Underwater Metal Detection Using Video Image Processing Techniques to Determine Location

by

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Abstract

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A system has been designed to detect metal and record a diver’s survey path. A metal detector circuit was constructed and further development prepared it for underwater use. A digital video camera was used to record the view of the bottom synchronously with the collection of the metal detector output. Digital video recorded the path and was subsequently captured using Nero Vision Express 2.0.0.22. It was then broken into frames using ACDSee 6.0. Two programs were used for image processing: Drexel University’s program to mosaic the frames and Phil Torr’s program to find the optical flow. Images were correlated with the stored metal detector readings using elapsed time and graphed in Microsoft Excel to show the detection of metal and the visual image of the metal. Using the image processed frames and the metal detection readings the diver can then have a map with detailed features and location of the metal detected. This map can also be used by the diver to start a new survey where he/she left off. Details of the processes involved in developing this system are presented as well as the results from testing including mosaic pictures of the diver’s path, optical flow,
and stored metal detector readings along with the corresponding pictures of metal detected.

The testing involved placing a false bottom on a pool to video as the metal detector and camera surveyed. The images were then correlated with the metal detector readings and graphed. The individual frames from the video were mosaiced and their optical flow was shown. This gives a qualitative map with quantitative data to the diver.
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<th>Description</th>
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<tbody>
<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
</tr>
<tr>
<td>BFO</td>
<td>Beat Frequency Oscillator</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DVL</td>
<td>Doppler Velocity Log</td>
</tr>
<tr>
<td>GHT</td>
<td>Generalized Hough Transform</td>
</tr>
<tr>
<td>GIB</td>
<td>GPS Intelligent Buoy</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GLONASS</td>
<td>Global Navigation Satellite System</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanographic and Atmospheric Administration</td>
</tr>
<tr>
<td>PIC</td>
<td>Peripheral Interface Control</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
</tr>
<tr>
<td>ROV</td>
<td>Remotely Operated Vehicle</td>
</tr>
<tr>
<td>R/V</td>
<td>Research Vessel</td>
</tr>
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</table>
Seg.: Segment

VETIS: Vehicle Tracking and Information System
List of Symbols

™: Trademark
kHz: Kilo Hertz
MHz: Mega Hertz
cm: Centimeter
x: Horizontal Vector
y: Vertical Vector
t: Time Vector
dx: Horizontal Displacement Vector
dy: Vertical Displacement Vector
V: Voltage
O: Ohms
µ: Micro
p: Pico
kO: Kilo Ohm
": Inches
p: Pi
F: Frequency
L: Inductance
C: Capacitance
Chapter 1
Introduction

1.1 Marine Archaeology

Some claim marine archaeology began in 1687, the year the 200-ton ship *James and Mary*, captained by William Phips, recovered 25 tons of silver from a wrecked Spanish galleon on a coral reef 60 miles north of Hispaniola (Walker, 1987). Some would say that was "the richest trove of sunken treasure yet", and it sparked the rave for underwater treasure hunting that has continued on and off until the present (Walker, 1987). Whether it was Captain Phips’ find or not, soon after, stock companies were formed and salvage boats were commissioned to find treasure lying on the ocean floor. The odds back then of finding something, were as Daniel Defoe claimed, "a Hundred Thousand to One!" (Walker, 1987). Without any technology to help aid treasure hunters in their search, the ocean is pretty large and deep. Today the odds for treasure salvors to find treasure are a little better. Meticulous research into archives can yield the names and valuables of ships that have sunk. Advancements in underwater technology, such as metal detectors,
magnetometers, side scan sonar, sand blowers, dredging mechanisms and lift bags can aid in the location and recovery of lost treasure. Traditionally, the thrill of treasure hunting and marine archaeology has been reserved for those involved in costly operations, but the dawn of inexpensive underwater metal detectors has created a way for the average diver to experience the thrill of finding “treasure”, whatever it may be (Finnern, 1992). Back in the early 1990s Fisher Research Laboratory came out with two underwater metal detectors for the average diver, the Impulse and the 1280-X Aquanaut, both selling for about $900 (Underwater, 1994). Now the market for underwater metal detectors has grown, and they can be bought for a few hundred dollars. When it comes to anything old found on the ocean bottom, it is the gold and the treasure that get people’s attention. However, the history and the significance as to how our ancestors used to live and travel is what stay with us forever. “The priceless commodity realized in treasure diving is to momentarily touch the past” (Finnern, 1992). The visions of the past conjured by each finding far outweigh the intrinsic value received from each discovery (Finnern, 1992).

Scuba equipment was first introduced in 1943 and the scientific study of underwater archaeological sites began. This was followed by the first underwater archaeological investigations in the late 1950s (Søreide, 2002). Since then, marine archaeologists have developed the necessary techniques to excavate and explore underwater sites. However, given the depth limitations of scuba equipment, many
of the marine archaeological sites have been confined to shallow water, which is considered to be less than 50 meters. Large areas can be explored using magnetometers, sub-bottom profilers and sidescan sonar use. A magnetometer is a passive device that measures the intensity of the Earth’s magnetic field at two nearby points and takes the difference. A sub-bottom profiler projects a narrow sonar beam down into the seafloor, and a receiver records the reflected sound. A sidescan sonar uses acoustic signals to locate objects on the seafloor. Each has its advantages, disadvantages and special uses. It was not until the 1980s that Remotely Operated Vehicles (ROVs) found their way into common use by marine archaeologists, extending the realm they could investigate to well beyond 50 meters. Soon after the ROVs came cameras mounted on the vehicles with advanced software to allow the marine archaeologists to not only see the wreck but actually feel like they were there, with high definition cameras and advanced bottom profilers.

In 1997, a breakthrough was achieved in precision mapping techniques. Detailed quantitative maps were made of underwater archaeology sites producing dramatic images with spatial resolution on the order of centimeters (Mindell, 2002). Closed-loop control of ROVs allowed precise sonar surveys and stable comprehensive photographic coverage with a digital camera (Whitcomb et. al, 1998). Images became so novel, the archaeologists needed to be taught how to understand and interpret the images so they could be used as scientific data (Singh
et. al, 2000b). Engineers then modified the images to be more useful to the archaeologists by adding specific artifact identifications to the photo mosaic. These images have now become important elements in archaeological analysis and publication (Ballard et. al, 2000; McCann et. al, forthcoming). The advancement of such technology came from such expeditions like the _Jason_ deployment on a Roman shipwreck near the Skerki Bank in the Tyrrhenian Sea known as “Isis” (Ballard et. al, 2000; McCann, 1994). Images were recorded by the vessel _Jason_, and it was determined that better technology needed to be developed to use the images. In 1999, during the Ashkelon survey, the technology of a high frequency narrow-beam sub bottom profiler was tested. This technology has the potential to peer inside buried shipwrecks without touching them (Mindell and Bingham, 2001a). If this system were combined with precision navigation and control it could be used to map buried sites in three dimensions with no need for physical intervention (Mindell, 2002). Archaeologists sometimes dig trenches through sites to see what the site has to offer. This technology, in its early stages, could replace trenches with sound waves. This could also be used with magnetometers to determine the most interesting areas of a buried shipwreck and narrow the focus of an excavation (Mindell, 2002).

The demand of marine archaeologists for Autonomous Underwater Vehicles (AUVs) better suited to their needs has started a slow change in technology. Not many AUVs are designed for the slow methodical survey work
necessary for archaeology work. Most AUVs are designed to cover as much area as possible given their battery life. To better accommodate marine archaeologists, more AUVs will need to be designed with a survey mode. They could also be equipped with magnetic and chemical sensors to identify iron or chemical signatures of particles (Mindell, 2002).

1.2 Archaeology Project Phases

There are four main phases to an archaeological project. The first is a large area search. The second phase is target identification. The third phase is a localized survey and the fourth and final phase is excavation (Mindell, 2002). The inspiration for this research came from work done in Key West with the Mel Fisher Heritage Society and RPM Nautical Foundation while on an internship during the summers of 2003 and 2004. Both organizations have rights to do archaeology surveys on various marine sanctuaries around the Florida Keys to find lost historic shipwrecks. All four of the phases of an archaeological project are performed by these two organizations. The research conducted for this thesis focuses on the design of a system that could possibly improve the third and fourth phases of such a project.
1.2.1 Large Area Search

The RPM Nautical Foundation’s survey boat is the fifty foot boat, R/V Lakota. This boat is used to tow an array of three magnetometers in west to east and east to west lanes. The survey boat can be seen in Figure 1.1.

[Image: Picture of RPM Nautical Foundation Survey Boat, R/V Lakota.]

The work performed on the internship entailed conducting surveys of an area in search of the remains of a historical shipwreck called the *Henrietta Marie*.

The area being surveyed off the coast of Key West, FL is called New Ground Reef. New Ground Reef is situated between Key West, FL north of the
Marques Islands and east of the Dry Tortugas. Its approximate location can be seen in Figure 1.2 (Malcom, 2000).

Figure 1.2. Map of the general location of New Ground Reef with X marking the general location of the *Henrietta Marie*.

This reef lies between the Florida Straits and the Gulf of Mexico, both historically highly traveled areas, especially from the 1500s to the present. It is also near the Gulf Stream current, which many mariners referred to as the great “highway” of the sea and would use on their travels. After 1513, this eastward flowing stream was the preferred route from the Caribbean basin to Europe. It was also crossed by ships sailing from the eastern seaboard to the ports of the northern Gulf of Mexico (Malcom, 2000).
1.2.2 Target Identification

This area was chosen because of the possibility for the New Ground Reef area to contain artifacts from numerous shipwrecks and other marine activity. Based on its geography, its uncharted reef and its high tropical storm likelihood, the potential is very large to find something of historical significance along with the rest of the remains from the *Henrietta Marie*. The main goal of RPM Nautical Foundation and the Mel Fisher Maritime Heritage Society, in this area, is to locate the remains of the *Henrietta Marie* and inventory any other sites that may be found on this highly traveled, remote and uninvestigated reef. Currently, New Ground Reef is considered a marine sanctuary, therefore these two organizations are working with National Oceanographic and Atmospheric Administration (NOAA) to have permission to investigate this reef and to obtain permits for any archeological excavations (Malcom, 2000).

The *Henrietta Marie* is a slave ship that sank in the summer of 1700, approximately thirty-five miles west of Key West, FL on New Ground Reef. This was her second voyage as a slaver and she was heading home to London after selling about two hundred slaves in Jamaica, carrying sugar, cotton, wood and indigo. The *Henrietta Marie* is the oldest slave ship ever excavated and is one of only a few such ships in American waters (Steinburgh, 2002).
The wreck of the *Henrietta Marie* was discovered in 1972 by Treasure Salvors, Inc., a Key West treasure hunting organization run by Mel Fisher, conducting magnetometer surveys in the area with hopes of finding the remains of the 1622 galleon *Nuestra Sexora de Atocha*. So far, only one fourth of her remains have been found. She had eight cannons on board and only two have been found. A major part of her hull and associated ballast pile and rigging have yet to be discovered. There are also many galley wares, tools and hand weapons left to be found (Malcom, 2000). Her remains lie spread across New Ground Reef. RPM Nautical Foundation as well as the Mel Fisher Heritage Society have narrowed in on finding the rest of her remains in this large area.

### 1.2.3 Localized Survey and Excavation

In order to localize the survey, a system of magnetometer surveys is conducted over a search area. The results from these surveys are then printed out on large maps that show the areas of the greatest magnetic field variations, called “hits”. Dive teams are then sent out with metal detectors and handheld magnetometers to investigate the “hit”. Divers are dropped from the boat according to GPS coordinates marking the location of the hits. If the position of the drop is correct, the diver will be able to locate the source of the hit and determine if it is something historically significant. If it is significant then
excavation and recover can begin. However, if the position of the drop is off, the diver wastes a lot of time searching around trying to locate the hit. If this is the case, the loss of time is significant for the rest of the day’s dives, and there is also the possibility that the hit was missed.

The goal of this research was to build a simple underwater metal detector and to incorporate an underwater video system onto it to provide a photo log of where the diver went while using the metal detector. The metal detector circuit was built and then encased in a waterproof housing creating the search wand. A digital video camera was fit in an underwater housing and then attached to the search wand. For the diver to hold the wand and camera system while keeping it at a constant distance from the bottom, an armrest and distance maintaining extension were added. The entire system was then tested in a pool at its various stages of development to verify its integrity. A final test was performed to analyze the capabilities of the entire system and to synchronize the underwater video with the metal detector readings using elapsed time. The images and readings were then post-processed to develop a detailed underwater map that can be used to return to the site and locate the metal or to continue a survey where it was left off. The scope of this project includes testing the final instrument in a pool and assessing improvement for the system. Improvements can be done with future work and development of this system. The purpose of conducting this research was to provide an understanding of the concepts used in marine archaeology from the
simplest device used in the field in shallow water to the advanced concepts of image processing used in deep water. This project was selected to encompass the varying degrees of technology used in marine archaeology. Hands on experience leads to the design of new and innovative devices for marine archaeologists to help find the history of how people traveled and migrated around the world.
Chapter 2
Archaeology Procedures and Instrumentation

2.1 Field Procedures

To begin the field work of the archaeological process, RPM Nautical Foundation conducts magnetometer surveys of major areas are conducted using a system of three magnetometers towed behind a survey boat. The magnetometers are Geometrics model 880 cesium magnetometers. They are towed five meters apart and sample the magnetic field at a rate of 0.3 per second while traveling at a speed of three to six knots. A diagram of the set up of the survey boat can be seen in Figure 2.1 (Malcom, 2000).
The survey lanes are spaced at 15 meters, which is approximately 1/100th of a nautical mile. Accurate and consistent lanes are maintained through use of Trimble “Hydropro Navigator” software. The survey area ranges in depth from three to twenty meters and the gear is adjusted accordingly by each cable winch located onboard. In very shallow areas, specially designed floats were made to keep the magnetometers from colliding with the bottom. These floats add very little distortion to the data (Malcom, 2000). The collected magnetometer readings are recorded with Geometrics “MagLog Lite” software which is then merged with global positioning data. The consolidated data is then interpreted using Boss
International “Surfer 7.0” software which charts the data along with the global positioning data (Malcom, 2000).

It is processed by taking latitude and longitude coordinates as well as depth and magnetic field variation to plot, over the map of the area, a contour of the “hits” that are a major variation in the magnetic field of the earth possibly caused by something metallic. An example of the data that Surfer processed can be seen in Figure 2.2.

![Figure 2.2](http://www.rpmnautical.org)

**Figure 2.2.** Surfer 7.0 plot showing positive magnetic poles of metallic objects as darker spikes and negative poles as lighter spikes. From [http://www.rpmnautical.org](http://www.rpmnautical.org)

Once these “hits” are mapped out, a dive team goes out to check out the area. If it is a small hit, a small dive team goes out with underwater metal detectors and the coordinates of the hits. Once the boat is over the specific coordinates of a hit, a
buoy is dropped and the divers go down with the metal detectors to find the source of the “hit”. If the data from Surfer shows a large hit, a larger dive team with a more complex system goes to check out the hits. If the area of the hit is pretty large, the boat will usually drop three or four buoys around the outer parts of the hit so exploration can be done within the marked buoy interior. The divers then head down with metal detectors to see if he/she can find the source as seen in Figure 2.3.

![Diver using underwater metal detector to locate metallic objects.](image)

**Figure 2.3.** Diver using underwater metal detector to locate metallic objects.

If no immediate source of a large anomaly is obvious then the procedure gets more complicated. A diver with a handheld magnetometer then goes down to
see if he/she can find a major reading in a certain concentrated area. A Discovery
Underwater handheld magnetometer can be seen in Figure 2.4.

\textbf{Figure 2.4.} Diver inspecting handheld underwater magnetometer prior to dive.

If the diver thinks he/she has localized an area they then the perimeter of the area is
staked. The diver then makes a grid with lines and stakes to run a more specific
test. A gradiometer is brought in and mounted vertically in a moveable holder.
With a system of diver-to-boat communication and gradiometer-to-boat reading
outputs, the readings are taken along a grid and plotted in Surfer to show the
contours of magnitudes of variation from the Earth’s ambient magnetic field.
Once a more specific location of the source of the hit is determined, digging begins. The boat is rigged with a dredging system, seen in Figure 2.5, which suck up sand from the area being worked on and deposits it down current away from the site.

![Dredging equipment on deck](image)

**Figure 2.5.** Dredging equipment curled on deck on dive boat for storage. Dredging equipment is assembled to the back of the boat and is run by a dedicated engine.

This allows delicate and precise work to be done until the object is uncovered, as seen in Figure 2.6. If anything significant is found, the area is photographed and
grids made. Specific pictures are taken in each grid and any items are tagged and cataloged. With the proper permits, artifacts can be removed for conservation and study.

Figure 2.6. Marine archaeologist dredging out sand from an excavation site.

2.2 Problems with Procedures

The problem with this system of procedures is the time required and room for error involved in originally locating the site to find the source of the hit. Time is a major issue when working with divers. Divers can only handle a certain number of dives per day with adequate surface time for safety. Every second a boat
is out on the water, it is costing the owner or company money to run the boat as
well as to pay the divers and boat crew. Dive teams, small or large, make mistakes.
There is an error in time from when the captain of the boat says he/she is at the
proper GPS coordinate to when the person dropping the buoys releases them.
Further error results based on position of the buoy release relative to the position of
the GPS antenna. The following, Figure 2.7, shows how much off the original
search area can be from the intended target area. The depth of this water is
approximately 30 feet with very little current. Each buoy is about four inches in
diameter and the distance from the buoys to the diver bubbles is approximately
thirty feet on the surface.
Figure 2.7. Actual picture of preliminary search area as opposed to actual target location. There is no current, as can be seen from the buoy in placid water, and the depth is about thirty feet.

On the surface of the water, this may not seem like a great distance, but on the bottom, things get complicated. Depending on currents, visibility and depth of the dive, there is limited time for the diver to locate the source of the hit. RPM Nautical Foundation had rented an underwater navigation unit from RJE for the summer during this survey. The unit was called a Cobra-Tac™ and could be used to tell the divers where they were underwater relative to some pre-programmed GPS coordinate established while on the surface. This piece of equipment was
experimented with to see if it could help solve the delays in finding the actual site of the “hit”.

### 2.3 Instrumentation

It is the quest to find something of historical significance that has spurred the marine archaeology community into the technological era. Relying on equipment made mainly for the oil industries and for the fields of geology and marine biology, archaeologists have found, recorded and excavated numerous wrecks over the years (Mindell, 2002). The area covered by a magnetometer is relatively small compared to sonar. The magnetometer is good for detecting a buried site containing metal which the sidescan sonar can not see (Søreide, 2002). Sidescan sonar, while very useful, provides no way to actually see what might be interpreted as a wreck. New technology better suited for marine archaeology is still in the making. The best solutions now use an array of the existing systems to combine the capabilities of each device. Sub-bottom profiling systems can detect buried material, but the technology has poor coverage, is a large investment, and is difficult to interpret (Søreide, 2002).
2.3.1 Documentation and Imaging

In shallow water, divers carry out documentation and excavation processes. Divers use log books, photographs, measurements, written observations, drawings, etc. (Søreide, 1996). In deep water, an alternative solution is required since divers can not practically perform these tasks. Divers can be used in deep water with special diving techniques but with this comes large risk (Adams, 1996). Few excavation attempts have been made by salvage companies in deep water, (Flow, 1996; Noonan, 1992). In either case, deep water or shallow water, the underwater imaging assists in accurately and completely documenting an archaeological site. A photo mosaic can be created by flying an ROV over an archaeological site with a downward-looking camera and combine the images to produce a larger site plan (Ballard et. al, 2000). Images can also be obtained from laser line scan and acoustic cameras (Søreide, 2002).

Archaeological practice requires mapping the sites and recording the location and orientation of any artifacts as precisely as possible before any mechanical intervention, recovery or excavation can occur. Spatial relationships are the cornerstone of an archaeological investigation and interpretation (Muckelroy, 1978; Bass, 1966; Delgado, 1997). Therefore, the position of each artifact must be carefully documented prior to any disturbance of the site as well as throughout excavation (Mindell, 2002). Careful documentation can be produced
through the use of underwater imaging to monitor the excavation, producing mosaics at various stages.

2.3.2 Metal Sensing

Magnetometers and gradiometers both measure the magnetic field variations of the Earth. There are three main types of magnetometers: proton, alkaline-vapor and fluxgate. The proton magnetometer induces a magnetic field, which causes the protons within that field to align. Local field strength is related to the time required for the protons to return to their regular alignment once the induced magnetic field is turned off (Blot, 1996). The second type of magnetometer is an alkaline-vapor magnetometer, which is faster than the proton magnetometer. It works the same way only allows for more continuous collection of data. These are very expensive. The third type of magnetometer is the fluxgate magnetometer, which is the most commonly used (Blot, 1996). This magnetometer has a metal core wound with copper wire. This magnetometer does not measure the total field strength like the other two. Its readings consist of only the portion of the magnetic field aligned with the sensor. These are the least expensive, but also the most sensitive to temperature and movement errors.

Gradiometers consists of two sensors placed adjacent to one another. The magnetic gradient can be found by taking the difference between sensor readings.
If the instrument is flipped, this allows magnetic offsets to be eliminated. The sensor closer to the ground will show greater effects of being near something metallic (Blot, 1996). The basic component of either a magnetometer or a gradiometer is a metal detector. There are two kinds of metal detector circuits examined in this research, beat frequency oscillator and frequency meter detectors.

The beat frequency oscillator (BFO) metal detector is the most common type of metal detector. It works by comparing the frequencies of a reference oscillator and another oscillator that incorporates an inductive sensor in its tuned circuit. Then, if a ferrous or nonferrous metal comes near the sensor, the sensor’s inductance changes which then changes the frequency of the search oscillator. The two oscillators are brought together. The difference in frequency, or beat frequency, then appears as an output of the two oscillators (Chtchedrine, 2001). There is an issue of sensitivity of such metal detectors, because small frequency difference are difficult to detect.

A frequency meter metal detector was built for this research. This has the same simple design as the BFO metal detector but without the low sensitivity and inability to distinguish between ferrous and nonferrous metals (Chtchedrine, 2001). The improvement in the device comes from measuring the period of the oscillation directly, instead of measuring frequency. A metal detector that can tell the difference between ferrous and non-ferrous metal measures the inductance of the search coil. The frequency of an oscillator changes as the inductance of the coil
changes. This change in inductance is brought about by the changes in permeability of the materials within the vicinity of the search coil. Permeability refers to the ability of a material to conduct magnetic lines of force. The inductance of the coil can be tuned by increasing or decreasing the number of turns in the coil. The greater the number of turns in a coil, the greater the inductance.

The concept of detection of non-ferrous metals is based on the search coil inducing a current in the metal object, such that the eddy current opposes the field producing it. In a material such as ferrite, the field is concentrated and enhanced, therefore producing an opposite effect. The magnetic effect of the eddy current in the non-ferrous (low permeability) metal will depend on the total number of electrons moving around which is proportional to the conductivity of the material (Walker, 1993). Eddy currents can be seen in Figure 2.8 (Becker, 2004).
Eddy currents are closed loops of currents that exist only in metallic materials.

Their generation is described in Faraday’s Law. Faraday’s Law states any change in the magnetic environment of a coil of wire will cause a voltage to be "induced" in the coil.
Chapter 3  
Underwater Navigation

To save time and money while looking for a “hit” underwater, it would be ideal to have an underwater GPS on the diver so he/she would know exactly where to go based on pre-programmed coordinates. It seems like a simple enough solution but it is not possible to receive GPS underwater because electromagnetic waves cannot travel underwater. Underwater navigation for divers has evolved from the extensive work done for underwater vehicles. Navigation of underwater vehicles is a very demanding task, especially in confined environments. The risk of damage, expense of running the vehicle and even recovering the vehicles makes improving their navigation systems a priority (Evans, 1996). Many different systems have been designed to help vehicles navigate underwater. For example, VETIS, or vehicle tracking and information system, is a flexible and cost effective way of navigation. It uses a PC Windows based fleet management system which combines Differential Global Positioning System (DGPS) positioning along with a Geographical Information System (GIS) and allows two way communications between the underwater vehicle and the ship (Evans, 1996).
There are three basic types of underwater navigation systems: inertial, acoustic and optical. These systems can be combined to make a unique system. Some systems match high resolution local depth maps against large, low resolution local reference maps (Beckman, 2000). Other systems use onboard multi-beam sonar to map a region and then use that map to navigate an area (Beckman, 2000). There are also systems that generate position estimates based on a comparison of the measured depth at the AUV’s position to available bathymetry data in the immediate area (Beckman, 2000).

3.1 Inertial Navigation

An Inertial Navigation System (INS) integrates the measured acceleration twice to determine displacement. INS works with an inertial measurement unit, a magnetic compass and a depth sensor (Barbour, 1998). INS suffers from error growth resulting from noise in the acceleration measurement. Some solutions to correct error growth include surfacing to get GPS coordinates, incorporating terrain matching methods or installing an acoustic transponder system (Beckman, 2000). Inertial systems can also use acoustic or optical sensors for better accuracy (Branca, 1998). All the additions to make the system accurate extend the already expensive cost of the inertial system significantly.
3.2 Acoustic Navigation

Many current GPS systems involve surface buoys towed by the diver, which bring an antenna to the surface of an underwater GPS receiver. This system is called a “false underwater GPS”. There is error involved with this based on the position of the buoy location relative to that of the diver. The distance between the two should be small to avoid great error. This means the dive cannot be made very deep and/or have a lot of current. Any time a diver has anything running from him/her to the surface, the potential for snags introduces a safety issue (Bennamoun, 1996).

Another underwater system is called the US-AF Youngberg system. This system uses buoys in the same manner that satellites are used in a GPS system. The buoys receive satellite information through radio waves. This information is then replaced by acoustic waves that travel from the buoys to the underwater mobiles. The underwater mobiles work similar to a GPS receiver. They contain a stabilized clock that measures the time of arrivals of the acoustic pulses transmitted sequentially by the buoys. This system needs four buoys within its range to calculate the four unknowns; X, Y, Z and clock drift. A similar method is called GIB, or GPS Intelligent Buoy, technology, which uses upwards-acoustic flow of data. This system needs two buoys within range to calculate its unknowns, X and Y (Bennamoun, 1996).
3.2.1 Cobra-Tac™

Cobra-Tac™ is a diver mapping and navigation console. It can map bottom topography, mark and relocate way points, give accurate waypoint navigation, perform grid or ladder searches and download mission data. It was developed by RD Instruments over the course of many years. It is operated without the need for acoustic baselines or floating surface buoys. Cobra-Tac™ integrates data from a Doppler velocity log (DVL), a fluxgate compass and pressure transducer along with a navigation computer (RD, 2004). This is the system RPM Nautical Foundation experimented with over the 2003 summer.

The unit is very easy to use. All that is required of the diver is to enter a geodetic starting position. The screen then tells the operator his or her position relative to the starting point underwater. A picture of a diver using Cobra-Tac™ can be seen in Figure 3.1 (RD, 2004).
The unit automatically compensates for current drift. It can be used to create multiple mission profiles using pre-established geodetic position fixes and download profiles to the diver unit directly from a PC or notebook computer. Cobra-Tac™ can also conduct accurate hydrographic surveys or beach reconnaissance and download data to create a variety of maps and charts. It can mark locations with real time longitude and latitude positions and use downloadable mapping data to relocate marked underwater sites (RD, 2004).

The geodetic position data from GPS, Loran, Global Navigation Satellite System (GLONASS), etc. is loaded and used as a benchmark for the navigation computer. The DVL uses a four-transducer sound head to measure speed and direction over the seafloor. Doppler Sensors calculate the velocity relative to the
ocean floor or water column by transmitting high frequency sounds in a narrow beam and estimating the center frequency of the returned spectrum (Jorgensen, 1993). They can have various arrays of transducers and technology. The information from the DVL goes to the navigation computer, which calculates position, speed, heading and distance to the next programmed waypoint. The position provided by the Doppler Velocity Log is a true position with minimal errors from current or drift. The error rate in the system is less than three to five percent of the distance traveled. The unit’s Liquid Crystal Display (LCD) display provides heading, range, depth, time, drift factor, battery life and altitude (RD, 2004).

The difficulty with using this system is it is large and hard to handle underwater if the diver is trying to use other equipment as well. It is also very expensive. If a system, such as Cobra-Tac™, could be integrated with a metal detector or handheld magnetometer, the diver could then know the exact position of the hit prior to the dive. Then the boat could position the diver close to the site allowing the diver to go directly to the designated area to begin work without delay or confusion. This system could even be added to a small diver propulsion vehicle so the diver could be neutrally buoyant above the bottom and move quickly from one location to another to either get to the intended location or check out multiple hits in one dive.
3.3 Visual Navigation

Optical sensing in clear water offers high data transfer rates and better resolution than acoustic methods (Branca, 1998). Video sequence analysis for underwater navigation has already been used broadly for aircraft trajectory estimation and mobile guidance applications. Video mosaicing is a rapidly growing area of research and development with greatly varying data acquired by different means with different quality for different purposes. Mosaicing is a seamless combination of a sequence of overlapping frames into a single high resolution image. As with the majority of the underwater technology field, there is no universal technique for image processing of underwater video images (Rzhanov, 2000). There are two currently accepted techniques; feature extraction and image analysis in the frequency domain (Gracias, 2002). Motion estimation can be made based on correspondences between feature points of several selected areas in two successive images (Aguirre, 1990). Images of the seabed typically lack sharp pronounced features used for feature extraction so a Fourier-Mellin transform and co-registration of adjacent frames in a video sequence can be used (Davis, 1998; Reddy, 1996). Analysis of planar views rather than panoramic views is often adequate in underwater imaging. The video is typically collected by an AUV or a diver with a vertically-oriented downward-facing camera at a constant height over the seabed moving in a straight line.
Two dimensional translations between two raster images can be determined using the phase shift theorem (Kuglin, 1975). The procedure for this involves taking a Fourier Transform of each image. The inverse of the Fourier Transform is then applied to a composite transform consisting of the magnitude of the transform of one of the input images and of the phase difference of the transforms. The resulting image shows a sharp offset which is equal to the translation vector between original images (Rzhanov, 2000). A single peak occurring as a result of the Fourier-Mellin Transform is caused by the fact that the Fourier Transforms of two spatially translated images differ by a constant phase shift (Rzhanov, 2000). Information about three dimensional motion can be obtained from two dimensional motion from the projection on the image plane of the camera and three dimensional object movements (Branca, 1998).

Real-time three dimensional motion estimation of a submersible from video images of the seafloor involves maintaining a set trajectory or determining vehicle position relative to a reference point during short range navigation along the seafloor. A mosaic image must be constructed of the bottom scene within the videoed area by registering consecutive frames (Xu, 1997). The first step in this process involves matching the images of selected prominent scene features. In Philip Torr’s program, used in this thesis, this step is called detecting corners. The second step is the computation of the motion of image points from one frame to the next; this is called correlation matching. The last step involves determining the
correspondence between image regions in two consecutive frames, called optical flow (Xu, 1997).

There are various drawbacks to this approach such as the extensive computation involved. Also, many assumptions need to be made in order to permit the computation of a unique solution for either the optical flow or match techniques. The system can be sensitive to many errors from camera noise, spatial and gray level quantization and image deformation (Xu, 1997). Any imaging underwater suffers from a lack of prominent features in an area to allow for feature extracting and matching. There have been techniques proposed to get around this problem such as estimation of camera motion based directly on brightness in an image sequence (Xu, 1997). Underwater imaging is also restricted in poor visibility conditions (Rzhanov, 2000). Another drawback is found when trying to image a large area of the seabed, which is done by photographing many small areas in natural or artificial light. Errors result when trying to compare images with natural lighting to those with artificial lighting. The use of an artificial light source creates lighting artifacts which are features of each frame and not the real overall image. Lighting artifacts tend to be prominent features which cause error. This can be corrected by de-trending. This entails creating a false surface fitted to the height map to represent pixel values of the frame which are then subtracted from the image. A height map represents varying heights of the surface. Prior knowledge
about the nature of the light source may suggest the best shape of the surface (Rzhanov, 2000).

Even though there are drawbacks for using underwater mosaics for navigation, there are many advantages that extend beyond the underwater navigation field. Mosaicing is a quick, easy and cheap way to navigate underwater. It is not necessarily the best option for some applications but it has the least amount of error of all the systems. It can be used in both deep and shallow water. Archaeologists can use mosaics to monitor site progress. Cultural resource managers can use mosaics to make seasonal site maps. Maps of deltas can document environmental changes such as scour (Mindell, 2002). A high profile expedition by Odyssey off the coast of Georgia recently used image processing techniques to document the wreck of the Republic. She sank in a hurricane in 1865 in 1,700 feet of water carrying what was then valued as $400,000 in coins. The team used a new Sonardyne long baseline acoustic system for their vehicle since the location was so localized, enabling them to create geographically correct photo mosaics of the site at nearly real-time speed (Handwerk, 2003).
Chapter 4
Procedure

4.1 Metal Detector

A frequency meter metal detector was built for this project. It is initially powered with the sensor far away from any target so the initial search oscillator frequency can be taken. This value is stored in its memory. The instrument then measures the search oscillator in real time. The previously stored “base” frequency is then subtracted from each reading to determine the frequency change and the result is processed for readout. The metal detector can distinguish between ferrous and nonferrous metals by measuring the sign and magnitude of the frequency difference and its sign (Chctchedrine, 2001).

The search oscillator for the metal detector uses an National Semi-Conductor LM556 dual timer. The search coil consists of approximately 100 turns of 24-gage magnet wire wound with a 190 mm diameter. Originally the coil only had approximately 62 turns but this was increased to enhance the sensitivity of the coil. A series of colored LEDs illuminate based on the magnitude and frequency difference. The LEDs are controlled by a Microchip PIC16F877 microcontroller,
running at 20 MHz. A National Semi- Conducto LM 7805 voltage regulator adjusts the initial input of nine volts to five volts. A continuously lit red LED indicates that the power is on while a green LED indicates the PIC is working. The circuit can be programmed to operate a speaker that will have a corresponding tone for frequency change. The program for the Microchip PIC16F877P is located in Appendix A. The following Table 4.1 lists the components used to create the metal detector circuit.
Table 4.1. Table listing all the components used to build the circuit board for the metal detector.

<table>
<thead>
<tr>
<th>List of products for metal detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Microchip PIC16F877P</td>
</tr>
<tr>
<td>(1) 32.785 kHz crystal</td>
</tr>
<tr>
<td>(1) National Semi-Conductor LM556</td>
</tr>
<tr>
<td>dual timer</td>
</tr>
<tr>
<td>(1) Quartz crystal 20 MHz</td>
</tr>
<tr>
<td>(9) LEDs</td>
</tr>
<tr>
<td>(5) 0.1 µF capacitors</td>
</tr>
<tr>
<td>(4) 330 Ω resistors</td>
</tr>
<tr>
<td>(1) 470 Ω resistor</td>
</tr>
<tr>
<td>(1) 220 Ω resistor</td>
</tr>
<tr>
<td>(1) serial port</td>
</tr>
</tbody>
</table>

The schematic for the circuit as well as the board layout can be found in Appendix B. As mentioned before, this metal detector has the ability to distinguish between ferrous and non-ferrous metals. Ferrous metals are primarily cast irons, stainless steels and low alloy steels. Non-ferrous metals are split into two categories. The first are the common metals, which are aluminum, copper, zinc, lead and nickel. The second category (usually the category of most interest) is the precious metals,
which are gold, silver and platinum.

The metal detector has a row of LEDs that represent the different ranges of frequencies. Before a metal is detected, many of them are flashing showing the different frequency changes. There is an orange light in the middle, which represents zero change in frequency. Whenever metals are brought near the metal detector the frequency difference is at maximum or minimum which are represented by the two outer lights—one that is green for low and one that is red for high. When a target that is primarily ferrous is found, the sensor inductance decreases, causing the search oscillator frequency to increase, thereby lighting the red light at the end of a row of LEDs. When a primarily non-ferrous target is found, the conductivity causes the sensors inductance to rise and the search oscillator frequency to decrease thereby lighting the last green light on the row of LEDs (Chtchedrine, 2001). The inductance changes in the coil are based on the permeability of the metal and the distance to the metal. The metal detector logs different measurements to excess program memory of the PIC.

To allow measurements to be synchronized with underwater pictures a clock was added to the circuit as a time base. The clock is a Maxim DS1307 chip run by a 32.768 kHz crystal. The PIC program stores the time and the frequency variations. A serial port allows connection of the circuit to a computer to offload data. The port uses a Maxim MAX232 chip. This circuit relies heavily on the
PIC’s software. Any changes, improvements or additions need to be made to the PIC’s program. The PIC program can be seen in Appendix A.

4.2 Underwater Metal Detector

To make the metal detector function underwater, two Otter boxes were purchased from Watertight Storage Company. One case, with internal dimensions 7 7/8" x 3 13/16" x 1 1/2" was purchased to house the circuit for the metal detector. The other case, internal dimensions 7 7/8" x 3 13/16" x 3 5/8", was purchased to house the underwater digital video camera beneath the first Otter box. The circuit box is clear so the diver can see the different LEDs light up. This can occur because of the size or type of metal found and the distance away from it. The camera box is clear so the camera can video the bottom as the metal detector moves along. A ¾" waterproof tank plug was attached to a ¾" forty-five degree angle PVC elbow connector creating a watertight connection to the sensor coil. This can be seen in Figure 4.1 below.
Figure 4.1. Waterproof circuit box potted with a tank connector into a forty-five degree angle PVC ¾" elbow to a two-foot piece of ¾" diameter PVC pipe. This was then connected to a ¾" two-foot long section of PVC pipe, which then connected to another ¾" forty-five degree angle PVC elbow connector epoxied into the coil. They were attached to one another with pipe glue. All of this was done with strength and stability in mind for the search coil. This can be seen in Figure 4.2 below.
To keep the search coil water tight, an epoxy mold was made out of 2" slices of larger PVC pipe the inner diameter of the coil is 6 3/4” with the outer diameter 9”. The mold was sanded flat on the bottom to get as close to the tabletop surface as possible. Each part was then waxed with mold release and the coil was set in the mold supported a few millimeters above the table surface by zip ties. Next, 105 resin epoxy was mixed with 205 fast hardener and poured all around the search coil and the ¾" forty-five degree angle PVC elbow connector supported inside the mold. Once the epoxy hardened and cooled the coil was removed from the mold and sanded down. Any cracks were then patched and re-sanded. The forty-five degree elbow coming out of the epoxied coil was also filled in with resin to help waterproof and reduce strain where the coil connects to the wire that runs...
up the two-foot section of PVC pipe to the circuit box. This can be seen in Figure 4.3 below.

Figure 4.3. Epoxied search coil containing approximately 100 turns of magnet wire epoxied to a ¾” forty-five degree angle elbow.

By placing the search coil in epoxy, the coil sensitivity decreased drastically since the magnetic field now had to find its way through the thick wall of epoxy. To make the coil more sensitive the metal detector program was changed to lower the values the PIC used to distinguish the different changes of inductance in the coil. The circuit was also changed to increase the oscillator frequency by lowering the values of the capacitors leading to the search coil from the search oscillator. This was done using the frequency equation, 4.1, for the oscillator:
where $C$ is the series combination of $C_1$ and $C_2$ which are the two capacitors connecting to the search coil, and $L$ is the inductance of the coil. Decreasing the value of $C$ increases the value of $F$ and vice versa. The values of the new capacitors were kept in a range of 4:1 to 6:1 (Chchedrine, 2001).

A printed circuit board was designed from the schematic in Appendix B. The board layout can also be seen in Appendix B. Various CAM files had to be made to send to Advanced Circuits, who fabricated the board. The various components of the circuit were then soldered into the board. The completed circuit board was then placed into the designated Otter box where the battery pack and coil were connected to the board.

Hose clamps were used to temporarily hold everything together and be an adjustable way of assembling the system. The camera Otter box was hose clamped to the two-foot long PVC pipe connecting the circuit box to the search coil. This worked well. Since the box is only clear at the top, the camera must also be fixed at an angle so it can see through the top. Therefore, the camera box has to be at an angle so the camera can see straight down. The forty-five degree pipe mount allows the camera to see straight down at the appropriate area. The hose clamps make the camera box easy to take off for independent use of the metal detector.

The circuit box was hose clamped to the two-foot long piece of one inch
diameter PVC in two places to keep it secure. The PVC pipe was mounted flush to the forty-five degree angle elbow coming out of the circuit box for maximum strength. Attached to the one-inch diameter PVC arm is the armrest made from a piece of four-inch diameter pipe about six inches long. The operator places his/her arm through the arm rest and can grab hold of the one-inch PVC arm near the circuit box to hold the metal detector while operating. The underwater metal detector with the camera attached can be seen in the Figure 4.4 below.

![Figure 4.4. Assembled underwater metal detector including arm, arm rest, camera box, circuit box and epoxied search coil.](image)

In order to keep the camera the same distance away from the sea floor, two green lasers were to be mounted between the arm rest and the circuit box in a “T”
formation with the PVC arm. As long as the diver kept the two beams of each laser overlapping at the bottom the camera would be a constant distance away from the bottom. Since this device was to be tested in a pool, an alternative solution using less time and money was set up. In order to keep the camera the same distance away from the bottom, a one-inch pipe saddle was snapped onto the one-inch PVC arm. From there a PVC pole with a wheel on the end can be snapped on and off of the device to keep the distance constant. This is a simple and removable feature that will aid in the image processing aspect of this project. The removable extension to maintain distance can be seen in Figure 4.5.

Figure 4.5. Complete assembled underwater metal detector including removable extension to maintain constant distance from sea floor.
4.3 Underwater Testing

Several underwater experiments were performed in a pool using the metal detector equipped with the digital video camera in its underwater housing. Each experiment showed flaws in the system, that were corrected until the final experiment was successful. The experimental process begins by hooking the metal detector circuit up to a laptop running a HyperTerminal. The HyperTerminal is configured to use a serial port and cable to communicate at 9600 bits per second with no hardware flow control. This enables the data to be offloaded from the PIC and examined while the metal detector is running. Before the metal detector is powered, the coil must be held under water to establish the initial search coil frequency. This typically takes a few minutes. If the metal detector is not placed in its testing environment before power is applied, then the metal detector oscillator frequency range will be wrong. The metal detector itself will work, but there will be no indication to the diver as to whether or not something is metal.

After the coil is placed in water, the battery is plugged into the metal detector at the same time the video camera begins recording. Since the camera outputs elapsed time, the metal detector was programmed to do the same. The metal detector program is set up to respond to a few commands while hooked up in HyperTerminal. Once the metal detector and the camera begin recording data, the elapsed time scrolls down the HyperTerminal screen. When an initial “s” is typed
into the HyperTerminal, the PIC begins to store the data. The metal detector can then be disconnected from the computer and sent out to collect data. The circuit and camera are then enclosed in their watertight casings. The metal detector records frequency differences four times. The camera takes pictures at 29.7 frames per second.

It was discovered from earlier testing that weight needed to be added to the system in order to maintain the regimented distance from the bottom. Eight pounds of weight were added to keep the system neutrally buoyant. It was also discovered that features needed to be added to the bottom in order for the video images to be meaningful. Therefore a false improvised ocean bottom scene was placed on the bottom of the pool with various metal pieces scattered around to create pictures the image processing programs could use. It was also determined, from earlier testing, that ripples on the water’s surface produced shadows on the bottom if it was sunny out. Therefore, testing was performed while it was overcast outside. An area of the pool is scanned with the system and it is pulled out of the water and dried off. The metal detector circuit is then plugged back into the PC running HyperTerminal and the “Capture Text” option is selected from the transfer icon on the tool bar.

Another “s” command is typed into the HyperTerminal to stop it from collecting more data. Then the “o” command can be typed to offload the data from the circuit. The data is displayed with the metal detector reading first followed by the minute and second. Table 4.2 shows some sample data.
Table 4.2. Example of the data taken from the metal detector. ....................

Data Example from Metal Detector

<table>
<thead>
<tr>
<th>Raw Data</th>
<th>MD Reading</th>
<th>Adjusted Reading</th>
<th>Time (min)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 7 49</td>
<td>14</td>
<td>14</td>
<td>7</td>
<td>49</td>
</tr>
<tr>
<td>1 7 49</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>49</td>
</tr>
<tr>
<td>13 7 49</td>
<td>13</td>
<td>13</td>
<td>7</td>
<td>49</td>
</tr>
<tr>
<td>16382 7 49</td>
<td>16382</td>
<td>-2</td>
<td>7</td>
<td>49</td>
</tr>
<tr>
<td>15 7 50</td>
<td>15</td>
<td>15</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>12 7 50</td>
<td>12</td>
<td>12</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>13 7 50</td>
<td>13</td>
<td>13</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>4 7 50</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>50</td>
</tr>
</tbody>
</table>

The very large metal detector readings represent negative numbers, subtracting 16384 from these numbers results in the correct negative value. Once the data is offloaded from the PIC it can be parsed into the metal detector data and clock data, as shown above. The only column added to the above table is an adjusted time column that sets the logged data at the four measurements per second rate in a format suitable for graphing. It was also discovered from previous testing that the clock sometimes would not work or would output strange extra numbers into the data. It was determined that this was a power issue and that the clock was sometimes not receiving the required five-volts. This was permanently corrected by adding a removable three-volt lithium backup battery to the clock to keep time even if the main supply is disconnected.
Chapter 5
Image Processing

5.1 Concept Understanding

Image processing techniques were added to this project to document the diver’s path while using the metal detector. After an initial dive with an underwater video camera attached to the metal detector, the images are post-processed. The processing provides the diver with a map and directions as to where to go as well as where the metal is located based on the data recorded by the metal detector. This thesis relies on previous papers on the subject of image processing as well as previously written programs written by Drexel University programmers and Philip Torr.
5.1.1 Mosaicing Techniques

A mosaic is a set of images which have been combined into a single and larger fused image. Video mosaics of the ocean floor can be used for such applications as undersea exploration, visual mapping, navigation, underwater forensics and pipe line inspections. The camera is usually mounted on ROVs or AUVs and it looks down at the seabed. The position of the vehicle can be found by integrating the motions from one image to the next image (Garcia, 2000).

There are two kinds of underwater mosaicing techniques; feature-based methods and featureless methods. Feature-based methods pick out features from the images and compare them between image pairs. This is called correspondence. From there, the motion parameters can be estimated. Featureless methods use transforms for image registration by minimizing a sum of squares difference (Garcia, 2000).

The method of feature-based mosaicing is used in this thesis to show a diver’s motion while using the constructed underwater metal detector over a known bottom. The importance of mosaicing to this thesis is its usefulness in documenting a marine archaeology site as well as showing motion of a diver for navigation. Advances in image processing now generate large, integrated digital photo mosaics of a site using both automated techniques and manual point and click feature identification (Mindell, 2001b). Closed loop control, precision photo
mosaics and microbathymetry helped archaeologists to get to an archeological site even when the depths were too great (Mindell, 2001b).

5.1.2 Optical Flow Techniques

The method used in this thesis to determine trajectory was the optical flow method, however, there are other methods. A Generalized Hough Transform (GHT) can be used to estimate vehicle trajectory by determining translation associated with selected feature points in an image. Performances of GHT can be enhanced by using a Kalman Filter which predicts the feature point’s positions on the next image (Aquirre, 1990).

Optical flow is a useful tool for many tasks in computer vision. It has been used in motion-segmentation, time-to-contact and three-dimensional reconstruction. The optical flow of an image sequence involves a set of vector fields relating each image to the next. Each vector field represents the evident displacement of each pixel from image to image (Andrews, 2003). Assuming the pixels conserve their intensity as the images are processed the “brightness conservation equation”, 5.1, can be used:

\[
I(x,y,t) = I(x + dx, y + dy, t + dt) \tag{5.1}
\]
where I is equal to the image sequence. The terms $[dx, dy]$ are the displacement vector for the pixels at coordinate $[x, y]$ (Andrews, 2003). Variables $t$ and $dt$ are frame and temporal displacements of the image sequence (Andrews, 2003).

### 5.2 Dry Experiment

To aid in understanding the concepts involved in image processing, a “dry” video experiment was performed to help simulate processing. Three different video segments were taken of busy backgrounds; two were taken of a book shelf, and the third was taken of a shelf filled with games. The third video was used for concept understanding since it was the shortest and easiest to work with. After the video was recorded, the camera was plugged into the computer. Using a computer program called Irfanview, an online product, the video was broken up into its frames and saved as bitmap images. From there the images could be used in the following programs.
5.2.1 Mosaic – Drexel University Program

The Drexel University program is used to make mosaics of images. Consecutive frames of the video images were selected from all the frames from the video. A selected frame is opened in Microsoft Paint and saved as a jpeg image. Names of the selected frames were then put into the program. The program then displays the first image in Matlab figure format. The user then picks two points on the first image, which brings up the second image. The user then picks the corresponding same two points in the second image in the same order. The program then overlaps the two images using the points selected to create a mosaic.

To continue this process, adding more images successively to the original two images, the resulting first image mosaic is saved as a Matlab figure and then copied into Microsoft Paint where the tick marks left from the Matlab program are cropped out of the mosaic. The tick marks were turned off on the figure but residue ticks still existed. This is visually demonstrated in Figure 5.1. It can be seen how the “SC” in the top game called “Scene It?” can be seen in the first image and not in the second. The edge of the table can be seen in the second image but not in the first. In the mosaic image both the “SC” and the edge of the table can be seen, since the first and second images are overlapped.
Figure 5.1. Two successive images combined into one mosaic image.

The resulting image is then used again, with the next image in sequence, combined with the original mosaic. This results in a new three-image mosaic. This process is repeated to produce the path the camera followed. The result of this process can be seen in Figure 5.2.
5.2.2 Optical Flow - Philip Torr Program

Philip Torr’s program was chosen to show optical flow between two images. The two images should be sequential in time but do not necessarily immediately following one another (Torr, 2002). As long as the two images contain most of the same features, they can be correlated. The Torr Tool box is
opened in Matlab (Torr, 2002). It is not necessary to change the original images from their bitmap format since this program can read a variety of image formats. This program loads two selected images into the tool box and processes them. An example of this program is shown using the two images in Figure 5.3.

![1st Image](image1.png) ![2nd Image](image2.png)

**Figure 5.3.** Two sequential images used for Phil Torr’s Program.

There is about an inch of wall that can be seen in the upper left corner of the first image, which is absent in the second image. In the second image, the “e” in “Scene It?” and the “Q” in the “Sequence” game comes into view. These differences show a shift of the camera to the right from the first image to the second. The program then detects distinctive corners in both images, as seen in Figure 5.4.
Next the program performs a correlation matching sequence which entails connecting corners from each image to determine their displacement as seen in Figure 5.5.

Figure 5.4. Phil Torr’s program “detecting corners” process.

Figure 5.5. Correlation Matching
The resulting optical flow estimates where the corners moved from one image to the next as seen in Figure 5.6.

![Figure 5.6. Optical Flow between two images](image)

This image shows the flow between images by the direction of the lines from the dots. The image shows the flow of the camera is from left to right. This can then be matched back to the original two images to better emphasize the flow shown in Figure 5.7.
Figure 5.7. Emphasis of the Optical Flow between two images.
Chapter 6
Results

6.1 Waterproof Test

Prior to any electronics being added to the system the integrity of the housings was tested. Tissues were placed in the circuit box and the camera box. Each section was then placed underwater to check for leaks. Figure 6.1 shows the wand being tested for leaks.

Figure 6.1. Initial underwater test of search wand with circuit box to test integrity of box and coil.
The camera housing is rated for 100 feet of water. The circuit box has a gasket seal, at the connection to the sensor coil, so the greater the pressure on the box the tighter the seal will become making it ideal for the testing conditions. A potential weak link in the system is where the coil connects to the two-foot long PVC pipe running to the circuit box. All tests were successful. The whole system was tested again after complete assembly with the hose clamps. This was done to ensure the boxes could handle any additional stress imparted to them in tightening the hose clamps. Tests were again successful.
6.2 Underwater Systems Test

Data taken from HyperTerminal after testing was plotted in a Microsoft Excel spreadsheet and the corresponding frames where linked with the graphs where metal was detected. Due to the position of the camera in relation to the search coil, all the images were collected approximately 1-½ seconds after the recorded metal detector reading. This time can vary with the speed of the diver, however, in this test case the lag time remained fairly consistent. The pictures have been adjusted to show the metal actually being detected. Figure 6.2 shows the second segment of testing results. The major spikes in the graph can be linked with the following pictures that were taken 1½ seconds after the metal detector reading.
The second graph, Figure 6.3, shows the third and cleanest segment of data. The metal detector values hover right around zero until the coil passed over something metallic, which is where the spikes in the data occur. The first peak corresponds to a bolt. The original pictures had to be cropped to cut out the constant view of the edge of the camera box for processing purposes, so the bolt is hard to see in these images, but it is easily seen in the two sequential images. The strip of metal the coil went over responded for a few seconds as can be seen from the data.
Figure 6.3. Graph and corresponding images of third segment of testing
The third graph, Figure 6.4, corresponds to the fourth segment of the data collection. This graph isn’t as nice as the other two, however, it is still obvious where the metal was detected and the corresponding pictures show the metal the coil went over.

**Figure 6.4.** Graph and corresponding images of fourth segment of testing
There is a lot of room for error involved with each test. In order for the pictures to correspond with the metal detector readings the camera must pass over the same area as the coil. This requires strict concentration on the diver’s part to be aware of where the coil went so he/she can keep the camera on the same path. There could also be deviations in the coil’s readings due to bits of metal in the concrete of the pool. There is rebar in the reinforced concrete that makes the pool which could cause fluctuations.

6.3 Post Image Processing

The experiment recorded ten minutes of video, of which, approximately four minutes of underwater footage could be used for processing. Nero Vision Express 2.0.0.22 was used to capture the video from the camera. The quality of the pictures is a result of the software used and the processor capabilities. To extract the frame, the quality of the digital video was changed to VCD quality, which is a video CD MPEG-1 video quality, and then separated out into frames using the imaging software ACDSee 6.0. This software produced 5,303 frames to work with from the short video. The frames were made into jpeg images since the Drexel Program required jpeg images. Philip Torr’s program could use any format picture.
6.3.1 Mosaics using Drexel University Program

The images lost some of their sharpness with processing. Even though a false scene was set in place to help aid with imaging, the scene could have contained more sharp edges to use for mosaicing corner recognition. The false bottom scene is shown in Figure 6.5.

Figure 6.5. Picture of false bottom used on the bottom of the pool during testing.
The mosaics came out well but became fuzzier after adding so many images together. This is because of the jpeg format and the Drexel University program. Figure 6.7 shows a mosaic of the second segment of testing. This segment ran for 18 seconds and produced the largest mosaic. The entire underwater camera and metal detector system were rotated around an area of no metal and then proceeded off in a diagonal direction. The various metals can be seen in the mosaic and used to interpret where the metal is, however reference can be made back to Figure 6.3 to get a better understanding of metal location based on the metal detector readings. A clearer picture of the metal is also present in the original frames of the pictures before the constant camera box corner was cropped out. The metal can be seen prominently in the videos.

The mosaics do not appear as a seamless picture as they should be. The dry experiment also produced the same black voids in the picture. This could be due to a lack of information about a particular area, an error in the program due to an inadequate number of distinct figures, loss in detail with the jpeg compression, and possibly operator error in cropping the pictures. It can be seen from the mosaics where the diver went and what was found, which was the goal of this research. The first mosaic, Figure 6.6, is the second segment of testing.
The second mosaic comes from the third segment of testing and can be seen in Figure 6.7. This was the best run in terms of data and clarity of the mosaic, considering the length of the segment and the duration of 15 seconds. The metal
can vaguely be seen in the mosaic with a better representation of the metal location coming from the corresponding graph and metal images in Figure 6.3.

The final mosaic shows the fourth segment of testing in Figure 6.8. This was the shortest segment, with a duration of seven seconds. This reduced the number of frames involved in the mosaic creating a clearer and nicer mosaic since it was a smaller image and detail was not lost from processing. Hints of the metal can be seen in Figure 6.8, however, a better representation of the location of the metal can be seen in the corresponding graph and individual frames in Figure 6.4.
6.3.2 Optical Flow using Philip Torr’s Program

Distinctive turns and directions of segments in the mosaics were taken and optical flow was found using Philip Torr’s program. The flow is not very distinctive in the optical flow pictures due to the quality of the images used and the limitations of the program for pictures taken in the underwater environment which lack numerous distinctive features and corners of objects. In Figure 6.9, each optical flow segment is set next to its corresponding segment of the mosaic and arrows show the direction of flow.
Figure 6.9. Optical flow of second segment.

The optical flow of the third segment can be seen in Figure 6.10.
Figure 6.10. Optical flow of third segment.

Optical flow of the forth segment can be seen in Figure 6.11.
The purpose of this thesis was to be able to tell how and where the diver went while using the underwater metal detector. This has sufficiently been show through the results section. The optical flow results add quantitative results to the qualitative mosaic maps. The flow lines are hard to see because of the size restriction of this thesis and transferring the Matlab figures into paint to be able to place them on the mosaics.
Chapter 7
Conclusions

The experiments performed in this thesis were successful. The objective was to build an underwater metal detector and be able to tell where the diver went while using it. Various concepts were tied together in this thesis. A self-logging metal detector capable of going underwater was produced. Image processing techniques used in underwater navigation were explored. Along the way a lot of ideas were discovered that might improve this experimental process.

7.1 Future Work

The metal detector designed for this project can be improved in the future based on experience gained. A processor could be added to the circuit allowing real time processing of the data, eliminating post processing except to get a mosaic for the marine archaeologists to use to document progress. The battery life of this instrument is long compared to other systems, which would allow a diver, after his/her bottom time was up, to hand off the metal detector to another diver to
continue where he/she left off. This feature would need a display to show the diver where the previous diver has already been.

A pressure sensor could be added to the circuit to incorporate depth into the data. Also, the program for the circuit could be improved by writing the program in C instead of PicBasic Pro allowing measurement of the period of the search oscillator instead of the frequency. Programming in C would also mean changing the code around to better accommodate the clock more precisely correlate the pictures taken with the digital video camera to the search oscillator frequencies.

As mentioned before, the imaging software could be improved by finding programs better suited for the conditions and requirements of this experiment. The programs used were sufficient but could be improved with more experience. The quality of the video could also be improved when loading it onto the computer by using DVD instead of VCD quality. The false bottom could be made with more corners and distinct features for processing. The program types could be changed from feature recognition to featureless and more texture or contrast recognition. To eliminate the delay added to the pictures when correlating them with the metal detector readings, the camera could be mounted directly above the coil so there would be no error in where the camera films in relation to where the metal detector readings are taken. In this case a program would be needed to eliminate the coil from the video images so processing could still occur.
References


McCann, Anna, et. al. forthcoming. Roman Wrecks at Skerki Bank. *Journal of Roman Archaeology*.


Appendix A

Metal Detector Program
written in PICBasicPro
' Aubrey Kozak Metal Detector
DEFINE OSC 20

'Set serial communication parameters
'Enable receiver
DEFINE HSER_RCSTA 90h
'Enable transmitter
DEFINE HSER_TXSTA 20h
'Set baud rate to 9600
DEFINE HSER_BAUD 9600
'Automatically clear over-run errors
DEFINE HSER_CLROERR 1

'Slow speed I2C bus for real-time clock communication (100 kHz, DS1307)
DEFINE I2C_SLOW 1

'*****Variable Declarations

'Oscillating variables
w1 VAR WORD
w2 VAR WORD
insig VAR WORD

'Time variables
cont VAR BYTE 'I2C control byte for real-time clock (bottom bit must be low in PBP, for R/W)
addr VAR BYTE 'real time clock variables
ds_sec VAR BYTE
ds_min VAR BYTE
ds_hr VAR BYTE
ds_day VAR BYTE
ds_dat VAR BYTE
ds_mon VAR BYTE
ds_yr VAR BYTE
ds_cont VAR BYTE
e_sec VAR BYTE
e_min VAR BYTE
sects VAR BYTE
mins VAR BYTE
hour VAR BYTE
wkdy VAR BYTE
mndy VAR BYTE
mnth VAR BYTE
year VAR BYTE
InChar VAR BYTE              'serial com buffer (for DFetc.)

DFIdx VAR WORD
DFStartAddress VAR WORD
DFEndAddress VAR WORD
DFStore VAR BYTE
Time VAR WORD                 'alternates min, sec data

i VAR WORD                    'loop index

'Delay to see Metal Detector is working
PAUSE 1000

HIGH PORTB.0

PAUSE 1000

LOW PORTB.0

'*****Main Program
'default initial time
secs = 33
mins = 33
hour = 9
wkdy = 3
mndy = 9
mnth = 7
year = 3

'enable & set real-time clock
addr = 0
ds_sec = 0'((secs / 10) << 4) | (secs // 10)  'enable oscillator,
  set seconds
ds_min = 0'((mins / 10) << 4) | (mins // 10)  'minutes
ds_hr = 0'((hour / 10) << 4) | (hour // 10)  'hours (24 hr clock)
ds_day = wkdy
'day of the week
ds_dat = 0'((mndy / 10) << 4) | (mndy // 10)  'date
ds_mon = 0'((mnth / 10) << 4) | (mnth // 10)  'month
ds_yr = 0'((year / 10) << 4) | (year // 10)  'year - last two
digits only
ds_cont= %00010000
'1second sq wave on pin 7 (open drain)

cont = %11010000
I2CWRITE PORTC.4, PORTC.3, cont, addr, [ds_sec, ds_min, ds_hr,
  ds_day, ds_dat,
  ds_mon, _
  ds_yr, ds_cont]

'Initialize data file address & index
DFStartAddress = 2096
(in dec. 2096)
DFEndAddress  = 6553
(in dec. 6553)
DFIdx = 0
'data file
DFStore = 0
'Sampling is initially turned off

'Metal Detector
COUNT PORTD.7,28,w1

'******Main Program Loop
WHILE (1)  
PAUSE 100  
'Infinite Loop
'cut sampling time down to 4 samples per second
'Metal Detector Loop
COUNT PORTD.7,28,w2

HIGH PORTB.0
HIGH PORTB.1
HIGH PORTB.2
HIGH PORTB.3
HIGH PORTB.4
HIGH PORTB.5
HIGH PORTB.6
HIGH PORTB.7

if w2 > w1 then
    if (w2 - w1) > 15 then LOW PORTB.7
    if ((w2 - w1) > 5) AND ((w2 - w1) <= 10) then LOW PORTB.6
    if (w2 - w1) <= 5 then LOW PORTB.5
endif

if w1 > w2 then
    if (w1 - w2) <= 5 then LOW PORTB.3
    if ((w1 - w2) > 5) AND ((w1 - w2) <= 10) then LOW PORTB.2
    if (w1 - w2) > 15 then LOW PORTB.1
endif

'HSEROUT [(w1-w2)+48]
HSEROUT [13]  'carriage
HSEROUT [10]

if (w2 = w1) then LOW PORTB.4
LOW PORTB.0

'Time Loop
if (DFEndAddress <= (DFStartAddress + DFIdx)) then
DFStore = 0                         'turn off sampling if data file is full
endif

DFStore = DFStore + 1

insig = abs(w2 - w1)        'insig equals absolute value of (w2 - w1)

'Start by checking for keyboard input- jump to NO INPUT if needed

HSERIN 100, NO_INPUT, [STR InChar\1]         'Get character from serial port
HSEROUT [InChar]
'Echo character back to terminal

if (InChar = "c") then DFIdx = 0                 'clears
if (InChar = "s") & (DFEndAddress > (DFStartAddress + DFIdx)) then DFStore =
DFStore ^ 1        'stores(exclusive or)
if (InChar = "o") then
    HSEROUT ["reading start"]
    for i = 0 to DFIdx STEP 2
        READCODE (DFStartAddress + i), insig
        HSEROUT [DEC insig]
        HSEROUT [" "]
        READCODE (DFStartAddress + i+1), Time
        HSEROUT [DEC (Time>>8)]
        HSEROUT [" "]
        HSEROUT [DEC (Time & 255)]
        HSEROUT [13]
    'carriage
    HSEROUT [10]
next i
end if
end if

NO_INPUT:

cont = %11010001
addr = 0
I2CRead PORTC.4, PORTC.3, cont, addr, [ds_sec, ds_min]

e_sec = ((ds_sec & 240)>>4)*10 + (ds_sec & 15)          'set in binary time
e_min = ((ds_min & 240)>>4)*10 + (ds_min & 15)

Time = (e_min << 8) + (e_sec)
'shift

HSEROUT [DEC e_min]
HSEROUT [" "]
HSEROUT [DEC e_sec]

if DFStore then
  WRITECODE (DFStartAddress + DFIDX), ((w2 - w1))
  WRITECODE (DFStartAddress + DFIDX), ((w2 > w1) OR (w1 > w2))
  WRITECODE (DFStartAddress + DFIDX), (w2 > w1)
  DFIdx = DFIdx + 1
  WRITECODE (DFStartAddress + DFIDX), Time
  DFIdx = DFIdx + 1
endif

WEND
Appendix B

Metal Detector Circuit
Schematic and Board Layout
Key for schematic:

<table>
<thead>
<tr>
<th>List of products for metal detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Microchip PIC16F877P</td>
</tr>
<tr>
<td>(1) 32.785 kHz crystal</td>
</tr>
<tr>
<td>(1) National Semi-Conductor LM556</td>
</tr>
<tr>
<td>dual timer</td>
</tr>
<tr>
<td>(1) Quartz crystal 20 MHz</td>
</tr>
<tr>
<td>(9) LEDS</td>
</tr>
<tr>
<td>(5) 0.1 µF capacitors</td>
</tr>
<tr>
<td>(4) 330 O resistors</td>
</tr>
<tr>
<td>(1) 470 O resistor</td>
</tr>
<tr>
<td>(1) 220 O resistor</td>
</tr>
<tr>
<td>(1) serial port</td>
</tr>
</tbody>
</table>