0.181793
3	4.1189	6.25636	0.148885	1	0.148885
4.09	4.07969	6.09685	0.164266	1.09	0.150703
5.25	4.10378	5.88465	0.213558	1.16	0.184102
6.23	4.06265	5.62985	0.2581	0.98	0.263367
7.24	4.02478	5.33595	0.296326	1.01	0.293392
8.31	3.95512	5.03325	0.310618	1.07	0.290297
9.41	3.86267	4.70736	0.338749	1.1	0.307954
10.44	3.80117	4.3949	0.318458	1.03	0.309182
11.56	3.7071	4.02192	0.384654	1.12	0.343441
12.5	3.60288	3.73778	0.302653	0.94	0.321972
13.61	3.49869	3.39963	0.353841	1.11	0.318775
14.62	3.476	3.0969	0.303575	1.01	0.300569
15.65	3.40363	2.72523	0.378652	1.03	0.367623
16.61	3.33045	2.39114	0.342012	0.96	0.356262
17.76	3.24083	2.02882	0.37324	1.15	0.324556
18.76	3.18495	1.67184	0.361326	1	0.361326
19.75	3.13022	1.33321	0.343023	0.99	0.346488
20.76	3.0609	0.934546	0.404646	1.01	0.40064
21.76	3.02605	0.581453	0.354808	1	0.354808
22.92	2.94608	0.162467	0.426548	1.16	0.367714
23.92	2.92267	-0.255895	0.419017	1	0.419017
24.92	2.9961	-0.656706	0.407482	1	0.407482

Table 4.9 – Robot swim velocity data, case 3, C_1=0.1, C_2=0.50, trial 3

CHAPTER 5

EXPERIMENTAL RESULTS

5.1 Experimental Trends

The analysis of the experimental results reveals a number of trends. Figures 5.1, 5.2, and 5.3 illustrate time dependant velocity data from the experimental trials; in each experimental grouping, a plateau forms. Figure 5.1 displays the data for the three successful trials in the C_1=0.1, C_2=0.05 case. The line graph demonstrates a plateau that indicates as $t \to \infty$, $U \to$ 0.375 ft/s.

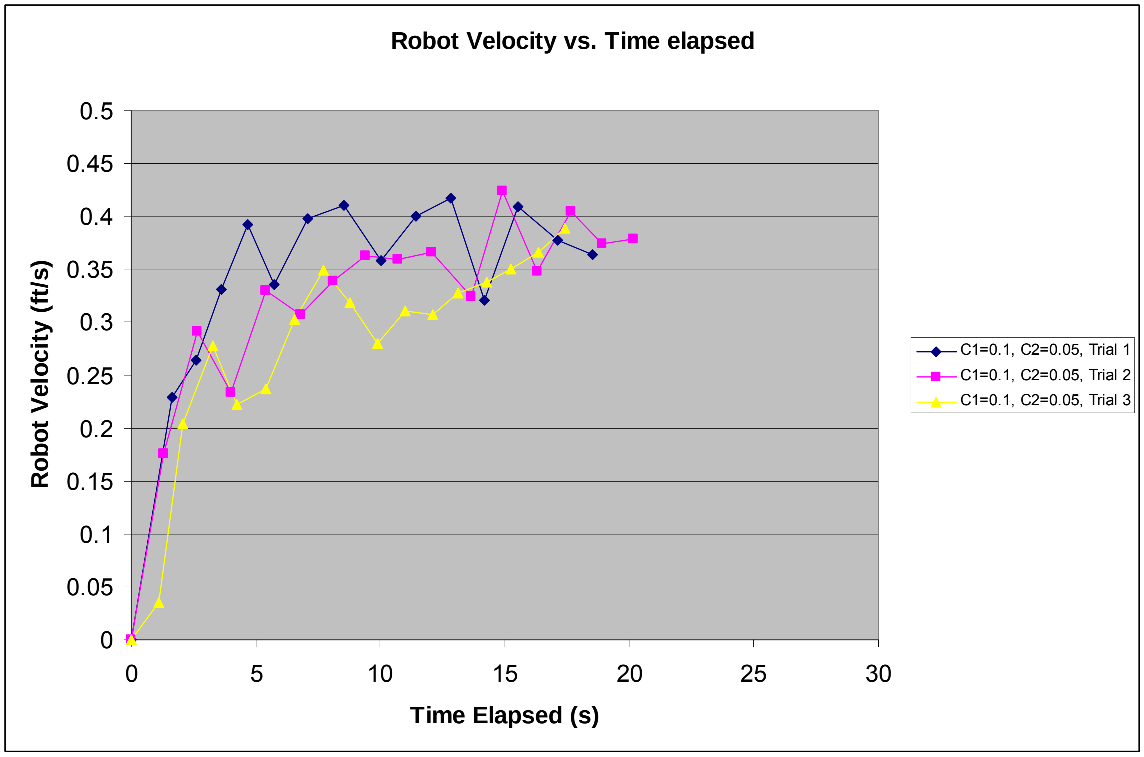


Figure 5.1 – Robot swim velocity vs. time elapsed, case 1, C_1=0.1, C_2=0.05

Figure 5.2 displays the data for the three successful trials in the $C_1=0.5$, $C_2=0.05$ case. The line graph demonstrates a plateau that indicates as $t \to \infty$, $U \to 0.40$ ft/s.

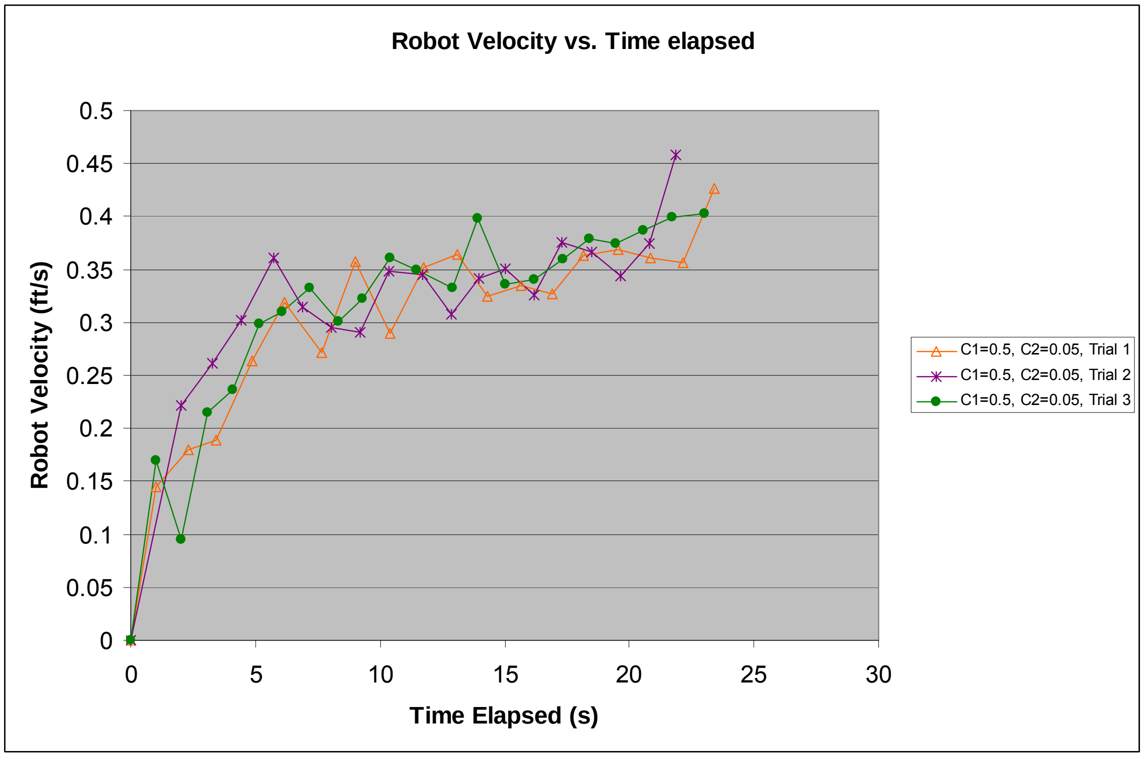


Figure 5.2 – Robot swim velocity vs. time elapsed, case 2, $C_1=0.5$, $C_2=0.05$

Figure 5.3 displays the data for the three successful trials in the $C_1=0.1$, $C_2=0.50$ case. The line graph demonstrates a plateau that indicates as $t \to \infty$, $U \to 0.42$ ft/s.

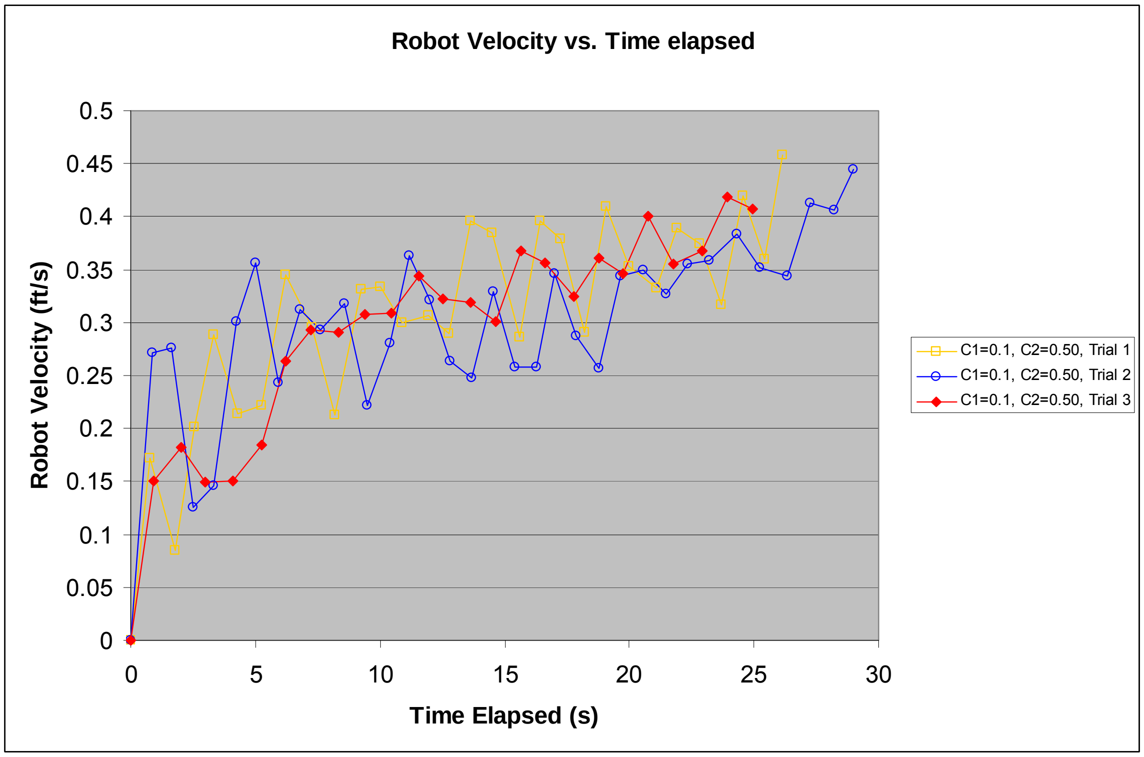


Figure 5.3 – Robot swim velocity vs. time elapsed, case 3, C_1=0.1, C_2=0.50

Figure 5.4 illustrates the comparison of the convergence value of velocity for each of the experimental cases with the propulsive force estimates developed in section 3.4. As one can see, the numerical model and laboratory results appear to validate one another; as propulsion force increases in the theoretical, propulsion speed increases in the experimental.

Another interesting trend found in the results from the numerical model is that for the high Strouhal numbers that prevailed in these experiments, the highest lifts generated by the foil were at extreme angles of attack, resulting at 79°, 84°, and 67° for case 1, case 2, and case 3 respectively. This finding is seemingly validated in the experimental data on thrust coefficient vs. foil effective angle of attack and Strouhal number in [54], where it is apparent that as St increases larger angles of attack become viable without stalling.

This behavior has implications for larger, mission scale, underwater robots where swim speeds are slower and the wake amplitudes are higher.

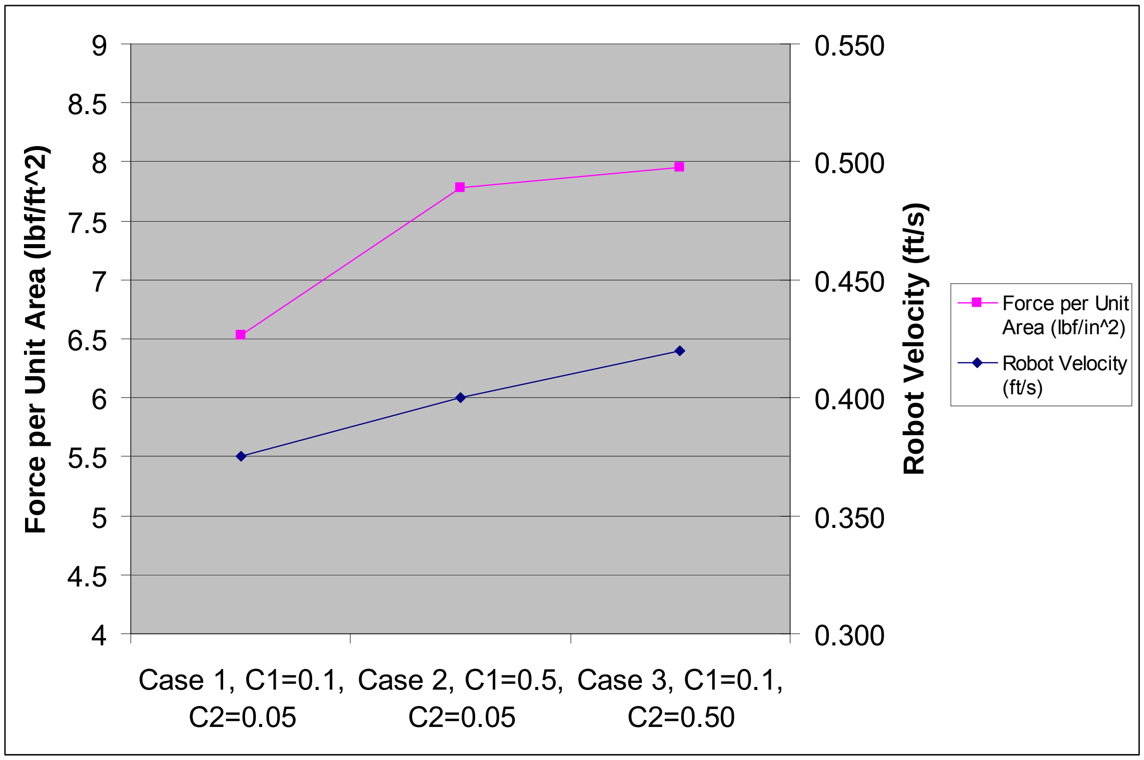


Figure 5.4 – Theoretical force per unit area of foil compared with experimental velocity attained

5.2 Result Discussion

The experimental data shows a discernable difference in the propulsive efficiency in the three experimental cases suggesting that C-term wave envelope coefficients can be used in an optimization approach. The optimization in propulsive efficiency appears to be driven primarily by the larger foil effective angles of attack generated by swim profiles with larger wave envelope coefficients.

The experimental results correlating with results from a numerical lift based model of fish swimming points to validation to the theory that carangiform swimmers rely primarily on hydrodynamic lift due to vortical effects for propulsion. The numerical model used determined lift, drag, and added mass effects in the generation of foil chordwise forces, and despite a simplification applied to the model to eliminate added mass effects, the numerical model correlated well with the experimental data.

CHAPTER 6

CONCLUSIONS

6.1 Concluding Analysis

The work completed in the scope of this project has been extensive and has provided an apparent experimental conclusion. In summation, the project consisted of a experiment planning and construction phase where a robotic fish was built, an experimental phase where three swim profiles were characterized, and an data resolution and interpretation phase.

A biomimetic carangiform robotic fish has been constructed as a functional experimental apparatus. The robot constructed possesses a propulsive section with five short links capable of fitting the sinusoids produced by Lighthill's model of fish tail motion with commendable accuracy. This robot is of solid construction suitable for heavy usage, is capable of pitch and yaw control, is nearly neutrally buoyant, and allows for expansion in features such as the inclusion of analog and digital sensors. It is viable for use in future work involving aquatic mobile robotics research.

The characterization of three cases of varied C-term wave envelope coefficients for Lighthill's model of fish motion has been accomplished theoretically, applied to a biomimetic fish robot using a link fitting technique, and tested experimentally. The three different swim profiles obtained from the cases have been evaluated against each other, as well as against a theoretical estimation of propulsive force. Of the three cases of C-term wave envelope coefficients tested, one has been identified as yielding the highest propulsion speed. This case of C-term coefficients provides optimal efficiency in comparison to the other two, as, in the experiments considered here, propulsion speed is analogous to propulsion efficiency because the power consumption of the system changes little due to the constant running current of the actuators.

A sophisticated experimental technique in which a virtual isometric image is rectified into a 2-dimensional planar representation to obtain velocity data from a mobile robot has been demonstrated. The methodology of utilizing a Matlab script and built in algorithms to track particles in still images and determine changes in X-Y coordinates has been detailed, and when used with temporal metadata inherent to the images, the acquisition of time dependant information now becomes possible.

6.2 Contribution to the Current Knowledge

This project incorporated two novel items of work. The first is the prediction of propulsive forces based on mechanical fish tail linkage kinematics using a lift based theory. The method was able to estimate the propulsive lift and drag on the oscillating foil, with estimates correlating to the experimental results. The implication of this is that the model can be used as a design tool in future linkage motion planning. The second novel item of work was the determination of trends in C-term wave envelope effects on propulsion speed and efficiency of a mobile robotic biomimetic fish. The trends in the fish motion wave envelope suggest that C-term coefficients that generate larger foil effective angles of attack are more efficient than those otherwise. This finding points the direction for future investigations into swim profile optimization.

6.3 Future Work

There exists potential for future work in both the realm of C-term wave envelope investigations and in the improvement of the robot fish lab apparatus. The most obvious avenue for future work is to try more C-term values to see if any further trends develop. Other variables to investigate as they relate to wave envelope are caudal fin shape, namely ones with higher lift coefficients, Strouhal number and the viability of tuning it to values used in other experiments to observe whether results are repeatable, and finally manipulation of C-terms to investigate specific foil effective angles of attack.

Future work that should be considered for completion on the robot fish apparatus itself is the addition of a fleshy covering for the tail section, to determine if propulsive force could be improved by preventing fluid flow lines from crossing the tail linkage. Autonomous control could be added to the robot so that it could conduct experiments on its own, removing the need for a person in the tank to stage it and the need for a strong signal from a land based radio transmitter.

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APPENDIX A

SERVOMOTOR STATE DETERMINATION

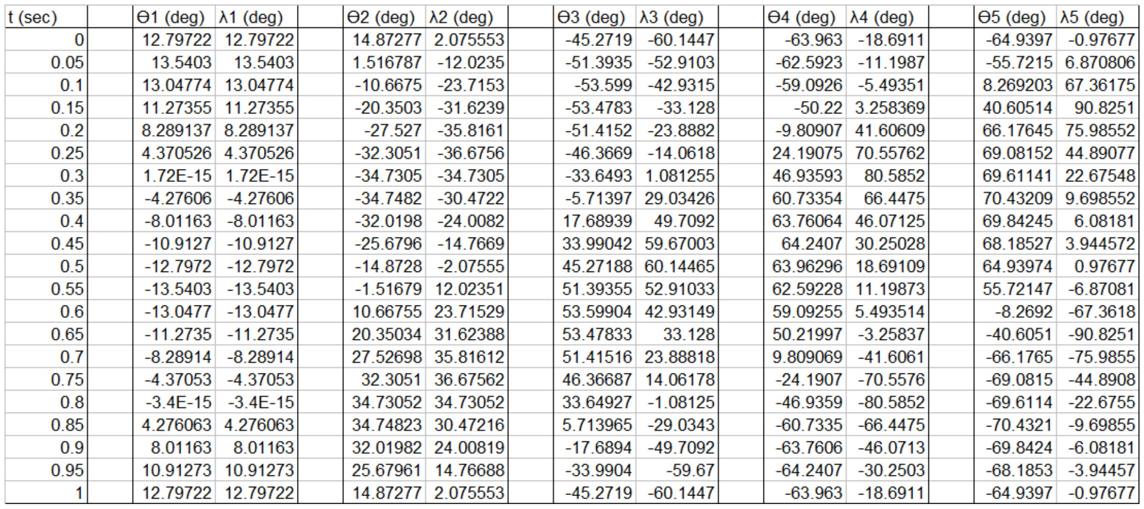
A.1 Case 1, $C_1 = 0.1$, $C_2 = 0.05$

The servomotor states were determined using the method outlined in paragraph 3.3. The first case involved a linear coefficient of 0.1 and a quadratic coefficient of 0.05. The Table A.1 was derived from an iterative scheme to fit endpoints to the curves derived from the Lighthill equation using tail links that were 2.9 inches long.

t (sec)		x1 (in.)	y1 (in.)		x2 (in.)	y2 (in.)		x3 (in.)	y3 (in.)		x4 (in.)	y4 (in.)		x5 (in.)	y5 (in.)
0		2.827964	0.642353		5.630809	1.386707		7.671	-0.67294		8.945	-3.28075		10.175	-5.91126
0.05		2.819396	0.678975		5.71838	0.755737		7.529	-1.51186		8.865	-4.08842		10.5	-6.48717
0.1		2.825129	0.654712		5.67501	0.117893		7.397	-2.21767		8.888	-4.70822		11.76	-4.29082
0.15		2.844045	0.566931		5.563037	-0.44157		7.29	-2.77358		9.145	-5.0016		11.347	-3.11392
0.2		2.869704	0.418089		5.441405	-0.92219		7.25	-3.18901		10.11	-3.68349		11.282	-1.02916
0.25		2.891567	0.220998		5.342688	-1.32884		7.345	-3.42904		9.99	-2.24085		11.026	0.469546
0.3		2.9	8.7E-17		5.283338	-1.65218		7.7	-3.2608		9.681	-1.1412		10.692	1.578957
0.35		2.891927	-0.21623		5.274755	-1.86915		8.162	-2.15804		9.58	0.372273		10.551	3.103998
0.4		2.871695	-0.40418		5.330503	-1.9418		8.094	-1.06042		9.377	1.542464		10.377	4.266611
0.45		2.847558	-0.54901		5.461129	-1.80569		7.865	-0.18484		9.126	2.428395		10.204	5.12158
0.5		2.827964	-0.64235		5.630809	-1.38671		7.671	0.672939		8.945	3.280747		10.175	5.911263
0.55		2.819396	-0.67897		5.71838	-0.75574		7.529	1.511864		8.865	4.088419		10.5	6.48717
0.6		2.825129	-0.65471		5.67501	-0.11789		7.397	2.217675		8.888	4.708219		11.76	4.290816
0.65		2.844045	-0.56693		5.563037	0.441572		7.29	2.773583		9.145	5.001601		11.347	3.113917
0.7		2.869704	-0.41809		5.441405	0.922193		7.25	3.189011		10.11	3.683485		11.282	1.029161
0.75		2.891567	-0.221		5.342688	1.328842		7.345	3.429044		9.99	2.240847		11.026	-0.46955
0.8		2.9	-1.7E-16		5.283338	1.652181		7.7	3.260804		9.681	1.141199		10.692	-1.57896
0.85		2.891927	0.21623		5.274755	1.869147		8.162	2.158043		9.58	-0.37227		10.551	-3.104
0.9		2.871695	0.404185		5.330503	1.941801		8.094	1.060421		9.377	-1.54246		10.377	-4.26661
0.95		2.847558	0.549009		5.461129	1.805691		7.865	0.184844		9.126	-2.4284		10.204	-5.12158
1		2.827964	0.642353		5.630809	1.386707		7.671	-0.67294		8.945	-3.28075		10.175	-5.91126

Table A.1 – Absolute x,y positional data for tail link end points, case 1; link 0 assumed start 0,0

Once a matrix of absolute positions of each link end point has been determined, it is transformed into absolute and relative tail link angles shown in Table A.2. Again, angle θ represents the absolute angle, relative to the x-axis, that the tail link must be rotated to. Angle λ represents the relative angle that the servo must rotate to correctly position the link. The previous tail link's absolute angle must be subtracted from the particular tail link’s absolute angle to compensate for the previous tail link’s rotation, and thus λ is obtained.



t (sec)		Θ1 (deg)	λ1 (deg)		Θ2 (deg)	λ2 (deg)		Θ3 (deg)	λ3 (deg)		Θ4 (deg)	λ4 (deg)		Θ5 (deg)	λ5 (deg)
0		12.79722	12.79722		14.87277	2.075553		-45.2719	-60.1447		-63.963	-18.6911		-64.9397	-0.97677
0.05		13.5403	13.5403		1.516787	-12.0235		-51.3935	-52.9103		-62.5923	-11.1987		-55.7215	6.870806
0.1		13.04774	13.04774		-10.6675	-23.7153		-53.599	-42.9315		-59.0926	-5.49351		8.269203	67.36175
0.15		11.27355	11.27355		-20.3503	-31.6239		-53.4783	-33.128		-50.22	3.258369		40.60514	90.8251
0.2		8.289137	8.289137		-27.527	-35.8161		-51.4152	-23.8882		-9.80907	41.60609		66.17645	75.98552
0.25		4.370526	4.370526		-32.3051	-36.6756		-46.3669	-14.0618		24.19075	70.55762		69.08152	44.89077
0.3		1.72E-15	1.72E-15		-34.7305	-34.7305		-33.6493	1.081255		46.93593	80.5852		69.61141	22.67548
0.35		-4.27606	-4.27606		-34.7482	-30.4722		-5.71397	29.03426		60.73354	66.4475		70.43209	9.698552
0.4		-8.01163	-8.01163		-32.0198	-24.0082		17.68939	49.7092		63.76064	46.07125		69.84245	6.08181
0.45		-10.9127	-10.9127		-25.6796	-14.7669		33.99042	59.67003		64.2407	30.25028		68.18527	3.944572
0.5		-12.7972	-12.7972		-14.8728	-2.07555		45.27188	60.14465		63.96296	18.69109		64.93974	0.97677
0.55		-13.5403	-13.5403		-1.51679	12.02351		51.39355	52.91033		62.59228	11.19873		55.72147	-6.87081
0.6		-13.0477	-13.0477		10.66755	23.71529		53.59904	42.93149		59.09255	5.493514		-8.2692	-67.3618
0.65		-11.2735	-11.2735		20.35034	31.62388		53.47833	33.128		50.21997	-3.25837		-40.6051	-90.8251
0.7		-8.28914	-8.28914		27.52698	35.81612		51.41516	23.88818		9.809069	-41.6061		-66.1765	-75.9855
0.75		-4.37053	-4.37053		32.3051	36.67562		46.36687	14.06178		-24.1907	-70.5576		-69.0815	-44.8908
0.8		-3.4E-15	-3.4E-15		34.73052	34.73052		33.64927	-1.08125		-46.9359	-80.5852		-69.6114	-22.6755
0.85		4.276063	4.276063		34.74823	30.47216		5.713965	-29.0343		-60.7335	-66.4475		-70.4321	-9.69855
0.9		8.01163	8.01163		32.01982	24.00819		-17.6894	-49.7092		-63.7606	-46.0713		-69.8424	-6.08181
0.95		10.91273	10.91273		25.67961	14.76688		-33.9904	-59.67		-64.2407	-30.2503		-68.1853	-3.94457
1		12.79722	12.79722		14.87277	2.075553		-45.2719	-60.1447		-63.963	-18.6911		-64.9397	-0.97677

Table A.2 – Absolute and relative tail link angle position, case 1

A.2 Case 2, $C_1 = 0.5$, $C_2 = 0.05$

The servomotor states for case 2 were determined using the same process described in paragraph A.1. The second case involved a linear coefficient of 0.5 and a quadratic coefficient of 0.05. The Table A.3 was derived from an iterative scheme to fit endpoints to the curves derived from the Lighthill equation, again, using tail links that were 2.9 inches long.

t (sec)	x1 (in.)	y1 (in.)	x2 (in.)	y2 (in.)	x3 (in.)	y3 (in.)	x4 (in.)	y4 (in.)	x5 (in.)	y5 (in.)
0	2.532701	1.412596	4.886121	3.10712	6.857	0.979462	7.835	-1.75222	8.634	-4.54029
0.05	2.472487	1.515522	5.327399	2.024914	6.735	-0.51211	7.679	-3.2546	8.528	-6.02798
0.1	2.466528	1.525201	5.293977	0.880581	6.551	-1.73325	7.52	-4.46768	8.486	-7.20323
0.15	2.531308	1.41509	5.068552	0.01067	6.305	-2.61176	7.35	-5.3159	8.572	-7.94772
0.2	2.67276	1.125325	4.856	-0.78456	6.11	-3.40004	7.3	-6.04631	10.195	-5.88736
0.25	2.83496	0.610739	4.722	-1.59075	6.033	-4.17929	7.605	-6.61525	9.712	-4.62232
0.3	2.9	2.29E-16	4.64	-2.32505	6.102	-4.83042	8.941	-4.23591	9.8	-1.4658
0.35	2.851294	-0.52926	4.57	-2.86746	6.435	-5.08904	8.504	-3.05731	9.353	-0.28232
0.4	2.74613	-0.93208	4.54	-3.21228	7.435	-3.37757	8.5	-0.68055	9.255	2.122268
0.45	2.630441	-1.22097	4.60652	-3.3435	7.199	-2.0427	8.187	0.682956	8.951	3.481053
0.5	2.532701	-1.4126	4.886121	-3.10712	6.857	-0.97946	7.835	1.75222	8.634	4.540288
0.55	2.472487	-1.51552	5.327399	-2.02491	6.735	0.512112	7.679	3.254597	8.528	6.027982
0.6	2.466528	-1.5252	5.293977	-0.88058	6.551	1.733249	7.52	4.467682	8.486	7.203225
0.65	2.531308	-1.41509	5.068552	-0.01067	6.305	2.611755	7.35	5.315901	8.572	7.947718
0.7	2.67276	-1.12532	4.856	0.784562	6.11	3.400036	7.3	6.04631	10.195	5.887358
0.75	2.83496	-0.61074	4.722	1.590745	6.033	4.179295	7.605	6.615252	9.712	4.622318
0.8	2.9	-4.6E-16	4.64	2.325051	6.102	4.830424	8.941	4.235905	9.8	1.465801
0.85	2.851294	0.529264	4.57	2.867455	6.435	5.089037	8.504	3.057313	9.353	0.282321
0.9	2.74613	0.932078	4.54	3.212283	7.435	3.37757	8.5	0.680548	9.255	-2.12227
0.95	2.630441	1.220974	4.60652	3.343499	7.199	2.042695	8.187	-0.68296	8.951	-3.48105
1	2.532701	1.412596	4.886121	3.10712	6.857	0.979462	7.835	-1.75222	8.634	-4.54029

Table A.3 – Absolute x,y positional data for tail link end points, case 2; link 0 assumed start 0,0

Once a matrix of absolute positions of each link end point has been determined, it is transformed into absolute and relative tail link angles shown in Table A.4. Again, angle θ represents the absolute angle, relative to the x-axis, that the tail link must be rotated to. Angle λ represents the relative angle that the servo must rotate to correctly position the link. The previous tail link's absolute angle must be subtracted from the particular tail link's absolute angle to compensate for the previous tail link's rotation, and thus λ is obtained.

t (sec)	Θ1 (deg)	λ1 (deg)	Θ2 (deg)	λ2 (deg)	Θ3 (deg)	λ3 (deg)	Θ4 (deg)	λ4 (deg)	Θ5 (deg)	λ5 (deg)
0	29.15029	29.15029	35.75488	6.604587	-47.1906	-82.9455	-70.3016	-23.1109	-74.0088	-3.70728
0.05	31.50639	31.50639	10.11663	-21.3898	-60.9775	-71.0941	-71.0058	-10.0284	-72.9794	-1.97354
0.1	31.73097	31.73097	-12.8432	-44.5741	-64.3165	-51.4734	-70.4872	-6.1707	-70.5504	-0.06317
0.15	29.20672	29.20672	-28.9655	-58.1722	-64.7566	-35.7911	-68.8713	-4.11471	-65.0937	3.777578
0.2	22.83278	22.83278	-41.1793	-64.012	-64.3844	-23.2052	-65.7871	-1.40267	3.142713	68.9298
0.25	12.1575	12.1575	-49.3979	-61.5554	-63.1396	-13.7417	-57.1646	5.97499	43.40636	100.5709
0.3	4.53E-15	4.53E-15	-53.1899	-53.1899	-59.7345	-6.54459	11.82747	71.56195	72.77151	60.94404
0.35	-10.5157	-10.5157	-53.682	-43.1663	-49.9868	3.695153	44.47919	94.466	72.98868	28.50949
0.4	-18.748	-18.748	-51.8074	-33.0594	-3.26769	48.53967	68.45193	71.71961	74.92397	6.472045
0.45	-24.8994	-24.8994	-47.0463	-22.147	26.64569	73.69203	70.07532	43.42963	74.72806	4.652742
0.5	-29.1503	-29.1503	-35.7549	-6.60459	47.19064	82.94551	70.30156	23.11092	74.00884	3.707284
0.55	-31.5064	-31.5064	-10.1166	21.38975	60.97747	71.0941	71.00585	10.02838	72.97939	1.973543
0.6	-31.731	-31.731	12.84316	44.57412	64.31652	51.47336	70.48722	6.1707	70.55039	0.063174
0.65	-29.2067	-29.2067	28.96548	58.1722	64.75658	35.7911	68.87129	4.114712	65.09371	-3.77758
0.7	-22.8328	-22.8328	41.17926	64.01204	64.38441	23.20515	65.78708	1.40267	-3.14271	-68.9298
0.75	-12.1575	-12.1575	49.3979	61.55541	63.13956	13.74165	57.16457	-5.97499	-43.4064	-100.571
0.8	-9.1E-15	-9.1E-15	53.18989	53.18989	59.73448	6.544593	-11.8275	-71.562	-72.7715	-60.944
0.85	10.51569	10.51569	53.68196	43.16627	49.98681	-3.69515	-44.4792	-94.466	-72.9887	-28.5095
0.9	18.74799	18.74799	51.80736	33.05937	3.267686	-48.5397	-68.4519	-71.7196	-74.924	-6.47204
0.95	24.89936	24.89936	47.04634	22.14699	-26.6457	-73.692	-70.0753	-43.4296	-74.7281	-4.65274
1	29.15029	29.15029	35.75488	6.604587	-47.1906	-82.9455	-70.3016	-23.1109	-74.0088	-3.70728

Table A.4 – Absolute and relative tail link angle position, case 2

A.3 Case 3, C_1 = 0.1, C_2 = 0.50

The servomotor states for case 3 were determined using the same process described in paragraph A.1. The third case involved a linear coefficient of 0.1 and a quadratic coefficient of 0.50. The Table A.5 was derived from an iterative scheme to fit endpoints to the curves derived from the Lighthill equation, again, using tail links that were 2.9 inches long.

t (sec)	x1 (in.)	y1 (in.)	x2 (in.)	y2 (in.)	x3 (in.)	y3 (in.)	x4 (in.)	y4 (in.)	x5 (in.)	y5 (in.)
0	2.127	1.97144	4.7985	3.101294	6.833	1.033534	7.817	-1.6938	8.618	-4.48196
0.05	2.02	2.081149	4.907	2.359305	6.541	-0.03751	7.524	-2.76554	8.378	-5.53838
0.1	1.97	2.129022	4.8	1.491446	6.262	-1.01253	7.27	-3.73378	8.215	-6.47674
0.15	1.986	2.112411	4.547	0.750099	5.961	-1.78186	7.027	-4.47805	8.136	-7.15849
0.2	2.1	1.998869	4.282	0.090087	5.689	-2.44651	6.852	-5.10329	8.369	-7.57475
0.25	2.431	1.581758	4.192	-0.72352	5.585	-3.26768	6.943	-5.82979	9.652	-4.79413
0.3	2.9	5.51E-16	4.638	-2.32159	6.099	-4.82598	8.939	-4.24086	9.799	-1.46973
0.35	2.735	-0.96442	4.711	-3.08647	6.721	-5.17751	8.552	-2.92986	9.387	-0.14982
0.4	2.497	-1.47579	4.68	-3.38492	7.57	-3.12775	8.582	-0.40753	9.322	2.398073
0.45	2.288	-1.7837	4.691	-3.40823	7.222	-1.99335	8.203	0.73642	8.965	3.536037
0.5	2.127	-1.97144	4.7985	-3.10129	6.833	-1.03353	7.817	1.693797	8.618	4.481959
0.55	2.02	-2.08115	4.907	-2.35931	6.541	0.037506	7.524	2.765538	8.378	5.538384
0.6	1.97	-2.12902	4.8	-1.49145	6.262	1.012526	7.27	3.733783	8.215	6.476735
0.65	1.986	-2.11241	4.547	-0.7501	5.961	1.781857	7.027	4.47805	8.136	7.158489
0.7	2.1	-1.99887	4.282	-0.09009	5.689	2.446506	6.852	5.103294	8.369	7.574755
0.75	2.431	-1.58176	4.192	0.723522	5.585	3.267683	6.943	5.829794	9.652	4.794131
0.8	2.9	-1.1E-15	4.638	2.321585	6.099	4.825982	8.939	4.240861	9.799	1.469732
0.85	2.735	0.964417	4.711	3.086471	6.721	5.177514	8.552	2.929857	9.387	0.149825
0.9	2.497	1.475794	4.68	3.384924	7.57	3.127754	8.582	0.407526	9.322	-2.39807
0.95	2.288	1.783698	4.691	3.408225	7.222	1.993352	8.203	-0.73642	8.965	-3.53604
1	2.127	1.97144	4.7985	3.101294	6.833	1.033534	7.817	-1.6938	8.618	-4.48196

Table A.5 – Absolute x,y positional data for tail link end points, case 3; link 0 assumed start 0,0

Once a matrix of absolute positions of each link end point has been determined, it is transformed into absolute and relative tail link angles shown in Table A.6. Again, angle θ represents the absolute angle, relative to the x-axis, that the tail link must be rotated to. Angle λ represents the relative angle that the servo must rotate to correctly position the link. The previous tail link's absolute angle must be subtracted from the particular tail link's absolute angle to compensate for the previous tail link's rotation, and thus λ is obtained.

t (sec)		Θ1 (deg)	λ1 (deg)		Θ2 (deg)	λ2 (deg)		Θ3 (deg)	λ3 (deg)		Θ4 (deg)	λ4 (deg)		Θ5 (deg)	λ5 (deg)
0		42.82633	42.82633		22.9249	-19.9014		-45.4645	-68.3894		-70.161	-24.6964		-73.9714	-3.81043
0.05		45.85422	45.85422		5.503348	-40.3509		-55.7162	-61.2196		-70.1842	-14.468		-72.8819	-2.69763
0.1		47.22169	47.22169		-12.6963	-59.918		-59.7205	-47.0242		-69.6745	-9.95399		-70.9902	-1.31567
0.15		46.76667	46.76667		-28.0105	-74.7772		-60.8183	-32.8078		-68.4275	-7.60921		-67.5232	0.904282
0.2		43.58663	43.58663		-41.179	-84.7656		-60.9837	-19.8047		-66.3588	-5.37506		-58.4581	7.900663
0.25		33.0505	33.0505		-52.6238	-85.6743		-61.2981	-8.67421		-62.075	-0.77695		20.92208	82.99708
0.3		1.09E-14	1.09E-14		-53.1805	-53.1805		-59.7418	-6.56132		11.64167	71.38349		72.75864	61.11697
0.35		-19.4237	-19.4237		-47.0412	-27.6175		-46.1321	0.909049		50.83284	96.96495		73.28203	22.44919
0.4		-30.5842	-30.5842		-41.1711	-10.5869		5.085143	46.25628		69.5934	64.50826		75.22427	5.630868
0.45		-37.9396	-37.9396		-34.0603	3.879263		29.20594	63.26625		70.23305	41.02711		74.77407	4.541013
0.5		-42.8263	-42.8263		-22.9249	19.90144		45.46452	68.38942		70.16095	24.69643		73.97138	3.810431
0.55		-45.8542	-45.8542		-5.50335	40.35088		55.71622	61.21957		70.18423	14.46801		72.88186	2.697626
0.6		-47.2217	-47.2217		12.6963	59.91799		59.72052	47.02422		69.67451	9.953987		70.99018	1.315673
0.65		-46.7667	-46.7667		28.01054	74.77721		60.81832	32.80778		68.42753	7.609208		67.52325	-0.90428
0.7		-43.5866	-43.5866		41.17896	84.76559		60.9837	19.80474		66.35876	5.375061		58.4581	-7.90066
0.75		-33.0505	-33.0505		52.62384	85.67434		61.29805	8.67421		62.075	0.776947		-20.9221	-82.9971
0.8		-2.2E-14	-2.2E-14		53.18051	53.18051		59.74182	6.561316		-11.6417	-71.3835		-72.7586	-61.117
0.85		19.42369	19.42369		47.04116	27.61747		46.13211	-0.90905		-50.8328	-96.9649		-73.282	-22.4492
0.9		30.58422	30.58422		41.17113	10.58691		-5.08514	-46.2563		-69.5934	-64.5083		-75.2243	-5.63087
0.95		37.93957	37.93957		34.06031	-3.87926		-29.2059	-63.2662		-70.2331	-41.0271		-74.7741	-4.54101
1		42.82633	42.82633		22.9249	-19.9014		-45.4645	-68.3894		-70.161	-24.6964		-73.9714	-3.81043

Table A.6 – Absolute and relative tail link angle position, case 3

APPENDIX B

ROBOT CONTROLLER SOFTWARE

B.1 clock.h

```
/*********************************************************************
*********
*
*     TITLE:            clock.h
*
*     VERSION:    0.3 (Beta)
*
*     DATE:       18-Dec-2003
*
*     AUTHOR:           R. Kevin Watson
*                       kevinw@jpl.nasa.gov
*
*     COMMENTS:
*
**********************************************************************
*********
*
*     CHANGE LOG:
*
*     DATE         REV  DESCRIPTION
*     -----------  ---  ---------------------------------------------
-----------
*     14-Dec-2003  0.1  RKW Original
*     16-Dec-2003  0.2  Accuracy bug: Changed the value of PR2 to 249
(was 250)
*     18-Dec-2003  0.3  Fixed 25 hour/day and 366 day/year bugs
*
**********************************************************************
********/

#ifndef _clock_h
#define _clock_h

// function prototypes
void Initialize_Timer_2(void);      // initializes the timer 2 hardware
void Timer_2_Int_Handler(void);     // timer 1 interrupt handler
void Display_Time(void);            //formats and displays the time
once a second

// global variables
extern volatile unsigned long msClock;    // one millisecond clock
located in clock.c
extern volatile unsigned long Clock;      // one second clock located
in clock.c
```

```
#endif // _clock_h
```

B.2 delays.h

```
#ifndef __DELAYS_H
#define __DELAYS_H

/* PIC 17Cxxx and 18Cxxx cycle-count delay routines.
 *
 *   Functions:
 *           Delay1TCY()
 *               Delay10TCY()  // 17Cxx only
 *               Delay10TCYx()
 *               Delay100TCYx()
 *               Delay1KTCYx()
 *               Delay10KTCYx()
 */

/* Delay of exactly 1 Tcy */
#define Delay1TCY() Nop()

#if __18CXX
#define PARAM_SCLASS auto
#else
#define PARAM_SCLASS static
#endif

/* Delay of exactly 10 Tcy */
#if    __18CXX
#define Delay10TCY() Delay10TCYx(1)
#else /* 17CXX */
far void Delay10TCY(void);
#endif

/* Delay10TCYx
 * Delay multiples of 10 Tcy
 * Passing 0 (zero) results in a delay of 2560 cycles.
 * The 18Cxxx version of this function supports the full range [0,255]
 * The 17Cxxx version supports [2,255] and 0.
 */
#if    __18CXX
void Delay10TCYx(PARAM_SCLASS unsigned char);
#else /* 17CXX */
far void Delay10TCYx(PARAM_SCLASS unsigned char);
#endif

/* Delay100TCYx
 * Delay multiples of 100 Tcy
 * Passing 0 (zero) results in a delay of 25,600 cycles.
 * The full range of [0,255] is supported.
 */
#if    __18CXX
void Delay100TCYx(PARAM_SCLASS unsigned char);
#else /* 17CXX */
```

```
far void Delay100TCYx(PARAM_SCLASS unsigned char);
#endif

/* Delay1KTCYx
 * Delay multiples of 1000 Tcy
 * Passing 0 (zero) results in a delay of 256,000 cycles.
 * The full range of [0,255] is supported.
 */
#if    __18CXX
void Delay1KTCYx(PARAM_SCLASS unsigned char);
#else /* 17CXX */
far void Delay1KTCYx(PARAM_SCLASS unsigned char);
#endif

/* Delay10KTCYx
 * Delay multiples of 10,000 Tcy
 * Passing 0 (zero) results in a delay of 2,560,000 cycles.
 * The full range of [0,255] is supported.
 */
#if    __18CXX
void Delay10KTCYx(PARAM_SCLASS unsigned char);
#else /* 17CXX */
far void Delay10KTCYx(PARAM_SCLASS unsigned char);
#endif

#endif
```

B.3 ifi_aliases.h

```
/*********************************************************************
**********
* FILE NAME: ifi_aliases.h <EDU VERSION>
*
* DESCRIPTION:
*  This file contains common macros (known as aliases in PBASIC) for
the
*  I/O pins of the Robot Controller and elements in the data sent
between the
*  User processor and the Master processor.
*
*  If you want to create your own macros, do so in the designated
section of
*  the user_routines.h file.
*
*  DO NOT EDIT THIS FILE!
**********************************************************************
*********/

#ifndef __ifi_aliases_h_
#define __ifi_aliases_h_

#include <adc.h>

/* PWM Control Definitions used in Setup_Who_Controls_Pwms(...) */
```

```
#define USER      0     /* User controls PWM outputs. */
#define MASTER    1     /* Master controls PWM outputs. */

/* PWM Type Definitions used in Setup_PWM_Output_Type(...) */
#define IFI_PWM   0     /* Standard IFI PWM output generated with
Generate_PWM(...) */
#define USER_CCP  1     /* User can use PWM pin as digital I/O or CCP
pin. */

/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for R/C PWM IN connectors -----------------------
----------
 *----------------------------------------------------------------------
----------
 *  Below are aliases for the PWM inputs received from the radio-
control receiver.
 */
#define PWM_in1         rxdata.oi_analog01
#define PWM_in2         rxdata.oi_analog02
#define PWM_in3         rxdata.oi_analog03
#define PWM_in4         rxdata.oi_analog04
#define PWM_in5         rxdata.oi_analog05
#define PWM_in6         rxdata.oi_analog06
#define PWM_in7         rxdata.oi_analog07
#define PWM_in8         rxdata.oi_analog08

/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for PWM OUT connectors ---------------------------
----------
 *----------------------------------------------------------------------
----------
 *  Below are aliases for the PWM output values located on the Robot
Controller.
 */
#define pwm01           txdata.rc_pwm01
#define pwm02           txdata.rc_pwm02
#define pwm03           txdata.rc_pwm03
#define pwm04           txdata.rc_pwm04
#define pwm05           txdata.rc_pwm05
#define pwm06           txdata.rc_pwm06
#define pwm07           txdata.rc_pwm07
#define pwm08           txdata.rc_pwm08

/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for DIGITAL IN/OUT - ANALOG IN connectors --------
----------
 *----------------------------------------------------------------------
----------
 */
#define INPUT   1
#define OUTPUT  0
```

```
/* Used in User_Initialization routine in user_routines.c file. */
/* Used to set pins as INPUTS (analog or digital) or OUTPUTS (digital
only). */
#define IO1             TRISAbits.TRISA0
#define IO2             TRISAbits.TRISA1
#define IO3             TRISAbits.TRISA2
#define IO4             TRISAbits.TRISA3
#define IO5             TRISAbits.TRISA5
#define IO6             TRISFbits.TRISF0
#define IO7             TRISFbits.TRISF1
#define IO8             TRISFbits.TRISF2
#define IO9             TRISFbits.TRISF3
#define IO10            TRISFbits.TRISF4
#define IO11            TRISFbits.TRISF5
#define IO12            TRISFbits.TRISF6
#define IO13            TRISHbits.TRISH4
#define IO14            TRISHbits.TRISH5
#define IO15            TRISHbits.TRISH6
#define IO16            TRISHbits.TRISH7

/* Aliases used to read the pins when used as INPUTS. */
#define rc_dig_in01     PORTAbits.RA0
#define rc_dig_in02     PORTAbits.RA1
#define rc_dig_in03     PORTAbits.RA2
#define rc_dig_in04     PORTAbits.RA3
#define rc_dig_in05     PORTAbits.RA5
#define rc_dig_in06     PORTFbits.RF0
#define rc_dig_in07     PORTFbits.RF1
#define rc_dig_in08     PORTFbits.RF2
#define rc_dig_in09     PORTFbits.RF3
#define rc_dig_in10     PORTFbits.RF4
#define rc_dig_in11     PORTFbits.RF5
#define rc_dig_in12     PORTFbits.RF6
#define rc_dig_in13     PORTHbits.RH4
#define rc_dig_in14     PORTHbits.RH5
#define rc_dig_in15     PORTHbits.RH6
#define rc_dig_in16     PORTHbits.RH7

/* Aliases used to drive the pins when used as OUTPUTS. */
#define rc_dig_out01    LATAbits.LATA0
#define rc_dig_out02    LATAbits.LATA1
#define rc_dig_out03    LATAbits.LATA2
#define rc_dig_out04    LATAbits.LATA3
#define rc_dig_out05    LATAbits.LATA5
#define rc_dig_out06    LATFbits.LATF0
#define rc_dig_out07    LATFbits.LATF1
#define rc_dig_out08    LATFbits.LATF2
#define rc_dig_out09    LATFbits.LATF3
#define rc_dig_out10    LATFbits.LATF4
#define rc_dig_out11    LATFbits.LATF5
#define rc_dig_out12    LATFbits.LATF6
#define rc_dig_out13    LATHbits.LATH4
#define rc_dig_out14    LATHbits.LATH5
#define rc_dig_out15    LATHbits.LATH6
#define rc_dig_out16    LATHbits.LATH7
```

```
/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for INTERRUPTS connectors (inputs) ---------------
----------
 *----------------------------------------------------------------------
----------
 *  Below are aliases for the input pins labelled INTERRUPTS on the EDU
Robot Controller.
 *  These pins are connected to PULL-UPS, meaning they are normally
HIGH (1).
 */
#define rc_dig_int1     PORTBbits.RB2
#define rc_dig_int2     PORTBbits.RB3
#define rc_dig_int3     PORTBbits.RB4
#define rc_dig_int4     PORTBbits.RB5
#define rc_dig_int5     PORTBbits.RB6
#define rc_dig_int6     PORTBbits.RB7

/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for SOLENOID OUT connectors (outputs) ------------
----------
 *----------------------------------------------------------------------
----------
 *  Below are aliases for the solenoid outputs located on the Robot
Controller.
 */
#define solenoid1       LATDbits.LATD0
#define solenoid2       LATDbits.LATD1
#define solenoid3       LATDbits.LATD2
#define solenoid4       LATDbits.LATD3
#define solenoid5       LATDbits.LATD4
#define solenoid6       LATDbits.LATD5

/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for each RC analog input -------------------------
----------
 *----------------------------------------------------------------------
----------
 *  Below are aliases for the analog input channels of the 18F8520.
 *  They correspond to the DIGITAL IN/OUT - ANALOG IN pins on the Robot
Controller.
 */
/* Used in Get_Analog_Value(...) routine. */
#define rc_ana_in01     ADC_CH0
#define rc_ana_in02     ADC_CH1
#define rc_ana_in03     ADC_CH2
#define rc_ana_in04     ADC_CH3
#define rc_ana_in05     ADC_CH4
#define rc_ana_in06     ADC_CH5
#define rc_ana_in07     ADC_CH6
#define rc_ana_in08     ADC_CH7
#define rc_ana_in09     ADC_CH8
```

```
#define rc_ana_in10     ADC_CH9
#define rc_ana_in11     ADC_CH10
#define rc_ana_in12     ADC_CH11
#define rc_ana_in13     ADC_CH12
#define rc_ana_in14     ADC_CH13
#define rc_ana_in15     ADC_CH14
#define rc_ana_in16     ADC_CH15

/* Used in Set_Number_of_Analog_Channels(...) routine in
user_routines.c file. */
#define NO_ANALOG       ADC_0ANA    /* All digital */
#define ONE_ANALOG      ADC_1ANA    /* analog: AN0      digital: AN1-
>15 */
#define TWO_ANALOG      ADC_2ANA    /* analog: AN0->1   digital: AN2-
>15 */
#define THREE_ANALOG    ADC_3ANA    /* analog: AN0->2   digital: AN3-
>15 */
#define FOUR_ANALOG     ADC_4ANA    /* analog: AN0->3   digital: AN4-
>15 */
#define FIVE_ANALOG     ADC_5ANA    /* analog: AN0->4   digital: AN5-
>15 */
#define SIX_ANALOG      ADC_6ANA    /* analog: AN0->5   digital: AN6-
>15 */
#define SEVEN_ANALOG    ADC_7ANA    /* analog: AN0->6   digital: AN7-
>15 */
#define EIGHT_ANALOG    ADC_8ANA    /* analog: AN0->7   digital: AN8-
>15 */
#define NINE_ANALOG     ADC_9ANA    /* analog: AN0->8   digital: AN9-
>15 */
#define TEN_ANALOG      ADC_10ANA   /* analog: AN0->9   digital: AN10-
>15 */
#define ELEVEN_ANALOG   ADC_11ANA   /* analog: AN0->10  digital: AN11-
>15 */
#define TWELVE_ANALOG   ADC_12ANA   /* analog: AN0->11  digital: AN12-
>15 */
#define THIRTEEN_ANALOG ADC_13ANA   /* analog: AN0->12  digital: AN13-
>15 */
#define FOURTEEN_ANALOG ADC_14ANA   /* analog: AN0->13  digital: AN14-
>15 */
/* There is no FIFTEEN_ANALOG! */
#define SIXTEEN_ANALOG  ADC_16ANA   /* All analog */

/*
 *---------------------------------------------------------------------
----------
 *---------- Aliases for CCP pins (PWM OUT 1-4 connectors) ------------
----------
 *---------------------------------------------------------------------
----------
 *  Below are aliases for the four PWM OUT pins which can be configured
for use
 *  as digital inputs or outputs.  They are CCP pins with special
features as
 *  detailed in the PIC18FXX20 Data Sheet on page 149.
 *
 *   The pin mapping is as follows:
 *   PWM OUT 1 -> CCP2
 *   PWM OUT 2 -> CCP3
 *   PWM OUT 3 -> CCP4
 *   PWM OUT 4 -> CCP5
 */
/* To set the direction (input or output) of the pins you use these
aliases. */
#define IO_CCP2         TRISEbits.TRISE7
#define IO_CCP3         TRISGbits.TRISG0
#define IO_CCP4         TRISGbits.TRISG3
#define IO_CCP5         TRISGbits.TRISG4

/* When using them as inputs you read the values with these aliases. */
#define IN_CCP2         PORTEbits.RE7
#define IN_CCP3         PORTGbits.RG0
#define IN_CCP4         PORTGbits.RG3
#define IN_CCP5         PORTGbits.RG4

/* When using them as outputs you drive a value with these aliases. */
#define OUT_CCP2        LATEbits.LATE7
#define OUT_CCP3        LATGbits.LATG0
#define OUT_CCP4        LATGbits.LATG3
#define OUT_CCP5        LATGbits.LATG4

/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for TTL connectors (serial port 2) ---------------
----------
 *----------------------------------------------------------------------
----------
 *  Below are aliases for the second serial port (USART2) pins labeled
TTL.
 */
#define usart2_TX       LATGbits.LATG1
#define usart2_RX       PORTGbits.RG2

/*
 *----------------------------------------------------------------------
----------
 *---------- Alias for Battery Voltage  -------------------------------
----------
 *----------------------------------------------------------------------
----------
 * current voltage = battery_voltage * 0.038 + 0.05;
 */
#define battery_voltage rxdata.rc_analog01

/*
 *----------------------------------------------------------------------
----------
 *---------- Aliases for User Modes  ----------------------------------
----------
 *----------------------------------------------------------------------
----------
 */
#define user_display_mode rxdata.rc_mode_byte.mode.user_display
#define autonomous_mode   rxdata.rc_mode_byte.mode.autonomous
```

```
#endif

/*----------------------------------------------------------------------
--------*/
/*----------------------------------------------------------------------
--------*/
/*----------------------------------------------------------------------
--------*/
```

B.4 ifi_default.h

```
/***********************************************************************
*********
* FILE NAME: ifi_default.h
*
* DESCRIPTION:
*  This file contains important data definitions.
*
*  DO NOT EDIT THIS FILE!
************************************************************************
********/

#ifndef __ifi_default_h_
#define __ifi_default_h_

#include "ifi_picdefs.h"

#ifdef UNCHANGEABLE_DEFINITION_AREA

/***********************************************************************
*********
                             ALIAS DEFINITIONS
************************************************************************
********/
                           /* DO NOT CHANGE! */

#define   DATA_SIZE          30
#define   SPI_TRAILER_SIZE   2
#define   SPI_XFER_SIZE      DATA_SIZE + SPI_TRAILER_SIZE

#define   RESET_VECTOR      0x800
#define   HIGH_INT_VECTOR   0x808
#define   LOW_INT_VECTOR    0x818


/***********************************************************************
*********
                            VARIABLE DECLARATIONS
************************************************************************
********/
                            /* DO NOT CHANGE! */
/* This structure contains important system status information. */
typedef struct
```

```
{
  unsigned int  :5;
  unsigned int  user_display:1;  /* User display enabled = 1, disabled
= 0 */
  unsigned int  autonomous:1;    /* Autonomous enabled = 1, disabled =
0 */
  unsigned int  disabled:1;      /* Competition enabled = 1, disabled =
0 */
} modebits;

/*********************************************************************
********/
                            /* DO NOT CHANGE! */
/* This structure allows you to address specific bits of a byte.*/
typedef struct
{
  unsigned int  bit0:1;
  unsigned int  bit1:1;
  unsigned int  bit2:1;
  unsigned int  bit3:1;
  unsigned int  bit4:1;
  unsigned int  bit5:1;
  unsigned int  bit6:1;
  unsigned int  bit7:1;
} bitid;

/*********************************************************************
********/
                            /* DO NOT CHANGE! */
/* This structure defines the contents of the data received from the
Master
 * microprocessor. */
typedef struct  {     /* begin rx_data_record structure */
  unsigned char packet_num;
  union
  {
    bitid bitselect;
    modebits mode;
/*rxdata.rc_mode_byte.mode.(user_display|autonomous|disabled)*/
    unsigned char allbits;    /*rxdata.rc_mode_byte.allbits*/
  } rc_mode_byte;
  union
  {
    bitid bitselect;          /*rxdata.oi_swA_byte.bitselect.bit0*/
    unsigned char allbits;    /*rxdata.oi_swA_byte.allbits*/
  } oi_swA_byte;
  union
  {
    bitid bitselect;          /*rxdata.oi_swB_byte.bitselect.bit0*/
    unsigned char allbits;    /*rxdata.oi_swB_byte.allbits*/
  } oi_swB_byte;
  union
  {
    bitid bitselect;          /*rxdata.rc_swA_byte.bitselect.bit0*/
    unsigned char allbits;    /*rxdata.rc_swA_byte.allbits*/
  } rc_swA_byte;
  union
  {
    bitid bitselect;          /*rxdata.rc_swB_byte.bitselect.bit0*/
    unsigned char allbits;    /*rxdata.rc_swB_byte.allbits*/
  } rc_swB_byte;
  unsigned char oi_analog01, oi_analog02, oi_analog03, oi_analog04;
/*rxdata.oi_analog01*/
  unsigned char oi_analog05, oi_analog06, oi_analog07, oi_analog08;
  unsigned char oi_analog09, oi_analog10, oi_analog11, oi_analog12;
  unsigned char oi_analog13, oi_analog14, oi_analog15, oi_analog16;
  unsigned char rc_main_batt, rc_backup_batt;
  unsigned char reserve[8];
} rx_data_record;

typedef rx_data_record *rx_data_ptr;

/*********************************************************************
********/
                            /* DO NOT CHANGE! */
/* This structure defines the contents of the data transmitted to the
master
 * microprocessor. */
typedef struct  {     /*begin tx_data_record structure*/
  union
  {
    bitid bitselect;          /*txdata.LED_byte1.bitselect.bit0*/
    unsigned char data;       /*txdata.LED_byte1.data*/
  } LED_byte1;
  union
  {
    bitid bitselect;          /*txdata.LED_byte2.bitselect.bit0*/
    unsigned char data;       /*txdata.LED_byte2.data*/
  } LED_byte2;
  union
  {
    bitid bitselect;          /*txdata.user_byte1.bitselect.bit0*/
    unsigned char allbits;    /*txdata.user_byte1.allbits*/
  } user_byte1;               /*for OI feedback*/
  union
  {
    bitid bitselect;          /*txdata.user_byte2.bitselect.bit0*/
    unsigned char allbits;    /*txdata.user_byte2.allbits*/
  } user_byte2;               /*for OI feedback*/
  unsigned char rc_pwm01, rc_pwm02, rc_pwm03, rc_pwm04;
/*txdata.rc_pwm01*/
  unsigned char rc_pwm05, rc_pwm06, rc_pwm07, rc_pwm08;
  unsigned char rc_pwm09, rc_pwm10, rc_pwm11, rc_pwm12;
  unsigned char rc_pwm13, rc_pwm14, rc_pwm15, rc_pwm16;

  unsigned char user_cmd;     /*reserved - for future use*/
  unsigned char cmd_byte1;    /*reserved - Don't use*/
  unsigned char pwm_mask;     /*<EDU> make sure you know how this works
before changing*/
  unsigned char warning_code; /*reserved - Don't use*/
  unsigned char user_byte3;   /*for OI feedback*/
  unsigned char user_byte4;   /*for OI feedback*/
  unsigned char user_byte5;   /*for OI feedback*/
  unsigned char user_byte6;   /*for OI feedback*/
  unsigned char error_code;   /*reserved - Don't use*/
  unsigned char packetnum;    /*reserved - Don't use*/
  unsigned char current_mode; /*reserved - Don't use*/
  unsigned char control;      /*reserved - Don't use*/
} tx_data_record;

typedef tx_data_record *tx_data_ptr;


/**********************************************************************
********/
                            /* DO NOT CHANGE! */
/* This structure defines some flags which are used by the system. */

typedef struct
{
  unsigned int  NEW_SPI_DATA:1;
  unsigned int  TX_UPDATED:1;
  unsigned int  FIRST_TIME:1;
  unsigned int  TX_BUFFSELECT:1;
  unsigned int  RX_BUFFSELECT:1;
  unsigned int  :3;
} packed_struct;

/**********************************************************************
********/

extern tx_data_record txdata;
extern rx_data_record rxdata;
extern packed_struct statusflag;

#else
#error  *** Error - Invalid Default File!
#endif

/**********************************************************************
*********
                           FUNCTION PROTOTYPES
***********************************************************************
********/

/* These routines reside in ifi_library.lib */
void InterruptHandlerHigh (void);
void Initialize_Registers (void);
void IFI_Initialization (void);
void User_Proc_Is_Ready (void);
void Putdata(tx_data_ptr ptr);
void Getdata(rx_data_ptr ptr);
void Clear_SPIdata_flag(void);
void Setup_PWM_Output_Type(int pwmSpec1,int pwmSpec2,int pwmSpec3,int
pwmSpec4);

#endif

/**********************************************************************
********/
```

```
/*******************************************************************
********/
/*******************************************************************
********/
```

B.5 ifi_picdefs.h

```
/*******************************************************************
*********
* FILE NAME: ifi_picdef.h
*
* DESCRIPTION:
*  This include file contains definitions for the 18f8520 PICmicro.
All
*  register definitions are explained in detail in the PIC18FXX20 Data
Sheet.
*
* USAGE:
*  Refer to this file to determine if a register is off-limits to the
user.
*  Registers and bits marked by "Reserved - Do not use" should not be
modified
*  by the user's code or else the Robot Controller will not function.

* WARNING:
*  DO NOT MODIFY THIS FILE!
********************************************************************
********/

#ifndef __ifi_picdefs_h_
#define __ifi_picdefs_h_

extern volatile near unsigned char       RCSTA2;
extern volatile near union {
  struct {
    unsigned RX9D:1;
    unsigned OERR:1;
    unsigned FERR:1;
    unsigned ADEN:1;
    unsigned CREN:1;
    unsigned SREN:1;
    unsigned RX9:1;
    unsigned SPEN:1;
  };
  struct {
    unsigned RCD8:1;
    unsigned :5;
    unsigned RC9:1;
  };
  struct {
    unsigned :6;
    unsigned NOT_RC8:1;
  };
  struct {
    unsigned :6;
    unsigned RC8_9:1;
  };
} RCSTA2bits;
extern volatile near unsigned char       TXSTA2;
extern volatile near union {
  struct {
    unsigned TX9D:1;
    unsigned TRMT:1;
    unsigned BRGH:1;
    unsigned :1;
    unsigned SYNC:1;
    unsigned TXEN:1;
    unsigned TX9:1;
    unsigned CSRC:1;
  };
  struct {
    unsigned TXD8:1;
    unsigned :5;
    unsigned TX8_9:1;
  };
  struct {
    unsigned :6;
    unsigned NOT_TX8:1;
  };
} TXSTA2bits;
extern volatile near unsigned char       TXREG2;
extern volatile near unsigned char       RCREG2;
extern volatile near unsigned char       SPBRG2;
extern volatile near unsigned char       CCP5CON;
extern volatile near union {
  struct {
    unsigned CCP5M0:1;
    unsigned CCP5M1:1;
    unsigned CCP5M2:1;
    unsigned CCP5M3:1;
    unsigned DCCP5Y:1;
    unsigned DCCP5X:1;
  };
  struct {
    unsigned :4;
    unsigned DC5B0:1;
    unsigned DC5B1:1;
  };
} CCP5CONbits;
extern volatile near unsigned            CCPR5;
extern volatile near unsigned char       CCPR5L;
extern volatile near unsigned char       CCPR5H;
extern volatile near unsigned char       CCP4CON;
extern volatile near union {
  struct {
    unsigned CCP4M0:1;
    unsigned CCP4M1:1;
    unsigned CCP4M2:1;
    unsigned CCP4M3:1;
    unsigned DCCP4Y:1;
    unsigned DCCP4X:1;
  };
  struct {
    unsigned :4;
    unsigned DC4B0:1;
    unsigned DC4B1:1;
  };
} CCP4CONbits;
extern volatile near unsigned            CCPR4;
extern volatile near unsigned char       CCPR4L;
extern volatile near unsigned char       CCPR4H;
extern volatile near unsigned char       T4CON;
extern volatile near struct {
  unsigned T4CKPS0:1;
  unsigned T4CKPS1:1;
  unsigned TMR4ON:1;
  unsigned T4OUTPS0:1;
  unsigned T4OUTPS1:1;
  unsigned T4OUTPS2:1;
  unsigned T4OUTPS3:1;
} T4CONbits;
extern volatile near unsigned char       PR4;
extern volatile near unsigned char       TMR4;
extern volatile near unsigned char       PORTA;
extern volatile near union {
  struct {
    unsigned RA0:1;
    unsigned RA1:1;
    unsigned RA2:1;
    unsigned RA3:1;
    unsigned RA4:1;     /* Reserved - Do not use */
    unsigned RA5:1;
    unsigned RA6:1;
  };
  struct {
    unsigned AN0:1;
    unsigned AN1:1;
    unsigned AN2:1;
    unsigned AN3:1;
    unsigned T0CKI:1;   /* Reserved - Do not use */
    unsigned AN4:1;
    unsigned OSC2:1;
  };
  struct {
    unsigned :2;
    unsigned VREFM:1;
    unsigned VREFP:1;
    unsigned :1;
    unsigned LVDIN:1;
    unsigned CLKO:1;
  };
} PORTAbits;
extern volatile near unsigned char       PORTB;
extern volatile near union {
  struct {
    unsigned RB0:1;     /* Reserved - Do not use */
    unsigned RB1:1;
    unsigned RB2:1;
    unsigned RB3:1;
    unsigned RB4:1;
    unsigned RB5:1;
    unsigned RB6:1;
    unsigned RB7:1;
  };
  struct {
    unsigned INT0:1;    /* Reserved - Do not use */
    unsigned INT1:1;
    unsigned INT2:1;
    unsigned INT3:1;
    unsigned KBI0:1;
    unsigned KBI1:1;
    unsigned KBI2:1;
    unsigned KBI3:1;
  };
  struct {
    unsigned :3;
    unsigned CCP2B:1;
    unsigned :1;
    unsigned PGM:1;
    unsigned PGC:1;
    unsigned PGD:1;
  };
} PORTBbits;
extern volatile near unsigned char       PORTC;
extern volatile near union {
  struct {
    unsigned RC0:1;
    unsigned RC1:1;     /* Reserved - Do not use */
    unsigned RC2:1;     /* Reserved - Do not use */
    unsigned RC3:1;     /* Reserved - Do not use */
    unsigned RC4:1;     /* Reserved - Do not use */
    unsigned RC5:1;     /* Reserved - Do not use */
    unsigned RC6:1;
    unsigned RC7:1;
  };
  struct {
    unsigned T1OSO:1;
    unsigned T1OSI:1;   /* Reserved - Do not use */
    unsigned CCP1:1;    /* Reserved - Do not use */
    unsigned SCK:1;     /* Reserved - Do not use */
    unsigned SDI:1;     /* Reserved - Do not use */
    unsigned SDO:1;     /* Reserved - Do not use */
    unsigned TX:1;
    unsigned RX:1;
  };
  struct {
    unsigned T13CKI:1;
    unsigned CCP2C:1;   /* Reserved - Do not use */
    unsigned :1;
    unsigned SCL:1;     /* Reserved - Do not use */
    unsigned SDA:1;     /* Reserved - Do not use */
    unsigned :1;        /* Reserved - Do not use */
    unsigned CK:1;
    unsigned DT:1;
  };
```

```
} PORTCbits;
extern volatile near unsigned char       PORTD;
extern volatile near union {
  struct {
    unsigned RD0:1;
    unsigned RD1:1;
    unsigned RD2:1;
    unsigned RD3:1;
    unsigned RD4:1;
    unsigned RD5:1;
    unsigned RD6:1;
    unsigned RD7:1;
  };
  struct {
    unsigned PSP0:1;
    unsigned PSP1:1;
    unsigned PSP2:1;
    unsigned PSP3:1;
    unsigned PSP4:1;
    unsigned PSP5:1;
    unsigned PSP6:1;
    unsigned PSP7:1;
  };
  struct {
    unsigned AD0:1;
    unsigned AD1:1;
    unsigned AD2:1;
    unsigned AD3:1;
    unsigned AD4:1;
    unsigned AD5:1;
    unsigned AD6:1;
    unsigned AD7:1;
  };
} PORTDbits;
extern volatile near unsigned char       PORTE;
extern volatile near union {
  struct {
    unsigned RE0:1;
    unsigned RE1:1;
    unsigned RE2:1;
    unsigned RE3:1;
    unsigned RE4:1;
    unsigned RE5:1;
    unsigned RE6:1;
    unsigned RE7:1;
  };
  struct {
    unsigned RD:1;
    unsigned WR:1;
    unsigned CS:1;
    unsigned :4;
    unsigned CCP2E:1;
  };
  struct {
    unsigned AD8:1;
    unsigned AD9:1;
    unsigned AD10:1;
    unsigned AD11:1;
    unsigned AD12:1;
    unsigned AD13:1;
    unsigned AD14:1;
    unsigned AD15:1;
  };
} PORTEbits;
extern volatile near unsigned char       PORTF;
extern volatile near union {
  struct {
    unsigned RF0:1;
    unsigned RF1:1;
    unsigned RF2:1;
    unsigned RF3:1;
    unsigned RF4:1;
    unsigned RF5:1;
    unsigned RF6:1;
    unsigned RF7:1;         /* Reserved - Do not use */
  };
  struct {
    unsigned AN5:1;
    unsigned AN6:1;
    unsigned AN7:1;
    unsigned AN8:1;
    unsigned AN9:1;
    unsigned AN10:1;
    unsigned AN11:1;
    unsigned SS:1;          /* Reserved - Do not use */
  };
  struct {
    unsigned :1;
    unsigned C2OUTF:1;
    unsigned C1OUTF:1;
    unsigned :2;
    unsigned CVREFF:1;     /* Reserved - Do not use */
  };
} PORTFbits;
extern volatile near unsigned char       PORTG;
extern volatile near union {
  struct {
    unsigned RG0:1;
    unsigned RG1:1;
    unsigned RG2:1;
    unsigned RG3:1;
    unsigned RG4:1;
  };
  struct {
    unsigned CCP3:1;
    unsigned TX2:1;
    unsigned RX2:1;
    unsigned CCP4:1;
    unsigned CCP5:1;
  };
  struct {
    unsigned :1;
    unsigned CK2:1;
    unsigned DT2:1;
  };
} PORTGbits;
extern volatile near unsigned char       PORTH;
extern volatile near union {
  struct {
    unsigned RH0:1;
    unsigned RH1:1;
    unsigned RH2:1;
    unsigned RH3:1;
    unsigned RH4:1;
    unsigned RH5:1;
    unsigned RH6:1;
    unsigned RH7:1;
  };
  struct {
    unsigned A16:1;
    unsigned A17:1;
    unsigned A18:1;
    unsigned A19:1;
    unsigned AN12:1;
    unsigned AN13:1;
    unsigned AN14:1;
    unsigned AN15:1;
  };
} PORTHbits;
extern volatile near unsigned char       PORTJ;
extern volatile near union {
  struct {
    unsigned RJ0:1;
    unsigned RJ1:1;
    unsigned RJ2:1;
    unsigned RJ3:1;
    unsigned RJ4:1;
    unsigned RJ5:1;
    unsigned RJ6:1;
    unsigned RJ7:1;
  };
  struct {
    unsigned ALE:1;
    unsigned OE:1;
    unsigned WRL:1;
    unsigned WRH:1;
    unsigned BA0:1;
    unsigned CE:1;
    unsigned LB:1;
    unsigned UB:1;
  };
} PORTJbits;
extern volatile near unsigned char       LATA;
extern volatile near struct {
  unsigned LATA0:1;
  unsigned LATA1:1;
  unsigned LATA2:1;
  unsigned LATA3:1;
  unsigned LATA4:1;     /* Reserved - Do not use */
  unsigned LATA5:1;
  unsigned LATA6:1;
```

```
} LATAbits;
extern volatile near unsigned char       LATB;
extern volatile near struct {
  unsigned LATB0:1;     /* Reserved - Do not use */
  unsigned LATB1:1;
  unsigned LATB2:1;
  unsigned LATB3:1;
  unsigned LATB4:1;
  unsigned LATB5:1;
  unsigned LATB6:1;
  unsigned LATB7:1;
} LATBbits;
extern volatile near unsigned char       LATC;
extern volatile near struct {
  unsigned LATC0:1;
  unsigned LATC1:1;     /* Reserved - Do not use */
  unsigned LATC2:1;     /* Reserved - Do not use */
  unsigned LATC3:1;     /* Reserved - Do not use */
  unsigned LATC4:1;     /* Reserved - Do not use */
  unsigned LATC5:1;     /* Reserved - Do not use */
  unsigned LATC6:1;
  unsigned LATC7:1;
} LATCbits;
extern volatile near unsigned char       LATD;
extern volatile near struct {
  unsigned LATD0:1;
  unsigned LATD1:1;
  unsigned LATD2:1;
  unsigned LATD3:1;
  unsigned LATD4:1;
  unsigned LATD5:1;
  unsigned LATD6:1;
  unsigned LATD7:1;
} LATDbits;
extern volatile near unsigned char       LATE;
extern volatile near struct {
  unsigned LATE0:1;
  unsigned LATE1:1;
  unsigned LATE2:1;
  unsigned LATE3:1;
  unsigned LATE4:1;
  unsigned LATE5:1;
  unsigned LATE6:1;
  unsigned LATE7:1;
} LATEbits;
extern volatile near unsigned char       LATF;
extern volatile near struct {
  unsigned LATF0:1;
  unsigned LATF1:1;
  unsigned LATF2:1;
  unsigned LATF3:1;
  unsigned LATF4:1;
  unsigned LATF5:1;
  unsigned LATF6:1;
  unsigned LATF7:1;     /* Reserved - Do not use */
} LATFbits;
extern volatile near unsigned char       LATG;
extern volatile near struct {
  unsigned LATG0:1;
  unsigned LATG1:1;
  unsigned LATG2:1;
  unsigned LATG3:1;
  unsigned LATG4:1;
} LATGbits;
extern volatile near unsigned char       LATH;
extern volatile near struct {
  unsigned LATH0:1;
  unsigned LATH1:1;
  unsigned LATH2:1;
  unsigned LATH3:1;
  unsigned LATH4:1;
  unsigned LATH5:1;
  unsigned LATH6:1;
  unsigned LATH7:1;
} LATHbits;
extern volatile near unsigned char       LATJ;
extern volatile near struct {
  unsigned LATJ0:1;
  unsigned LATJ1:1;
  unsigned LATJ2:1;
  unsigned LATJ3:1;
  unsigned LATJ4:1;
  unsigned LATJ5:1;
  unsigned LATJ6:1;
  unsigned LATJ7:1;
} LATJbits;
extern volatile near unsigned char       TRISA;
extern volatile near struct {
  unsigned TRISA0:1;
  unsigned TRISA1:1;
  unsigned TRISA2:1;
  unsigned TRISA3:1;
  unsigned TRISA4:1;     /* Reserved - Do not use */
  unsigned TRISA5:1;
  unsigned TRISA6:1;
} TRISAbits;
extern volatile near unsigned char       DDRA;
extern volatile near struct {
  unsigned RA0:1;
  unsigned RA1:1;
  unsigned RA2:1;
  unsigned RA3:1;
  unsigned RA4:1;     /* Reserved - Do not use */
  unsigned RA5:1;
  unsigned RA6:1;
} DDRAbits;
extern volatile near unsigned char       DDRB;
extern volatile near struct {
  unsigned RB0:1;     /* Reserved - Do not use */
  unsigned RB1:1;
  unsigned RB2:1;
  unsigned RB3:1;
  unsigned RB4:1;
  unsigned RB5:1;
  unsigned RB6:1;
  unsigned RB7:1;
} DDRBbits;
extern volatile near unsigned char       TRISB;
extern volatile near struct {
  unsigned TRISB0:1;     /* Reserved - Do not use */
  unsigned TRISB1:1;
  unsigned TRISB2:1;
  unsigned TRISB3:1;
  unsigned TRISB4:1;
  unsigned TRISB5:1;
  unsigned TRISB6:1;
  unsigned TRISB7:1;
} TRISBbits;
extern volatile near unsigned char       DDRC;
extern volatile near struct {
  unsigned RC0:1;
  unsigned RC1:1;     /* Reserved - Do not use */
  unsigned RC2:1;     /* Reserved - Do not use */
  unsigned RC3:1;     /* Reserved - Do not use */
  unsigned RC4:1;     /* Reserved - Do not use */
  unsigned RC5:1;     /* Reserved - Do not use */
  unsigned RC6:1;
  unsigned RC7:1;
} DDRCbits;
extern volatile near unsigned char       TRISC;
extern volatile near struct {
  unsigned TRISC0:1;
  unsigned TRISC1:1;    /* Reserved - Do not use */
  unsigned TRISC2:1;    /* Reserved - Do not use */
  unsigned TRISC3:1;    /* Reserved - Do not use */
  unsigned TRISC4:1;    /* Reserved - Do not use */
  unsigned TRISC5:1;    /* Reserved - Do not use */
  unsigned TRISC6:1;
  unsigned TRISC7:1;
} TRISCbits;
extern volatile near unsigned char       DDRD;
extern volatile near struct {
  unsigned RD0:1;
  unsigned RD1:1;
  unsigned RD2:1;
  unsigned RD3:1;
  unsigned RD4:1;
  unsigned RD5:1;
  unsigned RD6:1;
  unsigned RD7:1;
} DDRDbits;
extern volatile near unsigned char       TRISD;
extern volatile near struct {
  unsigned TRISD0:1;
  unsigned TRISD1:1;
  unsigned TRISD2:1;
  unsigned TRISD3:1;
  unsigned TRISD4:1;
  unsigned TRISD5:1;
  unsigned TRISD6:1;
  unsigned TRISD7:1;
```

```
} TRISDbits;
extern volatile near unsigned char       DDRE;
extern volatile near struct {
  unsigned RE0:1;
  unsigned RE1:1;
  unsigned RE2:1;
  unsigned RE3:1;
  unsigned RE4:1;
  unsigned RE5:1;
  unsigned RE6:1;
  unsigned RE7:1;
} DDREbits;
extern volatile near unsigned char       TRISE;
extern volatile near struct {
  unsigned TRISE0:1;
  unsigned TRISE1:1;
  unsigned TRISE2:1;
  unsigned TRISE3:1;
  unsigned TRISE4:1;
  unsigned TRISE5:1;
  unsigned TRISE6:1;
  unsigned TRISE7:1;
} TRISEbits;
extern volatile near unsigned char       TRISF;
extern volatile near struct {
  unsigned TRISF0:1;
  unsigned TRISF1:1;
  unsigned TRISF2:1;
  unsigned TRISF3:1;
  unsigned TRISF4:1;
  unsigned TRISF5:1;
  unsigned TRISF6:1;
  unsigned TRISF7:1;  /* Reserved - Do not use */
} TRISFbits;
extern volatile near unsigned char       DDRF;
extern volatile near struct {
  unsigned RF0:1;
  unsigned RF1:1;
  unsigned RF2:1;
  unsigned RF3:1;
  unsigned RF4:1;
  unsigned RF5:1;
  unsigned RF6:1;
  unsigned RF7:1;     /* Reserved - Do not use */
} DDRFbits;
extern volatile near unsigned char       DDRG;
extern volatile near struct {
  unsigned RG0:1;
  unsigned RG1:1;
  unsigned RG2:1;
  unsigned RG3:1;
  unsigned RG4:1;
} DDRGbits;
extern volatile near unsigned char       TRISG;
extern volatile near struct {
  unsigned TRISG0:1;
  unsigned TRISG1:1;
  unsigned TRISG2:1;
  unsigned TRISG3:1;
  unsigned TRISG4:1;
} TRISGbits;
extern volatile near unsigned char       DDRH;
extern volatile near struct {
  unsigned RH0:1;
  unsigned RH1:1;
  unsigned RH2:1;
  unsigned RH3:1;
  unsigned RH4:1;
  unsigned RH5:1;
  unsigned RH6:1;
  unsigned RH7:1;
} DDRHbits;
extern volatile near unsigned char       TRISH;
extern volatile near struct {
  unsigned TRISH0:1;
  unsigned TRISH1:1;
  unsigned TRISH2:1;
  unsigned TRISH3:1;
  unsigned TRISH4:1;
  unsigned TRISH5:1;
  unsigned TRISH6:1;
  unsigned TRISH7:1;
} TRISHbits;
extern volatile near unsigned char       DDRJ;
extern volatile near struct {
  unsigned RJ0:1;
  unsigned RJ1:1;
  unsigned RJ2:1;
  unsigned RJ3:1;
  unsigned RJ4:1;
  unsigned RJ5:1;
  unsigned RJ6:1;
  unsigned RJ7:1;
} DDRJbits;
extern volatile near unsigned char       TRISJ;
extern volatile near struct {
  unsigned TRISJ0:1;
  unsigned TRISJ1:1;
  unsigned TRISJ2:1;
  unsigned TRISJ3:1;
  unsigned TRISJ4:1;
  unsigned TRISJ5:1;
  unsigned TRISJ6:1;
  unsigned TRISJ7:1;
} TRISJbits;
extern volatile near unsigned char       MEMCON;     /* Reserved - Do
not use */
extern volatile near struct {
  unsigned WM0:1;
  unsigned WM1:1;
  unsigned :2;
  unsigned WAIT0:1;
  unsigned WAIT1:1;
  unsigned :1;
  unsigned EBDIS:1;
} MEMCONbits;     /* Reserved - Do not use */
extern volatile near unsigned char       PIE1;
extern volatile near union {
  struct {
    unsigned TMR1IE:1;
    unsigned TMR2IE:1;
    unsigned CCP1IE:1;
    unsigned SSPIE:1;     /* Reserved - Do not use */
    unsigned TX1IE:1;
    unsigned RC1IE:1;
    unsigned ADIE:1;
    unsigned PSPIE:1;     /* Reserved - Do not use */
  };
  struct {
    unsigned :4;
    unsigned TXIE:1;
    unsigned RCIE:1;
  };
} PIE1bits;
extern volatile near unsigned char       PIR1;
extern volatile near union {
  struct {
    unsigned TMR1IF:1;
    unsigned TMR2IF:1;
    unsigned CCP1IF:1;
    unsigned SSPIF:1;     /* Reserved - Do not use */
    unsigned TX1IF:1;
    unsigned RC1IF:1;
    unsigned ADIF:1;
    unsigned PSPIF:1;     /* Reserved - Do not use */
  };
  struct {
    unsigned :4;
    unsigned TXIF:1;
    unsigned RCIF:1;
  };
} PIR1bits;
extern volatile near unsigned char       IPR1;     /* Reserved - Do not
use */
extern volatile near union {
  struct {
    unsigned TMR1IP:1;
    unsigned TMR2IP:1;
    unsigned CCP1IP:1;
    unsigned SSPIP:1;
    unsigned TX1IP:1;
    unsigned RC1IP:1;
    unsigned ADIP:1;
    unsigned PSPIP:1;
  };
  struct {
    unsigned :4;
    unsigned TXIP:1;
    unsigned RCIP:1;
  };
} IPR1bits;             /* Reserved - Do not use */
```

```
extern volatile near unsigned char       PIE2;
extern volatile near struct {
  unsigned CCP2IE:1;
  unsigned TMR3IE:1;
  unsigned LVDIE:1;     /* Reserved - Do not use */
  unsigned BCLIE:1;     /* Reserved - Do not use */
  unsigned EEIE:1;
  unsigned :1;
  unsigned CMIE:1;
} PIE2bits;
extern volatile near unsigned char       PIR2;
extern volatile near struct {
  unsigned CCP2IF:1;
  unsigned TMR3IF:1;
  unsigned LVDIF:1;     /* Reserved - Do not use */
  unsigned BCLIF:1;     /* Reserved - Do not use */
  unsigned EEIF:1;
  unsigned :1;
  unsigned CMIF:1;
} PIR2bits;
extern volatile near unsigned char       IPR2;     /* Reserved - Do not
use */
extern volatile near struct {
  unsigned CCP2IP:1;
  unsigned TMR3IP:1;
  unsigned LVDIP:1;
  unsigned BCLIP:1;
  unsigned EEIP:1;
  unsigned :1;
  unsigned CMIP:1;
} IPR2bits;     /* Reserved - Do not use */
extern volatile near unsigned char       PIE3;
extern volatile near struct {
  unsigned CCP3IE:1;
  unsigned CCP4IE:1;
  unsigned CCP5IE:1;
  unsigned TMR4IE:1;
  unsigned TX2IE:1;
  unsigned RC2IE:1;
} PIE3bits;
extern volatile near unsigned char       PIR3;
extern volatile near struct {
  unsigned CCP3IF:1;
  unsigned CCP4IF:1;
  unsigned CCP5IF:1;
  unsigned TMR4IF:1;
  unsigned TX2IF:1;
  unsigned RC2IF:1;
} PIR3bits;
extern volatile near unsigned char       IPR3;     /* Reserved - Do not
use */
extern volatile near struct {
  unsigned CCP3IP:1;
  unsigned CCP4IP:1;
  unsigned CCP5IP:1;
  unsigned TMR4IP:1;
  unsigned TX2IP:1;
  unsigned RC2IP:1;
} IPR3bits;     /* Reserved - Do not use */
extern volatile near unsigned char       EECON1;     /* Use with
caution. */
extern volatile near struct {
  unsigned RD:1;
  unsigned WR:1;
  unsigned WREN:1;
  unsigned WRERR:1;
  unsigned FREE:1;     /* Use with caution. Could result in program
corruption. */
  unsigned :1;
  unsigned CFGS:1;
  unsigned EEPGD:1;
} EECON1bits;
extern volatile near unsigned char       EECON2;
extern volatile near unsigned char       EEDATA;
extern volatile near unsigned char       EEADR;
extern volatile near unsigned char       EEADRH;
extern volatile near unsigned char       RCSTA1;
extern volatile near union {
  struct {
    unsigned RX9D:1;
    unsigned OERR:1;
    unsigned FERR:1;
    unsigned ADEN:1;
    unsigned CREN:1;
    unsigned SREN:1;
    unsigned RX9:1;
    unsigned SPEN:1;
  };
  struct {
    unsigned :3;
    unsigned ADDEN:1;
  };
} RCSTA1bits;
extern volatile near unsigned char       TXSTA1;
extern volatile near struct {
  unsigned TX9D:1;
  unsigned TRMT:1;
  unsigned BRGH:1;
  unsigned :1;
  unsigned SYNC:1;
  unsigned TXEN:1;
  unsigned TX9:1;
  unsigned CSRC:1;
} TXSTA1bits;
extern volatile near unsigned char       TXREG1;
extern volatile near unsigned char       RCREG1;
extern volatile near unsigned char       SPBRG1;
extern volatile near unsigned char       PSPCON;     /* Reserved - Do
not use */
extern volatile near struct {
  unsigned :4;
  unsigned PSPMODE:1;
  unsigned IBOV:1;
  unsigned OBF:1;
  unsigned IBF:1;
} PSPCONbits;     /* Reserved - Do not use */
extern volatile near unsigned char       T3CON;
extern volatile near union {
  struct {
    unsigned TMR3ON:1;
    unsigned TMR3CS:1;
    unsigned T3SYNC:1;
    unsigned T3CCP1:1;
    unsigned T3CKPS0:1;
    unsigned T3CKPS1:1;
    unsigned T3CCP2:1;
    unsigned RD16:1;
  };
  struct {
    unsigned :2;
    unsigned T3NSYNC:1;
  };
  struct {
    unsigned :2;
    unsigned NOT_T3SYNC:1;
  };
} T3CONbits;
extern volatile near unsigned            TMR3;
extern volatile near unsigned char       TMR3L;
extern volatile near unsigned char       TMR3H;
extern volatile near unsigned char       CMCON;
extern volatile near struct {
  unsigned CM0:1;
  unsigned CM1:1;
  unsigned CM2:1;
  unsigned CIS:1;
  unsigned C1INV:1;
  unsigned C2INV:1;
  unsigned C1OUT:1;
  unsigned C2OUT:1;
} CMCONbits;
extern volatile near unsigned char       CVRCON;
extern volatile near struct {
  unsigned CVR0:1;
  unsigned CVR1:1;
  unsigned CVR2:1;
  unsigned CVR3:1;
  unsigned CVREF:1;
  unsigned CVRR:1;
  unsigned CVROE:1;
  unsigned CVREN:1;
} CVRCONbits;
extern volatile near unsigned char       CCP3CON;
extern volatile near union {
  struct {
    unsigned CCP3M0:1;
    unsigned CCP3M1:1;
    unsigned CCP3M2:1;
    unsigned CCP3M3:1;
    unsigned DCCP3Y:1;
    unsigned DCCP3X:1;
  };
  struct {
    unsigned :4;
    unsigned DC3B0:1;
    unsigned DC3B1:1;
  };
} CCP3CONbits;
extern volatile near unsigned            CCPR3;
extern volatile near unsigned char       CCPR3L;
extern volatile near unsigned char       CCPR3H;
extern volatile near unsigned char       CCP2CON;
extern volatile near union {
  struct {
    unsigned CCP2M0:1;
    unsigned CCP2M1:1;
    unsigned CCP2M2:1;
    unsigned CCP2M3:1;
    unsigned DCCP2Y:1;
    unsigned DCCP2X:1;
  };
  struct {
    unsigned :4;
    unsigned CCP2Y:1;
    unsigned CCP2X:1;
  };
  struct {
    unsigned :4;
    unsigned DC2B0:1;
    unsigned DC2B1:1;
  };
} CCP2CONbits;
extern volatile near unsigned            CCPR2;
extern volatile near unsigned char       CCPR2L;
extern volatile near unsigned char       CCPR2H;
extern volatile near unsigned char       CCP1CON;
extern volatile near union {
  struct {
    unsigned CCP1M0:1;
    unsigned CCP1M1:1;
    unsigned CCP1M2:1;
    unsigned CCP1M3:1;
    unsigned DCCP1Y:1;
    unsigned DCCP1X:1;
  };
  struct {
    unsigned :4;
    unsigned CCP1Y:1;
    unsigned CCP1X:1;
  };
  struct {
    unsigned :4;
    unsigned DC1B0:1;
    unsigned DC1B1:1;
  };
} CCP1CONbits;
extern volatile near unsigned char       CCPR1L;
extern volatile near unsigned            CCPR1;
extern volatile near unsigned char       CCPR1H;
extern volatile near unsigned char       ADCON2;
extern volatile near struct {
  unsigned ADCS0:1;
  unsigned ADCS1:1;
  unsigned ADCS2:1;
  unsigned :4;
  unsigned ADFM:1;
} ADCON2bits;
extern volatile near unsigned char       ADCON1;
extern volatile near struct {
  unsigned PCFG0:1;
  unsigned PCFG1:1;
  unsigned PCFG2:1;
  unsigned PCFG3:1;
  unsigned VCFG0:1;
  unsigned VCFG1:1;
} ADCON1bits;
extern volatile near unsigned char       ADCON0;
extern volatile near union {
  struct {
    unsigned ADON:1;
    unsigned GO_DONE:1;
    unsigned CHS0:1;
    unsigned CHS1:1;
    unsigned CHS2:1;
    unsigned CHS3:1;
  };
  struct {
    unsigned :1;
    unsigned DONE:1;
  };
  struct {
    unsigned :1;
    unsigned GO:1;
  };
  struct {
    unsigned :1;
    unsigned NOT_DONE:1;
  };
} ADCON0bits;
extern volatile near unsigned            ADRES;
extern volatile near unsigned char       ADRESL;
extern volatile near unsigned char       ADRESH;
extern volatile near unsigned char       SSPCON2;     /* Reserved - Do
not use */
extern volatile near struct {
  unsigned SEN:1;
  unsigned RSEN:1;
  unsigned PEN:1;
  unsigned RCEN:1;
  unsigned ACKEN:1;
  unsigned ACKDT:1;
  unsigned ACKSTAT:1;
  unsigned GCEN:1;
} SSPCON2bits;     /* Reserved - Do not use */
```

```
extern volatile near unsigned char       SSPCON1;     /* Reserved - Do
not use */
                                      /* SSPCON1bits  Reserved */
extern volatile near unsigned char       SSPSTAT;     /* Reserved - Do
not use */
extern volatile near union {
  struct {
    unsigned BF:1;
    unsigned UA:1;
    unsigned R_W:1;
    unsigned S:1;
    unsigned P:1;
    unsigned D_A:1;
    unsigned CKE:1;
    unsigned SMP:1;
  };
  struct {
    unsigned :2;
    unsigned I2C_READ:1;
    unsigned I2C_START:1;
    unsigned I2C_STOP:1;
    unsigned I2C_DAT:1;
  };
  struct {
    unsigned :2;
    unsigned NOT_W:1;
    unsigned :2;
    unsigned NOT_A:1;
  };
  struct {
    unsigned :2;
    unsigned NOT_WRITE:1;
    unsigned :2;
    unsigned NOT_ADDRESS:1;
  };
  struct {
    unsigned :2;
    unsigned READ_WRITE:1;
    unsigned :2;
    unsigned DATA_ADDRESS:1;
  };
  struct {
    unsigned :2;
    unsigned R:1;
    unsigned :2;
    unsigned D:1;
  };
} SSPSTATbits;     /* Reserved - Do not use */
extern volatile near unsigned char       SSPADD;     /* Reserved - Do
not use */
extern volatile near unsigned char       SSPBUF;     /* Reserved - Do
not use */
extern volatile near unsigned char       T2CON;
extern volatile near struct {
  unsigned T2CKPS0:1;
  unsigned T2CKPS1:1;
  unsigned TMR2ON:1;
```

```
    unsigned T2OUTPS0:1;
    unsigned T2OUTPS1:1;
    unsigned T2OUTPS2:1;
    unsigned T2OUTPS3:1;
  } T2CONbits;
  extern volatile near unsigned char       PR2;
  extern volatile near unsigned char       TMR2;
  extern volatile near unsigned char       T1CON;
  extern volatile near union {
    struct {
      unsigned TMR1ON:1;
      unsigned TMR1CS:1;
      unsigned T1SYNC:1;
      unsigned T1OSCEN:1;
      unsigned T1CKPS0:1;
      unsigned T1CKPS1:1;
      unsigned :1;
      unsigned RD16:1;
    };
    struct {
      unsigned :2;
      unsigned T1INSYNC:1;
    };
    struct {
      unsigned :2;
      unsigned NOT_T1SYNC:1;
    };
  } T1CONbits;
  extern volatile near unsigned char       TMR1L;
  extern volatile near unsigned            TMR1;
  extern volatile near unsigned char       TMR1H;
  extern volatile near unsigned char       RCON;     /* Reserved - Do not
  use */
  extern volatile near union {
    struct {
      unsigned NOT_BOR:1;
      unsigned NOT_POR:1;
      unsigned NOT_PD:1;
      unsigned NOT_TO:1;
      unsigned NOT_RI:1;
      unsigned :2;
      unsigned NOT_IPEN:1;
    };
    struct {
      unsigned BOR:1;
      unsigned POR:1;
      unsigned PD:1;
      unsigned TO:1;
      unsigned RI:1;
      unsigned :2;
      unsigned IPEN:1;
    };
  } RCONbits;     /* Reserved - Do not use */
  extern volatile near unsigned char       WDTCON;     /* Reserved - Do
  not use */
  extern volatile near union {
    struct {
```

```
    unsigned SWDTEN:1;
  };
  struct {
    unsigned SWDTE:1;
  };
} WDTCONbits;     /* Reserved - Do not use */
extern volatile near unsigned char       LVDCON;     /* Reserved - Do
not use */
extern volatile near union {
  struct {
    unsigned LVDL0:1;
    unsigned LVDL1:1;
    unsigned LVDL2:1;
    unsigned LVDL3:1;
    unsigned LVDEN:1;
    unsigned IRVST:1;
  };
  struct {
    unsigned LVV0:1;
    unsigned LVV1:1;
    unsigned LVV2:1;
    unsigned LVV3:1;
    unsigned :1;
    unsigned BGST:1;
  };
} LVDCONbits;     /* Reserved - Do not use */
extern volatile near unsigned char       OSCCON;     /* Reserved - Do
not use */
extern volatile near struct {
  unsigned SCS:1;
} OSCCONbits;                                        /* Reserved - Do
not use */
extern volatile near unsigned char       T0CON;      /* Reserved - Do
not use if you are using ifi_library.lib */
extern volatile near struct {
  unsigned T0PS0:1;
  unsigned T0PS1:1;
  unsigned T0PS2:1;
  unsigned PSA:1;
  unsigned T0SE:1;
  unsigned T0CS:1;
  unsigned T08BIT:1;
  unsigned TMR0ON:1;
} T0CONbits;                                     /* Reserved - Do not
use if you are using ifi_library.lib */
extern volatile near unsigned            TMR0;   /* Reserved - Do not
modify if you are using ifi_library.lib */
extern volatile near unsigned char       TMR0L;  /* Reserved - Do not
modify if you are using ifi_library.lib */
extern volatile near unsigned char       TMR0H;  /* Reserved - Do not
modify if you are using ifi_library.lib */
extern          near unsigned char       STATUS;
extern          near struct {
  unsigned C:1;
  unsigned DC:1;
  unsigned Z:1;
  unsigned OV:1;
  unsigned N:1;
} STATUSbits;
extern          near unsigned            FSR2;  /* Reserved - Do not
use */
extern          near unsigned char       FSR2L;  /* Reserved - Do not
use */
extern          near unsigned char       FSR2H;  /* Reserved - Do not
use */
extern volatile near unsigned char       PLUSW2;  /* Reserved - Do not
use */
extern volatile near unsigned char       PREINC2;  /* Reserved - Do not
use */
extern volatile near unsigned char       POSTDEC2;  /* Reserved - Do
not use */
extern volatile near unsigned char       POSTINC2;  /* Reserved - Do
not use */
extern          near unsigned char       INDF2;  /* Reserved - Do not
use */
extern          near unsigned char       BSR;  /* Reserved - Do not use
*/
extern          near unsigned            FSR1;  /* Reserved - Do not
use */
extern          near unsigned char       FSR1L;  /* Reserved - Do not
use */
extern          near unsigned char       FSR1H;  /* Reserved - Do not
use */
extern volatile near unsigned char       PLUSW1;  /* Reserved - Do not
use */
extern volatile near unsigned char       PREINC1;  /* Reserved - Do not
use */
extern volatile near unsigned char       POSTDEC1;  /* Reserved - Do
not use */
extern volatile near unsigned char       POSTINC1;  /* Reserved - Do
not use */
extern          near unsigned char       INDF1;  /* Reserved - Do not
use */
extern          near unsigned char       WREG;  /* Use at your own
risk. */
extern          near unsigned char       FSR0L;  /* Use at your own
risk. */
extern          near unsigned            FSR0;  /* Use at your own
risk. */
extern          near unsigned char       FSR0H;  /* Use at your own
risk. */
extern volatile near unsigned char       PLUSW0;  /* Use at your own
risk. */
extern volatile near unsigned char       PREINC0;  /* Use at your own
risk. */
extern volatile near unsigned char       POSTDEC0;  /* Use at your own
risk. */
extern volatile near unsigned char       POSTINC0;  /* Use at your own
risk. */
extern          near unsigned char       INDF0;  /* Use at your own
risk. */
extern volatile near unsigned char       INTCON3;
extern volatile near union {
  struct {
    unsigned INT1IF:1;
    unsigned INT2IF:1;
    unsigned INT3IF:1;
    unsigned INT1IE:1;
    unsigned INT2IE:1;
    unsigned INT3IE:1;
    unsigned INT1IP:1;     /* Reserved - Do not use */
    unsigned INT2IP:1;     /* Reserved - Do not use */  /* Must be set
to 0 (low priority) */
  };
  struct {
    unsigned INT1F:1;
    unsigned INT2F:1;
    unsigned INT3F:1;
    unsigned INT1E:1;
    unsigned INT2E:1;
    unsigned INT3E:1;
    unsigned INT1P:1;     /* Reserved - Do not use */
    unsigned INT2P:1;     /* Reserved - Do not use */
  };
} INTCON3bits;
extern volatile near unsigned char       INTCON2;
extern volatile near union {
  struct {
    unsigned RBIP:1;        /* Reserved - Do not use */
    unsigned INT3IP:1;      /* Reserved - Do not use */
    unsigned TMR0IP:1;      /* Reserved - Do not use */
    unsigned INTEDG3:1;
    unsigned INTEDG2:1;
    unsigned INTEDG1:1;
    unsigned INTEDG0:1;     /* Reserved - Do not use */
    unsigned NOT_RBPU:1;    /* Reserved - Do not use */
  };
  struct {
    unsigned :1;
    unsigned INT3P:1;     /* Reserved - Do not use */
    unsigned T0IP:1;      /* Reserved - Do not use */
    unsigned :4;
    unsigned RBPU:1;      /* Reserved - Do not use */
  };
} INTCON2bits;
extern volatile near unsigned char       INTCON;
extern volatile near union {
  struct {
    unsigned RBIF:1;
    unsigned INT0IF:1;  /* Reserved - Do not use */
    unsigned TMR0IF:1;  /* Reserved - Do not modify if you are using
ifi_library.lib */
    unsigned RBIE:1;
    unsigned INT0IE:1;  /* Reserved - Do not use */
    unsigned TMR0IE:1;  /* Reserved - Do not use if you are using
ifi_library.lib */
    unsigned PEIE:1;
    unsigned GIE:1;     /* Reserved - Do not use */
  };
  struct {
    unsigned :1;
    unsigned INT0F:1;   /* Reserved - Do not use */
    unsigned T0IF:1;
    unsigned :1;
    unsigned INT0E:1;   /* Reserved - Do not use */
    unsigned T0IE:1;
    unsigned GIEL:1;    /* Use of this bit could lead to unexpected
results */
    unsigned GIEH:1;    /* Reserved - Do not use */
  };
} INTCONbits;
extern          near unsigned char       PRODL;
extern          near unsigned            PROD;
extern          near unsigned char       PRODH;
extern volatile near unsigned char       TABLAT;
extern volatile near unsigned char       TBLPTRL;
extern volatile near unsigned short long TBLPTR;
extern volatile near unsigned char       TBLPTRH;
extern volatile near unsigned char       TBLPTRU;
extern volatile near unsigned char       PCL;
extern volatile near unsigned short long PC;
extern volatile near unsigned char       PCLATH;
extern volatile near unsigned char       PCLATU;
extern volatile near unsigned char       STKPTR;
extern volatile near union {
  struct {
    unsigned STKPTR0:1;
    unsigned STKPTR1:1;
    unsigned STKPTR2:1;
    unsigned STKPTR3:1;
    unsigned STKPTR4:1;
    unsigned :1;
    unsigned STKUNF:1;
    unsigned STKOVF:1;
  };
  struct {
    unsigned :7;
    unsigned STKFUL:1;
  };
} STKPTRbits;
extern          near unsigned short long TOS;
extern          near unsigned char       TOSL;
extern          near unsigned char       TOSH;
extern          near unsigned char       TOSU;

#if defined(BANKED)
#error  *** Error - Invalid 18f8520 header file!
#else
#define UNCHANGEABLE_DEFINITION_AREA 1
#endif
/*-----------------------------------------------------------------------
----
 * Some useful defines for inline assembly stuff
 *-----------------------------------------------------------------------
----*/
#define ACCESS 0
#define BANKED 1
```

```
/*-----------------------------------------------------------------------
----
 * Some useful macros for inline assembly stuff
 *-----------------------------------------------------------------------
----*/
#define Nop()    {_asm nop _endasm}
#define ClrWdt() {_asm clrwdt _endasm}
#define Sleep()  {_asm sleep _endasm}
#define Reset()  {_asm reset _endasm}

#define Rlcf(f,dest,access)  {_asm movlb f rlcf f,dest,access _endasm}
#define Rlncf(f,dest,access) {_asm movlb f rlncf f,dest,access _endasm}
#define Rrcf(f,dest,access)  {_asm movlb f rrcf f,dest,access _endasm}
#define Rrncf(f,dest,access) {_asm movlb f rrncf f,dest,access _endasm}
#define Swapf(f,dest,access) {_asm movlb f swapf f,dest,access _endasm
}

/*-----------------------------------------------------------------------
----
 * A fairly inclusive set of registers to save for interrupts.
 * These are locations which are commonly used by the compiler.
 *-----------------------------------------------------------------------
----*/
#define INTSAVELOCS TBLPTR, TABLAT, PROD

#endif
```

B.6 ifi_utilities.h

```
/***********************************************************************
*********
* FILE NAME: ifi_utilities.h
*
* DESCRIPTION:
*  This is the include file which corresponds to ifi_utilities.c
*  It contains some aliases and function prototypes used in that file.
*
* USAGE:
*  This file should not be modified by the user.
*  DO NOT EDIT THIS FILE!
***********************************************************************
********/

#ifndef __ifi_utilities_h_
#define __ifi_utilities_h_

#ifdef _SNOOP_ON_COM1    /* FOR FUTURE USE */
#define RXINTF              PIR3bits.RC2IF
#define RXINTE              PIE3bits.RC2IE
#define TXINTF              PIR3bits.TX2IF
#define TXINTE              PIE3bits.TX2IE
#define RCSTAbits           RCSTA2bits
#define RCSTA               RCSTA2
#define TXSTA               TXSTA2
```

```
#define TXREG              TXREG2
#define RCREG              RCREG2
#define SPBRG              SPBRG2
#define OpenUSART          Open2USART
#else
#define RXINTF             PIR1bits.RCIF
#define RXINTE             PIE1bits.RCIE
#define TXINTF             PIR1bits.TXIF
#define TXINTE             PIE1bits.TXIE
#define RCSTAbits          RCSTA1bits
#define RCSTA              RCSTA1
#define TXSTA              TXSTA1
#define TXREG              TXREG1
#define RCREG              RCREG1
#define SPBRG              SPBRG1
#define OpenUSART          Open1USART
#endif

/***********************************************************************
*********
                             MACRO DEFINITIONS
************************************************************************
********/

typedef enum
{
  baud_19 = 128,
  baud_38 = 64,
  baud_56 = 42,
  baud_115 = 21
} SERIAL_SPEED;


/***********************************************************************
*********
                           FUNCTION PROTOTYPES
************************************************************************
********/

void Hex_output(unsigned char temp);  /* located in ifi_library.lib */

#ifdef _FRC_BOARD
  /* located in ifi_library.lib */
void Generate_Pwms(unsigned char pwm_13,unsigned char pwm_14,
                   unsigned char pwm_15,unsigned char pwm_16);
#else
  /* located in ifi_library.lib */
void Generate_Pwms(unsigned char pwm_1,unsigned char pwm_2,
                   unsigned char pwm_3,unsigned char pwm_4,
                   unsigned char pwm_5,unsigned char pwm_6,
                   unsigned char pwm_7,unsigned char pwm_8);
#endif

/* These routines reside in ifi_utilities.c */
void Wait4TXEmpty(void);
void PrintByte(unsigned char odata);
void PrintWord(unsigned int odata);
void PrintString(char *bufr);
void DisplayBufr(unsigned char *bufr);
void PacketNum_Check(void);
void Initialize_Serial_Comms (void);
void Set_Number_of_Analog_Channels (unsigned char number_of_channels);
unsigned int Get_Analog_Value(unsigned char channel);

#endif


/*********************************************************************
********/
/*********************************************************************
********/
/*********************************************************************
********/
```

B.7 printf_lib.h

```
/*********************************************************************
*********
* FILE NAME: printf_lib.h
*
* DESCRIPTION:
*  This is the include file which corresponds to printf_lib.c
*
* USAGE:
*  If you add your own routines to that file, this is a good place
*  to add function prototypes.
**********************************************************************
********/

#ifndef __printf_lib_h_
#define __printf_lib_h_

int printf(rom const char *format, ...);

void printid(int data,int crtOn);
void printb(unsigned char data,int crtOn);
void printd(unsigned char data,int crtOn);
void printix(int data,int crtOn);
void printx(unsigned char data,int crtOn);
void debug_print(char *bufr,int data);
void debug_printb(char *bufr,unsigned int data);
void debug_println(char *bufr);

#endif


/*********************************************************************
********/
/*********************************************************************
********/
```

```
/*******************************************************************
********/
```

B.8 user_routines.h

```
/*******************************************************************
*********
* FILE NAME: user_routines.h
*
* DESCRIPTION:
*  This is the include file which corresponds to user_routines.c and
*  user_routines_fast.c
*  It contains some aliases and function prototypes used in those
files.
*
* USAGE:
*  If you add your own routines to those files, this is a good place to
add
*  your custom macros (aliases), type definitions, and function
prototypes.
********************************************************************
********/

#ifndef __user_program_h_
#define __user_program_h_


/*******************************************************************
*********
                            MACRO DECLARATIONS
********************************************************************
********/
/* Add your macros (aliases and constants) here.
*/
/* Do not edit the ones in ifi_aliases.h
*/
/* Macros are substituted in at compile time and make your code more
readable */
/* as well as making it easy to change a constant value in one place,
rather  */
/* than at every place it is used in your code.
*/
/*
 EXAMPLE CONSTANTS:
#define MAXIMUM_LOOPS   5
#define THE_ANSWER      42
#define TRUE            1
#define FALSE           0
#define PI_VAL          3.1415

 EXAMPLE ALIASES:
#define LIMIT_SWITCH_1  rc_dig_int1  (Points to another macro in
ifi_aliases.h)
```

```
#define MAIN_SOLENOID   solenoid1    (Points to another macro in
ifi_aliases.h)
*/

/* Used in limit switch routines in user_routines.c */
#define OPEN        1     /* Limit switch is open (input is floating
high). */
#define CLOSED      0     /* Limit switch is closed (input connected to
ground). */


/**********************************************************************
*********
                            TYPEDEF DECLARATIONS
***********************************************************************
********/
/* EXAMPLE DATA STRUCTURE */
/*
typedef struct
{
  unsigned int  NEW_CAPTURE_DATA:1;
  unsigned int  LAST_IN1:1;
  unsigned int  LAST_IN2:1;
  unsigned int  WHEEL_COUNTER_UP:1;
  unsigned int  :4;
  unsigned int wheel_left_counter;
  unsigned int wheel_right_counter;
} user_struct;
*/


/**********************************************************************
*********
                           FUNCTION PROTOTYPES
***********************************************************************
********/

/* These routines reside in user_routines.c */
void User_Initialization(void);
void Process_Data_From_Master_uP(void);
void Default_Routine(void);

/* These routines reside in user_routines_fast.c */
void InterruptHandlerLow (void);  /* DO NOT CHANGE! */
void User_Autonomous_Code(void);  /* Only in full-size FRC system. */
void Process_Data_From_Local_IO(void);


#endif
/**********************************************************************
********/
/**********************************************************************
********/
/**********************************************************************
********/
```

B.9 clock.c

```
/*******************************************************************
*********
*
*     TITLE:            clock.c
*
*     VERSION:    0.3 (Beta)
*
*     DATE:       18-Dec-2003
*
*     AUTHOR:           R. Kevin Watson
*                       kevinw@jpl.nasa.gov
*
*     COMMENTS:   This demonstrates the use of a timer and associated
interrupt.
*                       In this example we'll setup a timer to generate
an interrupt
*                       every millisecond (= 1000Hz rate). In response
to this interrupt,
*                       the microcontroller will execute a specific
piece of code called
*                       an interrupt handler (see
user_routines_fast.c). This interrupt
*                       handler will simply increment the global
variables "msClock" and
*                       "Clock". High-level user code can then access
these variables to
*                       create sophisticated state machines and highly
accurate sequencers.
*                       We'll just keep the time.
*
*
********************************************************************
*********
*
*     Change log:
*
*     DATE         REV  DESCRIPTION
*     -----------  ---  ---------------------------------------------
-----------
*     14-Dec-2003  0.1  RKW Original
*     16-Dec-2003  0.2  Accuracy bug: Changed the value of PR2 to 249
(was 250)
*     18-Dec-2003  0.3  Fixed 25 hour/day and 366 day/year bugs
*
********************************************************************
********/

#include "ifi_picdefs.h"
#include "printf_lib.h"
#include "clock.h"

volatile unsigned long msClock = 0; // 32-bit system clock running at
1KHz
```

```
                                                      // msClock will
roll-over every 49d 17h 2m 47s

volatile unsigned long Clock = 0;   // 32-bit system clock running at
1Hz
                                                      // Clock will
roll-over every 136 years

/***********************************************************************
*********
*
*     FUNCTION:         Initialize_Timer_2()
*
*     PURPOSE:          Initializes the timer 2 hardware.
*
*     CALLED FROM:      user_routines.c/User_Initialization()
*
*     PARAMETERS:       None
*
*     RETURNS:          Nothing
*
*     COMMENTS:         Place "#include "clock.h" in the includes
section
*                             of user_routines.c then call
Initialize_Timer_2()
*                             in user_routines.c/User_Initialization().
*
*                             Timer 2 documentation starts on page 141
of the data sheet.
*
*                             Timer 2 will be setup with these
parameters to generate
*                             a 1000Hz interrupt rate:
*
*                             1) The prescaler is set to divide the
10MHz system clock
*                             by 4 (i.e., 1:4) so that TMR2 will be
clocked at 2.5MHz.
*
*                             2) The PR2 register is set to 249 so that
the TMR2
*                             register will roll-over (i.e., transition
from 249 -> 0)
*                             at a 10,000Hz rate (2.5MHz/250).
*
*                             3) The postscaler is set to generate an
interrupt every
*                             tenth time the TMR2 register rolls-over
(10,000Hz/10=1000Hz).
*
*                             4) The timer 2 interrupt enable bit
(TMR2IE) is set to
*                             1 to enable the timer 2 interrupt.
*
*                             5) Finally, timer 2 is allowed to run by
setting the TMR2ON
*                             bit to 1.
```

```
*
***********************************************************************
********/
void Initialize_Timer_2(void)
{
      TMR2 = 0;                    // 8-bit timer 2 register (this is
readable and writable)
                                          //
      PR2   = 249;                        // timer 2 period register -
timer 2 increments to this
                                          // value then resets to zero
on the next clock and starts
                                          // all over again
                                          //
      T2CONbits.T2OUTPS0 = 1; // T2OUTPS3 T2OUTPS2 T2OUTPS1 T2OUTPS0
      T2CONbits.T2OUTPS1 = 0; //    0        0        0        0
      1:1 postscaler
      T2CONbits.T2OUTPS2 = 0; //    0        0        0        1
      1:2 postscaler
      T2CONbits.T2OUTPS3 = 1; //    0        0        1        0
      1:3 postscaler
                                          //    0        0        1
1           1:4 postscaler
                                          //    0        1        0
0           1:5 postscaler
                                          //    0        1        0
1           1:6 postscaler
                                          //    0        1        1
0           1:7 postscaler
                                          //    0        1        1
1           1:8 postscaler
                                          //    1        0        0
0           1:9 postscaler
                                          //    1        0        0
1           1:10 postscaler
                                          //    1        0        1
0           1:11 postscaler
                                          //    1        0        1
1           1:12 postscaler
                                          //    1        1        0
0           1:13 postscaler
                                          //    1        1        0
1           1:14 postscaler
                                          //    1        1        1
0           1:15 postscaler
                                          //    1        1        1
1           1:16 postscaler
                                          //
      T2CONbits.T2CKPS0 = 1;  // T2CKPS1  T2CKPS0
      T2CONbits.T2CKPS1 = 0;  //    0        0  1:1 prescaler (clock =
10MHz/each tick=100ns)
                                          //    0        1  1:4
prescaler (clock = 2.5MHz/each tick=400ns)
                                          //    1        x  1:16
prescaler (clock = 625KHz/each tick=1.6us) (T2CKPS0 doesn't matter)
                                          //
      PIE1bits.TMR2IE = 1;    // 0: disable timer 2 interrupt on PR2
match
                                          // 1: enable timer 2
interrupt on PR2 match
                                          //    if the prescaler is
enabled (i.e., greater than 1:1), this
                                          //    match will occur n
times (where n is the postscaler value)
                                          //    before an interrupt
will be generated
                                          //
      IPR1bits.TMR2IP = 0;    // 0: timer 2 overflow interrupt is low
priority (leave at 0 for IFI controllers)
                                          // 1: timer 2 overflow
interrupt is high priority
                                          //
      T2CONbits.TMR2ON = 1;   // 0: timer 2 is disabled
                                          // 1: timer 2 is enabled
(running)
}

/*******************************************************************
*********
*
*     FUNCTION:         Timer_2_Int_Handler()
*
*     PURPOSE:          If enabled, the timer 2 interrupt handler is
called when the
*                             TMR2 register matches the value stored in
the PR2 register.
*
*     CALLED FROM:      user_routines_fast.c/InterruptHandlerLow()
*
*     PARAMETERS:       None
*
*     RETURNS:          Nothing
*
*     COMMENTS:         The timer 2 module is documented in the
PIC18F8520
*                             data sheet starting on page 141.
*
********************************************************************
********/
void Timer_2_Int_Handler(void)
{
      // this function will be called when a timer 2 interrupt occurs

      static unsigned int divisor = 0;

      msClock++; // increment the millisecond clock

      // Do it this way so that we don't have to do anything as
      // time consuming as division -- which is really, really
      // slow on an 8-bit microcontroller without hardware
      // support for division -- within an interrupt handler,
      // which must execute very fast.
      if (++divisor >= 1000) // this can be adjusted up or down for
better time accuracy
      {
            divisor = 0;
            Clock++;    // increment the one second clock every
1/1000th time through
      }
}

/*******************************************************************
*********
*
*     FUNCTION:         Display_Time()
*
*     PURPOSE:          Formats and sends the time to the console
window
*                             once a second.
*
*     CALLED FROM:      user_routines.c/Process_Data_From_Master_uP()
*
*     PARAMETERS:       None
*
*     RETURNS:          Nothing
*
*     COMMENTS:
*
********************************************************************
********/
void Display_Time(void)
{
      static unsigned long Old_Clock = 0;
      static unsigned int Milliseconds = 0;
      static unsigned long Mseconds = 0;
      static unsigned char Seconds = 0;
      static unsigned char Minutes = 0;
      static unsigned char Hours = 0;
      static unsigned int Days = 0;

      if(msClock > Old_Clock) // only update the clock if it changes
      {
            printf("Elapsed milliseconds = %d\n", (unsigned)msClock);
      }

      if(msClock > 1000)
      {
            msClock = 0;
      }
}
```

B.10 ifi_startup.c

```
/*******************************************************************
*********
* FILE NAME: ifi_startup.c
```

```
*
* DESCRIPTION:
*  This file contains important startup code.
*
* USAGE:
*  This file should not be modified at all by the user.
*
*  DO NOT MODIFY THIS FILE!
***********************************************************************
********/

#include "ifi_default.h"

extern void Clear_Memory (void);
extern void main (void);

void _entry (void);     /* prototype for the startup function */
void _startup (void);
void _do_cinit (void);  /* prototype for the initialized data setup */

extern volatile near unsigned long short TBLPTR;
extern near unsigned FSR0;
extern near char FPFLAGS;
#define RND 6

#pragma code _entry_scn=RESET_VECTOR
void _entry (void)
{
_asm goto _startup _endasm

}

#pragma code _startup_scn
void _startup (void)
{
  _asm
    /* Initialize the stack pointer */
    lfsr 1, _stack lfsr 2, _stack clrf TBLPTRU, 0 /* 1st silicon
doesn't do this on POR */
    bcf  FPFLAGS,RND,0 /* Initialize rounding flag for floating point
libs */

    /* initialize the flash memory access configuration. this is
harmless */
    /* for non-flash devices, so we do it on all parts. */
    bsf 0xa6, 7, 0
    bcf 0xa6, 6, 0
  _endasm

loop:

      Clear_Memory();
  _do_cinit ();
  /* Call the user's main routine */
  main ();

  goto loop;
```

```
}                               /* end _startup() */

/* MPLAB-C18 initialized data memory support */
/* The linker will populate the _cinit table */
extern far rom struct
{
  unsigned short num_init;
  struct _init_entry
  {
    unsigned long from;
    unsigned long to;
    unsigned long size;
  }
  entries[];
}
_cinit;

#pragma code _cinit_scn
void
_do_cinit (void)
{
  /* we'll make the assumption in the following code that these statics
   * will be allocated into the same bank.
   */
  static short long prom;
  static unsigned short curr_byte;
  static unsigned short curr_entry;
  static short long data_ptr;

  /* Initialized data... */
  TBLPTR = (short long)&_cinit;
  _asm
    movlb data_ptr
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf curr_entry, 1
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf curr_entry+1, 1
  _endasm
    test:
  _asm
     bnz 3
    tstfsz curr_entry, 1
    bra 1
  _endasm
  goto done;
    /* Count down so we only have to look up the data in _cinit
     * once.
     *
     * At this point we know that TBLPTR points to the top of the
current
     * entry in _cinit, so we can just start reading the from, to, and
     * size values.
     */
  _asm
  /* read the source address */
```

```
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf prom, 1
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf prom+1, 1
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf prom+2, 1
    /* skip a byte since it's stored as a 32bit int */
    tblrdpostinc
    /* read the destination address directly into FSR0 */
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf FSR0L, 0
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf FSR0H, 0
    /* skip two bytes since it's stored as a 32bit int */
    tblrdpostinc
    tblrdpostinc
    /* read the destination address directly into FSR0 */
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf curr_byte, 1
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf curr_byte+1, 1
    /* skip two bytes since it's stored as a 32bit int */
    tblrdpostinc
    tblrdpostinc
  _endasm

  /* the table pointer now points to the next entry. Save it
   * off since we'll be using the table pointer to do the copying
   * for the entry.
   */
  data_ptr = TBLPTR;

  /* now assign the source address to the table pointer */
  TBLPTR = prom;

  /* do the copy loop */
  _asm
        /* determine if we have any more bytes to copy */
    movlb curr_byte
    movf  curr_byte, 1, 1
copy_loop:
    bnz 2 /* copy_one_byte */
    movf  curr_byte + 1, 1, 1
    bz 7  /* done_copying */

copy_one_byte:
    tblrdpostinc
    movf  TABLAT, 0, 0
    movwf POSTINC0, 0
    /* decrement byte counter */
    decf  curr_byte, 1, 1
    bc -8   /* copy_loop */
    decf  curr_byte + 1, 1, 1
    bra -7  /* copy_one_byte */

done_copying:
  _endasm
      /* restore the table pointer for the next entry */
  TBLPTR = data_ptr;
  /* next entry... */
  curr_entry--;
  goto test;
done:
;
}
```

B.11 ifi_utilities.c

```
/*******************************************************************
*********
* FILE NAME: ifi_utilities.c
*
* DESCRIPTION:
*  This file contains some useful functions that you can call in your
program.
*
* USAGE:
*  The user should NOT modify this file, so that if a new version is
released
*  by Innovation First then it can be easily replaced.
*  The user should add their own functions to either user_routines.c or
another
*  custom file.
*
********************************************************************
********/

#include <usart.h>
#include <spi.h>
#include <adc.h>
#include <capture.h>
#include <timers.h>
#include <string.h>
#include <pwm.h>
#include "delays.h"       /*defined locally*/
#include "ifi_aliases.h"
#include "ifi_default.h"
#include "ifi_utilities.h"
#include "user_routines.h"

int             ifi_packet_num1 = 0;
int             ifi_last_packet1 = 0;
char            ifi_printfBufr[80];
```

```
unsigned char   *ptr;
unsigned char   ifi_count;
unsigned char   ifi_analog_channels;


/*******************************************************************
*********
* FUNCTION NAME: Wait4TXEmpty
* PURPOSE:       Wait for serial transmit buffer to be empty.
* CALLED FROM:   anywhere
* ARGUMENTS:     none
* RETURNS:       void
********************************************************************
********/
/* Used when transmitting data serially.  It waits for each byte to
finish.   */
void Wait4TXEmpty(void)
{
#ifndef _SIMULATOR
  while (!TXINTF)
  {
    continue;
  }
#endif
}


/*******************************************************************
*********
* FUNCTION NAME: PrintByte
* PURPOSE:       A simple way to print a byte of data to the serial
port.
* CALLED FROM:   anywhere
* ARGUMENTS:     none
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     odata          unsigned char    I    byte of data to be
transmitted
* RETURNS:       void
********************************************************************
********/
void PrintByte(unsigned char odata)
{
  Hex_output((unsigned char) odata);
  TXREG = 13;  /* a carriage return */
  Wait4TXEmpty();
}


/*******************************************************************
*********
* FUNCTION NAME: PrintWord
* PURPOSE:       A simple way to print a word of data to the serial
port.
* CALLED FROM:   anywhere
* ARGUMENTS:     none
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     odata          unsigned int     I    word of data to be
transmitted
* RETURNS:       void
***********************************************************************
********/
void PrintWord(unsigned int odata)
{
  ptr = (unsigned char *) &odata;
  Hex_output(ptr[1]);
  Hex_output(ptr[0]);
  TXREG = 13;  /* add a carriage return */
  Wait4TXEmpty();
}


/**********************************************************************
*********
* FUNCTION NAME: PrintString
* PURPOSE:       Prints a string to the serial port.
* CALLED FROM:   anywhere
* ARGUMENTS:     none
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     bufr           pointer          I    word of data to be
transmitted
* RETURNS:       void
***********************************************************************
********/
void PrintString(char *bufr)
{
  static int len,I;

  strcpypgm2ram (ifi_printfBufr,(rom char *) bufr); /*Move from flash
to ram*/
  len = (int) strlen((const char *)ifi_printfBufr);
  if (len > 80) len = 80;

  for (I=0;I<len;I++)
  {
    TXREG = ifi_printfBufr[I];
    Wait4TXEmpty();
  }
}


/**********************************************************************
*********
* FUNCTION NAME: DisplayBufr
* PURPOSE:       Print the entire transmit or receive buffer over the
serial
*                port for viewing in a terminal program on your PC.
* CALLED FROM:   anywhere
* ARGUMENTS:
*     Argument       Type        IO   Description
*     --------       --------    --   -----------
*     *bufr          pointer     I    points to beginning of buffer to
transmit
* RETURNS:       void
***********************************************************************
********/
void DisplayBufr(unsigned char *bufr)
{
  for (ifi_count=0;ifi_count<26;ifi_count++)
  {
    Hex_output((unsigned char) *bufr++);
  }
  TXREG = 13;  /* add a carriage return */
  Wait4TXEmpty();
}


/**********************************************************************
*********
* FUNCTION NAME: PacketNum_Check
* PURPOSE:       Print the packet number over the serial port if a
packet gets
*                dropped.  Handy for seeing if you are dropping data.
* CALLED FROM:   anywhere
* ARGUMENTS:     none
* RETURNS:       void
***********************************************************************
********/
void PacketNum_Check(void)
{
  /*    to print only the 10th (packet num) byte*/
  ptr = (unsigned char *) &rxdata.packet_num;
  ifi_packet_num1 = (int) rxdata.packet_num;
  if (ifi_packet_num1 != ifi_last_packet1)
  {
    if (statusflag.FIRST_TIME == 1)
    {
      statusflag.FIRST_TIME = 0;
    }
    else
    {
      Hex_output((unsigned char) ifi_last_packet1);
      Hex_output((unsigned char) ifi_packet_num1);
      TXREG = 13;
      Wait4TXEmpty();

      statusflag.FIRST_TIME = 0;
    }
    ifi_last_packet1 = ifi_packet_num1;
  }/*   if (ifi_packet_num1 != ifi_last_packet1)*/
  ifi_last_packet1++;
  if (ifi_last_packet1 > 255)
  {
    ifi_last_packet1 = 0;
  }
}
```

```
/*******************************************************************
*********
* FUNCTION NAME: Initialize_Serial_Comms
* PURPOSE:       Opens the serial port 1 for communicating with your PC
at
*                115k baud, 8 bits, no parity, one stop bit, and no
flow control.
* CALLED FROM:   user_routines.c
* ARGUMENTS:     none
* RETURNS:       void
********************************************************************
********/
void Initialize_Serial_Comms (void)
{
  OpenUSART(USART_TX_INT_OFF &
    USART_RX_INT_OFF &
    USART_ASYNCH_MODE &
    USART_EIGHT_BIT &
    USART_CONT_RX &
    USART_BRGH_HIGH,
    baud_115);

  Delay1KTCYx( 50 ); /* Settling time */
}


/*******************************************************************
*********
* FUNCTION NAME: Set_Number_of_Analog_Channels
* PURPOSE:       Sets the variable used in Get_Analog_Value routine
(below)
*                to the number of analog channels desired by the user.
* CALLED FROM:   user_routines.c initialization, typically
* ARGUMENTS:
*      Argument            Type    IO   Description
*     -----------          -----   --   -----------
*     number_of_channels   alias   I    choose alias from ifi_aliases.h
* RETURNS:       void
********************************************************************
********/
void Set_Number_of_Analog_Channels (unsigned char number_of_channels)
{
  ifi_analog_channels = number_of_channels;
}


/*******************************************************************
*********
* FUNCTION NAME: Get_Analog_Value
* PURPOSE:       Reads the analog voltage on an A/D port and returns
the
*                10-bit value read stored in an unsigned int.
* CALLED FROM:   user_routines.c, typically
* ARGUMENTS:
*      Argument         Type        IO   Description
*     -----------   -------------   --   -----------
*     ADC_channel       alias       I    alias found in ifi_aliases.h
* RETURNS:       unsigned int
***********************************************************************
********/
unsigned int Get_Analog_Value (unsigned char ADC_channel)
{
  unsigned int result;

  OpenADC( ADC_FOSC_RC & ADC_RIGHT_JUST & ifi_analog_channels,
          ADC_channel & ADC_INT_OFF & ADC_VREFPLUS_VDD &
ADC_VREFMINUS_VSS );
  Delay10TCYx( 10 );
  ConvertADC();
  while( BusyADC() );
  ReadADC();
  CloseADC();
  result = (int) ADRESH << 8 | ADRESL;
  return result;
}


/**********************************************************************
********/
/**********************************************************************
********/
/**********************************************************************
********/
```

B.12 main.c

```
/**********************************************************************
*********
* FILE NAME: main.c <EDU VERSION>
*
* DESCRIPTION:
*  This file contains the main program loop.
*
* USAGE:
*  You should not need to modify this file.
*  Note the different loop speed for the two routines:
*     Process_Data_From_Master_uP
*     Process_Data_From_Local_IO
***********************************************************************
********/

#include "ifi_aliases.h"
#include "ifi_default.h"
#include "ifi_utilities.h"
#include "user_routines.h"

tx_data_record txdata;          /* DO NOT CHANGE! */
rx_data_record rxdata;          /* DO NOT CHANGE! */
packed_struct statusflag;       /* DO NOT CHANGE! */
```

```
/***********************************************************************
*********
* FUNCTION NAME: main
* PURPOSE:       Main program function.
* CALLED FROM:   ifi_startup.c
* ARGUMENTS:     none
* RETURNS:       void
* DO NOT DELETE THIS FUNCTION
************************************************************************
********/
void main (void)
{
#ifdef UNCHANGEABLE_DEFINITION_AREA
  IFI_Initialization ();        /* DO NOT CHANGE! */
#endif

  User_Initialization();        /* You edit this in user_routines.c */

  statusflag.NEW_SPI_DATA = 0;  /* DO NOT CHANGE! */

  while (1)   /* This loop will repeat indefinitely. */
  {
#ifdef _SIMULATOR
    statusflag.NEW_SPI_DATA = 1;
#endif

    if (statusflag.NEW_SPI_DATA)      /* 17ms loop area */
    {                                 /* I'm slow!  I only execute
every 17ms because */
                                      /* that's how fast the Master uP
gives me data. */
      Process_Data_From_Master_uP();  /* You edit this in
user_routines.c */
    }

    Process_Data_From_Local_IO();     /* I'm fast!  I execute during
every loop.*/
  } /* while (1) */
}  /* END of Main */


/***********************************************************************
********/
/***********************************************************************
********/
/***********************************************************************
********/
```

B.13 printf_lib.c

```
/***********************************************************************
*********
* FILE NAME: printf_lib.c
*
```

```
* DESCRIPTION:
*  This file contains generic routines that work like the standard C
I/O library.
*  These unsupported routines have been modified to work with the
Microchip
*  C compiler.  The printf routine is limited as follows:
*
*  1.  Only the %s, %lx, %d, %x, %u, %X directives are parsed.  An
additional %b
*      directive is parsed for those who like to view data in binary
(base 2).
*
*      Examples:
*
*            rom const char *StrPtr = "Hello world!";
*            int x = 15;
*            int y = 0x50;
*            long z = 0xdeadface;
*
*            printf("%s\n",StrPtr);                          will
display 'Hello world!'
*
*            printf("X = %d, Y = %x, Z = %lx\n",x,y,z);      will
display 'X = 15, Y = 0x50, Z = deadface'
*
*            printf("X = %b (base 2)\n",x);                  will
display 'X = 1111 (base 2)'
*
*            printf("X = %16b\n",x);                         will
display 'X = 0000000000001111'
*
*            printf("X = %04x\n",x);                         will
display 'X = 000f'
*
*  2.  All bytes (8 bits) or bit references (rc_dig_in01) must be type-
cast to a
*      16 bit word.  The %c directive is unsupported.
*
*      Examples:
*
*            unsigned char byte1 = 0xfa;
*            char byte2 = 25;
*
*            printf("1st byte = %x, 2nd byte =
%d\n",(int)byte1,(int)byte2);
*                                                            will
display '1st byte = fa, 2nd byte = 25
*            if (rc_dig_in01)
*              printf("On %d\n",(int)rc_dig_in01);           will
display 'On 1'
*            else
*              printf("Off %d\n",(int)rc_dig_in01);          will
display 'Off 0'
*
*  3.  The %s directive only supports a string of 40 bytes and the
format string
```

```
*      may not exceed 80 bytes.  The sprintf routine is not included.
Keep in
*      mind that the stack size has a 256 byte limit.
*
* USAGE:
*  These library routines  may be modified to suit the needs of the
user.
***********************************************************************
********/

#include "ifi_default.h"
#include "printf_lib.h"
#include "ifi_utilities.h"
#include "string.h"

/* the following should be enough for a 32 bit word */
#define PRINT_BUF_LEN 20

extern char ifi_printfBufr[]; /* declared in ifi_utilities.c */
rom char *nullStr = "(null)";

static char print_buf[PRINT_BUF_LEN];
static char scr[2];
static int  k;

/**********************************************************************
*********
* SUBROUTINE NAME: Write_Byte_To_Uart
* PURPOSE:       Writes a byte to the UART.
*     Argument       Type           IO   Description
*     --------       -----------    --   -----------
*         data       int            I    data to transmit to the UART
* RETURNS:       void
***********************************************************************
********/

static void Write_Byte_To_Uart(int data)
{
  TXREG = data;  /* a carriage return */
  Wait4TXEmpty();
}

#define PAD_RIGHT 1
#define PAD_ZERO  2

/**********************************************************************
*********
* FUNCTION NAME: prints
* PURPOSE:       Pads the output stream.
* RETURNS:       void
***********************************************************************
********/

static int prints(char *string, int width, int pad)
{
      register int pc = 0, padchar = ' ';
      if (width > 0) {
            register int len = 0;
            register char *ptr;
            for (ptr = string; *ptr; ++ptr) ++len;
            if (len >= width) width = 0;
            else width -= len;
            if (pad & PAD_ZERO) padchar = '0';
      }
      if (!(pad & PAD_RIGHT)) {
            for ( ; width > 0; --width) {
                  Write_Byte_To_Uart (padchar);
                  ++pc;
            }
      }
      for ( ; *string ; ++string) {
            Write_Byte_To_Uart (*string);
            ++pc;
      }
      for ( ; width > 0; --width) {
            Write_Byte_To_Uart (padchar);
            ++pc;
      }

      return pc;
}

/*********************************************************************
*********
* FUNCTION NAME: printi
* PURPOSE:       Converts the output stream to the proper width and
base.
* RETURNS:       void
**********************************************************************
********/

static int printi(int i, int b, int sg, int width, int pad, int
letbase)
{
      register char *s;
      register int t, neg = 0, pc = 0;
      register unsigned int u = i;

   print_buf[0] = 0xBE;
   print_buf[PRINT_BUF_LEN] = 0xEF;
      if (i == 0) {
            print_buf[0] = '0';
            print_buf[1] = '\0';
            return prints (print_buf, width, pad);
      }

      if (sg && b == 10 && i < 0) {
            neg = 1;
            u = -i;
      }

      s = print_buf + PRINT_BUF_LEN-1;
      *s = '\0';
      while (u) {
            t = u % b;
            if( t >= 10 )
                  t += letbase - '0' - 10;
            *--s = t + '0';
            u /= b;
      }

      if (neg) {
            if( width && (pad & PAD_ZERO) ) {
                  Write_Byte_To_Uart ('-');
                  ++pc;
                  --width;
            }
            else {
                  *--s = '-';
            }
      }

      return pc + prints (s, width, pad);
}

/***********************************************************************
*********
* FUNCTION NAME: print
* PURPOSE:       Parses the output stream.
* RETURNS:       void
***********************************************************************
********/

static int print(char *format, int *varg)
{
  char tmpBufr[40];
      register int width, pad;
      register int pc = 0;

      for (; *format != 0; ++format) {
            if (*format == '%') {
                  ++format;
                  width = pad = 0;
                  if (*format == '\0') break;
                  if (*format == '%') goto out;
                  if (*format == '-') {
                        ++format;
                        pad = PAD_RIGHT;
                  }
                  while (*format == '0') {
                        ++format;
                        pad |= PAD_ZERO;
                  }
                  for ( ; *format >= '0' && *format <= '9'; ++format) {
                        width *= 10;
                        width += *format - '0';
                  }
                  if( *format == 's' )
      {
        strcpypgm2ram(tmpBufr,(rom char *) *varg--);
        if (tmpBufr[0] == 0)
          strcpypgm2ram(tmpBufr,nullStr);
                        pc += prints (tmpBufr, width, pad);
                        continue;
                  }
                  if( *format == 'd' ) {
                        pc += printi (*varg--, 10, 1, width, pad, 'a');
                        continue;
                  }
                  if( *format == 'x' ) {
                        pc += printi (*varg--, 16, 0, width, pad, 'a');
                        continue;
                  }
                  if( *format == 'X' ) {
                        pc += printi (*varg--, 16, 0, width, pad, 'A');
                        continue;
                  }
                  if( *format == 'u' ) {
                        pc += printi (*varg--, 10, 0, width, pad, 'a');
                        continue;
                  }
                  if( *format == 'l' ) {    /* assumes lx */
                        pc += printi (*varg--, 16, 0, width, pad, 'a');
                        pc += printi (*varg--, 16, 0, width, pad, 'a');
                        format++;               /* skip over x*/
                        continue;
                  }
                  if( *format == 'b' ) {
                        pc += printi (*varg--, 2, 0, width, 2, 'a');
                        continue;
                  }
            }
            else {
            out:
      if (*format == '\n') *format = '\r';  /* replace line feed with
cr */
                  Write_Byte_To_Uart (*format);
                  ++pc;
            }
      }
      return pc;
}

/*********************************************************************
*********
* FUNCTION NAME: printf
* PURPOSE:       Formats an output stream.
* RETURNS:       void
**********************************************************************
********/

int printf(rom const char *format, ...)
{
    register int *varg = (int *)(&format);
    /*
```

```
       Since constant strings are kept in program (flash) memory, the
strcpypgm2ram
       routine copies the string from flash to ram.
    */
    strcpypgm2ram(ifi_printfBufr,(rom char *) format);

    varg--; /* adjust stack for Microchip C Compiler */
    return print(ifi_printfBufr, varg);
}

/*********************************************************************
********
*
* The following routines are examples how to use the printf library
routines
* to create your own output modules:
*
**********************************************************************
********/

/*********************************************************************
*********
* FUNCTION NAME: printid
* PURPOSE:       Prints a 16bit word (base 10) w/o a carriage return.
* RETURNS:       void
**********************************************************************
********/

void printid(int data,int crtOn)
{
  printi (data, 10, 1, 4, 2, 'a');
  if (crtOn)
    Write_Byte_To_Uart('\r');
}

/*********************************************************************
*********
* FUNCTION NAME: printd
* PURPOSE:       Prints an 8bit word (base 10) w/o a carriage return.
* RETURNS:       void
**********************************************************************
********/

void printd(unsigned char data,int crtOn)
{
  printi ((int) data, 10, 1, 3, 2, 'a');
  if (crtOn)
    Write_Byte_To_Uart('\r');
}

/*********************************************************************
*********
* FUNCTION NAME: printib
* PURPOSE:       Prints a 16bit binary word (base 2) w/o a carriage
return.
* RETURNS:       void
```

```
************************************************************************
********/

void printib(unsigned int data,int crtOn)
{
  printi (data, 2, 0, 16, 2, 'a');
  if (crtOn)
    Write_Byte_To_Uart('\r');
}

/***********************************************************************
*********
* FUNCTION NAME: printb
* PURPOSE:       Prints an 8bit binary word (base 2) w/o a carriage
return.
* RETURNS:       void
************************************************************************
********/

void printb(unsigned char data,int crtOn)
{
  printi ((int) data, 2, 0, 8, 2, 'a');
  if (crtOn)
    Write_Byte_To_Uart('\r');
}

/***********************************************************************
*********
* FUNCTION NAME: printix
* PURPOSE:       Prints a 16bit hex word (base 16) w/o a carriage
return.
* RETURNS:       void
************************************************************************
********/

void printix(int data,int crtOn)
{
  printi (data, 16, 0, 2, 0, 'a');
  if (crtOn)
    Write_Byte_To_Uart('\r');
}

/***********************************************************************
*********
* FUNCTION NAME: printx
* PURPOSE:       Prints an 8bit hex word (base 16) w/o a carriage
return.
* RETURNS:       void
************************************************************************
********/

void printx(unsigned char data,int crtOn)
{
  printi ((int) data, 16, 0, 2, 2, 'a');
  if (crtOn)
    Write_Byte_To_Uart('\r');
}
```

```
/*******************************************************************
*********
* FUNCTION NAME: debug_print
* PURPOSE:       Prints a header and a 16bit hex word (base 16) with a
carriage
*                return.
* RETURNS:       void
********************************************************************
********/

void debug_print(char *bufr,int data)
{
  strcpypgm2ram (ifi_printfBufr,(rom char *) bufr);
  for (k=0;k<strlen(ifi_printfBufr);k++)
    Write_Byte_To_Uart(ifi_printfBufr[k]);
  printix(data,1);
}

/*******************************************************************
*********
* FUNCTION NAME: debug_printb
* PURPOSE:       Prints a header and an 8bit binary word (base 2) with
a carriage
*                return.
* RETURNS:       void
********************************************************************
********/

void debug_printb(char *bufr,unsigned int data)
{
  strcpypgm2ram (ifi_printfBufr,(rom char *) bufr);
  for (k=0;k<strlen(ifi_printfBufr);k++)
    Write_Byte_To_Uart(ifi_printfBufr[k]);
  printib(data,1);
}

/*******************************************************************
*********
* FUNCTION NAME: debug_println
* PURPOSE:       Prints a header (assumming a carriage return is
supplied).
* RETURNS:       void
********************************************************************
********/

void debug_println(char *bufr)
{
  strcpypgm2ram (ifi_printfBufr,(rom char *) bufr);
  for (k=0;k<strlen(ifi_printfBufr);k++)
    Write_Byte_To_Uart(ifi_printfBufr[k]);
}


/*******************************************************************
********/
```

```
/*******************************************************************
********/
/*******************************************************************
********/
```

B.14 user_routines_fast.c

```
/*******************************************************************
*********
* FILE NAME: user_routines_fast.c <EDU VERSION>
*
* DESCRIPTION:
*  This file is where the user can add their custom code within the
framework
*  of the routines below.
*
* USAGE:
*  You can either modify this file to fit your needs, or remove it from
your
*  project and replace it with a modified copy.
*
* OPTIONS:  Interrupts are disabled and not used by default.
*
********************************************************************
********/

#include "ifi_aliases.h"
#include "ifi_default.h"
#include "ifi_utilities.h"
#include "user_routines.h"
#include "clock.h"

unsigned char Old_Port_B = 0xFF; // saved copy of port b

/*** DEFINE USER VARIABLES AND INITIALIZE THEM HERE ***/


/*******************************************************************
*********
* FUNCTION NAME: InterruptVectorLow
* PURPOSE:       Low priority interrupt vector
* CALLED FROM:   nowhere by default
* ARGUMENTS:     none
* RETURNS:       void
* DO NOT MODIFY OR DELETE THIS FUNCTION
********************************************************************
********/
#pragma code InterruptVectorLow = LOW_INT_VECTOR // put this code at
address 0x18

void InterruptVectorLow (void)
{
      _asm
      goto InterruptHandlerLow  // jump to InterruptHandlerLow(), below
      _endasm
}

#pragma code

/*********************************************************************
*********
*
*     FUNCTION:         InterruptHandlerLow()
*
*     PURPOSE:          Determines which individual interrupt handler
*                             should be called, clears the interrupt
flag and
*                             then calls the interrupt handler.
*
*     CALLED FROM:      InterruptVectorLow()
*
*     PARAMETERS:       None
*
*     RETURNS:          Nothing
*
**********************************************************************
********/
#pragma interruptlow InterruptHandlerLow

void InterruptHandlerLow()
{
      unsigned char Port_B;
      unsigned char Port_B_Delta;

      if (INTCONbits.TMR0IF) // timer 0 interrupt?
      {
            INTCONbits.TMR0IF = 0; // clear the timer 0 interrupt flag
[89]
//          Timer_0_Int_Handler(); // call the timer 0 interrupt
handler
      }
      else if (PIR1bits.TMR1IF) // timer 1 interrupt?
      {
            PIR1bits.TMR1IF = 0; // clear the timer 1 interrupt flag
[92]
//          Timer_1_Int_Handler(); // call the timer 1 interrupt
handler
      }
      else if (PIR1bits.TMR2IF) // timer 2 interrupt?
      {
            PIR1bits.TMR2IF = 0; // clear the timer 2 interrupt flag
[92]
            Timer_2_Int_Handler(); // call the timer 2 interrupt
handler (in clock.c)
      }
      else if (PIR2bits.TMR3IF) // timer 3 interrupt?
      {
            PIR2bits.TMR3IF = 0; // clear the timer 3 interrupt flag
[93]
//          Timer_3_Int_Handler(); // call the timer 3 interrupt
handler
```

```
      }
      else if (PIR3bits.TMR4IF) // timer 4 interrupt?
      {
            PIR3bits.TMR4IF = 0; // clear the timer 4 interrupt flag
[94]
//          Timer_4_Int_Handler(); // call the timer 4 interrupt
handler
      }
      else if (INTCON3bits.INT2IF) // external interrupt 1?
      {
            INTCON3bits.INT2IF = 0; // clear the interrupt flag [91]
//          Int_1_Handler(); // call the interrupt 1 handler
      }
      else if (INTCON3bits.INT3IF) // external interrupt 2?
      {
            INTCON3bits.INT3IF = 0; // clear the interrupt flag [91]
//          Int_2_Handler(); // call the interrupt 2 handler
      }
      else if (INTCONbits.RBIF) // external interrupts 3 through 6?
      {
            Port_B = PORTB; // remove the "mismatch condition" by
reading port b
            INTCONbits.RBIF = 0; // clear the interrupt flag [89]
            Port_B_Delta = Port_B ^ Old_Port_B; // determine which bits
have changed
            Old_Port_B = Port_B; // save a copy of port b for next time
around

            if(Port_B_Delta & 0x10) // did external interrupt 3 change
state?
            {
//                Int_3_Handler(Port_B & 0x10 ? 1 : 0); // call the
interrupt 3 handler
            }
            if(Port_B_Delta & 0x20) // did external interrupt 4 change
state?
            {
//                Int_4_Handler(Port_B & 0x20 ? 1 : 0); // call the
interrupt 4 handler
            }
            if(Port_B_Delta & 0x40) // did external interrupt 5 change
state?
            {
//                Int_5_Handler(Port_B & 0x40 ? 1 : 0); // call the
interrupt 5 handler
            }
            if(Port_B_Delta & 0x80) // did external interrupt 6 change
state?
            {
//                Int_6_Handler(Port_B & 0x80 ? 1 : 0); // call the
interrupt 6 handler
            }
      }
}

/**********************************************************************
*********
```

```
*
*     FUNCTION:         Process_Data_From_Local_IO()
*
*     PURPOSE:          Execute real-time code here. Code located here
will
*                             execute continuously as opposed to code
located in
*
      user_routines.c/Process_Data_From_Master_uP(), which
*                             only executes every 17 ms, when the
master processor
*                             sends a new data packet.
*
*     CALLED FROM:      main.c/main()
*
*     PARAMETERS:       None
*
*     RETURNS:          Nothing
*
**********************************************************************
********/

void Process_Data_From_Local_IO(void)
{
  /* Add code here that you want to be executed every program loop. */
}


/*********************************************************************
********/
/*********************************************************************
********/
/*********************************************************************
********/
```

B.15 user_routines.c ; Case 1, C1 = 0.1, C2 = 0.05

```
/*********************************************************************
*********
* FILE NAME: user_routines.c <EDU VERSION>
*
* DESCRIPTION:
*  This file contains the default mappings of inputs
*  (like switches, joysticks, and buttons) to outputs on the EDU RC.
*
* USAGE:
*  You can either modify this file to fit your needs, or remove it from
your
*  project and replace it with a modified copy.
*
**********************************************************************
********/

#include "ifi_aliases.h"
```

```
#include "ifi_default.h"
#include "ifi_utilities.h"
#include "user_routines.h"
#include "printf_lib.h"
#include "clock.h"      // adds timer functionality

/*** DEFINE USER VARIABLES AND INITIALIZE THEM HERE ***/
/* EXAMPLES: (see MPLAB C18 User's Guide, p.9 for all types)
unsigned char wheel_revolutions = 0; (can vary from 0 to 255)
unsigned int  delay_count = 7;       (can vary from 0 to 65,535)
int           angle_deviation = 142; (can vary from -32,768 to 32,767)
unsigned long very_big_counter = 0;  (can vary from 0 to 4,294,967,295)
*/


/*******************************************************************
*********
* FUNCTION NAME: Limit_Switch_Max
* PURPOSE:       Sets a PWM value to neutral (127) if it exceeds 127
and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     switch_state   unsigned char    I    limit switch state
*     *input_value   pointer           O   points to PWM byte value to
be limited
* RETURNS:       void
********************************************************************
********/
void Limit_Switch_Max(unsigned char switch_state, unsigned char
*input_value)
{
  if (switch_state == CLOSED)
  {
    if(*input_value > 127)
      *input_value = 127;
  }
}


/*******************************************************************
*********
* FUNCTION NAME: Limit_Switch_Min
* PURPOSE:       Sets a PWM value to neutral (127) if it's less than
127 and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     switch_state   unsigned char    I    limit switch state
*     *input_value   pointer           O   points to PWM byte value to
be limited
* RETURNS:       void
```

```
*******************************************************************
********/
void Limit_Switch_Min(unsigned char switch_state, unsigned char
*input_value)
{
  if (switch_state == CLOSED)
  {
    if(*input_value < 127)
      *input_value = 127;
  }
}


/*******************************************************************
*********
* FUNCTION NAME: Limit_Mix
* PURPOSE:       Limits the mixed value for the joystick drive.  2000
is used as a mathematical
*                offset when this function is called so that the number
presented to Limit_Mix
*                is not negative.  The funtion removes the 2000 offset
after operating.
* CALLED FROM:   Default_Routine, this file
* ARGUMENTS:
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     intermediate_value    int    I
* RETURNS:       unsigned char
*******************************************************************
********/
unsigned char Limit_Mix (int intermediate_value)
{
  static int limited_value;

  if (intermediate_value < 2000)
  {
    limited_value = 2000;
  }
  else if (intermediate_value > 2254)
  {
    limited_value = 2254;
  }
  else
  {
    limited_value = intermediate_value;
  }
  return (unsigned char) (limited_value - 2000);
}


/*******************************************************************
*********
* FUNCTION NAME: Setup_Who_Controls_Pwms
* PURPOSE:       Each parameter specifies what processor will control
the pwm.
*
* CALLED FROM:   User_Initialization
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     pwmSpec1              int     I   USER/MASTER (defined in
ifi_aliases.h)
*     pwmSpec2              int     I   USER/MASTER
*     pwmSpec3              int     I   USER/MASTER
*     pwmSpec4              int     I   USER/MASTER
*     pwmSpec5              int     I   USER/MASTER
*     pwmSpec6              int     I   USER/MASTER
*     pwmSpec7              int     I   USER/MASTER
*     pwmSpec8              int     I   USER/MASTER
* RETURNS:       void
***********************************************************************
********/
static void Setup_Who_Controls_Pwms(int pwmSpec1,int pwmSpec2,int
pwmSpec3,int pwmSpec4,
                                    int pwmSpec5,int pwmSpec6,int
pwmSpec7,int pwmSpec8)
{
  txdata.pwm_mask = 0xFF;         /* Default to master controlling all
PWMs. */
  if (pwmSpec1 == USER)           /* If User controls PWM1 then clear
bit0. */
    txdata.pwm_mask &= 0xFE;      /* same as txdata.pwm_mask =
txdata.pwm_mask & 0xFE; */
  if (pwmSpec2 == USER)           /* If User controls PWM2 then clear
bit1. */
    txdata.pwm_mask &= 0xFD;
  if (pwmSpec3 == USER)           /* If User controls PWM3 then clear
bit2. */
    txdata.pwm_mask &= 0xFB;
  if (pwmSpec4 == USER)           /* If User controls PWM4 then clear
bit3. */
    txdata.pwm_mask &= 0xF7;
  if (pwmSpec5 == USER)           /* If User controls PWM5 then clear
bit4. */
    txdata.pwm_mask &= 0xEF;
  if (pwmSpec6 == USER)           /* If User controls PWM6 then clear
bit5. */
    txdata.pwm_mask &= 0xDF;
  if (pwmSpec7 == USER)           /* If User controls PWM7 then clear
bit6. */
    txdata.pwm_mask &= 0xBF;
  if (pwmSpec8 == USER)           /* If User controls PWM8 then clear
bit7. */
    txdata.pwm_mask &= 0x7F;
}


/**********************************************************************
*********
* FUNCTION NAME: User_Initialization
* PURPOSE:       This routine is called first (and only once) in the
Main function.
*                You may modify and add to this function.
*                The primary purpose is to set up the DIGITAL IN/OUT -
ANALOG IN
```

```
*                pins as analog inputs, digital inputs, and digital
outputs.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
***********************************************************************
********/
void User_Initialization (void)
{
  rom const char *strptr = "IFI User Processor Initialized ...";

/* FIRST: Set up the pins you want to use as analog INPUTs. */
  IO1 = IO2 = INPUT;        /* Used for analog inputs. */
    /*
     Note: IO1 = IO2 = IO3 = IO4 = INPUT;
           is the same as the following:

           IO1 = INPUT;
           IO2 = INPUT;
           IO3 = INPUT;
           IO4 = INPUT;
    */

/* SECOND: Configure the number of analog channels. */
  Set_Number_of_Analog_Channels(TWO_ANALOG);     /* See ifi_aliases.h
*/

/* THIRD: Set up any extra digital inputs. */
  /* The six INTERRUPTS are already digital inputs. */
  /* If you need more then set them up here. */
  /* IOxx = IOyy = INPUT; */
  IO6 = IO8 = IO10 = INPUT;      /* Used for limit switch inputs. */
  IO12 = IO14 = IO16 = INPUT;    /* Used for limit switch inputs. */

/* FOURTH: Set up the pins you want to use as digital OUTPUTs. */
  IO3 = IO4 = OUTPUT;
  IO5 = IO7 = IO9 = OUTPUT;     /* For connecting to adjacent limit
switches. */
  IO11 = IO13 = IO15 = OUTPUT;  /* For connecting to adjacent limit
switches. */

/* FIFTH: Initialize the values on the digital outputs. */
  rc_dig_out03 = rc_dig_out04 = 0;
  rc_dig_out05 = rc_dig_out07 = rc_dig_out09 = 0;
  rc_dig_out11 = rc_dig_out13 = rc_dig_out15 = 0;

/* SIXTH: Set your initial PWM values.  Neutral is 127. */
  pwm01 = pwm02 = pwm03 = pwm04 = pwm05 = pwm06 = pwm07 = pwm08 = 127;

/* SEVENTH: Choose which processor will control which PWM outputs. */

Setup_Who_Controls_Pwms(MASTER,MASTER,MASTER,MASTER,MASTER,MASTER,MASTE
R,MASTER);

/* EIGHTH: Set your PWM output type.  Only applies if USER controls PWM
1, 2, 3, or 4. */
```

```
  /*   Choose from these parameters for PWM 1-4 respectively:
*/
  /*     IFI_PWM  - Standard IFI PWM output generated with
Generate_Pwms(...)          */
  /*     USER_CCP - User can use PWM pin as digital I/O or CCP pin.
*/
  Setup_PWM_Output_Type(IFI_PWM,IFI_PWM,IFI_PWM,IFI_PWM);

  /*
     Example: The following would generate a 40KHz PWM with a 50% duty
cycle
              on the CCP2 pin (PWM OUT 1):
          CCP2CON = 0x3C;
          PR2 = 0xF9;
          CCPR2L = 0x7F;
          T2CON = 0;
          T2CONbits.TMR2ON = 1;
          Setup_PWM_Output_Type(USER_CCP,IFI_PWM,IFI_PWM,IFI_PWM);
  */

/* Add any other user initialization code here. */

  Initialize_Serial_Comms();

  Initialize_Timer_2(); // initialize and start the clock

  Putdata(&txdata);             /* DO NOT CHANGE! */

  printf("%s\n", strptr);       /* Optional - Print initialization
message. */

  User_Proc_Is_Ready();         /* DO NOT CHANGE! - last line of
User_Initialization */
}


/***********************************************************************
*********
* FUNCTION NAME: Process_Data_From_Master_uP
* PURPOSE:       Executes every 17ms when it gets new data from the
master
*                microprocessor.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
************************************************************************
********/
//    Successful clock implimentation 2011 - 03 - 18 : 1536 hrs

void Process_Data_From_Master_uP(void)
{
  Getdata(&rxdata);   /* Get fresh data from the master microprocessor.
*/

  Display_Time(); // located in clock.c

  Default_Routine();  /* See below. */
  printf("PWM OUT 1 = %d, PWM OUT 2 = %d, PWM OUT 3 = %d, PWM OUT 4 =
%d\n", (int)pwm01, (int)pwm02, (int)pwm03, (int)pwm04);
  printf("PWM OUT 5 = %d, PWM OUT 6 = %d, PWM OUT 7 = %d, PWM OUT 8 =
%d\n", (int)pwm05, (int)pwm06, (int)pwm07, (int)pwm08);
  printf("PWM IN 1 = %d, PWM IN 2 = %d, PWM IN 3 = %d, PWM IN 4 =
%d\n", (int)PWM_in1, (int)PWM_in2, (int)PWM_in3, (int)PWM_in4);
/*  printf("PWM IN 5 = %d, PWM IN 6 = %d, PWM IN 7 = %d, PWM IN 8 =
%d\n", (int)PWM_in5, (int)PWM_in6, (int)PWM_in7, (int)PWM_in8);
  /* This snoops on the inputs being fed to the robot controller and
the outputs being fed to the individual servos */

  Putdata(&txdata);             /* DO NOT CHANGE! */
}


/*********************************************************************
*********
* FUNCTION NAME: Default_Routine
* PURPOSE:       Performs the default mappings of inputs to outputs for
the
*                Robot Controller.
* CALLED FROM:   this file, Process_Data_From_Master_uP routine
* ARGUMENTS:     none
* RETURNS:       void
**********************************************************************
********/
void Default_Routine(void)
{

 /*---------- Left Joystick Drive ------------------------------------
------------------------------------
  *-------------------------------------------------Alpha Build 2010 –
06 – 26 : 1224 hrs------------------
  *-------------------------------------------------------------------
------------------------------------
  *  This code independently handles Y and X axis inputs on the left
joystick for throttle
  *    manipulation and robot turning.
  *  Joystick forward  = Robot forward
  *  Joystick backward = Robot stop
  *  Joystick right    = Robot turns right
  *  Joystick left     = Robot turns left
  *  Connect the first tail link servo to PWM OUT 1 on the robot
controller.
  *  Connect the second tail link servo to PWM OUT 2 on the robot
controller.
  *  Connect the third tail link servo to PWM OUT 3 on the robot
controller.
  *  Connect the fourth tail link servo to PWM OUT 4 on the robot
controller.
  *  Connect the fifth tail link servo to PWM OUT 5 on the robot
controller.
  */
```

```
if (PWM_in1 >= 160)
      {
            if (msClock >= 1000)
                  {
                        pwm01 = 163;
                        pwm02 = 133;
                        pwm03 = 0;
                        pwm04 = 74;
                        pwm05 = 124;
                  }
            else if (msClock >= 950)
                  {
                        pwm01 = 158;
                        pwm02 = 169;
                        pwm03 = 0;
                        pwm04 = 42;
                        pwm05 = 116;
                  }
            else if (msClock >= 900)
                  {
                        pwm01 = 150;
                        pwm02 = 195;
                        pwm03 = 0;
                        pwm04 = 0;
                        pwm05 = 110;
                  }
            else if (msClock >= 850)
                  {
                        pwm01 = 139;
                        pwm02 = 213;
                        pwm03 = 45;
                        pwm04 = 0;
                        pwm05 = 100;
                  }
            else if (msClock >= 800)
                  {
                        pwm01 = 127;
                        pwm02 = 225;
                        pwm03 = 124;
                        pwm04 = 0;
                        pwm05 = 63;
                  }
            else if (msClock >= 750)
                  {
                        pwm01 = 115;
                        pwm02 = 231;
                        pwm03 = 167;
                        pwm04 = 0;
                        pwm05 = 0;
                  }
            else if (msClock >= 700)
                  {
                        pwm01 = 104;
                        pwm02 = 228;
                        pwm03 = 194;
                        pwm04 = 10;
                        pwm05 = 0;
                  }
            else if (msClock >= 650)
                  {
                        pwm01 = 95;
                        pwm02 = 216;
                        pwm03 = 220;
                        pwm04 = 118;
                        pwm05 = 0;
                  }
            else if (msClock >= 600)
                  {
                        pwm01 = 90;
                        pwm02 = 194;
                        pwm03 = 248;
                        pwm04 = 143;
                        pwm05 = 0;
                  }
            else if (msClock >= 550)
                  {
                        pwm01 = 89;
                        pwm02 = 161;
                        pwm03 = 255;
                        pwm04 = 159;
                        pwm05 = 108;
                  }
            else if (msClock >= 500)
                  {
                        pwm01 = 91;
                        pwm02 = 121;
                        pwm03 = 255;
                        pwm04 = 180;
                        pwm05 = 130;
                  }
            else if (msClock >= 450)
                  {
                        pwm01 = 96;
                        pwm02 = 85;
                        pwm03 = 255;
                        pwm04 = 212;
                        pwm05 = 138;
                  }
            else if (msClock >= 400)
                  {
                        pwm01 = 104;
                        pwm02 = 59;
                        pwm03 = 255;
                        pwm04 = 255;
                        pwm05 = 144;
                  }
            else if (msClock >= 350)
                  {
                        pwm01 = 115;
                        pwm02 = 41;
                        pwm03 = 209;
                        pwm04 = 255;
                        pwm05 = 154;
                  }
```

```
        else if (msClock >= 300)
              {
                    pwm01 = 127;
                    pwm02 = 29;
                    pwm03 = 130;
                    pwm04 = 255;
                    pwm05 = 191;
              }
        else if (msClock >= 250)
              {
                    pwm01 = 139;
                    pwm02 = 23;
                    pwm03 = 87;
                    pwm04 = 255;
                    pwm05 = 254;
              }
        else if (msClock >= 200)
              {
                    pwm01 = 150;
                    pwm02 = 26;
                    pwm03 = 60;
                    pwm04 = 244;
                    pwm05 = 255;
              }
        else if (msClock >= 150)
              {
                    pwm01 = 159;
                    pwm02 = 38;
                    pwm03 = 34;
                    pwm04 = 136;
                    pwm05 = 255;
              }
        else if (msClock >= 100)
              {
                    pwm01 = 164;
                    pwm02 = 60;
                    pwm03 = 6;
                    pwm04 = 111;
                    pwm05 = 255;
              }
        else if (msClock >= 50)
              {
                    pwm01 = 165;
                    pwm02 = 93;
                    pwm03 = 0;
                    pwm04 = 95;
                    pwm05 = 146;
              }
        else
              {
                    pwm01 = 163;
                    pwm02 = 133;
                    pwm03 = 0;
                    pwm04 = 74;
                    pwm05 = 124;
              }
  }                        /*  fish motion */
```

```
else if (PWM_in2 >= 160)
      {
            if (msClock >= 1000)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 163;
                        pwm04 = 133;
                        pwm05 = 0;
                  }
            else if (msClock >= 950)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 158;
                        pwm04 = 169;
                        pwm05 = 0;
                  }
            else if (msClock >= 900)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 150;
                        pwm04 = 195;
                        pwm05 = 0;
                  }
            else if (msClock >= 850)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 139;
                        pwm04 = 213;
                        pwm05 = 45;
                  }
            else if (msClock >= 800)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 127;
                        pwm04 = 225;
                        pwm05 = 124;
                  }
            else if (msClock >= 750)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 115;
                        pwm04 = 231;
                        pwm05 = 167;
                  }
            else if (msClock >= 700)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 104;
                        pwm04 = 228;
                        pwm05 = 194;
                  }
            else if (msClock >= 650)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 95;
                        pwm04 = 216;
                        pwm05 = 220;
                  }
            else if (msClock >= 600)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 90;
                        pwm04 = 194;
                        pwm05 = 248;
                  }
            else if (msClock >= 550)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 89;
                        pwm04 = 161;
                        pwm05 = 255;
                  }
            else if (msClock >= 500)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 91;
                        pwm04 = 121;
                        pwm05 = 255;
                  }
            else if (msClock >= 450)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 96;
                        pwm04 = 85;
                        pwm05 = 255;
                  }
            else if (msClock >= 400)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 104;
                        pwm04 = 59;
                        pwm05 = 255;
                  }
            else if (msClock >= 350)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 115;
                        pwm04 = 41;
                        pwm05 = 209;
                  }
            else if (msClock >= 300)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 127;
                        pwm04 = 29;
                        pwm05 = 130;
                  }
            else if (msClock >= 250)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 139;
                        pwm04 = 23;
                        pwm05 = 87;
                  }
            else if (msClock >= 200)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 150;
                        pwm04 = 26;
                        pwm05 = 60;
                  }
            else if (msClock >= 150)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 159;
                        pwm04 = 38;
                        pwm05 = 34;
                  }
            else if (msClock >= 100)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 164;
                        pwm04 = 60;
                        pwm05 = 6;
                  }
            else if (msClock >= 50)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 165;
                        pwm04 = 93;
                        pwm05 = 0;
                  }
            else
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 163;
                        pwm04 = 133;
                        pwm05 = 0;
                  }
      }                        /*  holder for turning commands */
```

```
else if (PWM_in2 <= 94)
      {
            if (msClock >= 1000)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 163;
                        pwm04 = 133;
                        pwm05 = 0;
                  }
            else if (msClock >= 950)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 158;
                        pwm04 = 169;
                        pwm05 = 0;
                  }
            else if (msClock >= 900)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 150;
                        pwm04 = 195;
                        pwm05 = 0;
                  }
            else if (msClock >= 850)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 139;
                        pwm04 = 213;
                        pwm05 = 45;
                  }
            else if (msClock >= 800)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 127;
                        pwm04 = 225;
                        pwm05 = 124;
                  }
            else if (msClock >= 750)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 115;
                        pwm04 = 231;
                        pwm05 = 167;
                  }
            else if (msClock >= 700)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 104;
                        pwm04 = 228;
                        pwm05 = 194;
```

```
        }
else if (msClock >= 650)
        {
                pwm01 = 191;
                pwm02 = 191;
                pwm03 = 95;
                pwm04 = 216;
                pwm05 = 220;
        }
else if (msClock >= 600)
        {
                pwm01 = 191;
                pwm02 = 191;
                pwm03 = 90;
                pwm04 = 194;
                pwm05 = 248;
        }
else if (msClock >= 550)
        {
                pwm01 = 191;
                pwm02 = 191;
                pwm03 = 89;
                pwm04 = 161;
                pwm05 = 255;
        }
else if (msClock >= 500)
        {
                pwm01 = 191;
                pwm02 = 191;
                pwm03 = 91;
                pwm04 = 121;
                pwm05 = 255;
        }
else if (msClock >= 450)
        {
                pwm01 = 191;
                pwm02 = 191;
                pwm03 = 96;
                pwm04 = 85;
                pwm05 = 255;
        }
else if (msClock >= 400)
        {
                pwm01 = 191;
                pwm02 = 191;
                pwm03 = 104;
                pwm04 = 59;
                pwm05 = 255;
        }
else if (msClock >= 350)
        {
                pwm01 = 191;
                pwm02 = 191;
                pwm03 = 115;
                pwm04 = 41;
                pwm05 = 209;
        }
        else if (msClock >= 300)
              {
                    pwm01 = 191;
                    pwm02 = 191;
                    pwm03 = 127;
                    pwm04 = 29;
                    pwm05 = 130;
              }
        else if (msClock >= 250)
              {
                    pwm01 = 191;
                    pwm02 = 191;
                    pwm03 = 139;
                    pwm04 = 23;
                    pwm05 = 87;
              }
        else if (msClock >= 200)
              {
                    pwm01 = 191;
                    pwm02 = 191;
                    pwm03 = 150;
                    pwm04 = 26;
                    pwm05 = 60;
              }
        else if (msClock >= 150)
              {
                    pwm01 = 191;
                    pwm02 = 191;
                    pwm03 = 159;
                    pwm04 = 38;
                    pwm05 = 34;
              }
        else if (msClock >= 100)
              {
                    pwm01 = 191;
                    pwm02 = 191;
                    pwm03 = 164;
                    pwm04 = 60;
                    pwm05 = 6;
              }
        else if (msClock >= 50)
              {
                    pwm01 = 191;
                    pwm02 = 191;
                    pwm03 = 165;
                    pwm04 = 93;
                    pwm05 = 0;
              }
        else
              {
                    pwm01 = 191;
                    pwm02 = 191;
                    pwm03 = 163;
                    pwm04 = 133;
                    pwm05 = 0;
              }
  }                       /*  holder for turning commands */
```

```
      else
            {
                  pwm01 = 127;
                  pwm02 = 127;
                  pwm03 = 127;
                  pwm04 = 127;
                  pwm05 = 127;
            }                       /*  servos idle */


 /*---------- Right Joystick Drive ------------------------------------
------------------------------------
  *----------------------------------Successful Implementation 2010 –
06 – 19 : 1606 hrs------------------
  *  This code calls the Limit_Mix funtion to mix the Y and X axis on
the right joystick for
  *    control surface manipulation.
  *  Right joystick up    = Pitch control surfaces down (turn robot
down)
  *  Right joystick back  = Pitch control surfaces up (turn robot up)
  *  Right joystick right = Roll robot right
  *  Right joystick left  = Roll robot left
  *  THIS SUBROUTINE MIXES PITCH AND ROLL INPUTS ON TRANSMITTER FOR
DETERMINING SERVO STATES.
  *  Connect the left fin servo to PWM OUT 6 on the robot controller.
  *  Connect the right fin servo to PWM OUT 7 on the robot controller.
  */

   pwm06 = Limit_Mix(2000 + PWM_in3 - PWM_in4 + 127); /* maps left fin
servo to right joystick U/D & R/L */

      if (pwm06 >= 148)
            {
            pwm06 = 147;
            }
      else if (pwm06 <= 108)
            {
            pwm06 = 107;
            }
      else
            {
            pwm06 = pwm06;
            }

   pwm07 = 255 - Limit_Mix(2000 + PWM_in3 + PWM_in4 - 127);       /*
"255-" because reverse rotation of left side */

      if (pwm07 >= 148)
            {
            pwm07 = 147;
            }
      else if (pwm07 <= 108)
            {
            pwm07 = 107;
            }
      else
            {
```

```
            pwm07 = pwm07;
            }

 /* ------ Other PWM OUTPUT Mapping -----------------------------------
-------------*/

   pwm08 = PWM_in8;                 /* dummy, not used */


} /* END Default_Routine(); */


/*******************************************************************
********/
/*******************************************************************
********/
/*******************************************************************
********/
```

B.16 user_routines.c ; Case 2, C1 = 0.5, C2 = 0.05

```
/*******************************************************************
*********
* FILE NAME: user_routines.c <EDU VERSION>
*
* DESCRIPTION:
*  This file contains the default mappings of inputs
*  (like switches, joysticks, and buttons) to outputs on the EDU RC.
*
* USAGE:
*  You can either modify this file to fit your needs, or remove it from
your
*  project and replace it with a modified copy.
*
********************************************************************
********/

#include "ifi_aliases.h"
#include "ifi_default.h"
#include "ifi_utilities.h"
#include "user_routines.h"
#include "printf_lib.h"
#include "clock.h"      // adds timer functionality

/*** DEFINE USER VARIABLES AND INITIALIZE THEM HERE ***/
/* EXAMPLES: (see MPLAB C18 User's Guide, p.9 for all types)
unsigned char wheel_revolutions = 0; (can vary from 0 to 255)
unsigned int  delay_count = 7;       (can vary from 0 to 65,535)
int           angle_deviation = 142; (can vary from -32,768 to 32,767)
unsigned long very_big_counter = 0;  (can vary from 0 to 4,294,967,295)
*/
```

```
/*******************************************************************
*********
* FUNCTION NAME: Limit_Switch_Max
* PURPOSE:       Sets a PWM value to neutral (127) if it exceeds 127
and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*      Argument       Type             IO   Description
*      --------       -------------    --   -----------
*      switch_state   unsigned char    I    limit switch state
*      *input_value   pointer           O   points to PWM byte value to
be limited
* RETURNS:       void
********************************************************************
********/
void Limit_Switch_Max(unsigned char switch_state, unsigned char
*input_value)
{
  if (switch_state == CLOSED)
  {
    if(*input_value > 127)
      *input_value = 127;
  }
}


/*******************************************************************
*********
* FUNCTION NAME: Limit_Switch_Min
* PURPOSE:       Sets a PWM value to neutral (127) if it's less than
127 and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*      Argument       Type             IO   Description
*      --------       -------------    --   -----------
*      switch_state   unsigned char    I    limit switch state
*      *input_value   pointer           O   points to PWM byte value to
be limited
* RETURNS:       void
********************************************************************
********/
void Limit_Switch_Min(unsigned char switch_state, unsigned char
*input_value)
{
  if (switch_state == CLOSED)
  {
    if(*input_value < 127)
      *input_value = 127;
  }
}


/*******************************************************************
*********
* FUNCTION NAME: Limit_Mix
* PURPOSE:       Limits the mixed value for the joystick drive.  2000
is used as a mathematical
*                offset when this function is called so that the number
presented to Limit_Mix
*                is not negative.  The funtion removes the 2000 offset
after operating.
* CALLED FROM:   Default_Routine, this file
* ARGUMENTS:
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     intermediate_value    int    I
* RETURNS:       unsigned char
**********************************************************************
********/
unsigned char Limit_Mix (int intermediate_value)
{
  static int limited_value;

  if (intermediate_value < 2000)
  {
    limited_value = 2000;
  }
  else if (intermediate_value > 2254)
  {
    limited_value = 2254;
  }
  else
  {
    limited_value = intermediate_value;
  }
  return (unsigned char) (limited_value - 2000);
}


/*********************************************************************
*********
* FUNCTION NAME: Setup_Who_Controls_Pwms
* PURPOSE:       Each parameter specifies what processor will control
the pwm.
*
* CALLED FROM:   User_Initialization
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     pwmSpec1              int     I   USER/MASTER (defined in
ifi_aliases.h)
*     pwmSpec2              int     I   USER/MASTER
*     pwmSpec3              int     I   USER/MASTER
*     pwmSpec4              int     I   USER/MASTER
*     pwmSpec5              int     I   USER/MASTER
*     pwmSpec6              int     I   USER/MASTER
*     pwmSpec7              int     I   USER/MASTER
*     pwmSpec8              int     I   USER/MASTER
* RETURNS:       void
**********************************************************************
********/
static void Setup_Who_Controls_Pwms(int pwmSpec1,int pwmSpec2,int
pwmSpec3,int pwmSpec4,
                                    int pwmSpec5,int pwmSpec6,int
pwmSpec7,int pwmSpec8)
{
  txdata.pwm_mask = 0xFF;         /* Default to master controlling all
PWMs. */
  if (pwmSpec1 == USER)           /* If User controls PWM1 then clear
bit0. */
    txdata.pwm_mask &= 0xFE;      /* same as txdata.pwm_mask =
txdata.pwm_mask & 0xFE; */
  if (pwmSpec2 == USER)           /* If User controls PWM2 then clear
bit1. */
    txdata.pwm_mask &= 0xFD;
  if (pwmSpec3 == USER)           /* If User controls PWM3 then clear
bit2. */
    txdata.pwm_mask &= 0xFB;
  if (pwmSpec4 == USER)           /* If User controls PWM4 then clear
bit3. */
    txdata.pwm_mask &= 0xF7;
  if (pwmSpec5 == USER)           /* If User controls PWM5 then clear
bit4. */
    txdata.pwm_mask &= 0xEF;
  if (pwmSpec6 == USER)           /* If User controls PWM6 then clear
bit5. */
    txdata.pwm_mask &= 0xDF;
  if (pwmSpec7 == USER)           /* If User controls PWM7 then clear
bit6. */
    txdata.pwm_mask &= 0xBF;
  if (pwmSpec8 == USER)           /* If User controls PWM8 then clear
bit7. */
    txdata.pwm_mask &= 0x7F;
}


/*******************************************************************
*********
* FUNCTION NAME: User_Initialization
* PURPOSE:       This routine is called first (and only once) in the
Main function.
*                You may modify and add to this function.
*                The primary purpose is to set up the DIGITAL IN/OUT -
ANALOG IN
*                pins as analog inputs, digital inputs, and digital
outputs.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
********************************************************************
********/
void User_Initialization (void)
{
  rom const char *strptr = "IFI User Processor Initialized ...";

/* FIRST: Set up the pins you want to use as analog INPUTs. */
  IO1 = IO2 = INPUT;        /* Used for analog inputs. */
    /*
     Note: IO1 = IO2 = IO3 = IO4 = INPUT;
           is the same as the following:
```

```
          IO1 = INPUT;
          IO2 = INPUT;
          IO3 = INPUT;
          IO4 = INPUT;
    */

/* SECOND: Configure the number of analog channels. */
  Set_Number_of_Analog_Channels(TWO_ANALOG);     /* See ifi_aliases.h
*/

/* THIRD: Set up any extra digital inputs. */
  /* The six INTERRUPTS are already digital inputs. */
  /* If you need more then set them up here. */
  /* IOxx = IOyy = INPUT; */
  IO6 = IO8 = IO10 = INPUT;      /* Used for limit switch inputs. */
  IO12 = IO14 = IO16 = INPUT;    /* Used for limit switch inputs. */

/* FOURTH: Set up the pins you want to use as digital OUTPUTs. */
  IO3 = IO4 = OUTPUT;
  IO5 = IO7 = IO9 = OUTPUT;     /* For connecting to adjacent limit
switches. */
  IO11 = IO13 = IO15 = OUTPUT;  /* For connecting to adjacent limit
switches. */

/* FIFTH: Initialize the values on the digital outputs. */
  rc_dig_out03 = rc_dig_out04 = 0;
  rc_dig_out05 = rc_dig_out07 = rc_dig_out09 = 0;
  rc_dig_out11 = rc_dig_out13 = rc_dig_out15 = 0;

/* SIXTH: Set your initial PWM values.  Neutral is 127. */
  pwm01 = pwm02 = pwm03 = pwm04 = pwm05 = pwm06 = pwm07 = pwm08 = 127;

/* SEVENTH: Choose which processor will control which PWM outputs. */

Setup_Who_Controls_Pwms(MASTER,MASTER,MASTER,MASTER,MASTER,MASTER,MASTE
R,MASTER);

/* EIGHTH: Set your PWM output type.  Only applies if USER controls PWM
1, 2, 3, or 4. */
  /*   Choose from these parameters for PWM 1-4 respectively:
*/
  /*     IFI_PWM  - Standard IFI PWM output generated with
Generate_Pwms(...)          */
  /*     USER_CCP - User can use PWM pin as digital I/O or CCP pin.
*/
  Setup_PWM_Output_Type(IFI_PWM,IFI_PWM,IFI_PWM,IFI_PWM);

  /*
     Example: The following would generate a 40KHz PWM with a 50% duty
cycle
              on the CCP2 pin (PWM OUT 1):
          CCP2CON = 0x3C;
          PR2 = 0xF9;
          CCPR2L = 0x7F;
          T2CON = 0;
          T2CONbits.TMR2ON = 1;
          Setup_PWM_Output_Type(USER_CCP,IFI_PWM,IFI_PWM,IFI_PWM);
  */

/* Add any other user initialization code here. */

  Initialize_Serial_Comms();

  Initialize_Timer_2(); // initialize and start the clock

  Putdata(&txdata);             /* DO NOT CHANGE! */

  printf("%s\n", strptr);       /* Optional - Print initialization
message. */

  User_Proc_Is_Ready();         /* DO NOT CHANGE! - last line of
User_Initialization */
}


/*******************************************************************
*********
* FUNCTION NAME: Process_Data_From_Master_uP
* PURPOSE:       Executes every 17ms when it gets new data from the
master
*                microprocessor.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
********************************************************************
********/
//    Successful clock implimentation 2011 - 03 - 18 : 1536 hrs

void Process_Data_From_Master_uP(void)
{
  Getdata(&rxdata);   /* Get fresh data from the master microprocessor.
*/

  Display_Time(); // located in clock.c

  Default_Routine();  /* See below. */



  printf("PWM OUT 1 = %d, PWM OUT 2 = %d, PWM OUT 3 = %d, PWM OUT 4 =
%d\n", (int)pwm01, (int)pwm02, (int)pwm03, (int)pwm04);
  printf("PWM OUT 5 = %d, PWM OUT 6 = %d, PWM OUT 7 = %d, PWM OUT 8 =
%d\n", (int)pwm05, (int)pwm06, (int)pwm07, (int)pwm08);
  printf("PWM IN 1 = %d, PWM IN 2 = %d, PWM IN 3 = %d, PWM IN 4 =
%d\n", (int)PWM_in1, (int)PWM_in2, (int)PWM_in3, (int)PWM_in4);
/*  printf("PWM IN 5 = %d, PWM IN 6 = %d, PWM IN 7 = %d, PWM IN 8 =
%d\n", (int)PWM_in5, (int)PWM_in6, (int)PWM_in7, (int)PWM_in8);
  /* This snoops on the inputs being fed to the robot controller and
the outputs being fed to the individual servos */

  Putdata(&txdata);             /* DO NOT CHANGE! */
}
```

```
/*******************************************************************
*********
* FUNCTION NAME: Default_Routine
* PURPOSE:       Performs the default mappings of inputs to outputs for
the
*                Robot Controller.
* CALLED FROM:   this file, Process_Data_From_Master_uP routine
* ARGUMENTS:     none
* RETURNS:       void
********************************************************************
********/
void Default_Routine(void)
{

 /*---------- Left Joystick Drive -----------------------------------
-----------------------------------
  *------------------------------------------------Alpha Build 2010 –
06 – 26 : 1224 hrs------------------
  *-----------------------------------------------------------------
-----------------------------------
  *  This code independently handles Y and X axis inputs on the left
joystick for throttle
  *    manipulation and robot turning.
  *  Joystick forward  = Robot forward
  *  Joystick backward = Robot stop
  *  Joystick right    = Robot turns right
  *  Joystick left     = Robot turns left
  *  Connect the first tail link servo to PWM OUT 1 on the robot
controller.
  *  Connect the second tail link servo to PWM OUT 2 on the robot
controller.
  *  Connect the third tail link servo to PWM OUT 3 on the robot
controller.
  *  Connect the fourth tail link servo to PWM OUT 4 on the robot
controller.
  *  Connect the fifth tail link servo to PWM OUT 5 on the robot
controller.
  */

      if (PWM_in1 >= 160)
            {
                  if (msClock >= 1000)
                        {
                              pwm01 = 209;
                              pwm02 = 146;
                              pwm03 = 0;
                              pwm04 = 62;
                              pwm05 = 117;
                        }
                  else if (msClock >= 950)
                        {
                              pwm01 = 197;
                              pwm02 = 190;
                              pwm03 = 0;
                              pwm04 = 4;
                              pwm05 = 114;
                        }
                  else if (msClock >= 900)
                        {
                              pwm01 = 180;
                              pwm02 = 220;
                              pwm03 = 0;
                              pwm04 = 0;
                              pwm05 = 109;
                        }
                  else if (msClock >= 850)
                        {
                              pwm01 = 157;
                              pwm02 = 249;
                              pwm03 = 117;
                              pwm04 = 0;
                              pwm05 = 47;
                        }
                  else if (msClock >= 800)
                        {
                              pwm01 = 127;
                              pwm02 = 255;
                              pwm03 = 145;
                              pwm04 = 0;
                              pwm05 = 0;
                        }
                  else if (msClock >= 750)
                        {
                              pwm01 = 93;
                              pwm02 = 255;
                              pwm03 = 166;
                              pwm04 = 110;
                              pwm05 = 0;
                        }
                  else if (msClock >= 700)
                        {
                              pwm01 = 63;
                              pwm02 = 255;
                              pwm03 = 192;
                              pwm04 = 131;
                              pwm05 = 0;
                        }
                  else if (msClock >= 650)
                        {
                              pwm01 = 45;
                              pwm02 = 255;
                              pwm03 = 228;
                              pwm04 = 139;
                              pwm05 = 116;
                        }
                  else if (msClock >= 600)
                        {
                              pwm01 = 37;
                              pwm02 = 253;
                              pwm03 = 255;
                              pwm04 = 144;
                              pwm05 = 127;
                        }
```

```
else if (msClock >= 550)
      {
            pwm01 = 38;
            pwm02 = 187;
            pwm03 = 255;
            pwm04 = 155;
            pwm05 = 133;
      }
else if (msClock >= 500)
      {
            pwm01 = 45;
            pwm02 = 108;
            pwm03 = 255;
            pwm04 = 192;
            pwm05 = 137;
      }
else if (msClock >= 450)
      {
            pwm01 = 57;
            pwm02 = 64;
            pwm03 = 255;
            pwm04 = 250;
            pwm05 = 140;
      }
else if (msClock >= 400)
      {
            pwm01 = 74;
            pwm02 = 34;
            pwm03 = 255;
            pwm04 = 255;
            pwm05 = 145;
      }
else if (msClock >= 350)
      {
            pwm01 = 97;
            pwm02 = 5;
            pwm03 = 137;
            pwm04 = 255;
            pwm05 = 207;
      }
else if (msClock >= 300)
      {
            pwm01 = 127;
            pwm02 = 0;
            pwm03 = 109;
            pwm04 = 255;
            pwm05 = 255;
      }
else if (msClock >= 250)
      {
            pwm01 = 161;
            pwm02 = 0;
            pwm03 = 88;
            pwm04 = 144;
            pwm05 = 255;
      }
else if (msClock >= 200)
```

```
                        {
                              pwm01 = 191;
                              pwm02 = 0;
                              pwm03 = 62;
                              pwm04 = 123;
                              pwm05 = 255;
                        }
                  else if (msClock >= 150)
                        {
                              pwm01 = 209;
                              pwm02 = 0;
                              pwm03 = 26;
                              pwm04 = 115;
                              pwm05 = 138;
                        }
                  else if (msClock >= 100)
                        {
                              pwm01 = 217;
                              pwm02 = 1;
                              pwm03 = 0;
                              pwm04 = 110;
                              pwm05 = 127;
                        }
                  else if (msClock >= 50)
                        {
                              pwm01 = 216;
                              pwm02 = 67;
                              pwm03 = 0;
                              pwm04 = 99;
                              pwm05 = 121;
                        }
                  else
                        {
                              pwm01 = 209;
                              pwm02 = 146;
                              pwm03 = 0;
                              pwm04 = 62;
                              pwm05 = 117;
                        }
            }                       /*  fish motion */
      else if (PWM_in2 >= 160)
            {
                  if (msClock >= 1000)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 209;
                              pwm04 = 146;
                              pwm05 = 0;
                        }
                  else if (msClock >= 950)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 197;
                              pwm04 = 190;
                              pwm05 = 0;
                        }
                  else if (msClock >= 900)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 180;
                              pwm04 = 220;
                              pwm05 = 0;
                        }
                  else if (msClock >= 850)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 157;
                              pwm04 = 249;
                              pwm05 = 117;
                        }
                  else if (msClock >= 800)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 127;
                              pwm04 = 255;
                              pwm05 = 145;
                        }
                  else if (msClock >= 750)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 93;
                              pwm04 = 255;
                              pwm05 = 166;
                        }
                  else if (msClock >= 700)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 63;
                              pwm04 = 255;
                              pwm05 = 192;
                        }
                  else if (msClock >= 650)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 45;
                              pwm04 = 255;
                              pwm05 = 228;
                        }
                  else if (msClock >= 600)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 37;
                              pwm04 = 253;
                              pwm05 = 255;
                        }
```

```
else if (msClock >= 550)
      {
            pwm01 = 63;
            pwm02 = 63;
            pwm03 = 38;
            pwm04 = 187;
            pwm05 = 255;
      }
else if (msClock >= 500)
      {
            pwm01 = 63;
            pwm02 = 63;
            pwm03 = 45;
            pwm04 = 108;
            pwm05 = 255;
      }
else if (msClock >= 450)
      {
            pwm01 = 63;
            pwm02 = 63;
            pwm03 = 57;
            pwm04 = 64;
            pwm05 = 255;
      }
else if (msClock >= 400)
      {
            pwm01 = 63;
            pwm02 = 63;
            pwm03 = 74;
            pwm04 = 34;
            pwm05 = 255;
      }
else if (msClock >= 350)
      {
            pwm01 = 63;
            pwm02 = 63;
            pwm03 = 97;
            pwm04 = 5;
            pwm05 = 137;
      }
else if (msClock >= 300)
      {
            pwm01 = 63;
            pwm02 = 63;
            pwm03 = 127;
            pwm04 = 0;
            pwm05 = 109;
      }
else if (msClock >= 250)
      {
            pwm01 = 63;
            pwm02 = 63;
            pwm03 = 161;
            pwm04 = 0;
            pwm05 = 88;
      }
else if (msClock >= 200)
```

```
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 191;
                        pwm04 = 0;
                        pwm05 = 62;
                  }
            else if (msClock >= 150)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 209;
                        pwm04 = 0;
                        pwm05 = 26;
                  }
            else if (msClock >= 100)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 217;
                        pwm04 = 1;
                        pwm05 = 0;
                  }
            else if (msClock >= 50)
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 216;
                        pwm04 = 67;
                        pwm05 = 0;
                  }
            else
                  {
                        pwm01 = 63;
                        pwm02 = 63;
                        pwm03 = 209;
                        pwm04 = 146;
                        pwm05 = 0;
                  }
      }                       /*  holder for turning commands */
else if (PWM_in2 <= 94)
      {
            if (msClock >= 1000)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 209;
                        pwm04 = 146;
                        pwm05 = 0;
                  }
            else if (msClock >= 950)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 197;
                        pwm04 = 190;
                        pwm05 = 0;
                  }
            else if (msClock >= 900)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 180;
                        pwm04 = 220;
                        pwm05 = 0;
                  }
            else if (msClock >= 850)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 157;
                        pwm04 = 249;
                        pwm05 = 117;
                  }
            else if (msClock >= 800)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 127;
                        pwm04 = 255;
                        pwm05 = 145;
                  }
            else if (msClock >= 750)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 93;
                        pwm04 = 255;
                        pwm05 = 166;
                  }
            else if (msClock >= 700)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 63;
                        pwm04 = 255;
                        pwm05 = 192;
                  }
            else if (msClock >= 650)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 45;
                        pwm04 = 255;
                        pwm05 = 228;
                  }
            else if (msClock >= 600)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 37;
                        pwm04 = 253;
                        pwm05 = 255;
                  }
```

```
else if (msClock >= 550)
      {
            pwm01 = 191;
            pwm02 = 191;
            pwm03 = 38;
            pwm04 = 187;
            pwm05 = 255;
      }
else if (msClock >= 500)
      {
            pwm01 = 191;
            pwm02 = 191;
            pwm03 = 45;
            pwm04 = 108;
            pwm05 = 255;
      }
else if (msClock >= 450)
      {
            pwm01 = 191;
            pwm02 = 191;
            pwm03 = 57;
            pwm04 = 64;
            pwm05 = 255;
      }
else if (msClock >= 400)
      {
            pwm01 = 191;
            pwm02 = 191;
            pwm03 = 74;
            pwm04 = 34;
            pwm05 = 255;
      }
else if (msClock >= 350)
      {
            pwm01 = 191;
            pwm02 = 191;
            pwm03 = 97;
            pwm04 = 5;
            pwm05 = 137;
      }
else if (msClock >= 300)
      {
            pwm01 = 191;
            pwm02 = 191;
            pwm03 = 127;
            pwm04 = 0;
            pwm05 = 109;
      }
else if (msClock >= 250)
      {
            pwm01 = 191;
            pwm02 = 191;
            pwm03 = 161;
            pwm04 = 0;
            pwm05 = 88;
      }
else if (msClock >= 200)
```

```
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 191;
                              pwm04 = 0;
                              pwm05 = 62;
                        }
                  else if (msClock >= 150)
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 209;
                              pwm04 = 0;
                              pwm05 = 26;
                        }
                  else if (msClock >= 100)
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 217;
                              pwm04 = 1;
                              pwm05 = 0;
                        }
                  else if (msClock >= 50)
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 216;
                              pwm04 = 67;
                              pwm05 = 0;
                        }
                  else
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 209;
                              pwm04 = 146;
                              pwm05 = 0;
                        }
            }                       /*  holder for turning commands */
      else
            {
                  pwm01 = 127;
                  pwm02 = 127;
                  pwm03 = 127;
                  pwm04 = 127;
                  pwm05 = 127;
            }                       /*  servos idle */


 /*---------- Right Joystick Drive ------------------------------------
-----------------------------------
  *---------------------------------Successful Implementation 2010 –
06 – 19 : 1606 hrs------------------
  *  This code calls the Limit_Mix funtion to mix the Y and X axis on
the right joystick for
  *    control surface manipulation.
  *  Right joystick up    = Pitch control surfaces down (turn robot
down)
  *  Right joystick back  = Pitch control surfaces up (turn robot up)
  *  Right joystick right = Roll robot right
  *  Right joystick left  = Roll robot left
  *  THIS SUBROUTINE MIXES PITCH AND ROLL INPUTS ON TRANSMITTER FOR
DETERMINING SERVO STATES.
  *  Connect the left fin servo to PWM OUT 6 on the robot controller.
  *  Connect the right fin servo to PWM OUT 7 on the robot controller.
  */

   pwm06 = Limit_Mix(2000 + PWM_in3 - PWM_in4 + 127); /* maps left fin
servo to right joystick U/D & R/L */

      if (pwm06 >= 148)
            {
            pwm06 = 147;
            }
      else if (pwm06 <= 108)
            {
            pwm06 = 107;
            }
      else
            {
            pwm06 = pwm06;
            }

   pwm07 = 255 - Limit_Mix(2000 + PWM_in3 + PWM_in4 - 127);       /*
"255-" because reverse rotation of left side */

      if (pwm07 >= 148)
            {
            pwm07 = 147;
            }
      else if (pwm07 <= 108)
            {
            pwm07 = 107;
            }
      else
            {
            pwm07 = pwm07;
            }

 /* ------ Other PWM OUTPUT Mapping ----------------------------------
-------------*/

   pwm08 = PWM_in8;                 /* dummy, not used */


} /* END Default_Routine(); */


/*******************************************************************
********/
/*******************************************************************
********/
```

```
/*******************************************************************
********/
```

B.17 user_routines.c ; Case 3, C1 = 0.1, C2 = 0.50

```
/*******************************************************************
*********
* FILE NAME: user_routines.c <EDU VERSION>
*
* DESCRIPTION:
*  This file contains the default mappings of inputs
*  (like switches, joysticks, and buttons) to outputs on the EDU RC.
*
* USAGE:
*  You can either modify this file to fit your needs, or remove it from
your
*  project and replace it with a modified copy.
*
********************************************************************
********/

#include "ifi_aliases.h"
#include "ifi_default.h"
#include "ifi_utilities.h"
#include "user_routines.h"
#include "printf_lib.h"
#include "clock.h"      // adds timer functionality

/*** DEFINE USER VARIABLES AND INITIALIZE THEM HERE ***/
/* EXAMPLES: (see MPLAB C18 User's Guide, p.9 for all types)
unsigned char wheel_revolutions = 0; (can vary from 0 to 255)
unsigned int  delay_count = 7;       (can vary from 0 to 65,535)
int           angle_deviation = 142; (can vary from -32,768 to 32,767)
unsigned long very_big_counter = 0;  (can vary from 0 to 4,294,967,295)
*/


/*******************************************************************
*********
* FUNCTION NAME: Limit_Switch_Max
* PURPOSE:       Sets a PWM value to neutral (127) if it exceeds 127
and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     switch_state   unsigned char    I    limit switch state
*     *input_value   pointer           O   points to PWM byte value to
be limited
* RETURNS:       void
********************************************************************
********/
```

```
void Limit_Switch_Max(unsigned char switch_state, unsigned char
*input_value)
{
  if (switch_state == CLOSED)
  {
    if(*input_value > 127)
      *input_value = 127;
  }
}


/*******************************************************************
*********
* FUNCTION NAME: Limit_Switch_Min
* PURPOSE:       Sets a PWM value to neutral (127) if it's less than
127 and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     switch_state   unsigned char    I    limit switch state
*     *input_value   pointer           O   points to PWM byte value to
be limited
* RETURNS:       void
********************************************************************
********/
void Limit_Switch_Min(unsigned char switch_state, unsigned char
*input_value)
{
  if (switch_state == CLOSED)
  {
    if(*input_value < 127)
      *input_value = 127;
  }
}


/*******************************************************************
*********
* FUNCTION NAME: Limit_Mix
* PURPOSE:       Limits the mixed value for the joystick drive.  2000
is used as a mathematical
*                offset when this function is called so that the number
presented to Limit_Mix
*                is not negative.  The funtion removes the 2000 offset
after operating.
* CALLED FROM:   Default_Routine, this file
* ARGUMENTS:
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     intermediate_value    int    I
* RETURNS:       unsigned char
********************************************************************
********/
unsigned char Limit_Mix (int intermediate_value)
{
  static int limited_value;

  if (intermediate_value < 2000)
  {
    limited_value = 2000;
  }
  else if (intermediate_value > 2254)
  {
    limited_value = 2254;
  }
  else
  {
    limited_value = intermediate_value;
  }
  return (unsigned char) (limited_value - 2000);
}


/*******************************************************************
*********
* FUNCTION NAME: Setup_Who_Controls_Pwms
* PURPOSE:       Each parameter specifies what processor will control
the pwm.
*
* CALLED FROM:   User_Initialization
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     pwmSpec1              int     I   USER/MASTER (defined in
ifi_aliases.h)
*     pwmSpec2              int     I   USER/MASTER
*     pwmSpec3              int     I   USER/MASTER
*     pwmSpec4              int     I   USER/MASTER
*     pwmSpec5              int     I   USER/MASTER
*     pwmSpec6              int     I   USER/MASTER
*     pwmSpec7              int     I   USER/MASTER
*     pwmSpec8              int     I   USER/MASTER
* RETURNS:       void
*******************************************************************
********/
static void Setup_Who_Controls_Pwms(int pwmSpec1,int pwmSpec2,int
pwmSpec3,int pwmSpec4,
                                    int pwmSpec5,int pwmSpec6,int
pwmSpec7,int pwmSpec8)
{
  txdata.pwm_mask = 0xFF;         /* Default to master controlling all
PWMs. */
  if (pwmSpec1 == USER)           /* If User controls PWM1 then clear
bit0. */
    txdata.pwm_mask &= 0xFE;      /* same as txdata.pwm_mask =
txdata.pwm_mask & 0xFE; */
  if (pwmSpec2 == USER)           /* If User controls PWM2 then clear
bit1. */
    txdata.pwm_mask &= 0xFD;
  if (pwmSpec3 == USER)           /* If User controls PWM3 then clear
bit2. */
    txdata.pwm_mask &= 0xFB;
  if (pwmSpec4 == USER)           /* If User controls PWM4 then clear
bit3. */
    txdata.pwm_mask &= 0xF7;
  if (pwmSpec5 == USER)           /* If User controls PWM5 then clear
bit4. */
    txdata.pwm_mask &= 0xEF;
  if (pwmSpec6 == USER)           /* If User controls PWM6 then clear
bit5. */
    txdata.pwm_mask &= 0xDF;
  if (pwmSpec7 == USER)           /* If User controls PWM7 then clear
bit6. */
    txdata.pwm_mask &= 0xBF;
  if (pwmSpec8 == USER)           /* If User controls PWM8 then clear
bit7. */
    txdata.pwm_mask &= 0x7F;
}


/***********************************************************************
*********
* FUNCTION NAME: User_Initialization
* PURPOSE:       This routine is called first (and only once) in the
Main function.
*                You may modify and add to this function.
*                The primary purpose is to set up the DIGITAL IN/OUT -
ANALOG IN
*                pins as analog inputs, digital inputs, and digital
outputs.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
************************************************************************
********/
void User_Initialization (void)
{
  rom const char *strptr = "IFI User Processor Initialized ...";

/* FIRST: Set up the pins you want to use as analog INPUTs. */
  IO1 = IO2 = INPUT;        /* Used for analog inputs. */
    /*
     Note: IO1 = IO2 = IO3 = IO4 = INPUT;
           is the same as the following:

           IO1 = INPUT;
           IO2 = INPUT;
           IO3 = INPUT;
           IO4 = INPUT;
    */

/* SECOND: Configure the number of analog channels. */
  Set_Number_of_Analog_Channels(TWO_ANALOG);     /* See ifi_aliases.h
*/

/* THIRD: Set up any extra digital inputs. */
  /* The six INTERRUPTS are already digital inputs. */
  /* If you need more then set them up here. */
  /* IOxx = IOyy = INPUT; */
  IO6 = IO8 = IO10 = INPUT;      /* Used for limit switch inputs. */
  IO12 = IO14 = IO16 = INPUT;    /* Used for limit switch inputs. */

/* FOURTH: Set up the pins you want to use as digital OUTPUTs. */
  IO3 = IO4 = OUTPUT;
  IO5 = IO7 = IO9 = OUTPUT;     /* For connecting to adjacent limit
switches. */
  IO11 = IO13 = IO15 = OUTPUT;  /* For connecting to adjacent limit
switches. */

/* FIFTH: Initialize the values on the digital outputs. */
  rc_dig_out03 = rc_dig_out04 = 0;
  rc_dig_out05 = rc_dig_out07 = rc_dig_out09 = 0;
  rc_dig_out11 = rc_dig_out13 = rc_dig_out15 = 0;

/* SIXTH: Set your initial PWM values.  Neutral is 127. */
  pwm01 = pwm02 = pwm03 = pwm04 = pwm05 = pwm06 = pwm07 = pwm08 = 127;

/* SEVENTH: Choose which processor will control which PWM outputs. */

Setup_Who_Controls_Pwms(MASTER,MASTER,MASTER,MASTER,MASTER,MASTER,MASTE
R,MASTER);

/* EIGHTH: Set your PWM output type.  Only applies if USER controls PWM
1, 2, 3, or 4. */
  /*   Choose from these parameters for PWM 1-4 respectively:
*/
  /*     IFI_PWM  - Standard IFI PWM output generated with
Generate_Pwms(...)          */
  /*     USER_CCP - User can use PWM pin as digital I/O or CCP pin.
*/
  Setup_PWM_Output_Type(IFI_PWM,IFI_PWM,IFI_PWM,IFI_PWM);

  /*
     Example: The following would generate a 40KHz PWM with a 50% duty
cycle
              on the CCP2 pin (PWM OUT 1):
          CCP2CON = 0x3C;
          PR2 = 0xF9;
          CCPR2L = 0x7F;
          T2CON = 0;
          T2CONbits.TMR2ON = 1;
          Setup_PWM_Output_Type(USER_CCP,IFI_PWM,IFI_PWM,IFI_PWM);
  */

/* Add any other user initialization code here. */

  Initialize_Serial_Comms();

  Initialize_Timer_2(); // initialize and start the clock

  Putdata(&txdata);             /* DO NOT CHANGE! */

  printf("%s\n", strptr);       /* Optional - Print initialization
message. */
```

```
  User_Proc_Is_Ready();         /* DO NOT CHANGE! - last line of
User_Initialization */
}


/*******************************************************************
*********
* FUNCTION NAME: Process_Data_From_Master_uP
* PURPOSE:       Executes every 17ms when it gets new data from the
master
*                microprocessor.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
********************************************************************
********/
//    Successful clock implimentation 2011 - 03 - 18 : 1536 hrs

void Process_Data_From_Master_uP(void)
{
  Getdata(&rxdata);   /* Get fresh data from the master microprocessor.
*/

  Display_Time(); // located in clock.c

  Default_Routine();  /* See below. */



  printf("PWM OUT 1 = %d, PWM OUT 2 = %d, PWM OUT 3 = %d, PWM OUT 4 =
%d\n", (int)pwm01, (int)pwm02, (int)pwm03, (int)pwm04);
  printf("PWM OUT 5 = %d, PWM OUT 6 = %d, PWM OUT 7 = %d, PWM OUT 8 =
%d\n", (int)pwm05, (int)pwm06, (int)pwm07, (int)pwm08);
  printf("PWM IN 1 = %d, PWM IN 2 = %d, PWM IN 3 = %d, PWM IN 4 =
%d\n", (int)PWM_in1, (int)PWM_in2, (int)PWM_in3, (int)PWM_in4);
/*  printf("PWM IN 5 = %d, PWM IN 6 = %d, PWM IN 7 = %d, PWM IN 8 =
%d\n", (int)PWM_in5, (int)PWM_in6, (int)PWM_in7, (int)PWM_in8);
  /* This snoops on the inputs being fed to the robot controller and
the outputs being fed to the individual servos */

  Putdata(&txdata);             /* DO NOT CHANGE! */
}


/*******************************************************************
*********
* FUNCTION NAME: Default_Routine
* PURPOSE:       Performs the default mappings of inputs to outputs for
the
*                Robot Controller.
* CALLED FROM:   this file, Process_Data_From_Master_uP routine
* ARGUMENTS:     none
* RETURNS:       void
********************************************************************
********/
void Default_Routine(void)
{
 /*---------- Left Joystick Drive -----------------------------------
------------------------------------
  *-------------------------------------------------Alpha Build 2010 –
06 – 26 : 1224 hrs------------------
  *-----------------------------------------------------------------------
------------------------------------
  *  This code independently handles Y and X axis inputs on the left
joystick for throttle
  *    manipulation and robot turning.
  *  Joystick forward  = Robot forward
  *  Joystick backward = Robot stop
  *  Joystick right    = Robot turns right
  *  Joystick left     = Robot turns left
  *  Connect the first tail link servo to PWM OUT 1 on the robot
controller.
  *  Connect the second tail link servo to PWM OUT 2 on the robot
controller.
  *  Connect the third tail link servo to PWM OUT 3 on the robot
controller.
  *  Connect the fourth tail link servo to PWM OUT 4 on the robot
controller.
  *  Connect the fifth tail link servo to PWM OUT 5 on the robot
controller.
  */

      if (PWM_in1 >= 160)
            {
                  if (msClock >= 1000)
                        {
                              pwm01 = 248;
                              pwm02 = 71;
                              pwm03 = 0;
                              pwm04 = 57;
                              pwm05 = 116;
                        }
                  else if (msClock >= 950)
                        {
                              pwm01 = 234;
                              pwm02 = 116;
                              pwm03 = 0;
                              pwm04 = 11;
                              pwm05 = 114;
                        }
                  else if (msClock >= 900)
                        {
                              pwm01 = 213;
                              pwm02 = 157;
                              pwm03 = 0;
                              pwm04 = 0;
                              pwm05 = 111;
                        }
                  else if (msClock >= 850)
                        {
                              pwm01 = 182;
                              pwm02 = 205;
                              pwm03 = 124;
                              pwm04 = 0;
                              pwm05 = 64;
                        }
                  else if (msClock >= 800)
                        {
                              pwm01 = 127;
                              pwm02 = 255;
                              pwm03 = 146;
                              pwm04 = 0;
                              pwm05 = 0;
                        }
                  else if (msClock >= 750)
                        {
                              pwm01 = 34;
                              pwm02 = 255;
                              pwm03 = 151;
                              pwm04 = 129;
                              pwm05 = 0;
                        }
                  else if (msClock >= 700)
                        {
                              pwm01 = 4;
                              pwm02 = 255;
                              pwm03 = 183;
                              pwm04 = 142;
                              pwm05 = 105;
                        }
                  else if (msClock >= 650)
                        {
                              pwm01 = 0;
                              pwm02 = 255;
                              pwm03 = 220;
                              pwm04 = 148;
                              pwm05 = 124;
                        }
                  else if (msClock >= 600)
                        {
                              pwm01 = 0;
                              pwm02 = 255;
                              pwm03 = 255;
                              pwm04 = 155;
                              pwm05 = 131;
                        }
                  else if (msClock >= 550)
                        {
                              pwm01 = 0;
                              pwm02 = 241;
                              pwm03 = 255;
                              pwm04 = 168;
                              pwm05 = 135;
                        }
                  else if (msClock >= 500)
                        {
                              pwm01 = 6;
                              pwm02 = 183;
                              pwm03 = 255;
                              pwm04 = 197;
                              pwm05 = 138;
                        }
                  else if (msClock >= 450)
                        {
                              pwm01 = 20;
                              pwm02 = 138;
                              pwm03 = 255;
                              pwm04 = 243;
                              pwm05 = 140;
                        }
                  else if (msClock >= 400)
                        {
                              pwm01 = 41;
                              pwm02 = 97;
                              pwm03 = 255;
                              pwm04 = 255;
                              pwm05 = 143;
                        }
                  else if (msClock >= 350)
                        {
                              pwm01 = 72;
                              pwm02 = 49;
                              pwm03 = 130;
                              pwm04 = 255;
                              pwm05 = 190;
                        }
                  else if (msClock >= 300)
                        {
                              pwm01 = 127;
                              pwm02 = 0;
                              pwm03 = 108;
                              pwm04 = 255;
                              pwm05 = 255;
                        }
                  else if (msClock >= 250)
                        {
                              pwm01 = 220;
                              pwm02 = 0;
                              pwm03 = 103;
                              pwm04 = 125;
                              pwm05 = 255;
                        }
                  else if (msClock >= 200)
                        {
                              pwm01 = 250;
                              pwm02 = 0;
                              pwm03 = 71;
                              pwm04 = 112;
                              pwm05 = 149;
                        }
                  else if (msClock >= 150)
                        {
                              pwm01 = 255;
                              pwm02 = 0;
                              pwm03 = 34;
                              pwm04 = 106;
                              pwm05 = 130;
```

```
                        }
                  else if (msClock >= 100)
                        {
                              pwm01 = 255;
                              pwm02 = 0;
                              pwm03 = 0;
                              pwm04 = 99;
                              pwm05 = 123;
                        }
                  else if (msClock >= 50)
                        {
                              pwm01 = 255;
                              pwm02 = 13;
                              pwm03 = 0;
                              pwm04 = 86;
                              pwm05 = 119;
                        }
                  else
                        {
                              pwm01 = 248;
                              pwm02 = 71;
                              pwm03 = 0;
                              pwm04 = 57;
                              pwm05 = 116;
                        }
            }                       /*  fish motion */
      else if (PWM_in2 >= 160)
            {
                  if (msClock >= 1000)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 248;
                              pwm04 = 71;
                              pwm05 = 0;
                        }
                  else if (msClock >= 950)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 234;
                              pwm04 = 116;
                              pwm05 = 0;
                        }
                  else if (msClock >= 900)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 213;
                              pwm04 = 157;
                              pwm05 = 0;
                        }
                  else if (msClock >= 850)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 182;
                              pwm04 = 205;
                              pwm05 = 124;
                        }
                  else if (msClock >= 800)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 127;
                              pwm04 = 255;
                              pwm05 = 146;
                        }
                  else if (msClock >= 750)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 34;
                              pwm04 = 255;
                              pwm05 = 151;
                        }
                  else if (msClock >= 700)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 4;
                              pwm04 = 255;
                              pwm05 = 183;
                        }
                  else if (msClock >= 650)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 0;
                              pwm04 = 255;
                              pwm05 = 220;
                        }
                  else if (msClock >= 600)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 0;
                              pwm04 = 255;
                              pwm05 = 255;
                        }
                  else if (msClock >= 550)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 0;
                              pwm04 = 241;
                              pwm05 = 255;
                        }
                  else if (msClock >= 500)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 6;
                              pwm04 = 183;
                              pwm05 = 255;
                        }
                  else if (msClock >= 450)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 20;
                              pwm04 = 138;
                              pwm05 = 255;
                        }
                  else if (msClock >= 400)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 41;
                              pwm04 = 97;
                              pwm05 = 255;
                        }
                  else if (msClock >= 350)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 72;
                              pwm04 = 49;
                              pwm05 = 130;
                        }
                  else if (msClock >= 300)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 127;
                              pwm04 = 0;
                              pwm05 = 108;
                        }
                  else if (msClock >= 250)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 220;
                              pwm04 = 0;
                              pwm05 = 103;
                        }
                  else if (msClock >= 200)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 250;
                              pwm04 = 0;
                              pwm05 = 71;
                        }
                  else if (msClock >= 150)
                        {
                              pwm01 = 63;
                              pwm02 = 63;
                              pwm03 = 255;
                              pwm04 = 0;
                              pwm05 = 34;
                              }
                          else if (msClock >= 100)
                              {
                                  pwm01 = 63;
                                  pwm02 = 63;
                                  pwm03 = 255;
                                  pwm04 = 0;
                                  pwm05 = 0;
                              }
                          else if (msClock >= 50)
                              {
                                  pwm01 = 63;
                                  pwm02 = 63;
                                  pwm03 = 255;
                                  pwm04 = 13;
                                  pwm05 = 0;
                              }
                          else
                              {
                                  pwm01 = 63;
                                  pwm02 = 63;
                                  pwm03 = 248;
                                  pwm04 = 71;
                                  pwm05 = 0;
                              }
                      }                       /*  holder for turning commands */
                  else if (PWM_in2 <= 94)
                      {
                          if (msClock >= 1000)
                              {
                                  pwm01 = 191;
                                  pwm02 = 191;
                                  pwm03 = 248;
                                  pwm04 = 71;
                                  pwm05 = 0;
                              }
                          else if (msClock >= 950)
                              {
                                  pwm01 = 191;
                                  pwm02 = 191;
                                  pwm03 = 234;
                                  pwm04 = 116;
                                  pwm05 = 0;
                              }
                          else if (msClock >= 900)
                              {
                                  pwm01 = 191;
                                  pwm02 = 191;
                                  pwm03 = 213;
                                  pwm04 = 157;
                                  pwm05 = 0;
                              }
                          else if (msClock >= 850)
                              {
                                  pwm01 = 191;
                                  pwm02 = 191;
                                  pwm03 = 182;
```

```
                        pwm04 = 205;
                        pwm05 = 124;
                  }
            else if (msClock >= 800)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 127;
                        pwm04 = 255;
                        pwm05 = 146;
                  }
            else if (msClock >= 750)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 34;
                        pwm04 = 255;
                        pwm05 = 151;
                  }
            else if (msClock >= 700)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 4;
                        pwm04 = 255;
                        pwm05 = 183;
                  }
            else if (msClock >= 650)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 0;
                        pwm04 = 255;
                        pwm05 = 220;
                  }
            else if (msClock >= 600)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 0;
                        pwm04 = 255;
                        pwm05 = 255;
                  }
            else if (msClock >= 550)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 0;
                        pwm04 = 241;
                        pwm05 = 255;
                  }
            else if (msClock >= 500)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 6;
                        pwm04 = 183;
                        pwm05 = 255;
                  }
            else if (msClock >= 450)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 20;
                        pwm04 = 138;
                        pwm05 = 255;
                  }
            else if (msClock >= 400)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 41;
                        pwm04 = 97;
                        pwm05 = 255;
                  }
            else if (msClock >= 350)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 72;
                        pwm04 = 49;
                        pwm05 = 130;
                  }
            else if (msClock >= 300)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 127;
                        pwm04 = 0;
                        pwm05 = 108;
                  }
            else if (msClock >= 250)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 220;
                        pwm04 = 0;
                        pwm05 = 103;
                  }
            else if (msClock >= 200)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 250;
                        pwm04 = 0;
                        pwm05 = 71;
                  }
            else if (msClock >= 150)
                  {
                        pwm01 = 191;
                        pwm02 = 191;
                        pwm03 = 255;
                        pwm04 = 0;
                        pwm05 = 34;
```

```
                        }
                  else if (msClock >= 100)
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 255;
                              pwm04 = 0;
                              pwm05 = 0;
                        }
                  else if (msClock >= 50)
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 255;
                              pwm04 = 13;
                              pwm05 = 0;
                        }
                  else
                        {
                              pwm01 = 191;
                              pwm02 = 191;
                              pwm03 = 248;
                              pwm04 = 71;
                              pwm05 = 0;
                        }
            }                       /*  holder for turning commands */
      else
            {
                  pwm01 = 127;
                  pwm02 = 127;
                  pwm03 = 127;
                  pwm04 = 127;
                  pwm05 = 127;
            }                       /*  servos idle */


 /*---------- Right Joystick Drive ----------------------------------
------------------------------------
  *-----------------------------------Successful Implementation 2010 –
06 – 19 : 1606 hrs------------------
  *  This code calls the Limit_Mix funtion to mix the Y and X axis on
the right joystick for
  *    control surface manipulation.
  *  Right joystick up    = Pitch control surfaces down (turn robot
down)
  *  Right joystick back  = Pitch control surfaces up (turn robot up)
  *  Right joystick right = Roll robot right
  *  Right joystick left  = Roll robot left
  *  THIS SUBROUTINE MIXES PITCH AND ROLL INPUTS ON TRANSMITTER FOR
DETERMINING SERVO STATES.
  *  Connect the left fin servo to PWM OUT 6 on the robot controller.
  *  Connect the right fin servo to PWM OUT 7 on the robot controller.
  */

   pwm06 = Limit_Mix(2000 + PWM_in3 - PWM_in4 + 127); /* maps left fin
servo to right joystick U/D & R/L */
```

```
      if (pwm06 >= 148)
            {
            pwm06 = 147;
            }
      else if (pwm06 <= 108)
            {
            pwm06 = 107;
            }
      else
            {
            pwm06 = pwm06;
            }

   pwm07 = 255 - Limit_Mix(2000 + PWM_in3 + PWM_in4 - 127);       /*
"255-" because reverse rotation of left side */

      if (pwm07 >= 148)
            {
            pwm07 = 147;
            }
      else if (pwm07 <= 108)
            {
            pwm07 = 107;
            }
      else
            {
            pwm07 = pwm07;
            }

 /* ------ Other PWM OUTPUT Mapping -----------------------------------
-------------*/

   pwm08 = PWM_in8;                 /* dummy, not used */


} /* END Default_Routine(); */


/*********************************************************************
********/
/*********************************************************************
********/
/*********************************************************************
********/
```