The Design of a Free Swimming Robot Pike

by

John Muir Kumph

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering

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Abstract

The design developed and detailed in this thesis solves the engineering challenges of constructing an autonomous fish-like robotic mechanism. It packages the complete mechanics of a free-swimming robot fish inside the exact shape of a Pike {Esox niger}. By building a robot with the same shape and the same kinematic characteristics as a real fish, we hope to build a robot with similar hydrodynamic performance. The technology developed to construct this robot is explained in this thesis. And technological developments needed to accomplish the designed mechanism are also explained in detail.

Thesis Supervisor: Michael Triantafyllou
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Above is a cross section of the robot near the nose cone. The pectoral fins servos, the power and signal feedthroughs for the nose cone, the hinge mount for the tail fin servo, the mount for the main body servo linkage and the mounts for the spline are shown.

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Chapter 1

Introduction

This thesis details the design of a free swimming robot fish. First we explain why one would want to build a robot fish. Then we follow through the reasoning that lead us to our final design. The design is explored in detail, and guidelines for the use of the robot are given. Finally we conclude with some suggestions for future design modifications of this robot fish.

1.1 Fish Terminology

Fish are unlike most terrestrial animals, and as such, it is beneficial to briefly discuss natural fish. A wide variety of fish, including the Pike have morphology similar to that of the fish in figure 1-1. The figure shows the locations of the various fins as well as the general shape. Throughout this thesis we will refer to the artificial components of the robot with the names given to their natural counterparts.

1.2 Fish, excellent swimmers, very agile

Fish are nature’s excellent swimmers. Not all fish have evolved to swim the same, but they each have evolved to perform optimally in their environment. Some fish are predators which outrun their prey. Others swim together in schools with harmony and precision. They each have adapted to become excellent survivors in their environment.
Pike Fin Locations

Figure 1-1: Above is a figure of a common type of fish, which is similar in shape to a pike.

Fish can swim for long periods of time on little energy, and with great agility. It would be desirous to have man made vehicles that could perform as well or better than fish. In one particular field of vehicle engineering the characteristics of fish are most desired.

1.3 Autonomous Underwater Vehicles

Autonomous Underwater Vehicles (AUVs) present us with the next hope for underwater exploration, research, communication, and construction. They would be superior to manned vehicles in some ways. Manned vehicles present a multitude of problems for underwater vehicles. They require a large pressure hull to accommodate the operator, who must be paid and taken care of. For underwater exploration this means that the operator must be supported by a surface crew, which is very expensive.

An autonomous vehicle could theoretically swim the oceans for months, return with pictures and video and then be sent out again after being tested. If an autonomous vehicle suffered a catastrophic malfunction, the risk to humans would be
<table>
<thead>
<tr>
<th></th>
<th>Tuna</th>
<th>Odyssey II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>4 m/sec</td>
<td>1 m/sec</td>
</tr>
<tr>
<td>Duration</td>
<td>unknown</td>
<td>3 hours</td>
</tr>
<tr>
<td>Turning Radius</td>
<td>&lt; 1 body length</td>
<td>5 body lengths</td>
</tr>
</tbody>
</table>

Table 1.1: A comparison of a Blue Fin tuna and the Odyssey II, which are the same length.

substantially less than with a manned vehicle. Space exploration has the same problems, and the use of unmanned probes has been invaluable. With so little known about the oceans, unmanned ocean probes could be a boon to the exploration of the oceans, as unmanned probes have helped space exploration. The cost of exploring the oceans is currently very expensive, however with AUVs the cost could be a fraction of the price.

Fish are natural autonomous vehicles. They live in the world of water that is the world AUV's would like to explore. Naturally, it would be beneficial to look to fish for queues as to how to design a successful AUV.

1.4 Fish Capabilities

The first thing one notices when looking at fish are their high performance and dynamic characteristics. They move through the water with precision and speed.

Table 1.1 shows a comparison of abilities between a blue fin tuna and the Odyssey II, an autonomous underwater vehicle. Obviously fish swim well, but how much of their performance can be easily copied? Fish may swim for days on end, but they may eat constantly. And we are not attempting to mimic biological digestion. They may be excellent autonomous vehicles, but more for their highly adaptable brains, not their hydrodynamic characteristics.

However, there has been research which suggests that fish are not only highly
adaptable biological organisms, but that their hydrodynamic characteristics are far superior to human made conventional underwater methods of propulsion.

**Previous Fish Research**

- **Gray’s Paradox**

  Sir James Gray towed rigid models of dolphins in the water and found the power necessary to pull them. He also determined the power of a dolphin’s muscles. He concluded that a dolphin’s muscles have 1/6th the power necessary to propel a dolphin’s body at speeds between 15 and 20 knots. This was named Gray’s paradox. His research into the energy traits of aquatic animals is supported by other biologists, who have concluded that other aquatic animals do not have the energy needed to propel themselves through the water by factors ranging from 4 to 7. The energy to tow a fish model must be greater than for a fish to propel itself.

  Different explanations have been proposed for this phenomenon. Some have proposed that fish oils on the surface reduce the drag of the body, and some have proposed that the exact motion of the fish reduces the drag of the body[1]. Coating fish models with various oils has reduced their drag, but not substantially. The exact motion of the fish is of interest, because a wide variety of fish exhibit two similar hydrodynamic characteristics.

- **Strouhal Frequency**

  One characteristic most flapping foil underwater animals have is their strouhal frequency (defined by equation 3.1). We hope that building a robot which operates at this frequency will let it swim with very little energy. Figure 3-1 shows various fish and their range of strouhal frequencies. A wide variety of fish swim at a strouhal frequency of 0.3. By designing a robot with the capability of swimming at this frequency, we should be able to partially mimic fish.

- **Characteristic Undulation**
Most fish also exhibit a characteristic undulation. A traveling wave is generated to go down their body. As the traveling wave goes down their body, the magnitude of the wave increases. Figure 3-2 shows the motion of a fish as it swims.

We are concentrating on making a robot which will mimic the motion of a fish in both its bending shape and its strouhal frequency. This is so that we can create a high performance vehicle, which has two main purposes. The first is to give researchers in the area of hydrodynamics a tool to study the mechanics of fish swimming. The other longer term goal is to use the technology borrowed from nature to build high performance under water vehicles, which will allow long duration autonomous underwater missions.

1.5 Choice of Species to Mimic

There are many possible fish to mimic. Our goal in mimicking a pike is to obtain a fish which, like a pike, can maneuver and accelerate well. This will allow the dynamics of fish control to be investigated with a high performance craft.

Pike have been documented to accelerate at rates up to 12G’s, with short peaks of 25G’s [3]. These high rates of acceleration prompted us to select the pike shape for a study into the control of a free swimming fish.

In the next chapter we will go over exactly what motivated us to attempt to make the robot pike free swimming, and then we will give an overview of the preliminary design of the fish.
Chapter 2

Preliminary Design

Eventually, we would like to build an autonomous robot fish. However, it is too complicated to make such a leap of technology in one step. The immediate goal is to build a vehicle which will allow the fluid mechanics of a maneuvering fish to be investigated. In order to ascertain the scope of the design, we open up the possibilities for a short time to allow us some creativity in the preliminary design. Below we describe the technological challenges before a free swimming AUV could be built. Then we will narrow the focus to a goal for the design. Once we have narrowed the focus, we will go over relevant previous design work and then the preliminary design of the robot pike.

2.1 Problems to Overcome

At the stage of the project during the making of the free swimming robot pike, there were many engineering challenges which needed to be solved. They were:

1. turning and maneuvering with a tail

2. packaging a complete robot in a fish shape

3. outfitting the robot with sensors and computers so that it can navigate in the short range
4. designing the appropriate algorithms for short range navigation and autonomy

5. outfitting the robot with sensors, computers so that it could navigate in the long range

6. designing the appropriate algorithms for long range navigation and autonomy

While normally it is best to isolate single problems and solve them one at a time, and then design a system which incorporates all of the solutions, in our case it proved to be desirous to solve both problems 1 and 2 with the same machine. We arrived at this goal by eliminating the alternatives.

One could follow one of the following alternatives:

a. solve only problem (1)

In theory, one could solve the problem of turning and maneuvering with a fish that was driven from actuators and computers above (see figure 2-1). A gantry mounted fish would be automatically be stable, and no actuators would need to be inside the fish. The mechanisms would be on the gantry, which followed the fish. The actuators would have a transmission that would go through a very stiff umbilical cord or shaft.

However, there are problems with a gantry mounted system. A quick gantry is very expensive to purchase. And the mechanical coupling between the fish and the actuators above would make it difficult to actually measure fish maneuvering, and one might only be able to satisfactorily measure the dynamics of a fish with a gantry.

b. solve problem (1) and with a partial solution of (2)

If the actuators were to be packaged in the robot, but not the power source, thin flexible electrical wires could be run to the fish (see figure 2-2). This solution would have been easier but only by a small amount, because packaging the power on board is only a little more work than packaging the motors. Also, the wires, though flexible and small, would still interfere with the fish’s motion. The depth of the fish would have been especially difficult to change, since the wires would have to get longer and shorter.
Figure 2-1: One possible solution to studying the dynamics of fish swimming would have been to use a high speed gantry to drive the motors and computers around above the fish. This solution would have been bulky and expensive. It would have been difficult to experiment with, because the fish would ultimately be mechanically coupled with the gantry.
Figure 2-2: The fish could have been supplied with power and/or control with an umbilical cord. This would still have interfered with maneuvering, especially depth control.

2.2 Final Design Goals

So we arrived at the goal of designing a free-swimming fish. We are not building an autonomous fish, which would have enough artificial intelligence to swim around on its own. We are building a free-swimming robot. However, if it is possible we would like to allow our design to be expanded in the future so that a short range level of autonomy could be achieved. Below are the goals of the design.

- expandable: make the design expandable so that one could outfit this robot with the necessary sensors and computers for autonomous control at some point in the future.
- durable: the design must not break under normal operation
- high endurance: making the design able to operate for a long period of time
- maintainability: the ability to fix and replace parts that do need fixing.
• free swimming robot pike: all actuators and power source are on the robot, no wires are attached to fish.

In order to implement these design goals well and with efficiency, previous work into robot fish was studied. And after that, some preliminary design work was undertaken. Below is a description of the previous work.

2.3 Previous Work

A large amount of work relating to this thesis was done before the design of a robot pike was ever attempted. This work provided invaluable knowledge. In going over the previous work, it is hoped that the reader will gain some knowledge about the current state of the art in robot fish building.

2.3.1 Laser Fish

A small swimming robot fish using a bending spline backbone was developed by June 1994 for use in a small towing tank[7]. Modeled after a tuna, this fish was hoped to be able to be used in a small DPIV (Digital Particle Image Velocimetry) tank. The fish used three bending segments to approximate the motion of a real tuna. Having seen it working, it was convincing that it could approximate the motion of a fish. The Laser Fish was mounted to by a strut to a carriage, and was meant to swim in a straight line like its successor "Charlie".

2.3.2 Charlie the Robotuna

A previous swimming robot was built in February 1994[2]. This robot was modeled after a Tuna, and its name was "Charlie". Charlie became the centerpiece of research into the propulsive characteristics of a flapping foil fish. It had six independent links to approximate the motion of a real fish. It was mounted by a strut to its carriage, which contained its motors, amplifiers and control computer. Its coupling with the strut made it much easier to control than a free swimming fish, but also made it
very difficult to investigate turning and stability. It is an excellent platform for investigating the propulsive characteristics of a flapping foil body, and the data from it has suggested that it takes far less energy to swim through the water with its tail, than with a conventional propeller.

2.3.3 Computer Controlled Tugboat, Toot

A small autonomous tugboat was built to test different ways of controlling a free water-born vehicle. The existing hobbyist model RC technology was a cost effective way to control up to eight servos. The boat was put under computer control by controlling the RC transmitter from a digital to analog converting board inside a PC based computer. (work done by: Pehr Anderson and Gillian Lee)

2.4 Preliminary Work on Robot Pike

2.4.1 Model Yellow Sub

In order to explore the design of small underwater vehicles, a working remote control submarine was built. Purchased from a hobby company, the sub was meant for hobbyists, but proved to be invaluable in learning how to construct underwater vehicles. The sub allowed issues of buoyancy, space constraints, endurance, and reliability to be explored with an inexpensive 22" long submarine. The battery life of the sub, proved to be one of the most difficult aspects of using the sub.

2.4.2 Digitization of Fiberglass Model

The shape of the robot pike was taken from a 22" long taxidermist’s fiberglass model of a Chain Pickerel {Esox niger} (see figure 2-3). By using profile gauges, cross sections of the fish were taken and then traced onto paper. The cross sections were digitized and imported into a CAD program, where they were modified so that they were smooth and bilaterally symmetric. Since the taxidermists model had a deformed shape, the profile of the fish was determined by lining up the cross sections so that
Figure 2-3: Above is a picture of the fiberglass model used for the shape of the robot. It is a model of a chain pickerel \{Esox niger\} with a 22" fork length. By using profile gauges, a set of cross sections was obtained.

they fit a profile drawing of a chain pickerel from an aquatic zoology handbook[6].

Figure 2-4 shows the cross sections from the pike before they were smoothed. Figure 2-5 shows the cross sections after smoothing. Once the cross sections were done, a plan and a profile view were made, and layout design could begin. One benefit to digitizing the shape of the pike is that the shape could be scaled to any size in the computer. Later in the design it became apparent that a 22" long fish would be too small to use with the cheap submersible servos, so the shape was scaled up to 32" long.

2.4.3 Flexible Spline Testing

In order to determine the number of independent bending sections which were needed to approximate the motion of a real fish, a model was built to explore the shapes generated from a flexible spline of three segments. We sought to replicate the motion of a fish during turning and forward swimming with our robot (see figure 3-2). By bending segments of a beam with moment, we made a series of arcs with various radii of curvature (see figure 2-6). These pictures suggested that three sections would be
Figure 2-4: The raw pike cross sections, which were digitized from the fiberglass model, required smoothing to be useful.

Figure 2-5: The smoothed pike cross sections, which were digitized from the fiberglass model and then smoothed by hand with AutoCAD.
Figure 2-6: Above is a sequence of pictures of a spline, composed of three segments which bend in arcs. When compared to a real fish swimming, it is close.

sufficient to approximate the motion of a fish.

2.4.4 Free Moving Computer Controlled Pike

A kinematic model of the robotic pike was built using a small Onset Model 8 computer and three model servos. This model allowed us to explore the power and motion of a body driven by three servos (see figure 2-7). This working mockup provided our imaginations with a tool to test the quickness and controllability of a model RC servo driven robot.

2.4.5 Water Proof Servo Technology

Inexpensive, light submersible servo technology was developed during the design of this robot (see figure 2-8). Without submersible servo technology, this robot could not exist, so a large part of the preliminary design was done to determine whether a cheap way of building water proof servos could be developed. By building off the existing technology of model airplane servos, an inexpensive underwater servo system
Figure 2-7: A working mock-up of the robot pike was built using model airplane servos and a small Onset Model 8 computer to control the servos.

was designed.

The model airplane servo (see figure 4-8) is waterproofed by mounting it to an acetal faceplate, which is then bolted to a waterproof housing. Various transmissions can be designed to fit inside the waterproof housing. The water proof housing provides a hermetic seal for the transmission, so that it is protected from the environment. The waterproof housing is also an ideal place to put sensors to monitor the servo. The servo is sealed to the faceplate permanently. Since the servo is only permanently attached to the faceplate, the failure of an inexpensive servo does not cost very much nor is it difficult to repair.

A water proof servo assembly was built to test the design (see figure 2-8). Various forms of semi-permanent and permanent waterproofing were tested, so that when the final design of the pike was finished a reliable servo system would be in place.

**Problems with water proof servo**

There were specific difficulties in implementing the water proof servo technology. The problems are described below. By documenting these problems, it helps avoiding them in the future.
Figure 2-8: A working model airplane servo was built to test the technology. Various sealants were tested in chlorinated water. The servo housing is 2.9" long.

- The water proofing of the wire proved difficult. The wire to the servo was a 3 wire ribbon cable. The sealants obtained could not flex as much as the wire without shearing against the surface of the wire. If the wire flexed, water would wick slowly into the servo between the wire and the sealant. This would cause the servo to fail. This was avoided by strain relieving the wire and then sealing the wire where it did not bend.

- The waterproofing of the bottom of the servo had to be done with a castable, flexible material which did not expand too much when submerged in water for a long period of time. Epoxy, while it does expand in water is the current solution, until a better one is found and implemented.

**Properties of water proof servo**

The properties of the water proof servo are briefly described below. These properties must be taken into account in deciding how to use this technology.

- Specific Density is Close to Unity
This allows the user of the servo to place the servo in the design without having to consider how to place a large amount of flotation for the servo. Since one of the design goals is neutral buoyancy everywhere, it is especially important that the servo assembly be close to neutrally buoyant.

- Low Power

The actual power of the servo is low. This is a product of using a standard size model airplane servo. By replacing the model airplane servo with a better servo system, the power of this system could be significantly changed.

- Bulky and Large

The size and shape of the water proof servo are far from ideal. It’s bulky and somewhat large. The servo will be difficult to place; however since it has a low density it is easy to ballast. In figure 2-8 is a picture of the servo prototype.
Chapter 3

Theory

3.1 Flapping Foil Propulsion

3.1.1 Strouhal Frequency

Fish swim with a characteristic frequency, their strouhal frequency. It is defined as,

\[ St = \frac{A \nu}{v} \]  
(3.1)

where \( A \) is the double amplitude (peak to peak) of the tail motion, \( \nu \) is the frequency in hertz, and \( v \) is the velocity of the fish. In figure 3-1 are shown various fish and their strouhal frequencies. The most common frequency is 0.3. It is believed that this frequency of motion allows the fish to swim with high efficiencies.

3.1.2 Shape of Fish Undulation

Fish have a characteristic undulation during normal swimming (see figure 3-2). This propulsive wave is very close to a traveling sinusoidal wave going down the body of the fish. As it goes down the length of the fish it increases in amplitude.

During turning, a fish has a different characteristic motion. A sequence of a fish turning is shown in figure 3-3. The turning fish also sends a propulsive wave down the body of the fish, but this wave does is of much longer wavelength, and of higher
Figure 3-1: Above are various fish and their strouhal frequencies. It shows how a wide range of fish swim with a strouhal frequency near 0.3 amplitude. In order to swim like a fish we will need to replicate these two motions.

3.2 Bending Beam Theory

Using a bendable beam of rectangular cross section, one can generate smooth curves, which allow for a more controlled interaction with a dense fluid such as water. By applying a pure moment to a beam, the beam is deformed into an arc. The angle of curvature of the beam is related to the moment, and the characteristics of the beam as shown below.

$$\theta = \frac{12ML}{EWt^3}$$ (3.2)

where $M$ is the moment being exerted on the beam, $L$ is length of the centerline of the beam, $E$ is the Young’s Modulus of the material the beam is made out of, $W$ is the width of the beam, and $t$ is the height of the beam[4]. By using this equation, one can determine the moment necessary to bend the beam so that its ends are at an angle $\theta$. The actuators which bend a beam must be strong enough to supply
Figure 3-2: Above is shown a sequence of pictures of the Giant Danio, a 4" long fish. The sequence of pictures shows the characteristic undulation of the fish. The circular patterns indicate the motion of water around the fish. Picture courtesy of Jamie Anderson PhD.

Figure 3-3: Above is a sequence of pictures of the Giant Danio, a 4" long fish. The sequence of pictures shows fish during a turn. The circular patterns indicate the motion of water around the fish. Picture courtesy of Jamie Anderson PhD.
Figure 3-4: The geometry of the beam of length \( L \), in bending, is shown in the schematic. A linkage of length \( W \), which connects in a straight line between the ends of the arms of length \( d \), pulls and pushes the arms, bending the beam. For small displacements of the linkage, the beam is bent into a shape close to an arc. The arc has a radius of curvature, and an amount of bend \( \theta \).

this much moment. The moment a linear actuator can supply depends on how much leverage it has.

Our linear actuator is placed offset from the centerline of the beam, by an distance \( d \), and connected by a linkage to two moment arms which exert a moment on the beam we are bending (see figure 3-4). The actuator can bend the beam by shortening or lengthening the linkage which is between the two moment arms. The distance that the actuator must travel to bend the beam with an angle \( \theta \) is given by

\[
\theta = \frac{\Delta}{d} \tag{3.3}
\]

Where \( \Delta \) is the change in length of the linkage, caused by the movement of the linear actuator and \( d \) is the distance the linkage is offset from the centerline of the beam. This equation only holds for small angles (less than 30°), because as the angle increases, the beam goes into a buckling mode of bending.
These equations allow one to determine if an actuator can bend a beam into an angle, provided that the angle is low. If our actuator is not capable of bending the beam in a certain design, either the actuator can be moved, or the beam can be redesigned. The beam cannot be of any size or shape, because it must be able to undergo the repeated flexing without breaking.

### 3.3 Fatigue and Spline Life

Since we are using bending splines in the design, and we would like to have a high endurance design, the fatigue properties of materials need to be known. This will allow us to design parts with a long enough life to be useful to the project. For steel we design for less than 1% strain. For a highly resilient plastic such as Delrin, we design for less than 5% strain.

### 3.4 Law of Archimedes

The fish must be neutrally buoyant during normal swimming, because the fish should not have a tendency to rise to the surface or sink to the bottom. A neutrally buoyant fish will be easier to control, and will respond to its fins motions instead of the forces of gravity. However, when designing vessels in water, another rule must be obeyed.

#### 3.4.1 Passive Stability

The fish must be passively stable in the water. Its should not have a tendency to turn on its side or upside down. It must not have a tendency to pitch or roll. This will also make it easier to control. In order to obtain passive stability, the center of mass of the underwater body must be below the center of buoyancy (see figure 3-5).

#### 3.4.2 Bending Fish’s Passive Stability

Since the fish is bending, its neutral buoyancy constraint is enhanced. Figure 3-6 shows an unstable fish bending. If a fish has local concentrations of mass, even if the
Figure 3-5: Above is a diagram of a rigid underwater body. The rigid body must be kept afloat by buoyancy, which must be above the center of mass so that the system is stable.
Figure 3-6: For a fish to keep its passive stability, it must have its center of mass below its center of buoyancy in any configuration. The figure above shows what happens when there are local concentrations of mass in the fish. Even though the fish is stable when it is straight, when it bends the center of mass and center of buoyancy move away from each other, causing the fish to roll. To avoid this, the fish will be neutrally buoyant everywhere along the length of the fish.

center of mass is below the center of buoyancy in its unbent configuration, then in its bent shape the center of mass will not be below the center of buoyancy. This will lead to a tendency to roll during maneuvering.

In order to have passive stability, the fish must have its center of mass below its center of buoyancy in any configuration. If the fish is neutrally buoyant everywhere, then the fish is stable in any configuration. So a goal of uniform neutral buoyancy is established.
3.5 Energy Requirements

3.5.1 Power of fish

The batteries on board need to be able to supply the power required by the servos. Each servo requires an average power of

\[ P = VA \]  \hspace{1cm} (3.4)

where \( V \) is the voltage of servo, and \( A \) is the current drawn from the servo. All together the power required for a fish with no other power draw besides \( k \) servos is simply

\[ P_{fish} = \sum_{n=0}^{n=k} P_n \]  \hspace{1cm} (3.5)

where \( P_n \) is the power required by the nth servo.

3.5.2 Batteries required

It is desired to be able to swim the fish for long periods without changing the batteries. This will allow easier experimentation with the fish when it is built. Batteries should be chosen for a minimum one hour life of swimming, before needing changing or recharging. The time in hours that a battery pack will supply a fish is

\[ t = \frac{VW}{P_{fish}} \]  \hspace{1cm} (3.6)

where \( V \) is the voltage of the batteries, equal to the voltage of the fish system, and \( W \) is the charge stored in the batteries, measured in Amp-hours.

3.6 Skin Strain

When the body flexes, the skin stretches. The amount that it stretches is given by
\[ \epsilon = \frac{\theta w}{2} \] (3.7)

where \( \epsilon \) is the strain of the skin, \( w \) is average width of the segment, and \( \theta \) is the angle of bend for the section. The material that the fishes skin is made out of, must be able to undergo this much strain.
Chapter 4

Final Design

In this chapter we present the actual design of the robot. Our aim is to describe the reasoning and decisions that led us to this design. We start by describing the major design decisions and trade-offs. Then the selection of materials is described. After that, the overall design is explained, along with the design algorithm. The reasoning behind the component selection is then given and finally the assembly of major components is described.

4.1 Design Decisions and Tradeoffs

The design of the fish is based upon the goals, which are itemized in section 2.2. Using certain theoretical knowledge, design decisions could be made about what the actual robot would be like. Below is a listing of the critical design decisions which helped form the final design.

4.1.1 Control of Fish

The fish is to be controlled by a supervisory controller. The navigation will be performed by a human, and a computer will interpret the controls so that the fish can perform as expected. The computer will, after interpreting the controls of the person, send the appropriate signals to a radio transmitter. Inside the fish is a radio receiver,
which then sends the control signals to each servo.

4.1.2 Three Bending Segments

By using only three segments, the size of the fish could be kept down, while still using inexpensive actuators. This means that the shape of the fish while swimming cannot be made to resemble exactly the shape of a real fish. But the picture (see figure 2-6) of the bending splines suggest that we can obtain the shape closely.

4.1.3 Flexibility

The desired flexibility is very high, with external skin strain in the range of 50-100%. Components which in an inflexible body would be easy to package, are in danger of colliding with other components. Components must be mounted carefully to allow maximum flexibility.

The rigid components inside the robot needed to be able to move such that they:

- didn’t collide with each other
- didn’t push up against the flexible hull of the robot
- would not suffer from the repeated motions of swimming

In order that the components would not fall prey to the above problems, we decided to implement the following design aspects:

- Put large bulky components where the fish does not bend very much; in the forward part of the body.
- Place the rigid components to be away from the skin.
- All bearings and hinges are design for a million or more cycles.
4.1.4 Flooded Hull

Making a waterproof hull has advantages and disadvantages. The reasons for waterproofing the hull are:

1. The fish can be filled with air to provide a large amount of buoyancy, allowing the components to become heavier and stronger, and possibly cheaper.

2. Filling the robot with a nonconducting fluid, such as air or silicone oil, would allow the electrical components to remain unsealed. This would save space.

The reasons for not waterproofing the hull are:

1. Modern seals do not reseal themselves in a non-clean environment. So any opening of the robot would require conspicuous cleaning before resealing of the hull.

2. Any leak would destroy the electrical connections which are not sealed. However, sealing the components against the water removes one of the reasons for making a sealed hull.

3. A sealed flexible skin would be much more difficult to fabricate than a nonsealed flexible skin.

Because a flexible waterproof hull would be difficult to open and then reseal, and it would also be more difficult to manufacture, it was decided to use a flooded hull. This made it so that many components would have to become waterproof.

4.1.5 Waterproof Components

Each component not capable of operating in chlorinated water is waterproofed individually. While this takes more space, and a little more weight than the components do individually, this makes the system more durable. A single leak will not destroy all the components. However, because there are more seals, it is more likely that their will be a single leak. Because the system is meant to accommodate an array of sensors
Figure 4-1: Above is a drawing of the fish showing the various layers of the design. Specifically, it shows the skin and the spiral wound spring exoskeleton.

and actuators, some of which are very expensive, we opted to make each component sealed on its own with a reliable seal. This will make water proof connectors desirable in the design.

4.1.6 Spiral Wound Spring Skin Technology

The shape of the robot is given by a spiral wound spring underneath the flexible skin (see figure 4-1). This allows nearly the entire volume of the fish to be used for actuators, sensors, and linkages. This spiral wound spring is cast on a wooden mold, and then assembled to the fishes structure. This significantly simplified the design of the robot fish. The design and fabrication of this spring and skin was a significant undertaking unto itself [5].

4.1.7 Missing Ventral Fins

By watching the motions of fish, it was determined that the elimination of the ventral fins would not significantly reduce the performance of a robot fish whose desired
activities are turning and forward swimming. Fish primarily use these fins for hovering activities. With the ventral and pectoral fins they can move backwards, sideways and slowly forward. We will lose the ability to mimic these motions. But we are designing a robot fish, which can maneuver and turn, not hover. The elimination of the ventral fins allows the robot to stay smaller. Another reason for not attempting to implement the ventral fins is that it is unclear how many degrees of freedom would be needed to control these fins the same way a fish does. By comparing a submarine with a fish, one can see that the pectoral fins are like the hydrofoils on a submarine, and control the dive rate of the fish.

4.2 Material Selection

In a robot which must be strong enough to swim and turn, flexible enough to mimic a fish’s movements, and light enough to nearly float, material selection is very important. This design is filled with careful selection of materials so that the design objectives could be filled. Below is a description of the types of components, the material selected, and the reasoning behind the decision.

4.2.1 Rigid Structural Elements

For most structural elements, the choice of acetal plastic as a material is desired. Its low water absorption, its high tensile strength (8.8KSI), its low specific gravity (1.42)[4], and its corrosion resistant properties make it an excellent candidate for underwater structures.

4.2.2 Spiral Spring Exoskeleton

The spiral spring that forms the fish is made from Cast fiberglass, using West system epoxy. This allowed us to cast the exact shape of the spiral spring, and keep the component very light.

The spline that connects to the spiral spring exoskeleton is 1/16” delrin. The fish
needs to be able to bend a significant amount. Delrin, a resilient plastic works well in this application, having been tested in "Charlie" (see section 2.3.2).

4.2.3  Bearings

Near Mechanical Feedthroughs

The bearings near feedthroughs were chosen to be teflon bushings with a flange, for the ease of manufacture. This was an inexpensive method of putting a bearing, with both linear and rotary abilities right next to a feedthrough. See figure 4-12 for an assembly drawing of the feedthrough and bearing.

Flooded Bearings

Stainless steel ball bearings were chosen so as to minimize friction and maximize the life span of the structure. 1/8” ID, 1/4” OD bearings could support the relatively low loads that swimming would put on the structure. While stainless steel has a very high density, the very small amount of it in these tiny bearings can be offset by a small amount of buoyant material.

4.2.4  Transmission

Cables

- Inside Housing Teflon coated stainless steel cables provide the least friction, but plain stainless steel cables will suffice as well.

- On Pulleys 1/64” stainless steel aircraft cable is strong enough for our application, and it can go around pulleys with diameters as low as 5/16”. This allows easy cable routing.

Cable Housing

PEEK tubing is light and very strong and it has abrasion resistant qualities that make it desirable as a tubing material.
4.2.5 Fins

Caudal Fin and Pectoral Fins

A wooden laminate provides the form, with a surface of epoxy and fiberglass to give it strength. There is an acetal plate to give it a centerline and mounting plate.

Dorsal and Anal Fins

Made with stainless steel wire and Skin Flex(TM). Skin Flex(TM) is a castable rubber, which will allow these fins to bend during turning and swimming.

4.2.6 O-Rings

Buna-N orings are sufficient for sealing in the low pressures this fish will encounter.

4.3 Overall Final Design Description

4.3.1 Design Algorithm

The Final design was arrived at by an iterative process of conceptualizing the design, drawing it in the layout drawing (see final layout drawing in figure 4-2) and then detailing areas of the design. If a problem with the design was encountered, usually during the detailing of a subassembly or a component, then the assembly drawing was consulted to determine how to solve the problem. If the problem could easily be fixed (ie. making a part stronger, by making it thicker), then the assembly drawing was updated. If a problem required a more involved solution, then the assembly drawing was used as the working drawing, and the individual parts would later be modified.

The assemblies and individual parts done later in the design were more likely to be modified, because it was easier to modify a single part than multiple parts already detailed earlier in the design. By carefully selecting to detail the critical components first, a fairly straight forward design was produced.
Figure 4-2: The final layout drawing is shown. It shows the way in which the various components, over 400 individual parts, interrelate. Many of the parts are small regular components, but there are 75 separate fish only components. These components must all fit together and work together. In a design where there is a high degree of interaction among the components, it is critical to have a valid assembly drawing.
4.3.2 Overall design

The previous sections of this thesis have explained a good number of constraints which guide this design. It is beneficial to itemize them.

Constraints and Solutions

- The robot is flexible hulled.
  The spiral wound spring with a spline gives a good flexible hull.

- Weight must be located near the bottom.
  Batteries go on the bottom. Space is left near the top of the flexible hull to put flotation.

- Cross sections must be close to neutrally buoyant.
  All large acetal parts have holes drilled in them, which will be filled with expanding foam. This will lighten them up considerably. The servos, while bulky are light. The nose cone will be weighted with lead shot.

- We are using the bulky but cheap water proof servo technology.
  These servos will be used to drive the body and the pectoral fins. They are placed in the main body, where the fish does not flex much, and there is room for them.

- There must be a medium sized pressure hull to accommodate future sensors and computers.
  The nose cone of the robot will be rigid and dry. Power and signals will go, via feedthroughs, into this pressure hull.

- Must have a large storage of batteries.
  Two flexible changeable battery packs will be placed in the belly of the fish. They each have 1.5 Amp-hours of battery life.
• Robot is radio controlled at first.

The radio control receiver will be placed in the nose cone.

• Transmissions should be highly efficient.

Cable driven or direct linkage transmissions are used.

4.3.3 Description of Layout Drawing

The layout drawing is shown in figure 4-2. This drawing was the main documentation for the robot during its design. Since it was a computer drawing, all the sizes were recorded in the drawing. By consulting this drawing all the parts and their relevant dimensions could be found. In the drawing are the plan and profile drawings along with various critical cross sections. There are a few close-ups which show particularly interesting sections of the layout drawing.

In figure 4-3 is a cross sectional drawing of the robot near the nose cone of the fish. The drawing shows the location of the two pectoral fin servos, the mount for the tail fin servo, the mount for the main body linkage, and the power and signal feedthroughs for the nose cone.

At the other section of the body is the second bulkhead. Figure 4-4 shows the cross section of the body near the tail. The other connection for the main body servo, the cut-out for the pulley servo cables, and the mounts for the spiral spring.

Figure 4-5 shows a closeup of the profile of the fish. The fiberglass spring is shown wrapping its way down the fish. Near the bulkheads it terminates. The first two bulkheads are where the main body servo provides the moment source to bend the first section of the body. The tail section of the body is bent by the pulley servo and all the pulleys in the tail. The cable housing can be seen snaking its way from the dual acting servo to the tail.
Figure 4-3: Above is a cross section of the robot near the nose cone. The pectoral fins servos, the power and signal feedthroughs for the nose cone, the hinge mount for the tail fin servo, the mount for the main body servo linkage and the mounts for the spline are shown.

Figure 4-4: Above is a cross section of the robot near the tail filled with pulleys. The main body servo linkage mount, the spline mounts, the mount for the pulley servo, its pulley blocks, and the cut out for the cables are all shown.
Figure 4-5: The profile assembly of the robot is shown above. It shows how the parts interrelate in this view. The position of the three large servos is shown, along with how they are used to drive the robot.
4.4 Selection of Components

4.4.1 Transmission

Figure 4-6 shows a plan view of the pike, in which are the various transmissions.

Main Body Linkage

The main body servo is connected to a linkage running between its bulkheads. The linkage is connected to the bulkheads by means of ball bearing hinges. The tail pulleys also use ball bearings, but instead of a linkage they use cables to transmit the motion of their actuator (the pulley servo).

Tail Pulleys

The tail pulleys are shown in the plan view, but it is easier to see how they work by looking at figure 4-7. Each “free” pulley works by running off of relative motion between it and its corresponding “fixed” pulley, except for the first free pulley. The first free pulley is driven with cables by the pulley servo (see figure 4-9). The second free pulley is driven from the first fixed pulley, which is attached to the bulkhead. The second free pulley moves because rotation of the first tail link moves the axis of the second free pulley, but the cables prevent the second free pulley from rotating along with the first tail link. The cables, which are laced with one cross-over between the first fixed pulley and the second free pulley, rotate the second free pulley. The second free pulley is mounted to the second tail link and rotates with it. The motion of the second tail link then causes the motion of the third tail link; and so on. This motion is multiplied six times.

The kinematics of this pulley system are simple, even though the conceptualization is not. When the pulley servo actuates with an angle $\theta$, the tail links will each turn that amount; giving a total bending angle of $6\theta$. The torque of each segment is simply $1/6$ of the torque at the servo. Because this transmission is made with preloaded ball bearings and aircraft cable, its friction is very low. The friction in the caudal tail fin drive will not be as low because it uses a cable housing to transmit the power.
Figure 4-6: The plan view of the pike is shown. The various transmissions are labeled along with the actuators.
Figure 4-7: A closeup of the tail shows the tail links and how they operate.
**Caudal Tail Fin Cable Housing**

The cable housing can be seen in figure 4-6 snaking down the body of the fish. The cable housing is made with thin PEEK tubing. Inside the cable housing is 1/64” aircraft cable. The friction in this transmission can be kept down by lubricating the housing with water proof grease and also keeping the absolute curvature of the housing to a minimum. When routing the cable housing it will be desirable to keep it as straight as possible.

Each servo system was designed so that it would operate with the various transmissions as well as possible. Below are the descriptions of how the servos interact with the transmissions.

### 4.4.2 Design of Specific Servo Systems

Each servo system in this design was tailored for its specific purpose. This allowed the size of the robot to be much smaller than it would have been with only one servo system design.

**Main Body Servo**

The main servo, not having to flex the body very much, was implemented with a scotch yoke and linkage to the two main bulkheads of the fish. One side of the linkage, going to the tail bulkhead is attached to the servo shaft. The other side of the linkage, going to the nose bulkhead, is attached the the servo housing. The motion of the servo results in the linear movement of the servo shaft, and a change in the length of the linkage. This change in the length of the linkage results in a bend of the spline, which runs between the two main bulkheads. In section 3.2 the force and displacement required to bend a spline are given, and using those equations we determined that this servo can bend the body 30°.
Tail Servo

The tail servo is driving a section of the body which needs to bend a lot. The tail must be able to bend at least $90^\circ$. This requirement means that a direct linkage bending a spline is infeasible. A direct linkage is like a chord going from the actuation points on the ribs or bulkheads, through the servo. Since a linkage is a straight line, the linkage would have to go through the outside of the fish to bend the spline at such a steep angle. So a linkage cannot be used as this point in the fish.

The traits of this transmission are that power must be transmitted very well at this section, it must bend at least $90^\circ$, and there is some space. The transmission chosen was a sequence of pulley driven links. Because this section of the fish has both a high power transmission efficiency and a large degree of curvature, it is very complex. In figure 4-9 is an assembly drawing of this servo.

Tail Fin Servo

The caudal tail fin is the main source of propulsion in a fish. It provides thrust by having an angle of attack with the oncoming water. This pitch angle is very
Figure 4-9: The assembly drawing of the tail pulley servo.

important, and is controlled separately by its own servo. This means that, the tail fin servo controls a hinge which the caudal tail fin is attached to. Since it is impossible to fit our cheap submersible servos near the tail, we use a cable transmission to drive the tail fin. By converting the single scotch yoke servo system, used for the main body section, into a double scotch yoke, a pull-pull cable system can be driven. Since the forces on this system are low, and space is at a premium, a cable housing to transmit the cable tension was chosen. If the cable goes through very many turns, it loses efficiency in transmitting power.

**Pectoral Fin Servo**

The pectoral fins are controlled by miniature model airplane servos. These servos are mounted to a waterproof mitre box which redirects the axis of movement outside the hull of the fish. The fins are mounted on the output shaft of the servo.
Figure 4-10: The assembly drawing of the dual action tail fin servo. The dual action servo controls a pull-pull cable transmission, which drives the caudal tail fin.

Figure 4-11: The assembly drawing of the right pectoral fin servo system. It uses a mitre gear to redirect the axis of movement outside the hull of the fish.
Figure 4-12: The mechanical feedthroughs in this design utilize O-rings, a small amount of vacuum grease, and stainless steel ground shafting. The water and exterior of the housing only contacts the O-ring and clamp. This allows a low friction waterproof feedthrough.

4.4.3 Design of Mechanical Feedthroughs

Waterproof mechanical feedthroughs were designed into the servo housings utilizing O-rings. In figure 4-12 is a cross sectional drawing of the assembly of a feedthrough used in this design. Since the pressures the robot will encounter are low, a teflon bearing is used as one of the sides of the O-ring groove. The other side of the groove is an O-ring clamp. This clamp makes the manufacture of this system much easier.

4.4.4 Batteries

Nickel Metal Hydride batteries supply medium amounts of current (peak 9A), and provide large power densities (1.5Ah for AA sized) in a rechargeable package. They have a large self discharge rate (50mA), but for experimental runs in the tank this is fine.
4.5 Control System

The first control system will be that of a supervisory control system. A person navigates the robot, while a computer interprets the commands of the person. The computer sends the servo commands to a transmitter which sends the commands over a radio link.

The radio control system is one used by many hobbyists. The transmitter sends out a signal to the receiver which decodes the signal and sends a PWM signal to each servo. The PWM signal is at 30-40 Hz, and is of length 1000μsec - 2000μsec long. The length of the pulse determines the command position of the servo system. One can put this radio control system under control of a computer by opening up the transmitter and replacing the voltage signals which come out of the potentiometers and switches, with voltage signals coming from a digital to analog board in a computer.

A program runs on the computer which take its input from a person, and sends coordinated signals to the radio transmitter and hence the servo system. This program has two very important modes.

In normal swimming mode, it takes the desired speed of the fish and sends a traveling sinusoidal wave down the fish by running the servos on the fish out of phase at a frequency defined by the strouhal number constraint. If the servo is a scotch yoke servo, then it is not a linear transmission, so a lookup table should be used to translate the desired movement to the command given to the servo.

In a turning procedure, the program must send a traveling wave down the fish at the speed which the fish is moving. Since the computer does not know how fast the fish is actually moving, it takes the speed it is trying to swim at as the speed it actually is moving.

These algorithms are very simple, and they are expected to be improved upon in the future testing of the fish. Putting a computer on board the fish, where it can interact with sensors on the fish is highly recommended.
4.6 Assembly of components

4.6.1 Actuators

Below are the steps to assembling a waterproof servo.

1. Pastewax is applied to the servo housing bolts, which are then screwed into their threaded holes, this keeps the epoxy from filling the holes. Pastewax is also applied to prevent epoxy from leaking to the gasket face of the faceplate.

2. The servos are bolted and expoxied to their faceplates.

3. PTFE flanged bearings are inserted into the feedthrough holes in the servo housings.

4. A small amount of Black Locktite(TM), or other viscous cyano-acrylic glue is used to glue the O-ring clamps to the servo housing, being sure to apply the glue sparingly.

5. For the linear servos, a 2-56 smooth sided cap bolt is bolted to the servo arm.

6. For the pulley servo and the pectoral servos, the servo disk is bolted to a shaft coupling.

7. A non hardening gasket material is used to seal the boundary between the servo housing and the faceplate.

4.6.2 Electrical Wires

Electrical wires, since they are flexible, and most sealants are not, must be strain relieved and sealed.

4.6.3 Batteries

The batteries are waterproofed with tool dip. The wires are permanently bonded to the threaded feedthroughs with epoxy. More than two battery packs are made,
so that in case it is necessary, a change of batteries can be made. An RCA audio connector, or other radial symmetric connector is bonded to the center of the threaded feedthrough.
Chapter 5

Use and Testing of Robot

The robot pike requires proper care to have a long useful life without breaking down. Below are some guidelines to its operation along with some directions as to how to take care of it.

5.1 Care of Robot

5.1.1 Environment and Appropriate Operating Conditions

Because the robot is flooded with the liquid it swims in, it is important that any dyes or contaminants that are in the water will not harm the robot. The robot is designed for operating in fresh or chlorinated, but should operate in salt water, provided it is flushed liberally with fresh water after use. The robot is especially sensitive to abrasives in the water, as they will get into the flooded bearings and wear them down.

5.1.2 Lubrication required

There are many bearing surfaces in this design proper lubrication is necessary and it is described below.

- Stainless Steel Bearings
The stainless steel bearings are lubricated by the water.

- Scotch Yoke The scotch yoke mechanism inside the linear servo housings is lubricated with a heavy grease.

- O-ring Lubrication A small amount of vacuum grease is used to help the orings perform well in their job of sealing out the water. It also provides lubrication, so that the shaft slides easily in and out.

## 5.2 Use of Robot

The robot is not meant for harsh environments. Though it is free swimming, care must be taken to not break the components. This is especially true when the fish is out of the water. Stepping on or otherwise crushing the robot will break it significantly.

### 5.2.1 Piloting Fish through Water

Care should be taken not to ram the robot into walls. Repeated crashes will break the fiberglass nose cone.

### 5.2.2 Replacing Batteries

To replace the batteries the steps below should be taken:

1. Remove the fish from the water.
2. Drain and wipe the fish down so that it is dry on near the nose cone.
3. Remove the nose cone.
4. Unscrew the two connectors for the battery packs.
5. Replace the battery packs with freshly charged one.
6. Place nose cone back on fish.
5.3 Calibration Procedures

The servo system needs to be calibrated, so that proper control can be given to the fish. This should be done with the fish in the water fixed to a strut.
Chapter 6

Recommendations for Future Use and Testing

6.1 Changing the servos

By replacing the model airplane servos with more powerful motors, the robot can be made significantly more powerful. The motors used now are not meant for actuation, but rather control of control surfaces. However, they are very inexpensive and light. A replacement servo system should be selected with careful attention to any additional weight it might have.

6.2 Onboard Computer

Along with making the servos more powerful, one may want to put an onboard computer, for controlling the servos or collecting data. Collecting data would be very useful, and along with the proper sensors, would allow monitoring of power use so that performance of this craft could be compared to that of a propeller driven craft.

The nose cone will accommodate an Onset model 8 computer, which is fully capable of controlling servos and collecting data. This 32bit computer would be ideal as an onboard computer.
6.3 Addition of Radio Serial Transceiver

Currently the robot has only half duplex communication via the radio control system to the robot. It would be beneficial to have two way communication through the radio if there was an onboard computer. This would allow the status of the robot to be monitored without a cable.

6.4 Suggestions for future design of robot

A large number of modifications to the control system of this robot can be made so that it could become partially or fully autonomous.

6.4.1 Semi-Autonomous control

By the use of an external tracking system, either visual or acoustic, the position of the robot could be known. If the robot has access to this information, it could swim on its own.

6.4.2 Fully Autonomous control

If the goal is to make this robot fully autonomous in unmapped environments, it would need to respond to its immediate environment with information to allow it long term goals. By putting a GPS system on board, the long term goals could be established. And by equipping the fish with DSP based vision system, it could respond to its immediate environment. The DSP based vision system, already developed, but not yet miniaturized, could be based on the Cheap Vision Machine.
Appendix A

Fabrication Drawings for a Robot Pike

The fabrication drawings are shown in this appendix. Some drawings, due to their complexity are difficult to read. The Ocean Engineering Towing Tank at MIT houses the full size drawings.
Figure A-1: The 1/8" shafting for the robot pike
Figure A-2: The large feedthrough lets wires pass from the nose cone to the body of the robot. The control and power wires for the servos pass through this feedthrough.
Figure A-3: A part of the drive linkage for the main body servo.

Notes:
1. Make 1 piece
2. Drill and deburr all threaded holes
3. Questions? Call John at (617) 233-4346
4. Mat: Delrin
Figure A-4: A part of the drive linkage for the main body servo.

Notes:
1. Make 1 piece
2. Break and debur all sharp edges
3. Questions? Call John at (617) 562-4346
4. Mail: Dr. Henn

Dimensions:
- 4-40 UNC through
- Drill no. 43 x 0.020" lyf
- Counterbore 05/32 x 0.10"
- 2-56 UNC through
- 0.681
- 0.681
- 1.025
- 1.025
- 0.191 lyf.
- 0.191 lyf.
- 0.121
- 0.121
- 0.379
- 0.379
- 0.160
- 0.160
- 0.223
- 0.223
- 0.383
- 0.383
- 0.186
- 0.186
- 0.681
- 0.681
- 0.125
- 0.125
- 0.000
- 0.000

Date: Dec 27, 1996
Rev: A
Scale: 2:1
MIT TowneBank
M. Kramer
Figure A-5: A part of the drive linkage for the main body servo.

Notes:
1. Place all sharp edges round.
2. Break and deburr all sharp edges.
3. Questions? Call John at (617) 253-4348
4. Material: Delrin

**Figure Details:**
- Scale: 1:1
- Date: Dec 27, 1995
- J. M. Kumpt
- "Design Block linkage mount" for main servo linkage
- Tolerance Block: ±0.002 in
- Dimensions and annotations as shown in the diagram.

---

72
Figure A-6: A part of the drive linkage for the main body servo.
Figure A-7: A part of the drive linkage for the main body servo.
Figure A-8: Main body drive linkage mount

Notes:
1) Make 2 pieces
2) Break and deburr all sharp edges
3) Questions? Call John at (617)253-4348
4) mat: Delrin

Scale: 1/2
MIT Towtank

Date: Dec. 20, 1995
Rev: A

Tolerance Block mounting block and hinge
xx 40.000
xxx 10.000
First servo drive linkage
xx 48.5
J. M. Kumpf
Figure A-9: Pivot piece for duo servo

Notes:
1) Make 1 piece
2) Break all sharp edges
3) Call John at 857-7652 about 4 ft. 0.10" chain

J. M. Kumpf

MIT Towtank

Scale 1:1

Date: Dec 27, 1995
Rev A

Tolerance Block: duo servo pivot, tail drive
xx = 0.005
xxx = 0.015
Figure A-10: Hinge mount for duo servo housing

Notes:
1) Make 1 piece
2) break and debur all sharp edges
3) Questions? Call John at (617)253-4348
4) mat: Delrin

Scale: 2:1
MIT Towtank

Date: Dec 20, 1995
Rev: A

Tolerance Block mounting block for duo servo drive linkage
Notes:

1) Make chamfer 0.15" long, 45°.
2) Break and deburr all sharp edges.
3) Question: Call John at (617) 523-4346.
4) Mail: Einem

Teem to 0.125" x 0.96".

Reference:

- Spring loaded arm for pulley

Scale 2:1
MIL TOW TANK

Part:
xxxx 0.001
xxxx 0.005
xxxx 0.010
xxx 0.025
xx 0.06
xx 0.0125
M.T. Kumpf

Date: Dec. 13, 1995
Rev. A

Figure A-11: First half of spring loaded pulley servo arm
Figure A-12: Second half of spring loaded pulley servo arm

Notes:
1) 2 pieces
2) 30° bevel all sharp edges
3) Questions? Call John at (617)253-4346
4) Matt: Delrin
Figure A-13: First pulley block
Figure A-14: Second pulley block
Figure A-15: Sheave to route pulley servos cables

Note:
1) Make 4 pieces through all sharp edges.
2) Break and deburr all sharp edges.
4) Mat: Delrin
Figure A-16: Battery Power Feedthrough

Notes:

1. Make 2 pieces
2. Break and deburr all sharp edges
3. Questions call John at 617/256-4346
4. Walmart Delrin

Threaded retainer
1/8" Through 1/2"

0.849" OD
0.500" OD
0.494" OD
0.288" ID
0.150" ID
Figure A-17: Pectoral fin servo cover

Notes:
1) Make 2 pieces
2) Break and debur all sharp edges
3) Materials: Delrin
4) Cut and debur all sharp edges

Scale: 1:1

Date: Dec 28, 1995

J. M. Kumpf

MIT Tow Tank

Tolerance Block
cover

0.160

Max. radius .005
scratches

0.140

1.100

0.140

1.000

1.000

1.100

Department
Figure A-19: Pectoral fin servo housing, left side
Figure A-20: Pectoral fin servo housing, right side

Key:
- 4-40 UNC thread 1.00" thread form
- Material finish: average 20 grit
- Material edge: machine break and draft all sharp edges

Notes:
- Material finish: '0' finish on all radii
- Material edge: machine break and draft all sharp edges

Dimensions:
- 0.375" bore
- 0.25" clearance
- 0.040" wall thickness
- 0.125" thickness
- 0.0625" wall thickness

Date: Dec 28, 1985
Rev: A

W. Kumpf

Micro Box
Figure A-21: Pectoral fin servo servo-coupling

Counterbore ø5/16 x 0.040" Ream ø0.1260" through

4) Mail: Press (617)253-4346
3) Questions? Call John at edge
2) Break and debur all sharp
1) Make 2 pieces

Drill no. 41 through
4 Pieces
0.0675
0.0675
0.261
0.261
0.339
0.339
0.380
0.380
0.030
0.030
0.017
0.017
0.025
0.025
45° 0.06"
Chamfer
0.338
0.338
0.099
Figure A.23: Duo servo cable housing mount

Notes:
1) Make 1 piece
2) Break and deburr all sharp edges
3) Polish screws and join all
4) Weld: Debn
(617) 453-4448
Figure A-26: Duo servo scotch yoke slot and shaft clamp

Notes:
1) Make 2 pieces
2) Sharp edges or burr all
3) Break and deburr all
4) Drill hole #43 x 0.20" counterbore #85/32" x 0.090"
5) #0.055 chase slot
6) #0.050 chase slot

Dimensions:
- 0.550 taper
- 0.050 chamfer
- 0.450 diameter
- 0.300 diameter
- 0.220 diameter
- 0.080 diameter
- 0.047 diameter
- 0.271 diameter
- 0.260 diameter
- 0.221 diameter
- 0.078 diameter
- 0.147 diameter
- 0.147 diameter
- 0.068 diameter

Dimensions in inches.
Figure A-28: Pulley servo O-ring clamp

Notes:
1) Tolerance Block 0.373 - 0.245 = 0.128
2) Do not break edges
3) Questions call John at (617)253-4346
4) Matt: Delrin

Scale: 4:1
MIT Towner

Tolerance Block 0.373 - 0.245 = 0.128
pulley servo

J. M. Kumpf

Date: Dec 22, 1985
Rev: A

95
Figure A-29: Pulley servo faceplate

Notes:
1) make 1 piece
2) break and deburr all sharp edges
3) questions? Call John at (617)325-4346
4) Matt: Daum

Scale 1:1
MIT Towtank
xx
40.5
J. M. Kumpf

Tolerance Block
Pulley servo assembly
Face plate for pulley servo
xx
xxx
xxx
10.005

8-32 UNC thread through 6 holes

Dimensions in inches unless otherwise noted.
Figure A-30: Pulley servo drive pulley

Notes:
1) Make 1 piece
2) Break and debur all sharp edges
3) Questions? Call John at 617/253-4348
4) Matt: Delm
Figure A-32: Pulley servo servo-coupling

Notes:
1) Make 1 piece
2) Break and debur all sharp edges
3) Questions? Call John at 617-253-4248
4) Mat: Brass

Scale: 2:1

MIT: T. W. Tognolini

J. M. Kumpf

Date: Dec 22, 1995
Rev: A
Figure A-33: Single action servo housing
Figure A-35: Single action servo scotch yoke slot and clamp for shaft

Notes:
1) Make 1 piece
2) break and debur all sharp edges
3) call John at (617) 735-4646
4) Mat: Brass
Figure A-36: Single action servo shafting
Figure A-37: Collar bulkhead terminates nose cone
Figure A-41: Tail bulkhead terminates tail spring assembly

Notes:
1) Make 1 piece, edge break and deburr all sharp edges.
2) Questions? Call John at (67)253-4348.
3) Material: Delrin

Scale: 2:1

MIT Towing Tank

Tolerance Block tail bulkhead tail spring assembly

Date: Dec 28, 1995
Rev A

J. M. Kumpf
Figure A-42: Solid wooden laminate tail form gives shape for skin near tail fin

Instructions:
1) Cut out profile from basswood
2) Drill holes as marked
3) Glue together with hot-melt glue
   and make sure holes are clear of link
4) Glue Plexiglas into hole

---

Scale: 1/16th
Date: 26 Mar 1956
Figure A-43: Pike skin template
Figure A-44: T for main body spring assembly

Notes:
1) Make 21 pieces edges
2) Break and debur all sharp edges
3) Mail: Delrin questions? Call John
4) at (617)253-4348

Reference: Skin Asmbl
Scale: 2:1MT Towntank
Date: Oct. 12, 1995
M. Kumpl
Figure A-45: Bottom fore mount for main body spring assembly

Notes:
1. Make 2 pieces
2. Break and deburr all sharp edges
3. Questions call John at 617255-4346
4. Material: Delrin

Tolerance

Bottom fore spine

Scale: 1:6

MIL-TOWTANK

M. Kumper

Spine Assembly

Mount

Datum

 drone Comics text
Figure A-46: Bottom rear mount for main body spring assembly

Key to Features:

4) Material: Delrin
617/253-4346
1) Questions Call John
2) Break and Deburr all

Note:

b. counterbore 8/32 x 0.17
b. drill no. 16 x 0.18
4) Center drill UNC through

Features:

- 2 pieces
- 0.049
- 0.034
- 0.042
Figure A-47: Bottom fore mount for tail spring assembly

Notes:
1) Brake pieces brake and deburr all sharp edges.
2) 2 pieces brake and deburr all sharp edges.
3) 2 pieces brake and deburr all sharp edges.
4) Call John at (617) 253-4348
5) Questions? Call John at (617) 253-4348.

 JP: skin assembly
 J.T: mount
 M: Block
 K: tail bottom spline
 T: 4.05" 4.05" 4.05"

Date: Oct. 18, 1995
Rev. A
Figure A-48: T for tail spring assembly

4-40 UNC through
and drill No. 30 x 0.20-
Sawcut 1/16" x 0.25" deep

Notes:
1) Make 1 piece
2) Break all sharp edges
3) Questions? Call John at
4) mail: Delim

J. M. Kumpf
Figure A-49: Top fore mount for tail spring assembly

Notes:
1) make 1 piece
2) break and debur all sharp edges
3) Questions? Call John at 461-6565

Scale: 2:1
M. Kumpf
Date: Oct 18, 1996
Rev: A

Mark: 40G
Skin Assembly
Tail Top Spline Mount

116
Figure A-50: Small clamp holds tail spline to small T in tail spring assembly

Notes:
1) Make 24 pieces
2) Break and deburr all sharp edges
3) Questions? Call John at 617/253-4346

Material:
4 AWG 20 or 1/8" SS sheet

Reference:
MIT Towe Tank

Drawing:
Rev A
Figure A-53: Top rear mount for main body spring assembly

Notes:
2 pieces

Reference Block

Spline mount
top rear
Skin assembly
M. Kumpf
MIT Towtank

Date: Oct 16, 1995
Rev: A

Scale: 2:1
Figure A-54: Fin pulley, note hole for roll pin

Notes:
1) Not a piece
2) Break and debur all sharp edges
3) Questions? Call John at (617) 253-4348
4) Matt, Dehrn

Scale: 21
MIT Tow Tank
Date: Dec 8, 1995
Rev: A

Block:
Tail Fin pulley
Tail assembly
J. M. Kent
Figure A-55: Fixed pulley for tail assembly

Notes:
1) Make 6 pieces
2) Break and deburr all sharp edges
3) Questions? Call John at 917/436-4346
4) M. Darn

Dimensions:
- Ø0.500
- Ø0.531
- 0.016
- 0.314
- 0.330
Figure A-56: Typical free pulley for tail assembly

Notes:
1) Make 6 pieces
2) Break and deburr all sharp edges
3) Questions? Call John at (312) 543-4946
4) Matt: Delrin
counterbore #0.2495" x 0.086"
Figure A-57: First pulley, free pulley design with larger diameter

Notes:
1) Make 1 piece
2) Break and deburr all sharp edges
3) Questions? Call John at 313-229-0530
4) Matt Derin

Dimensions:
- Diam. 0.625" (dotted line)
- Diam. 0.2495" (reamed through)
- Diam. 0.3125" x 0.086"

Scale: 1" = 0.005"
Figure A-58: Left half of tail link

Notes:
1) Make 4 pieces
2) Bore and debur all
3) Questions? Call John
4) Matt: Delrin

45° chamfer 0.05"
0.385
0.068
0.385
0.288
0.435
0.078
0.278
0.032

ream to 0.126" through
countersink #1/32 x 0.032"

0.385
0.688
0.385
0.068

0.178
0.178
0.164
0.164
0.616
0.616
0.716
0.716

Scale: 1:51
Date: Dec. 6, 1996
Rev: A

MIT Towlkamp
Figure A-60: Clamp to hold onto caudal tail fin and drive shaft

Instructions:
1. Make parts A and B
2. Bolt them together with 3/16" shim between them
3. Ream out hole as shown in assembly

Notes:
1. Make all sharp edges
2. No. 43 drill through .086" thick scrap mail
3. Malt 301 stainless steel

Scale: 2:1
Date: Dec 8, 1995
J. M. Kumpf
Rev A
Figure A-61: Left half of fifth tail link

Note:

1) Make 1 piece
2) Break and deburr all sharp edges
3) Question mark call John
4) Mall: Delrin

Reference:

LH Linkage tail assembly
LH Block
LH LH Linkage

Dimensions:

- 0.370 x 0.36
- 0.616
- 0.154

45° 0.05° chamfer
Counterbore 87/32 x 0.015
Ream to 0.126" through

0.278
0.078
0.435

0.228
0.078
0.435

0.368
0.068
0.686

1.365

0.376
Figure A-62: Sixth tail link, holes for buoyancy

Notes:
1. Piece edges break and debur all sharp
2. Questions? Call John at 617-253-4346
3. Material: Delrin
4. Scale: 1:1.000
5. Date: Dec 8 1995
6. Rev: A
7. 6th link
8. Tail linkage assembly
Figure A-63: Tail linkage mount, goes to hip bulkhead

Notes:
1. Piece break and debur all sharp edges.
2. Questions? Call John at (617)253-4348
3. Matt: Derin

Drill no. 30 through counter-bore 9/64 x 0.115
Figure A-64: Right half of first tail link.

Notes:
1) Make 1 piece
2) Break and debur all
3) Questions?
   Call John at
   (617)352-5267
4) Note: Delrin

- Dimensions and notes for the tail linkage assembly, including countsunk holes 45° x 0.010" deep and 45° 46-degree chamfer.
Bibliography


THE THESIS PROCESSING SLIP

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