University of Michigan
Mechanical Engineering Capstone Design
ME 450 WN 2024

Field Localization Strategies for Diamondback Terrapins

Final Report

Jack Evans
Mobin Mazloomian
Zane Seal
Yichen Wang

Project Sponsor:
Dr. Margaret Lamont, Research Biologist
United States Geological Survey

Section Instructor:
Dr. K. Alex Shorter, Associate Professor
University of Michigan

EXECUTIVE SUMMARY

Climate change, coastal development, and declining water quality are putting saltwater marshes at risk. Diamondback Terrapins–a small coastal turtle species–are vital to these ecosystems, controlling potentially harmful snail populations and serving as an indicator species. In St. Joseph Bay, Florida, USGS researchers plan to use movement data to better understand the behavior and ecological role of Diamondback Terrapins. This data will in turn help track the changing health of saltwater marshes to inform conservation efforts along the entire east coast of the United States. However, traditional approaches to marine wildlife localization are optimized for larger animals, so they aren't suited to gather this data. This project explored alternative localization techniques to gain improved knowledge of Diamondback Terrapin movement patterns.

Through background research of multiple forms (reading publications, interviewing stakeholders, and studying off-the-shelf solutions), our team developed a comprehensive list of specifications that quantify the performance of a successful solution. For this semester, the scope of the project was limited to selecting and testing technologies, so only localization-based specifications were retained. These specifications include achieving (1) position uncertainty < 1 [m], (2c) linear range > 61.5 [km], (3) battery life > 90 [days], and (4) 95 [%] transmission reliability. Because benchmarking of off-the-shelf solutions and localization technologies indicated that no individual existing device meets these specifications, the team followed a structured ideation and concept selection process to develop a novel approach.

Decomposing the design problem into localization and data transmission, the team opted to combine GPS (satellite tracking) with GSM (cellular networks, SMS messaging). With GPS collecting position data intermittently while the device is surfaced, data is stored locally until the Diamondback Terrapin returns to a coastal saltwater marsh (within the ≈35 [km] GSM range) to transmit data to researchers. This solution capitalizes on the global range and high accuracy of GPS alongside the simplicity of GSM to localize and transmit without ground stations. A prototype was constructed with GPS and GSM breakout boards, a GSM antenna, an Arduino Nano, and six AA batteries, with a total cost of $319.26. With some specifications (2a, 2b, 2c) met by design, verification testing was conducted to calculate a GPS accuracy of ±8.17 [m] (not meeting specification 1), and a GSM transmission success rate of 100 [%] *with coverage (meeting specification 4). Validation testing was completed to yield a positive qualitative analysis of the device and its feasibility for future use. A normal-operation lifetime expectancy was calculated as 80 [hrs] with a sampling rate of 0.2 [Hz].

Although this solution outperforms many off-the-shelf options it does have notable shortcomings. First, if it's determined that the measured 8.57 [m] position uncertainty is unacceptable, future iterations will need to explore higher-cost and more complex localization solutions such as GPS RTK. Second, with a size much larger than the allotted 40 [g], the current design must be translated to a PCB (estimated mass of 19.960 [g] without battery) before it can be implemented. Despite these challenges, the GPS/GSM hybrid system demonstrates great potential for applications to Diamondback Terrapin field localization with some future work necessary by those experienced with electrical engineering and embedded systems.

ABSTRACT

Diamondback Terrapins serve as an indicator species for the at-risk saltwater marsh habitats that line the coast of St. Joseph Bay in Northern Florida. As such, movement data will assist researchers to better understand the behavior and ecological role they play, as well as track the changing health of saltwater marshes to inform conservation efforts. Because traditional approaches to marine wildlife localization are optimized for larger animals, they aren't suited to gather this data. This project will explore alternative localization and data transmission techniques, primarily including GPS and GSM, to gain improved knowledge of Diamondback Terrapin movement patterns.

TABLE OF CONTENTS

INTRODUCTION

Project Overview

Saltwater marshes are an important estuary habitat lining the east coast of the United States. They act as storm buffers, stabilizers to shorelines, and crucially, as marine nurseries [1]. Further, many marine ocean species begin their life cycle in salt marshes due to their regular influx of nutrients with changing tides. In the state of Florida, 70% of commercial and recreational sea life begin their lives in the salt marsh, making these habitats extremely important for fishing industries [2]. In recent years, increasing coastal urban development, declining water quality, and impacts from climate change (coastal erosion, sea level rise, storm extremification) have put saltwater marshes into decline.

Diamondback Terrapins are a small species of turtle native to these saltwater marshes and wetlands along the east coast of the United States [2]. They are an indicator species for the health of the salt marshes and also play an important role in controlling grass-eating snail populations [3]. However, some agencies including the IUCN (International Union for Conservation of Nature) are unaware that Diamondback Terrapins even live in these regions [3], suggesting a significant gap in knowledge about the role and presence of this key indicator species. In order to better conserve saltwater marshes, researchers and ecologists need to gain a better understanding of how Diamondback Terrapins use these essential habitats.

This challenge was presented to the ME 450 team by our sponsor: USGS researcher Dr. Margaret Lamont. Her past research tracked movement patterns of 10 Diamondback Terrapins in Saint Joseph Bay, a large 260 km^2 estuary along the Gulf of Mexico for up to 5 months. Previously, she used Argos' penguin trackers which were unable to provide accuracies below 500 m [3]. This was nowhere near accurate enough for researching the narrow shorelines which make up the saltwater marshes, as seen in **Figure 1**. Another previous tracker used acoustic devices that required many expensive water stations and only detected underwater locations.

For her upcoming research, Dr. Lamont would like to tag and localize a similar number of specimens in the Bay for at least 3 months [3] with improved accuracy. Crucially, our solution needed two complementary subsystems to provide location data to researchers: localization and communication. Without the ability to transmit location data off of the device, it wouldn't be possible to find the turtles and retrieve any stored information. This semester, our project consisted of determining an effective localization strategy to meet our sponsor's research needs. Key constraints included: range greater than the size of St Joseph Bay, high accuracy, sufficient operation duration, cost associated with trackers and ground/water stations, and the ability to transmit data.

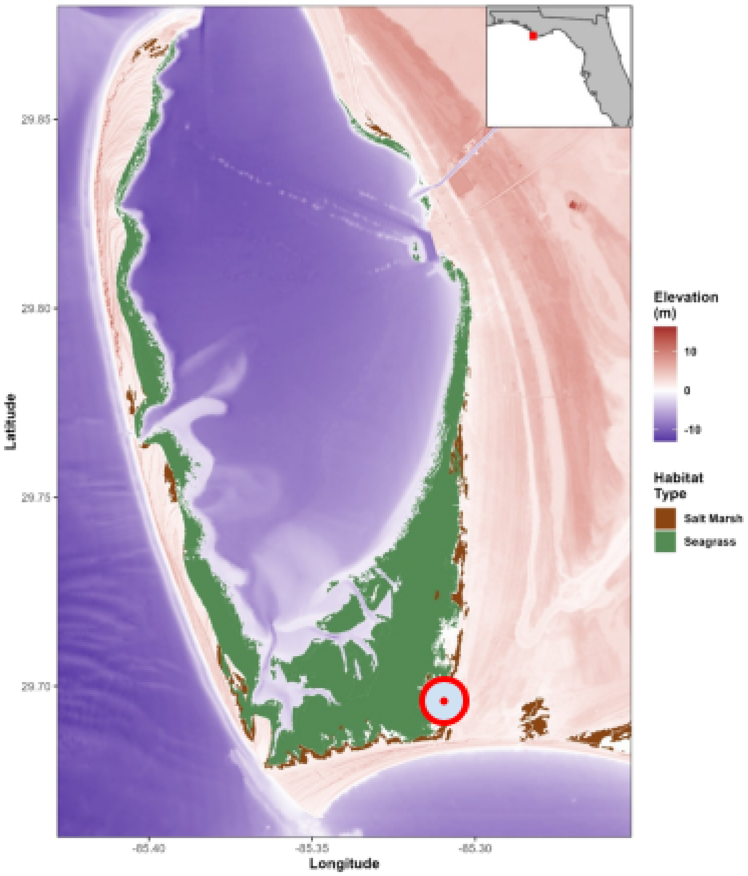


Figure 1. Saint Joseph Bay's saltwater marsh and seagrass habitats. Red circle displays a radius of 500 m: the accuracy of Argos tracking.

Localization refers to determining the position of objects in space. For the purposes of tracking animals outdoors, there are a multitude of solutions that share a few common technologies. Most rely on radiofrequency trilateration or triangulation, including GPS, Argos, and Iridium based systems, where radio signals are used to locate the position of a receiver or transmitter. This is visualized in **Figure 2** below.

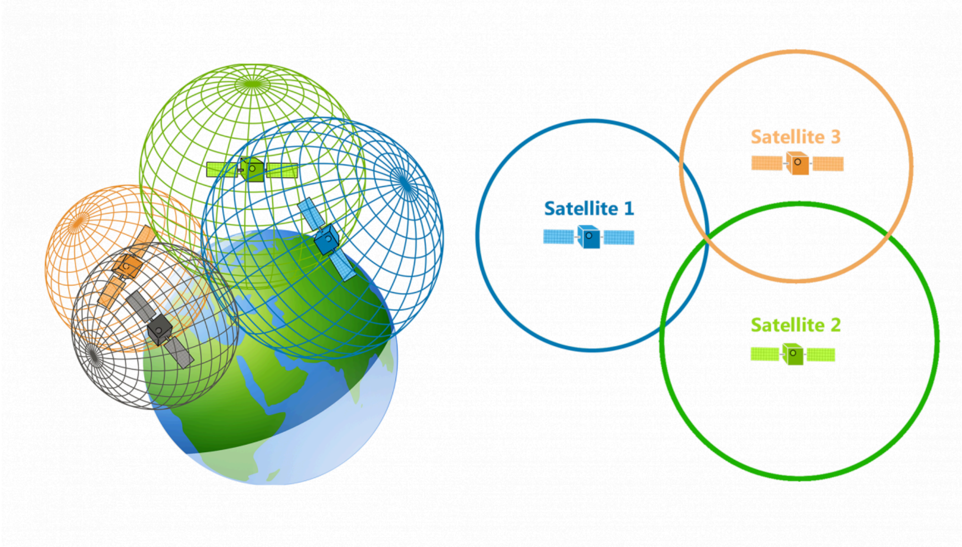


Figure 2. GPS localization visualized. By knowing the distance from multiple GPS satellites, a precise location can be determined with trilateration. Image: [4]

Previous research has used forms of satellite and ground-based radio telemetry and sonar localization to track the movement of individual terrapins over their homerange. Argos, a wildlife-based satellite tracking system proved to be too large and too inaccurate to meet the sponsor's requirements. Ground-based radio systems were designed for airborne bird species and were too unreliable for tracking on the ground. Lastly, sonar systems only monitored underwater location so it was insufficient to track semi-aquatic terrapins. Typical forms of localization utilize trilateration, which requires signals emitted or received from at least four known locations to a device affixed to the terrapin. The principal challenge of this project will be to determine which localization technologies are most suitable given limitations to size, existing infrastructure, and range. In this project, we seek to choose, evaluate, and combine existing technologies to refine the accuracy of localization measurements and provide more useful tracking information to our sponsor.

Stakeholder Analysis

As our team was developing a solution to the localization problem, it became important to consider all of the parties who would be affected by our work. In order to assess these implications that go beyond the scope of the design problem, we created a list of stakeholders, shown below in **Figure 3**.

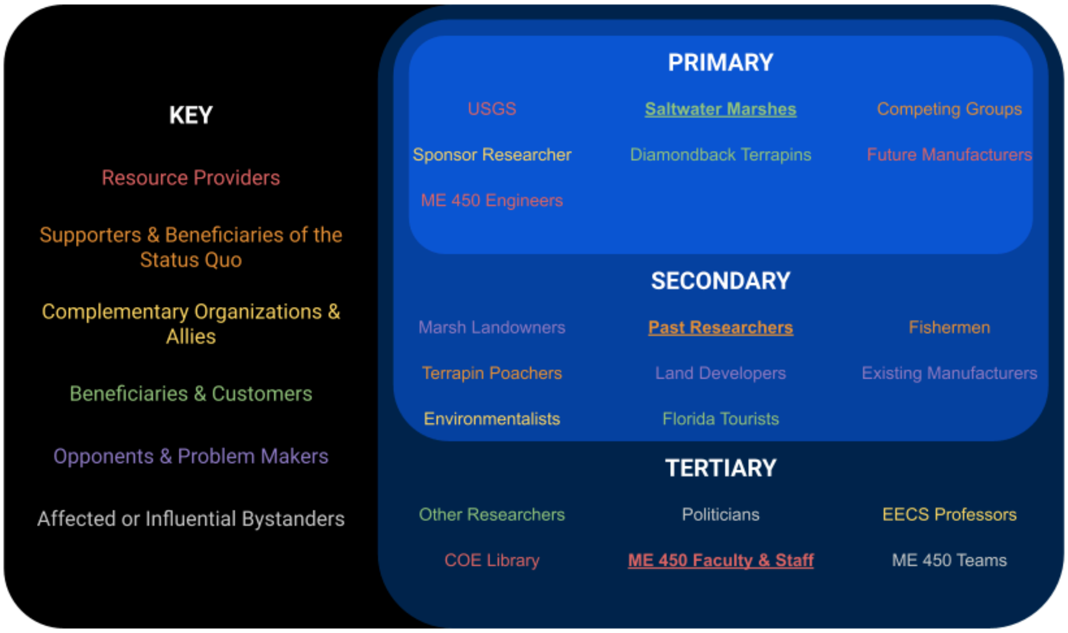


Figure 3. Stakeholder analysis chart categorizing each of our listed stakeholders. The key assigns a color code for each category, and the rank indicates how directly the problem impacts the stakeholder, and the stakeholder impacts the problem.

As seen in **Figure 3**, certain stakeholders may be benefited or harmed by the solution, or they may simply have an influence on the solution. One of the primary positively-affected stakeholders includes our sponsor, Dr. Lamont. She is directly involved with the problem, as she influenced what our requirements and specifications are for the solution, and it's our responsibility to meet these needs. Other notable positively-affected stakeholders include the local terrapin population and the salt marsh ecosystems. If we can successfully localize the vulnerable terrapins, and thus determine where they live, then their population can be better conserved. This will have implications for the rest of the populations in the ecosystem, including the snail population, which can potentially overgraze the essential cord grass if left unchecked. Finally, healthy salt marshes are essential for local fish and crustacean ecosystems, having a positive indirect impact on regional fisheries.

The terrapins themselves may also be a negatively-affected stakeholder. If the localization system is too heavy, it may limit their movement and harm their lifestyle and well-being. Furthermore, if they migrate less as a result of the weight, then our system would not even be able to fully localize them in a representative manner. The terrapins, as well as other wildlife, fisheries, and the saltwater marshes as a whole, may also be negatively impacted if there are any battery leakages. Therefore, all of these particular stakeholders, who would otherwise be "beneficiaries" of our solution, may be harmed if our solution is too large or likely to pollute the ecosystem.

Competing groups and existing localization system manufacturers represent more stakeholders who would be negatively impacted by our solution, being beneficiaries of the status quo or even direct opponents of our work. This includes Geo Society, whose work on the terrapins may be rendered obsolete if our sponsor, USGS, discovers more information about the terrapins' locations as a result of using our solution. Argos, who is the company that manufactured solutions previously used by the USGS, may also be harmed if our system is found to be significantly more accurate and reliable than their system.

Terrapin poachers may also be harmed if there are stricter conservation regulations and harsher penalties in place as a result of improved research on at-risk populations. Additionally, landowners on St Joseph Bay may be negatively affected by our solution, or they may negatively impact our ability to create an effective solution. This is because any ground structures that we implement in order to facilitate data recovery or increase the range and accuracy of our design may be placed on their property, which they may not allow. As of the final design no external infrastructure is necessary, but the existence of contested land ownership did play a fundamental role in the selection of our design concept.

Lastly, it is important to consider the stakeholders who are not necessarily positively or negatively affected, but have an influence on our design choice. This includes the ME 450 staff and other ME 450 teams. While they are not directly affected by the problem, nor even involved in the design process, they have provided valuable critiques during our team's design reviews. They also, as fellow engineers, have knowledge to provide to our team, which may influence the effectiveness of our solution. Further, the college of engineering (COE) library is another example of a resource provider, sharing texts on engineering analysis, quantifying localization uncertainty, benchmarking, and more.

Ultimately, it is important to consider that our design decisions may negatively impact one group while positively impacting another. It is our job to make a solution that positively impacts as many stakeholders as possible while still solving the problem of Diamondback Terrapin localization. For example, in the context of our final design, having a solution with GSM as the transmission technique would appease the landowners on St Joseph Bay and reduce any maintenance labor imposed on the USGS, even if having the extra GSM module on board the terrapin may weigh it down more than just using Argos.

Benchmarking

Before our team began developing a localization solution, it was important to research existing off-the-shelf products as benchmarks in order to establish a standard of accuracy, size, and range. In the context of the problem proposed by the sponsor, Dr. Lamont, we learned that the existing products used to localize the terrapins are too large in size or have insufficient accuracies. For example, Argos, an existing wildlife tracker, has an accuracy in the 100 [m] range [5], far too loose to track small Diamondback Terrapins. The many researched off-the-shelf wildlife localization products are compared in **Table 1** below, where each product is assessed based on a standard set of abilities.

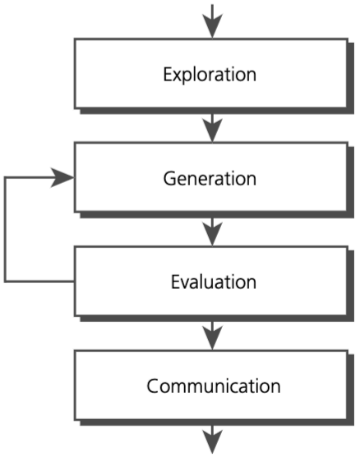
Table 1. Off-the-shelf Localization Comparison

Product	**Data Return**	**Size**	**Accuracy**	**Range**
Argos [5] [6]	Yes	Good	Moderate	Global
Motus [7]	Yes	Very good	Poor	<50km
Iridium Tracking [8][9]	Yes	Poor	Good	Global
Snapper GPS [10]	No	Very good	Good	Global
iSiTech [11]	Yes	Very good	Good	<1km
WildFi [12]	Yes	Good	Good	<1km

From **Table 1** above, it can be clearly seen that none of the specific products for wildlife localization meet all the needs of this project. Products with good accuracy may have a large size or lack data return, for example. Diamondback Terrapin tracking exists in a niche which requires high accuracy, a small device size, and a long transmission range. All analyzed solutions either do not meet the accuracy requirement and cannot produce useful data, or are too heavy to be effectively implemented on a Diamondback Terrapin.

Design Process

For the purposes of the current project, we have opted to introduce concepts from Cross's Design Model (**Figure 4**) [13] as a variation of the ME 450 design model. The Cross Model helped to outline our project in a manner that principally aimed to evaluate combinations of components which would combine together to meet our project requirements. The generation + evaluation cycle of various localization techniques reflected our selection process after an initial problem exploration and definition. Following successful evaluation, we ultimately landed on a final solution. We developed a new model to closer align with our project as shown in **Figure 5**. The major stages are Exploration + Problem Definition, Generation + Selection (using a functional decomposition), and Testing + Evaluating looping back to Generation + Selection, before reaching a Final Selection + Validation stage.



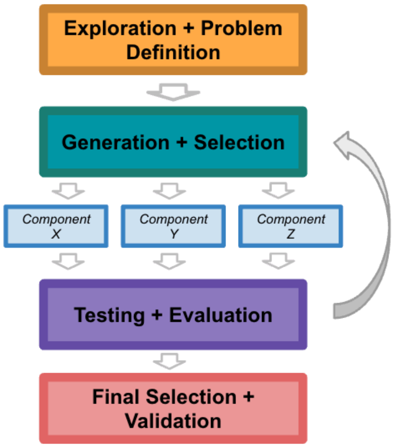


Figure 4. Cross's Design Model

Figure 5. Chosen Design Process

The Exploration + Problem Definition stage seeks to more rigorously define the abstract problem. Within this stage our team conducted our background research of salt marshes, Diamondback Terrapins, traditional wildlife localization methods, and the research question of our sponsor. We interviewed our sponsor to identify the needs and obtain a list of requirements to translate to engineering specifications. Through this process we narrowed down our project scope to focus on the electronic systems which could meet the localization requirements, as opposed to a project focused on materials and physical packaging.

The next stage of our design model is Generation + Selection. To create a solution for the stated problem we need various ways to generate solutions to meet the requirements. Our team performed literature reviews on different localization methods and conducted various rounds of concept generation and selection (**Appendix B**). A key component of this stage was the functional decomposition of the various subsystems of a successful solution. We determined that we'd need to make separate decisions and select hardware for each of the following functions: location data collection, data processing, data transmission, and a power supply. Each component was a separate subsect of the final system with collective and overlapping contributions to the overall engineering specifications.

The third stage is Testing + Evaluation. Evaluation consisted of researching the specifications of prospective components to determine whether they would meet our specifications. Potential solutions were compared based on how well they meet our engineering specifications and how well they interact with the other components (discussed in **Appendix B**, in **Table B3**). Once we landed on the most promising alpha design combination, we purchased the components and began testing to obtain our own experimental results. Components from Generation were tested, iterated, then kept or scrapped depending on how well they meet our specifications. If a component is deemed unsatisfactory, the loop brings us back to the Generation + Selection stage where a new component (or multiple) were selected in the context of the existing system.

The last stage was Final Selection + Validation where our design is solidified and verified as a single system which would meet all of the initial set of requirements. This consisted of larger-scale, fully-integrated tests of the complete localization solution to assess the qualitative behavior of the device. Validation testing completed this semester is only an initial round, and more will need to be conducted before practical implementation.

REQUIREMENTS & SPECIFICATIONS

Initial project requirements were developed by consulting our sponsor, Dr Margaret Lamont. We began with a full list of requirements for a final tag solution including the physical requirements of the container and packaging (a full list of initial requirements can be found in **Appendix A**). However, the scope of our problem statement narrowed down to determining a satisfactory localization strategy as opposed to fully constructing a physical localization device. **Table 2** outlines the necessary requirements and specifications our team used to develop a localization strategy.

Table 2. Localization-Focused Requirements & Specifications

	Requirement	Specification(s)	Source(s)	Measuring Strategies
1	Accurate localization within home range	Position uncertainty < 1 [m]	Dr. Lamont	Compare location data to known locations.
2	Sufficient range around St. Joseph Bay	Cover area > 260 [km2] Infrastructure range > 5 [km] Linear range > 61.5 [km]	[3]	SMS coverage mapping and cell tower mapping
3	Continuous operation for at least three months	Battery life > 90 [days]	Dr. Lamont [3]	Power testing of components and of the entire whole system.
4	Integrated transmission of collected data	Transmission success rate > 95 [%]	Dr. Lamont	SMS tests; coverage mapping.

The above four requirements summarize the requirements which a successful localization solution must meet. They are ordered by priority, however these top four were each deemed essential to the project.

The first requirement was a location accuracy requirement to provide useful data in determining the behavior of the terrapins. Previous solutions had accuracies of hundreds of meters or more [3][5], which could not provide detailed enough information for Dr. Lamont's research. 1 [m] was selected as a reasonable goal through our conversations with Dr. Lamont and through a benchmarking process of existing technologies. Accuracy was measured by comparing location results to known locations and included steps to remove systematic errors.

Requirement two reflects the range needed for data collection. Because Dr. Lamont is working within St. Joseph Bay, the size of the bay was used as an area specification (260 [km^2] [3]). Infrastructure range refers to the minimum range of any stationary infrastructure, for which 5 [km] was the minimum range. Linear range refers to the distance from "home range" the device should be able to continuously track the terrapins. Linear range of 61.5 [km] was obtained from previous research regarding maximum terrapin distance traveled over a similar timespan [3]. Because our design used GPS for data collection, range was only a concern for data transmission which utilized existing cell towers. This consisted of mapping cell coverage across St. Joseph Bay and by researching the range of the cell towers.

Requirement three directly refers to Dr. Lamont's request for the device to be tracked over the span of three months. As the scope of our project was limited to electronic hardware, that translated to a power requirement. To determine the power usage and the corresponding total amount of energy needed to be stored, power tests were formulated for individual components as well as the entire system.

Requirement four necessitates data transmission be integrated into our device. This was essential to offload location data from the terrapins without tracking them down independently. We decided on a 95 [%] success rate to account for two standard deviations of transmission error assuming a normal distribution. We performed stationary and mobile tests and made iterative adjustments to our software to help reach this specification.

As the scope of the project widens to physical prototyping, the other requirements defining physical limitations, resilience, and overall cost can also begin to be taken into account, which are detailed in **Appendix A**.

ENGINEERING ANALYSIS

Assessing Localization Technologies

The first set of engineering analyses that our team conducted was characterizing how each of the major localization technologies worked, and then comparing them using the same criteria that we used to benchmark their commercial implementations in the Introduction section. This would later aid in concept generation.

Through researching existing solutions and an analysis of the problem as a whole, we divided the problem into two major parts: data collection and data recovery. Data collection can be quantified in its accuracy and range, while recovery can be quantified in its range, and whether or not it requires additional infrastructure. Some technologies have a combined solution that encompasses both collection and recovery. All technologies can be evaluated based on their overall power consumption and package size.

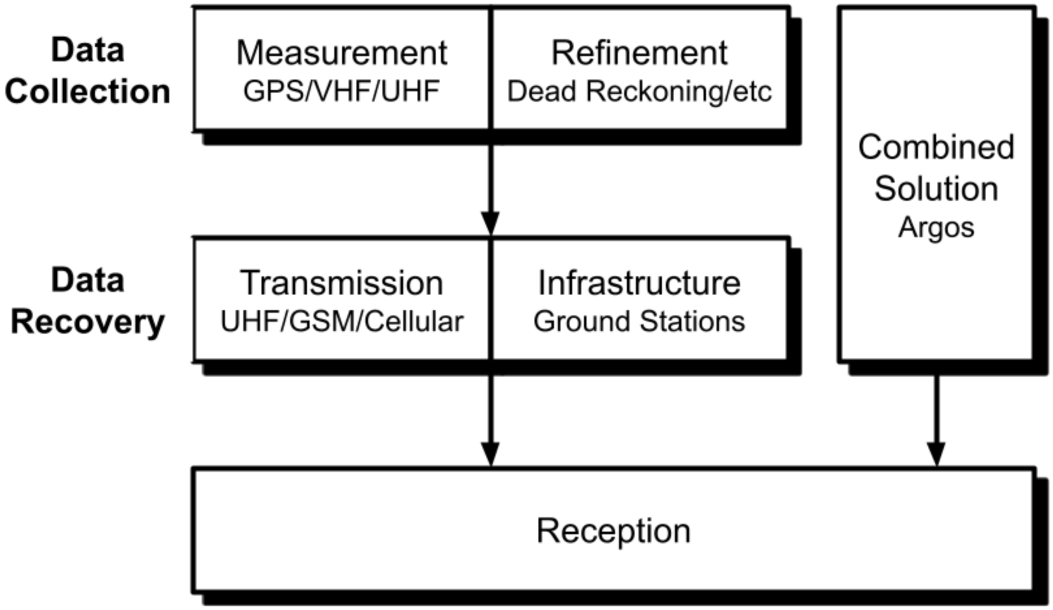


Figure 6. Block diagram illustration of data collection (localization) and data recovery (transmission) subsystems.

Not all radiofrequency based approaches for wildlife localization function the same way. With GPS, a receiver is aboard the terrapin and receives RF signals from a large number of GPS satellites. The receiver then uses the timestamp accompanying these signals, as well as its own internal clock, in order to determine the distance between itself and the many satellites. The intersection points between these distance lines are considered to be the potential locations of the receiver. Called trilateration, this highly accurate process is explored further later in this report with a Matlab simulation. However, because the GPS tag is a receiver, it cannot offload the data remotely to a researcher by itself. Alternatively, VHF technologies primarily work by having a transmitter aboard the terrapin that transmits low range RF signals to ground stations placed in the field. These ground stations triangulate the received signals in order to get a position solution for the Diamondback Terrapin. Bluetooth and Wi-Fi tracking have the same principles as VHF, using fixed Bluetooth or Wi-Fi access points as the receivers. However, they were found to have a much lower transmission range, being more suitable for indoor applications. However, these triangulation technologies have the advantage over GPS in that, being transmitters, they can remotely offload the position data to researchers. GPRS technologies involve these GPS receivers, but use GPRS mobile communication to transmit the position data to cell towers. In **Table 3** below, we compare the many analyzed localization technologies, including Bluetooth, WiFi, GPS, GPRS and VHF. Each of these technologies showed promise for use in this project. A more detailed breakdown of potential solutions is discussed in the "Discussion of Best Concepts" in **Appendix B**.

Table 3. Localization Technology Comparison

Product	Data Return	Size	Accuracy	Range
Bluetooth [14]	Yes	Poor	Moderate	<1km
Wi-Fi [15]	Yes	Poor	Moderate	<1km
GPS [16][17]	No	Good	Good	Global
GSM/GPRS [18]	Yes	Good	Poor	<50km
VHF/RFID [19]	Yes	Moderate	Moderate	<10km

Similar to the comparison of off-the-shelf localization solutions, no single technology appears able to meet all the specifications of this project. Therefore, it became apparent that a complete solution should come from a combination of multiple technologies. Multiple combinations of data collection and transmission technologies were considered throughout the design process.

GPS Simulations

As previously discussed, our team has researched GPS as the primary method that uses trilateration to calculate position solutions. Upon choosing GPS to be the data collection system, it became important to gain an understanding of its uncertainty, especially as a function of the number of satellites used for trilateration, in order to confirm that the system would meet our accuracy specifications. Therefore, our team decided to simulate the trilateration calculation that a GPS receiver would typically use to determine its own position, using Matlab.

In short, this simulation involves assigning an arbitrary receiver position and using Matlab's *gnssconstellation* function to retrieve the current positions of the GPS satellites in their orbits. The distances between the receiver and each satellite, also known as pseudo-ranges, are then calculated. An arbitrary receiver position is used because, in real life, a receiver would compare its internal clock's time to the timestamp attached to the satellites' signals, and then multiply that time difference by the speed of light in order to obtain the distances. However, this cannot be easily simulated in Matlab since there is no satellite timestamp function. This is also not necessary for characterizing uncertainty of trilateration itself.

The positions of the satellites are visualized in Earth-centered, Earth-fixed coordinates (ECEF), which are Cartesian coordinates with the center of the Earth at (0,0,0). The previously calculated pseudo-ranges between each satellite position and the arbitrary receiver position are the radii of spheres centered around each satellite. This visualization of the spheres centered at satellite positions with radii of pseudo-ranges can be seen below in **Figure** 7.

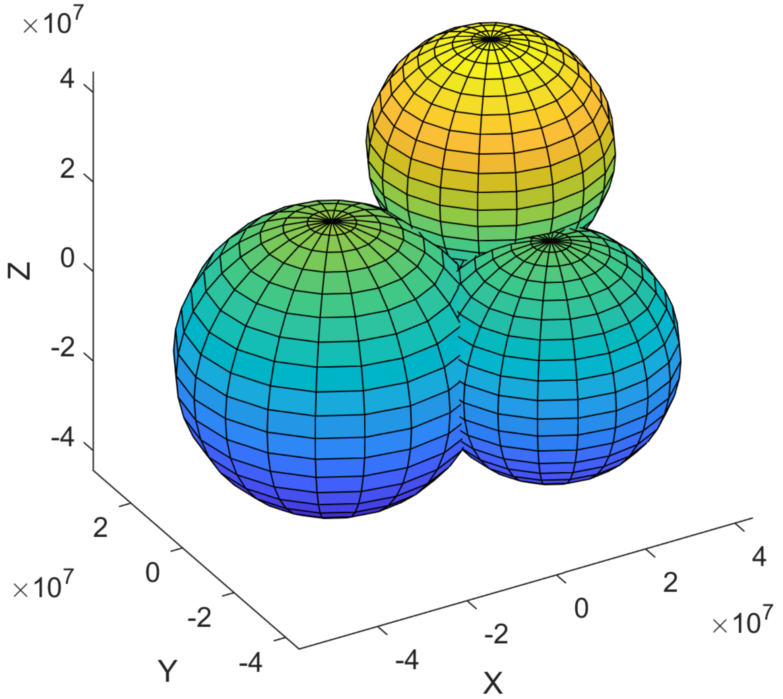


Figure 7. Spheres centered on satellite positions in ECEF coordinates, with radii representing distances between the satellites and the receiver.

The spheres in **Figure** 7 can next be used for trilateration by finding the points of intersection between all three, representing potential locations of the receiver. In Matlab, the intersection points between the three spheres cannot be feasibly indexed. Instead, we decided to implement a least-squares regression function between the pseudoranges and the difference between the satellite positions and a variable receiver position. This function was minimized, resulting in a variable receiver position that closely matched the chosen arbitrary receiver position. Functionally, this calculation achieves the same result as indexing the intersection points between the spheres of pseudo-ranges. In fact, this method closely mimics the trilateration method used by real receivers [20].

After calculating an estimate of the receiver position using trilateration, the Matlab simulation also includes an uncertainty analysis between that estimate and the true arbitrary receiver position. The absolute error between the two positions was calculated over multiple trials, and then averaged. Many sets of trials were also run with a different number of satellites. The percent difference of the average absolute errors of two trials, where one trial implemented one more satellite than the other, was then calculated. Multiple pairs of trials were used to make this percent difference in uncertainty calculation, and our team determined that increasing the number of satellites by one reduces the absolute error by an average of 5.52 [%] in the expected range of satellites.

Upon retrieving position data from our localization system, this simulation was revisited in order to confirm this finding about uncertainty. After replacing the arbitrary position with a position calculated by the receiver, new pseudoranges were found with the satellite locations at that current simulation time. For simplicity, the simulations were done with the average position coordinates calculated at the first trials for each of the four locations of the verification test. For example, the manhole in front of the bell tower is located at 42.2920° latitude, -83.7159° longitude. Meanwhile, the receiver's average estimate for that location in the first trial was 42.2921° latitude, -83.7160° longitude. This receiver's position was input into the Matlab script, which then output its own estimate of that receiver's position. This was repeated for different amounts of satellites, in the same fashion as previously described. For these simulations at the four locations, the absolute error was reduced by an average of 7.81 [%] when a satellite was added. This nearly matches the 5.52 [%] reduction seen before using an arbitrary receiver position.

DESIGN DESCRIPTION

Concept Generation & Selection

With information gathered through benchmarking and engineering analysis, our team followed a structured concept generation/selection process. Sixty unique solutions to the design problem were brainstormed and discussed before using a tiered down selection exercise to yield only the most promising ones, shown below in **Figure 8**. A functional decomposition between (1) localization and (2) data transmission better structured solutions to meet the requirements and specifications, as well as promoting new approaches to the problem. From this process, which is explored in detail in **Appendix B**, we chose to use a combination of GPS localization with GSM data transmission.

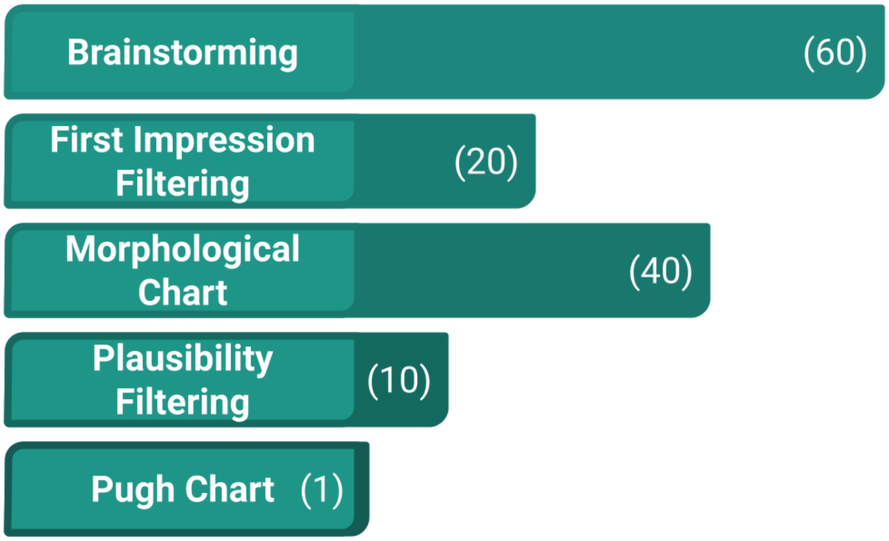


Figure 8. Concept generation and downselection overview. Phases included brainstorming, first impression filtering, morphological chart/functional decomposition, plausibility filtering, and a pugh chart. Numbers and bar sizes indicate the amount of concepts at the termination of each phase.

Selected Concept

GPS localization, discussed in detail in the engineering analysis section, uses a satellite constellation to provide information such that the device can perform computations to determine its own location. With a large constellation of > 31 satellites, GPS has essentially global range, and can be expected to collect data at any time the device is above the surface of the water. With minor onboard processing, information gathered directly from satellites can be easily translated into coordinates.

GSM data transmission uses cellular networks to send packets of data in the form of SMS (Short Message Service) messages. Using a SIM (Subscriber Identity Module) card, a GSM-enabled device can identify itself to the GSM network, which will in turn allocate resources as necessary. TDMA (Time Division Multiple Access) and FDMA (Frequency Division Multiple Access) are used to assign the device a time slot and frequency for transmission. With this structure, GSM is optimized to send small packets of information through messages of < 160 characters.

In order to transmit data, a GSM-enabled device must be in range of a base transceiver station, which is used to communicate information throughout the broader network, as shown in **Figure 9** below. Base transceiver stations are designed with varying transmission ranges, but can have a maximum reach of 35 [km], limited by the time advance associated with TDMA. In the rural and suburban areas surrounding St. Joseph Bay in Northern Florida, it's expected that most stations will achieve close to this 35 [km] range [21].

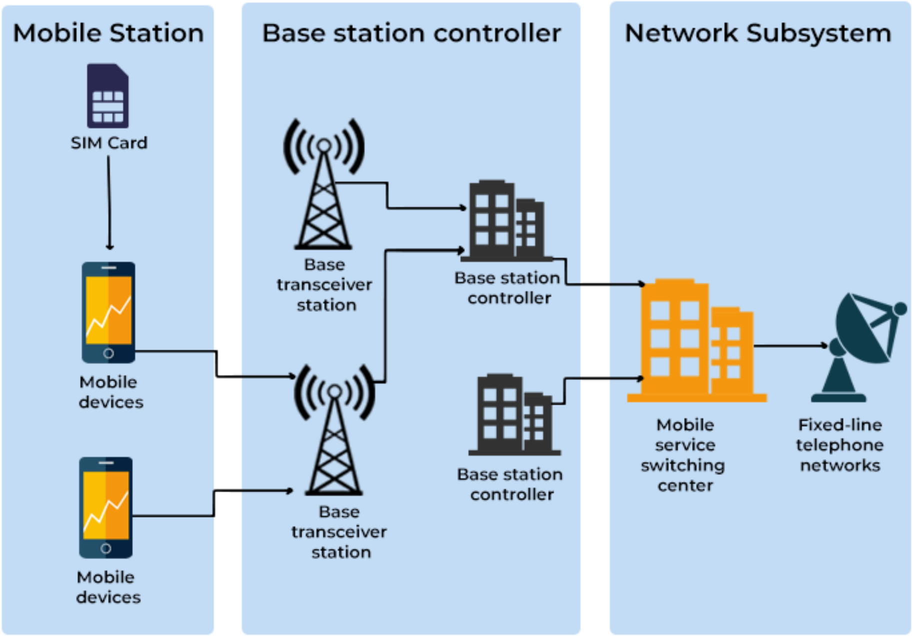


Figure 9. GSM network infrastructure schematic. A *GSM-enabled device* with an activated *SIM card* communicates information to a *base transceiver station*, which either passes information directly to a different *GSM-enabled device* or deeper into the network for longer-distance communication. (image: [21])

In practical operation all hardware will be affixed to the shell of the turtle. When the turtle is above the surface of the water, the GPS subsystem will collect data and perform initial processing to determine the device location at regular intervals. These location data points will be passed to a microprocessor, which will aggregate them into data packets of less than 160 characters. The microprocessor will store this information until the device is within range of a GSM base transceiver station, at which point it will be transmitted in the form of an SMS message. Because Diamondback Terrapins primarily inhabit *coastal* saltwater marshes, it's anticipated that they will regularly be within GSM coverage to transmit position data, even if they temporarily visit other ecosystems in more remote areas. This routine operation of the selected concept is visualized in **Figure 10** below.

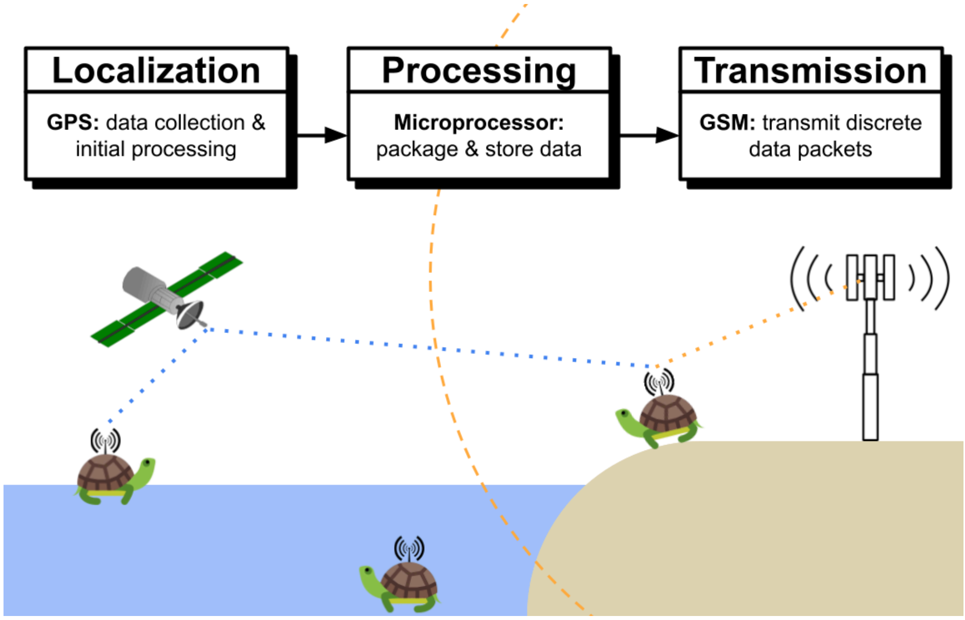


Figure 10. High level data flow and operation of selected concept. With GPS continuously collecting data while surfaced, a microprocessor packages and stores data until it's within GSM coverage, at which point it's transmitted in discrete packets.

Build Description

For ease of prototyping and testing breakout boards were selected for each subsystem (localization, processing, and transmission). A compatible power supply was selected independently and arbitrarily, ensuring only efficient testing. The GPS breakout board selected was the Adafruit Ultimate GPS v3, which was tested both with and without an external active antenna. An Arduino Nano was selected as the microprocessor, primarily due to its small size and compatibility with other components. The GSM breakout board was chosen as the Adafruit FONA 3G, and was combined with an external antenna and SIM card for communication with 3G GSM networks. Finally, a bank of six AA batteries was used to power the device and to facilitate streamlined measurements of power consumption. The interaction between these devices in the context of Diamondback Terrapin localization is visualized in **Figure 11** below.

Each subsystem was tested independently, with the Adafruit Ultimate GPS v3 exchanged for the Adafruit Ultimate GPS USB for interfacing directly to a computer. The results of these tests are discussed in the following verification and validation section. Under ideal circumstances, the combined system of these components should be able to localize quickly with an accuracy of ± 1 [m], and transmit data reliability through SMS messages.

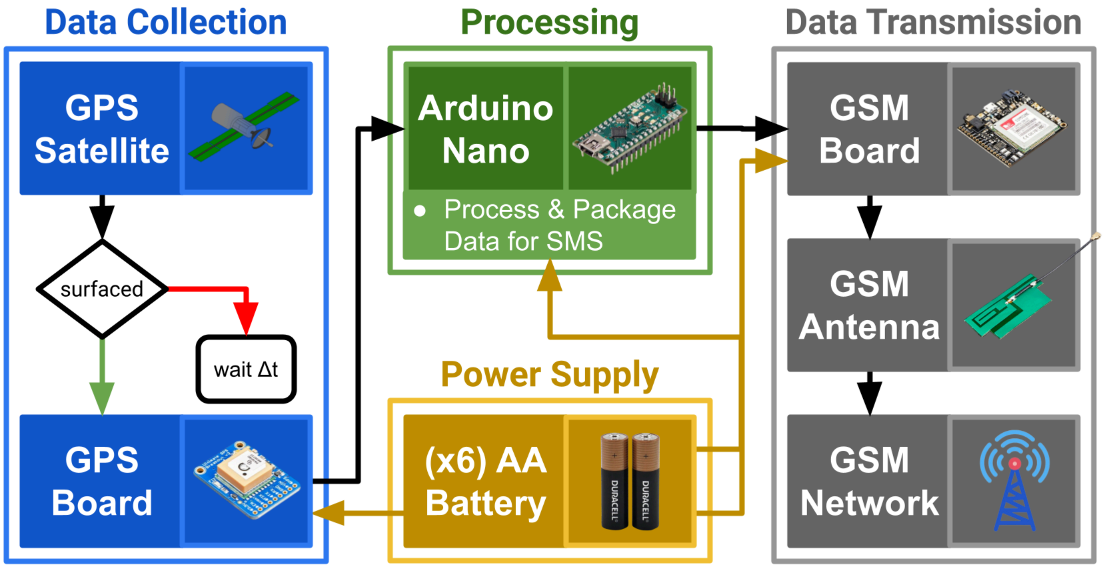


Figure 11. Functional Decomposition and intended interfacing of selected design components. Location data is gathered at time intervals of Δt while surfaced using the Adafruit Ultimate GPS v3, which is processed through the Arduino Nano and transmitted to the GSM network using the Adafruit FONA 3G.

As shown in **Figure 11** above, the device will first check whether it's surfaced before attempting to collect a data point. In the current prototype, this condition is assessed by whether the GPS breakout board can successfully achieve a GPS fix, but in future iterations of the prototype this functionality will be implemented with a saltwater switch to conserve power. At time intervals of Δt, GPS satellite information is translated into location data in the form of a timestamp and coordinates. Limited by the SMS character limit of 160 characters, five localization measurements are aggregated into a single packet. In the current prototype, complete packets are immediately transmitted through the GSM breakout board, but future iterations implemented in rural areas must include the capability to assess an adequate GSM connection first.

Without the capability to assess GSM connectivity, the current prototype includes a buffer which stores unsent messages. When the device identifies a transmission failure, instead of losing the acquired data, the packet is added to the buffer and will be transmitted with the next message instead. This mitigates any risk of data loss associated with poor GSM coverage and better mimics the device operation in rural St. Joseph Bay.

Catering to the iterative design process discussed in the introduction, prototyping pins were attached to each breakout board such that breadboarding wires can easily be reconnected and components reconfigured. Connections between components are shown below in **Figure 12**.

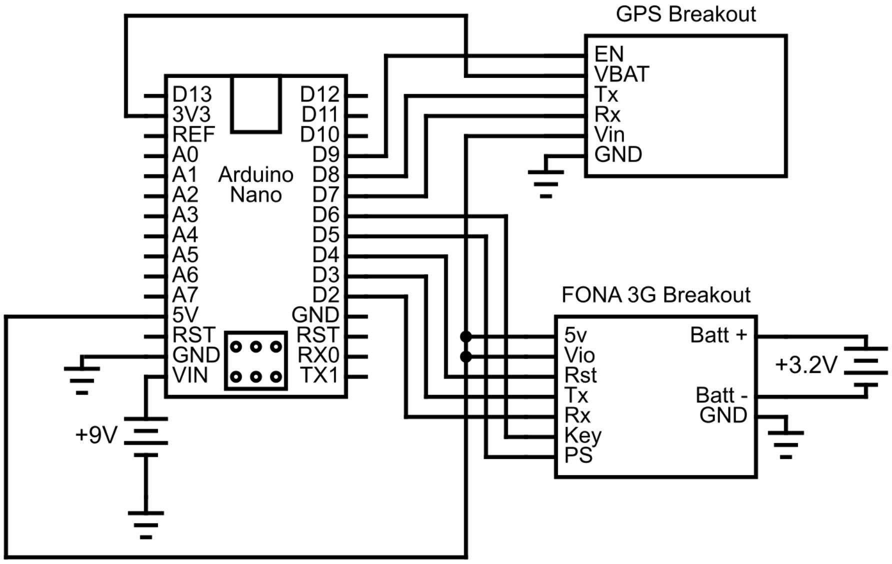


Figure 12. Wiring diagram for GPS breakout board, Arduino Nano, and GSM breakout board, as implemented in the build design.

For clear presentation and protection while testing, breakout boards were mounted on ¼ [in] thick clear acrylic, which was laser cut with equipment in the University of Michigan Mechanical Engineering Undergraduate Machine Shop. The layout of components, formatted for laser cutting, is shown below in **Figure 13**.

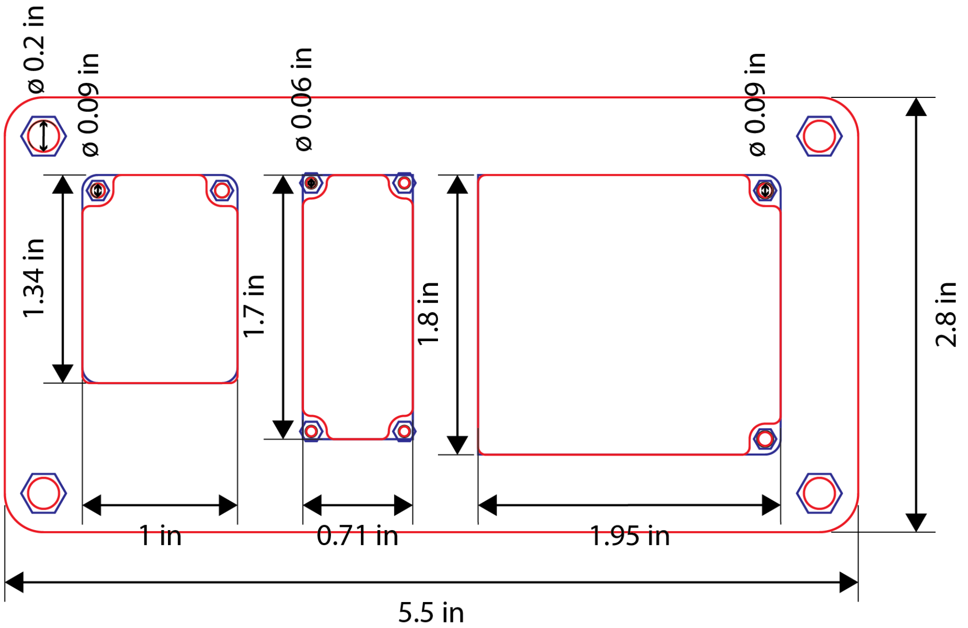


Figure 13. Layout of breakout boards on acrylic. The GPS breakout board is on the left (1 x 1.34 [in]), the Arduino Nano is in the center (0.71 x 1.7 [in]), and the GSM breakout board is on the right (1.95 x 1.8 [in]). The complete structure is 5.5 x 2.8 [in] and 1 ¼ [in] in height.

Stainless steel (18-8) standoffs of ½ [in] length were used to mount breakout boards on the acrylic shown in **Figure 13** above, with standoffs of 1 [in] length used to mount the second sheet of acrylic on top. This structure and necessary power supply(-ies) was then encased in a rigid, waterproof, box for protection during longer-term validation testing. This assembly is shown below in **Figure 14**.

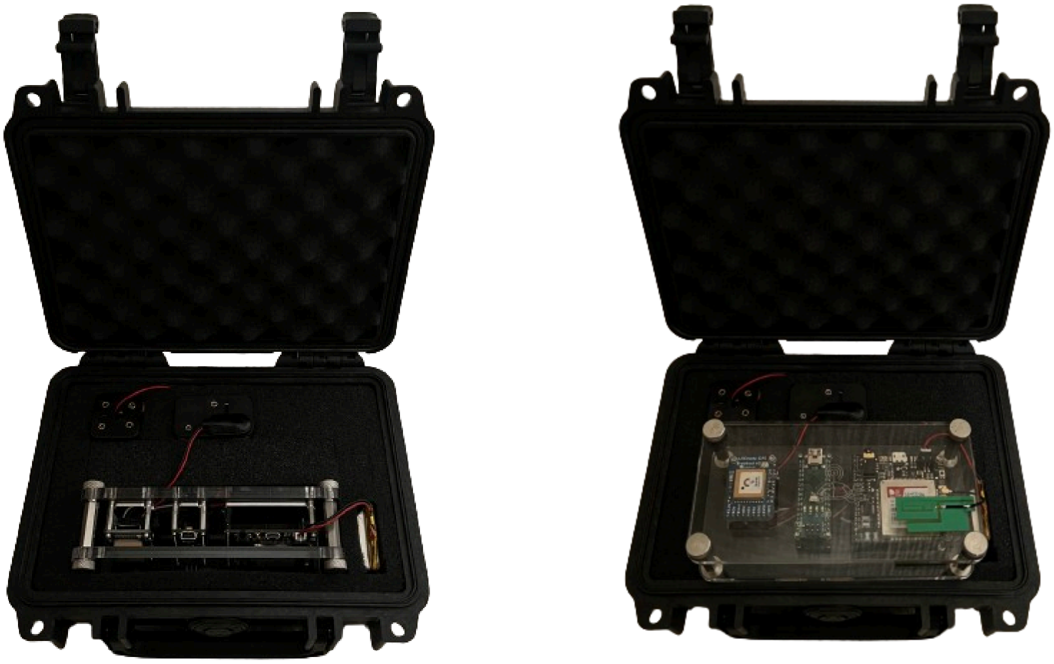


Figure 14. Complete assembly of build design. On the left the localization hardware is placed in its travel configuration with foam on all sides, while on the right it rests on top for a clearer view. In both views, both active and spare batteries are also shown with, connected with red and black wires.

The total cost of all components included in this prototype is $319.26, with breakout boards making up $134.80 and mounting hardware making up $106.08. The most expensive component was the Adafruit FONA 3G GSM breakout board, with a cost of $79.95. All components included in the build design and their respective costs are included in the bill of materials in **Appendix C**.

VERIFICATION & VALIDATION

Verification of Specification 1: Accuracy

Per our sponsor, the most important specifications of our design pertained to the accuracy and precision of our localization. Specification #1 is as stated: "provides location measurements within ± 1 [m] of true location.” With GPS as our chosen localization method, we were able to create a verification plan to ensure this important requirement is met.

To test for accuracy and precision, our team identified landmarks which could easily be marked on Google Maps. With 6 decimal points of precision in decimal-degree coordinates, we used Earth’s geometry to discover Google Maps has a precision of 11.13 [cm] N/S and 5.80 [cm] E/W at Ann Arbor’s latitude. These conversion factors allow for otherwise ambiguous units to be given a much more useful and universal meaning, and better characterize our device’s effectiveness.

Four locations were selected within a mile of each other and tests were conducted at landmarks which are easily observable on Google Maps. Both with and without an external antenna the GPS module was timed to achieve a satellite fix, directly measuring the TTFF. Following this, three samples were collected before disconnecting the module and attempting to achieve two more fixes. The measured coordinates were compared to known locations, results which are summarized in **Table 4** below including an accuracy and bias analysis.

Table 4. GPS Accuracy Verification by Antenna

Location	**External Antenna**			**Integrated Antenna**		
	TTFF (s)	△N (m)	△W (m)	TTFF (s)	△N (m)	△W (m)
Bell Tower Manhole in the Grove	23	7.86	6.28	37	4.71	0.48
	20	0.01	1.00	31	3.35	0.71
	29	8.79	6.73	29	4.77	3.15
Duderstadt Streetmost Brick Triangle	25	4.73	0.55	25	4.29	0.29
	29	4.79	2.93	26	10.17	7.41
	24	-1.09	3.16	26	3.61	1.61
Lurie Blue Lot (row 5, spots 4/5)	18	5.05	-1.76	32	12.41	2.27
	29	10.98	2.66	31	10.80	1.69
	17	4.06	4.85	39	7.71	4.07
Wave Field First Manhole	29	12.37	1.75	31	6.12	1.75
	27	8.28	4.26	30	10.39	0.97
	24	7.79	3.13	26	13.05	2.49
Average (s or m)	25	6.14	2.96	30	7.61	2.24
Accuracy (m)		17.05			18.48	
Bias-Adjusted Accuracy (m)		9.39			8.17	

To calculate the overall accuracy, Google Maps’ decimal degrees (DD.DD) coordinates were converted to the GPS output format, NMEA degree minutes (DDMM.MM) [22]. Measurements were averaged over a given fix and subtracted from the known coordinates before being converted to meters to achieve △W and △N. The accuracy was then found as twice the standard deviation from the known location to ensure 95 % of measurements are within the calculated range. That resulted in accuracies of 16.33 and 17.70 [m] for the external and integrated antenna, respectively. Precision was finally found using twice the standard deviation within the samples for each fix (differing from accuracy which was based on the "true" location as the statistical average). Precision yielded values of 0.89 and 1.11 [m], for the external and integrated antenna, respectively. Bias was determined by averaging the △N and △W revealing a strong NW bias of 6.14 N, 2.96 W [m] for the external antenna and 7.61 N, 2.24 W [m]. Adjusting for this bias, the integrated antenna yielded a higher accuracy of 8.17 [m] TTFF averaged 25 seconds with the external antenna and 30 seconds with the internal antenna. These minor differences suggest that a large external antenna (which adds significant additional mass) will not be necessary for a final design.

Our accuracy does not meet the specification of ± 1[m]. Precision data within a GPS fix yields precise results, with measurements confined to a small radius close to one meter. However between fixes, there is still significant variation. This can be seen in **Figure 15**. Consistently positive delta values also suggest that there may be a systematic bias in the GPS localization towards Northwest error as seen in **Figure 16**. This could be due to a number of issues including calculation error, rounding error, or incorrectly mapping a true location to correct coordinates within Google Maps. More trials may be necessary to determine whether the GPS will eventually settle on the true location or follow a consistent pattern of bias.

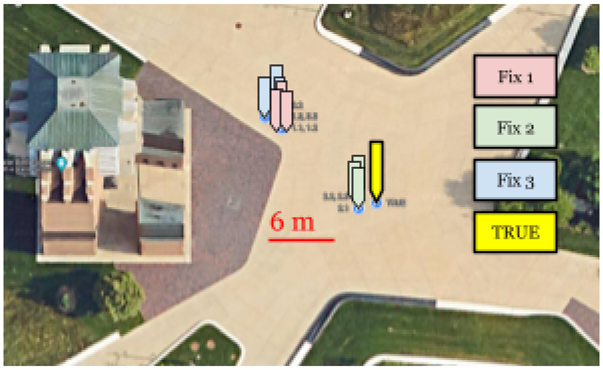


Figure 15. Example tested location - Bell Tower Manhole in The Grove. "True location" and locations of each of the 3 collected GPS fixes are labeled for quick comparison.

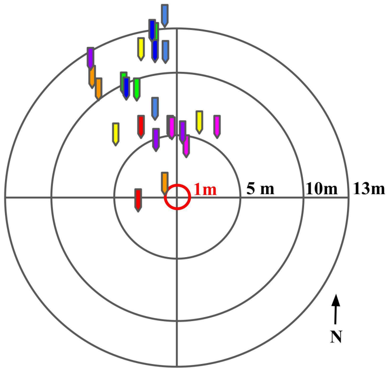
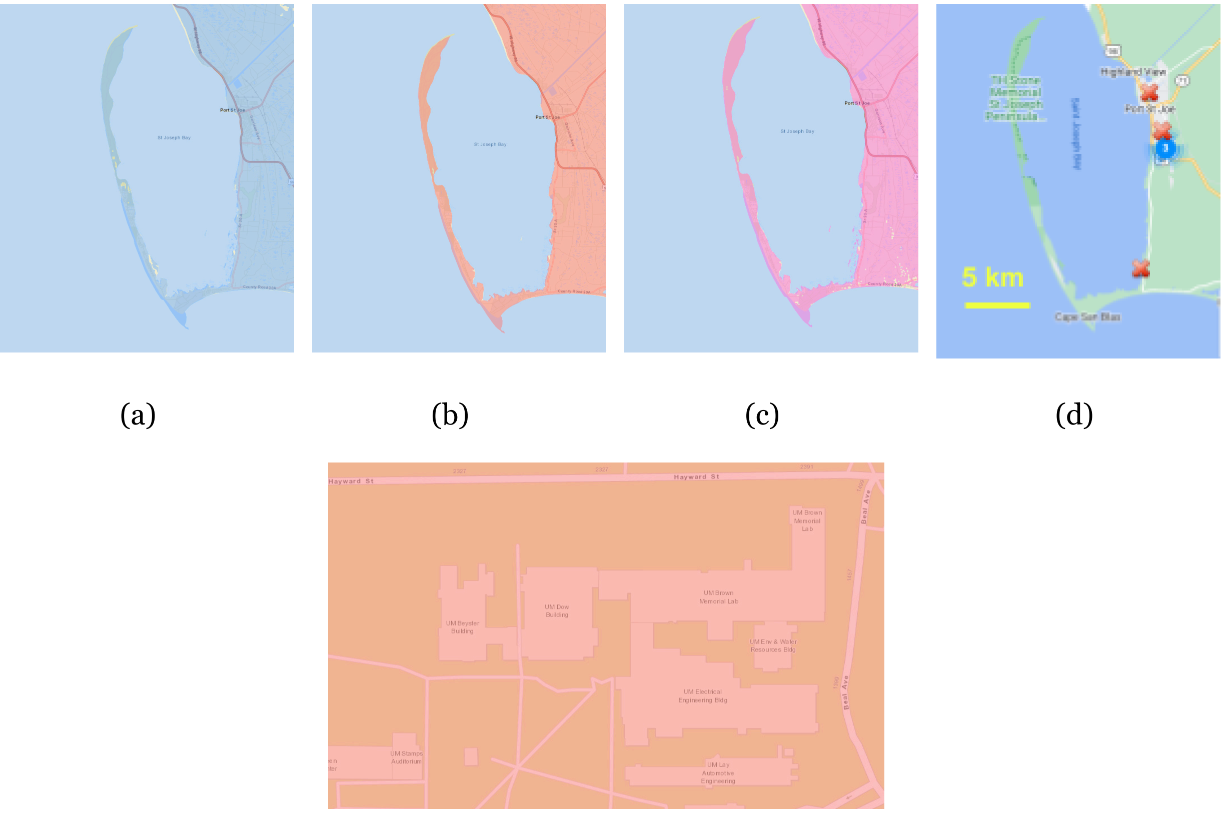


Figure 16. Each fix relative to its "true location", with the average bias of 6.88 N, 2.60 W [m].

Verification of Specifications 2 & 4: Range and Transmission

GSM was the method selected to transmit data from the terrapin. GSM's transmission addresses two important requirements: requirement #2 "track maximum terrapin movement around St. Joseph Bay" and requirement #4 "data is transmitted without collecting devices." Requirement #2 corresponds to three specifications: transmission able to cover an area greater than 260 [km^2], a linear range greater than 61.5 [km], and transmission infrastructure range must be greater than 5 [km]. Requirement #4 corresponds to another specification: over 95 [%] reliability in successful transmit attempts.

GPS, as a *global* positioning system automatically meets the range requirement for collecting location data across the area range and the terrapin's above water linear range. Regarding transmission, GSM utilizes an existing national cell tower network. We tested the SMS system outdoors on Michigan's North Campus which had ubiquitous coverage shown in **Figure 17** (e) and demonstrated 100 [%] reliability. Using FCC cellular maps [23] as shown in **Figure 17** (a-d), we can estimate the area covered in the bay to be sufficient to meet our 95 [%] reliability requirement.



(a) (b) (c) (d)

(e)

Figure 17. (a) AT&T coverage of St Joseph Bay. (b) Verizon coverage of St Joseph Bay. (c) T-Mobile coverage of St Joseph Bay. (d) Cellular tower map [23]. (e) Verizon coverage at University of Michigan - North Campus. Regions shaded in color represent the regions where cellular service is covered by a GSM carrier.

It is clear that all GSM-compatible coverage spans the vast majority of the land on St Joseph Bay. Although data for the water of St. Joseph Bay isn't reported, the surrounding land indicates there will likely be sufficient coverage, at least in the coastal saltwater marshes. GSM infrastructure is already widespread and commonly has a range above 5 [km], reaching up to 35 [km] [24], meeting the second half of specification 2.

Our team also conducted a test for GSM speed and reliability at various altitudes of the same location. Each SMS test was successful, indicating a success rate of 100 [%] and satisfying the first half of specification 4. This was to be expected as cellular coverage in the area of testing was ubiquitous [23]. It's unclear how SMS reliability will be affected by non uniform coverage and further tests at different sites may be necessary.

Verification of Specification 3: Power Consumption

An essential part of our system's capability to track terrapins in the wild is the ability to function continuously for up to 90 days, in order to evaluate the movement of terrapins over a complete summer season when they're active. Because of time constraints, we cannot conduct a trial that lasts the whole 90 days, or simulate the power on and off behavior while deployed. Therefore, we have analyzed the power consumption of the system while conducting relevant tasks, including taking location measurements, idling between measurements, and transmitting collected data. Each of the subsystem's continuous power consumption was also calculated.

A circuit of differential amplifiers and shunt resistors was implemented on a breadboard along with all three breakout boards to separately measure the current draw of subsystems under different conditions. This circuit is shown in **Figure 18** below.

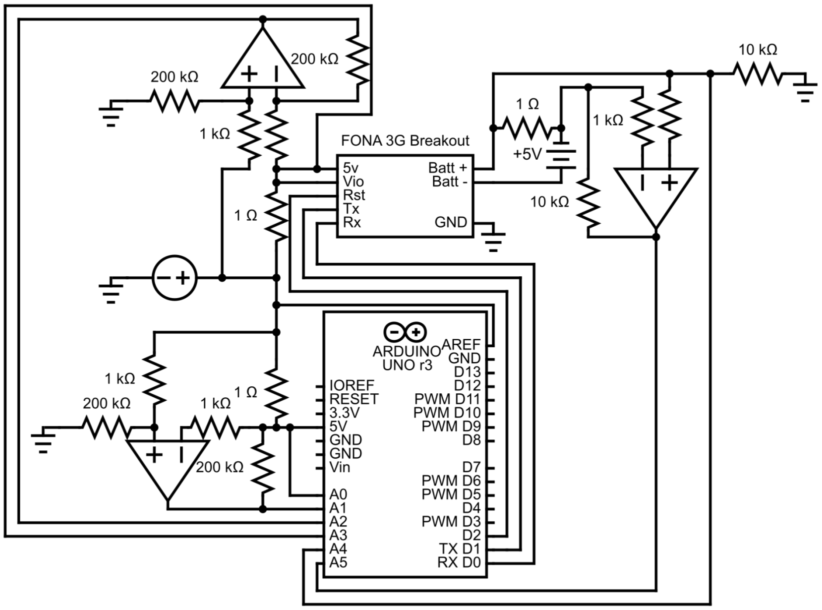


Figure 18. Power consumption verification breadboard used to measure individual component power draw. This circuit was designed and implemented around a previous prototype iteration with different wiring, although the results gathered are still relevant.

Using the experimental data and knowledge of the power saving behavior we have designed, we estimated an overall power consumption of the system, as well as how it relates to the measurement frequency of our system. The preliminary results of these tests and analysis are shown in **Figure 19** below.

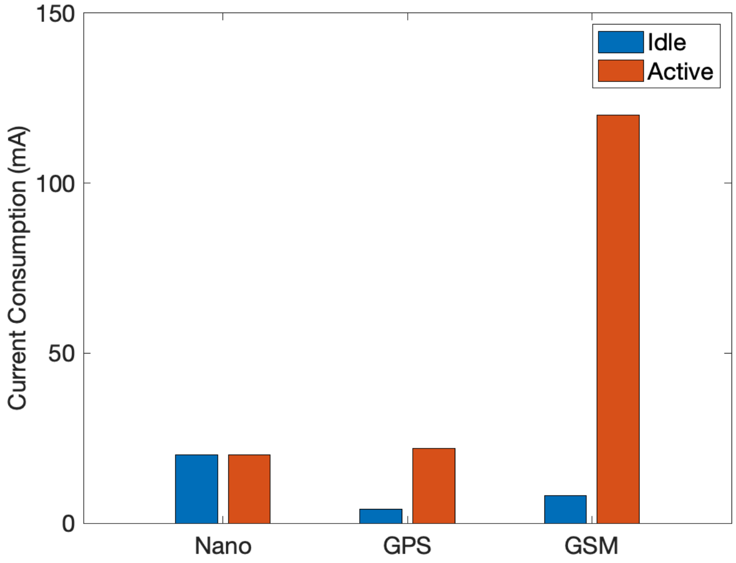


Figure 19. Current draw of components in idle and functioning states. Arduino Nano does not have an idle state.

Notably, our system functions in two discrete stages: First, the system takes five measurements using the GPS subsystem; Then, the tracker transmits the measured data through the SMS network for analysis using the GSM subsystem. When a system is not being actively used, it is switched off to save power. The Arduino Nano microcontroller is always switched on, due its necessity to record and package data. Because the GPS subsystem is switched off after each successful measurement, it requires approximately 30 seconds after switching on to acquire another fix and measurement. If the measurement interval is less than 30 seconds, the GPS subsystem is not switched off, and can acquire another fix much faster. The GSM subsystem requires around 30 seconds after power on to initialize and finish transmission of packets before powering back off. According to the behavior described above, the current consumption and projected device longevity was calculated and is shown in **Figure 20**. It can be seen that longevity increases asymptotically with increasing time between measurements, and approaches around 85 hours of continuous operation. However, when the device is deployed, it will only be switched on when the terrapin subject is out of the water. Therefore, it is impossible to calculate the actual performance in the field using these measurements, due to the high possible variability in the behavior and movement of the terrapin.

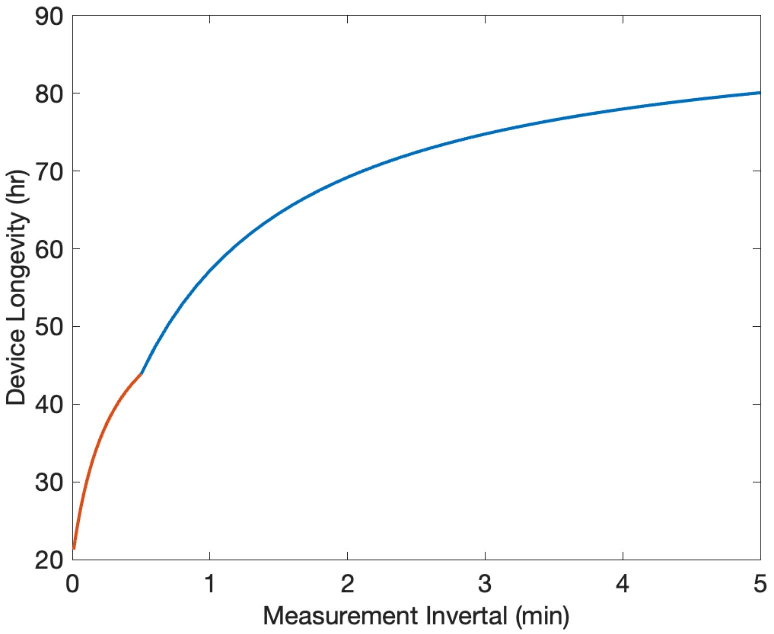


Figure 20. Device longevity as a function of measurement interval with the power bank of 6 AA batteries. This plot makes the assumption that the Diamondback Terrapin is never submerged. While this is known to be untrue, the behavior is qualitatively correct and the values represent a conservative estimate of device longevity.

Further improvements to power consumption are likely to be seen when the chips are integrated into one PCB, as opposed to separate breakout boards. Each breakout board contains a large amount of miscellaneous hardware that remains powered on, but is completely unused for our applications. For example, each extraneous LED can draw up to 5mA of current, which is highly significant for our application.

Validation

With device assembly completed and verification testing underway, our team moved on to validation testing simultaneously. Two major tests were conducted: a preliminary small-scale assessment, and a final assessment of larger scale. These tests were focused on recreating normal operations that would be experienced while attached to a Diamondback Terrapin in St. Joseph Bay and providing data to form a qualitative analysis of the device's success.

First, the device was carried on a University of Michigan Blue Bus following the Bursley-Baits bus route. Collecting data points at one minute time intervals and automatically transmitting complete packets, the device recorded data for a complete loop of the bus. Collected data is shown below in **Figure 21**, alongside a comparison to the known path of the bus in **Figure 22**.

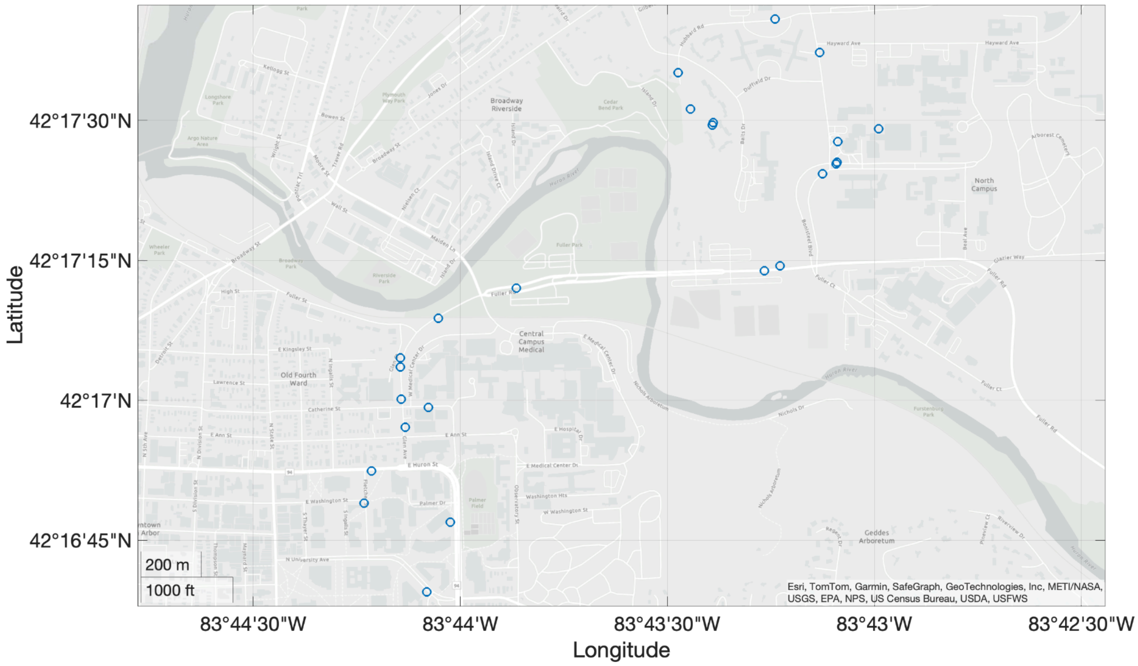


Figure 21. Location data collected for one complete loop of the University of Michigan Bursley-Baits Bus. 24 points were taken over 32 [min] and 27 [sec]. Data points were attempted at 1 [min] intervals, with additional time for gathering a GPS fix and transmitting complete packets.

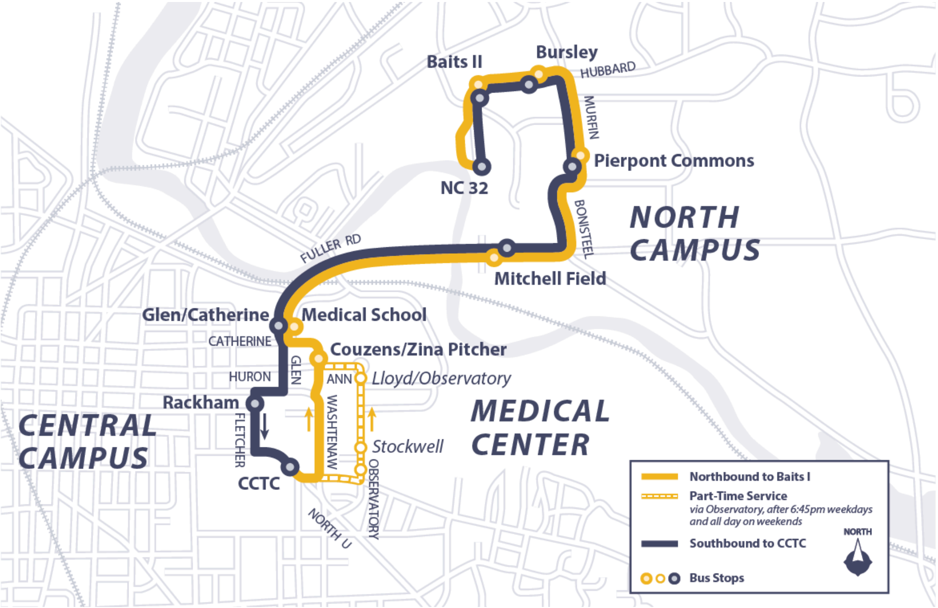


Figure 22. Generic University of Michigan Bursley-Baits Bus route. Visual is a topographic map in the form of a schematic diagram and is not to scale. (image: [25])

From preliminary analysis, the collected data adequately provides a qualitative idea of the device track. Using timestamps associated with each location data point, the device speed can also be estimated. Building on the previous bus route test, the device was next transported in a vehicle on the highway over a distance more comparable to the size of St. Joseph Bay. Collected data is shown in **Figure 23** below, while the actual route is shown in **Figure 24**.

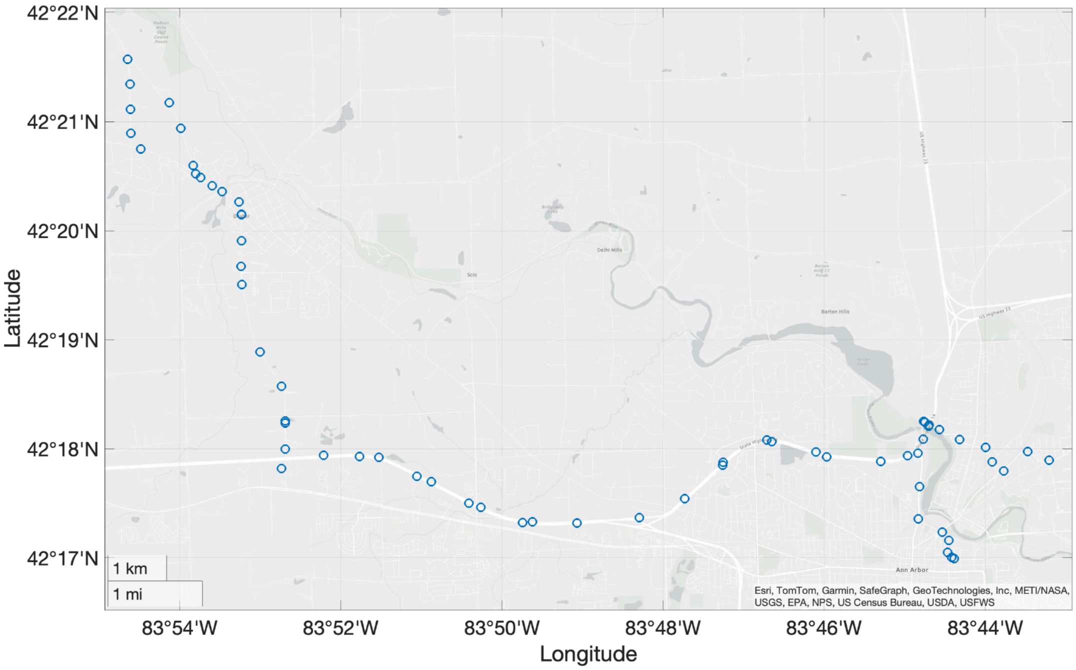


Figure 23. Location data collected for a round-trip highway path. Data points were attempted at 30 [sec] intervals, with 65 taken over 40 [min] and 30 [sec]. This path covered a maximum distance of 12.98 [km], on the same scale of the 9.7 x 24.0 [km] St Joseph Bay.

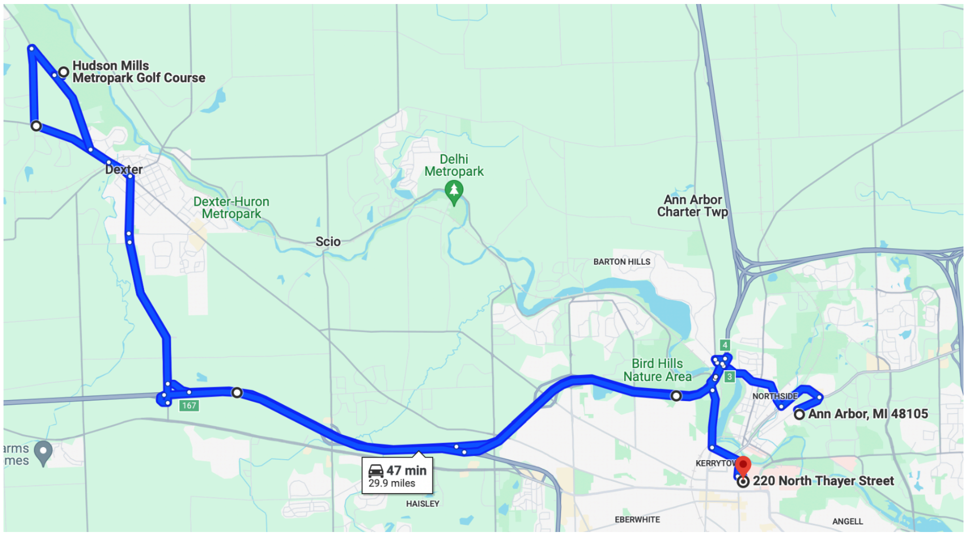


Figure 24. Google Maps route followed during large-scale validation data collection.

It’s worth mentioning that both of the validation tests conducted are at much shorter time-scales than defined by specification 3, as time was a major limitation in this semester’s work. To remedy this, sampling rate and transit speed were approximately scaled accordingly. For example, a Diamondback Terrapin may travel 12.98 [km] , collecting 65 samples at a rate of 1 [sample/hour] for 2 [days] and 17 [hours]. Following from this analysis, the test visualized above can be thought of as qualitatively the same, just sped up ≈ 96.3 times.

Although the device has successfully passed the two validation tests shown above, providing consistent and accurate localization results, validation testing is not complete. There are some aspects of normal operation that aren't able to be adequately replicated in Southern Michigan. Weather conditions, the presence of man-made obstacles, and the availability of high-quality GSM base transceiver stations will undoubtedly have some effect on the data collected, although it’s currently unknown how significant it will be. With further testing in the saltwater marshes of St. Joseph Bay, where the solution is to be implemented, data can be collected that’s far more representative of actual intended performance. These tests may include mounting the device on a watercraft and following an estimated path for Diamondback Terrapin movement, combined with intermittent submersion to better mimic routine loss of GPS and GSM connectivity. It will also be necessary to collect long-term data, over the complete 90 [days] outlined in specification 3. The outcome of these tests is vital to the design process, and the results have the potential to inform necessary changes to requirements and specifications, and even the build design itself.

DISCUSSION

Problem Definition Revisions

Developing localization strategies for Diamondback Terrapins is a multidisciplinary problem. In addition to mechanical and electrical engineering, a cohesive solution must be informed by biology, with a strong understanding of Diamondback Terrapin ecology, and how they interact with delicate saltwater marsh ecosystems. While the scope of this semester’s project focused on localization technologies, deploying a complete tracking system would involve additional understanding of materials science, solid mechanics, and fluid mechanics, as shown in **Figure 25** below.

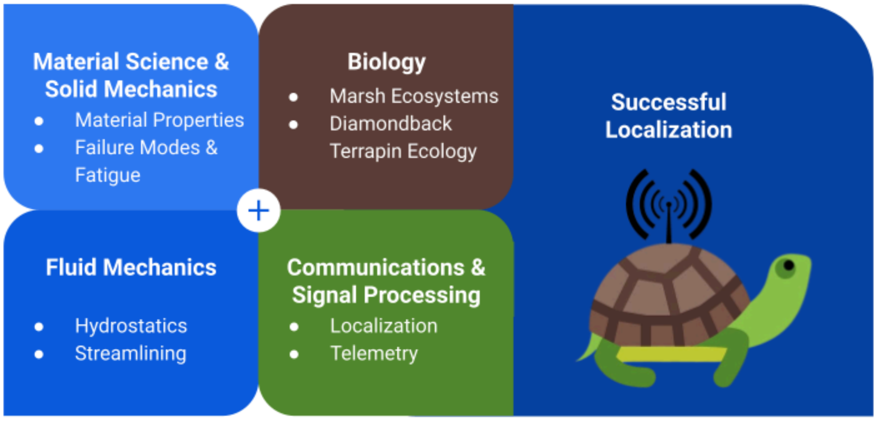


Figure 25. Domain analysis for implementation of a complete solution to Diamondback Terrapin field localization. For this semester's project, focusing on localization technologies, only biology and communications & signal processing are relevant.

While the narrowed scope of this semester's project was beneficial in allowing for a more focused analysis of the localization aspects of the problem, it's worth noting that all the involved domains are very intertwined. For example, achieving a highly accurate localization subsystem may require more massive components and batteries, leaving less material available for structural support and waterproofing. If this subsystem generates excess heat or fluid drag, it may have an impact on the Diamondback Terrapin it's tracking, ultimately manipulating the data. That said, with more time it would be helpful to broaden the scope of the project, and analyze all aspects of the design problem in tandem. This would build a better understanding of the necessary compromises a successful solution must make, and ultimately lead to less problems in later design phases.

In reality, all design processes are limited by time and available resources. Were the scope of the problem to remain constrained to localization technologies, an improved understanding of Diamondback Terrapin ecology alone would have been fundamental to better defining the design problem. Using additional interviews with researchers, further reading of previous publications, and travel to saltwater marsh ecosystems, we may have been able to better establish necessary device longevity and sampling rate, two parameters that remain somewhat ambiguous. For example, if it's observed that terrapins move slowly and continuously, a much lower sampling rate may be required to develop a full understanding of their motion than if they travel quickly and intermittently. While the solution that's been developed is versatile and broadly applicable, a more focused approach with more background information may better fit the design problem.

Finally, wildlife localization is not a new or unique challenge, even if the currently discussed application to Diamondback Terrapins is. In addition to studying the capabilities of previous off-the-shelf solutions throughout the benchmarking process, it would have also been beneficial to study their design processes. Many of the challenges faced throughout our design process are also likely not unique, and we may have been able to take inspiration from how past engineers have overcome them to work more efficiently and develop a superior solution.

Design Critique

Strengths

In comparison to off-the-shelf benchmarked solutions, the localization system developed in this project boasts numerous advantages. With the use of GPS data collection it's capable of achieving global range without any additional infrastructure, such as ground stations needed by VHF or WiFi systems. While we didn't achieve our intended position accuracy of < 1 [m], our system still boasts improved accuracy over many systems which achieve ≈100 [m] or 1 [km] scale metrics. Finally, a primary strength of our system is how it uses an integrated GSM architecture to leverage cellular networks and return data without needing to collect the device or deploy collection antennas.

Weaknesses

Although our device has achieved some success, it does still have some notable shortcomings, or weaknesses. With this semester's project only focusing on localization technologies, the developed solution is far too large to actually mount to a Diamondback Terrapin. In tracking applications, any hardware affixed to the animal is typically minimized below 5 [%] of their bodyweight [3]. This non-localization specification is defined in **Appendix A**, and is ≈40 [g] for a large adult Diamondback Terrapin. The mass of the current hardware is far too large to implement practically. This weakness must be addressed, likely by translating components to a single printed circuit board (PCB) in future semesters, which is discussed further in the future work section below.

In addition to the large device size, the accuracy of our design solution is much larger than our intended ±1 [m], which can be addressed in two ways. First, it may be useful to reevaluate the necessity of achieving this level of accuracy, as the current ±8.57 [m] may be enough to understand the movement of the Diamondback Terrapins. Notably, this is already a major improvement over the data available from most off-the-shelf localization devices. If it's determined that achieving this accuracy is necessary it will undoubtedly be necessary to explore alternative data collection subsystems. One promising option is GPS RTK (real time kinematic), which can achieve an accuracy of < 1 [cm], shown below in **Figure 26**.

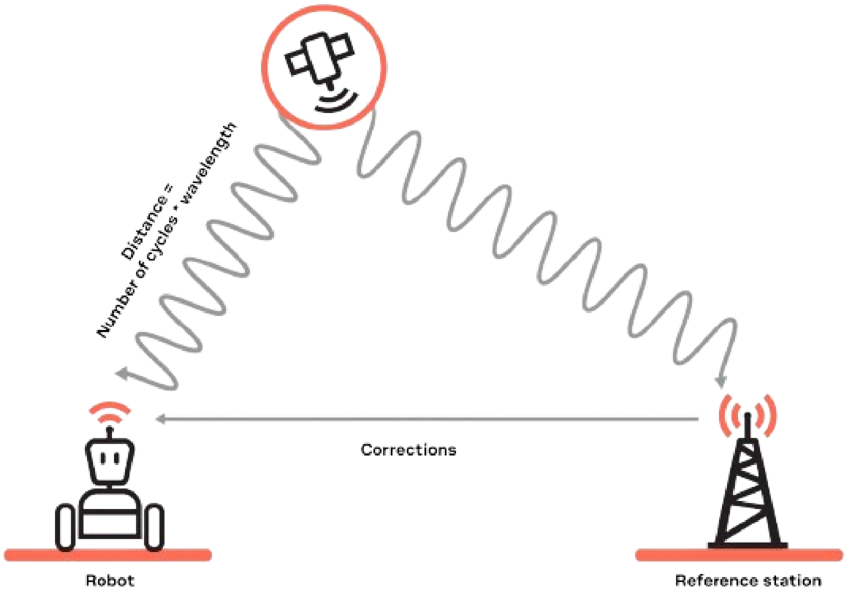


Figure 26. GPS RTK normal operation. Whereas typical GPS requires no additional infrastructure, GPS RTK uses a ground station at a known location to provide correction data and achieve a high level of accuracy. (image: [26]).

While GPS RTK appears to completely solve the accuracy issue of the current design, it doesn't come without costs, both financial and operational. Purchasing, mounting, and maintaining ground stations is expensive and challenging, especially in a delicate marine environment. That said, there may be functional public-use correction stations in the St. Joseph Bay area to provide GPS RTK functionality at lower cost. Still, the improved accuracy of GPS RTK is not global, only having a major effect for ≈20 [km]. These tradeoffs must be considered in great detail, and it's likely that the current hardware is sufficient for almost all Diamondback Terrapin localization applications.

Risks

From the power consumption verification testing previously discussed, it was discovered that GSM operation and transmission has a much greater power consumption than any other included functionality. As such, we made the decision to completely switch off the GSM breakout board between transmissions, allowing the GPS breakout board to operate primarily alone. In order to minimize the number of transmissions sent, we also decided to aggregate location data into larger messages. With the SMS limit of < 160 characters, our device is able to fit five data points with a timestamp, latitude, and longitude. Although this solution is beneficial for device longevity, it does delay data retrieval and risk some data loss. For example, if a GPS data point is collected while the device is within GSM range, the data point may be stored, while it could be immediately offloaded. If the device then leaves GSM range, this point must be stored until it returns to GSM range, and may be lost in extreme cases if the onboard memory reaches capacity.

FUTURE WORK

Overview

As our current design is only a build design to evaluate the technologies used in the tracking system, further miniaturization and integration of the three subsystems onto one consolidated PCB is necessary to arrive at a solution that can be deployed in the field. Each of the three subsystems has a central chip that is essential to the functioning of the system: the ATMega328 microcontroller, the MTK3339 GPS chipset, and the SIM5320 GSM module. These three components together have a small combined footprint and mass, and will be a significant decrease in device size compared to the alpha design. Moreover, antennas, currently installed as extraneous parts, can be integrated into the PCB itself to reduce size and mass. A proposed design for the PCB is illustrated below in **Figure 27**. The integrated patch antennas will be printed on the opposite side of the components, oriented upwards, which is discussed further in the section that follows.

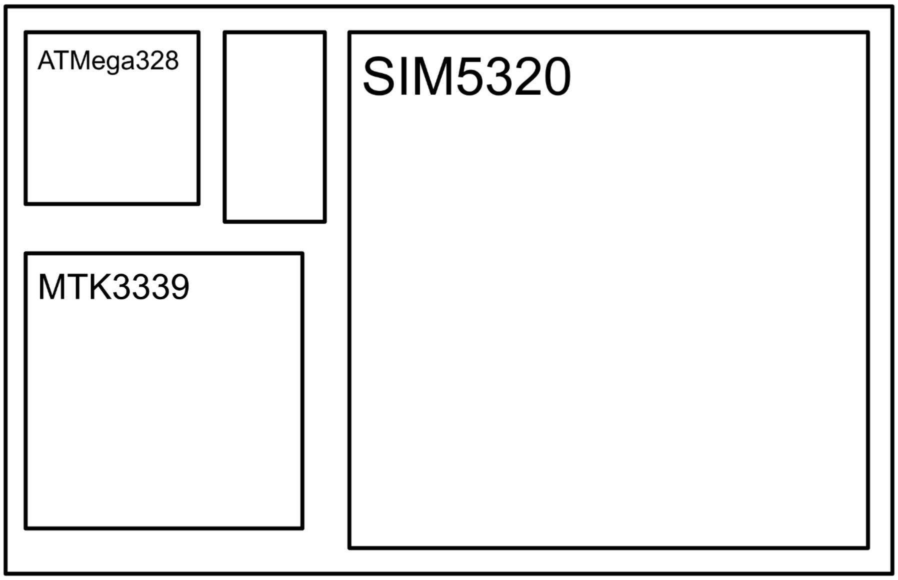


Figure 27. High-level sketch of possible PCB design. Component sizes are approximate, and PCB size and mass is explored more later in this section.

Antenna Design

In purchasing components for the alpha design it was observed that off-the-shelf GPS antennas are often bulky and massive, being optimized for rugged outdoor applications. While the localization solution researched in this project will be outside, it must also be optimized for size in order to fit on the small Diamondback Terrapins. As such, we did a deep dive into how a GPS antenna can be designed to minimize mass for this application.

At a high level, antennas apply a voltage to electrodes to create localized areas of high and low charge density. Through the use of an alternating current (AC) to translate these areas at some frequency *f*, a propagating electromagnetic wave can be created. Changing the shape of the antenna can then alter the positions of these charged areas and, in turn, affect the shape of the electromagnetic wave. This effect also works in reverse, where an externally propagating wave moves charges in the antenna to induce an electric current. A dipole antenna, consisting of two bent electrodes, is one of the simplest antenna designs, and is shown below in **Figure 28**.

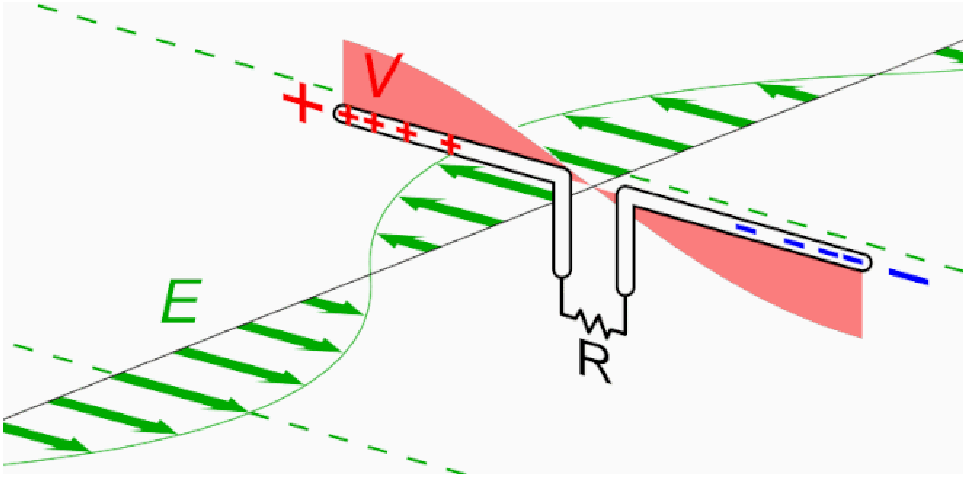


Figure 28. Simple dipole antenna design for clear visualization of fundamental principles. Alternating current can propagate an electromagnetic wave, or an electromagnetic wave can induce an alternating current [27].

In all antenna designs, moving charges will take some time to relocate, and there will be a resonance frequency dependent on both material properties and geometry. Although the antenna can be used at frequencies other than its designed frequency, it will have substantially less efficient operation. In many antennas, including the dipole antenna in **Figure 28** above, the optimal length (of both electrodes combined) is determined to be a half wavelength of the designated frequency.

While dipole antennas like the one above are simple to visualize, they can be large and have weak signal strength. An option optimized for size, and generally better suited to this application, is called a microstrip patch antenna. These antennas are flat and thin, generally made of copper traces printed directly onto a printed circuit board (PCB), and produce a directional wave, well suited for GPS applications with satellites directly above. By altering their size, they can be optimized for any resonance frequency. An illustration of patch antenna dimensions is shown below in **Figure 29**.

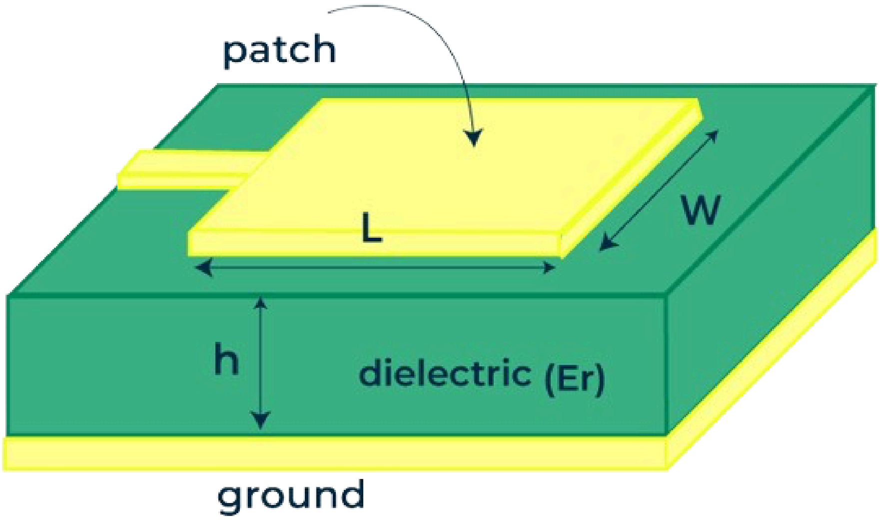


Figure 29. Small-scale microstrip patch antenna diagram. Yellow components are copper traces while green represents the PCB substrate with known dielectric properties [28].

To design a microstrip patch antenna for GPS, the resonant frequency was selected as L1, or f = 1575.42 [MHz] [29]. Using standard PCB materials and dimensions, the substrate was selected as FR4, with dielectric constant ε = 0.4 [28], and the thickness h was chosen to be 1.57 [mm] [30]. Using equations shown in **Figure 30** below [31][32], the optimal width to maximize radiation efficiency was calculated as 60.176 [mm]. Using this result, an effective dielectric constant for the material, factoring in geometry, was found to be 0.38. Finally, the ideal length of the antenna was determined to be 47.333 [mm], slightly less than the L1 quarter wavelength of 47.625 [mm]. This result is intentional and expected, as fringing effects between the patch and ground plane cause it to behave slightly larger than it actually is.

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon + 1}} = \frac{(299792458)}{2(1575420000)}\sqrt{\frac{2}{(4.0) + 1}} = 0.060176\,[m] = \mathbf{60.176}\,[\boldsymbol{mm}]$$

$$\varepsilon_{eff} = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-0.5} = \frac{(4.0) + 1}{2} + \frac{(4.0) - 1}{2}\left(1 + 12\frac{(0.00157)}{(0.060176)}\right)^{-0.5} = 3.8$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)} = 0.412(0.00157)\frac{((3.8) + 0.3)\left(\frac{(0.060176)}{(0.00157)} + 0.264\right)}{((3.8) - 0.258)\left(\frac{(0.060176)}{(0.00157)} + 0.8\right)} = 0.000738\,[m]$$

$$L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{eff}}} = \frac{(299792458)}{2(1575420000)\sqrt{(3.8)}} = 0.048809\,[m]$$

$$L = L_{eff} - 2\Delta L = (0.048809) - 2(0.000738) = 0.047333\,[m] = \mathbf{47.333}\,[\boldsymbol{mm}]$$

Figure 30. GPS microstrip patch antenna design calculations. These are optimized for a resonant frequency of GPS L1 = 1575.42 [MHz] on a 1.57 [mm] thickness FR4 PCB.

While the current system design is primarily focused on testing an external GPS antenna and the integrated ceramic antenna, this analysis provides another feasible path. Namely, if future iterations are very limited by device mass the microstrip patch antenna described above may be a good option. For example, this antenna could even be constructed on one surface of a PCB, with localization modules mounted on the opposite side to conserve space. There's some potential for this design to actually decrease the mass of the overall system (minimally), as some layers of the PCB would be etched away.

Preliminary Mass Analysis

The maximum size of the completed device is the calculated dimensions of a GPS microstrip patch antenna, or 60.176 x 47.333 x 1.570 [mm] (V = 4.472 [cm^3]). Constructed out of FR4, a common PCB material with density 1.85 [g/cm^3] [33], this board would have a mass of 8.273 [g]. From datasheets, the ATmega328-PU has a mass of 2.0875 [g], the MTK3339 has a mass of 4.0 [g], and the SIM5320 has a mass of 5.6 [g]. In total, these components have a conservative mass of 19.960 [g], leaving 20.040 [g] for the battery to meet the mass specification in **Appendix A**. Making a preliminary selection of a lithium-sulfur (Li-S) battery with energy density of 450 [Wh/kg] [34], the chosen battery might have ≈9,018 [mWh] of energy storage capacity. With this selection, a new plot is created for device longevity as a function of sampling rate, shown below in **Figure 31**.

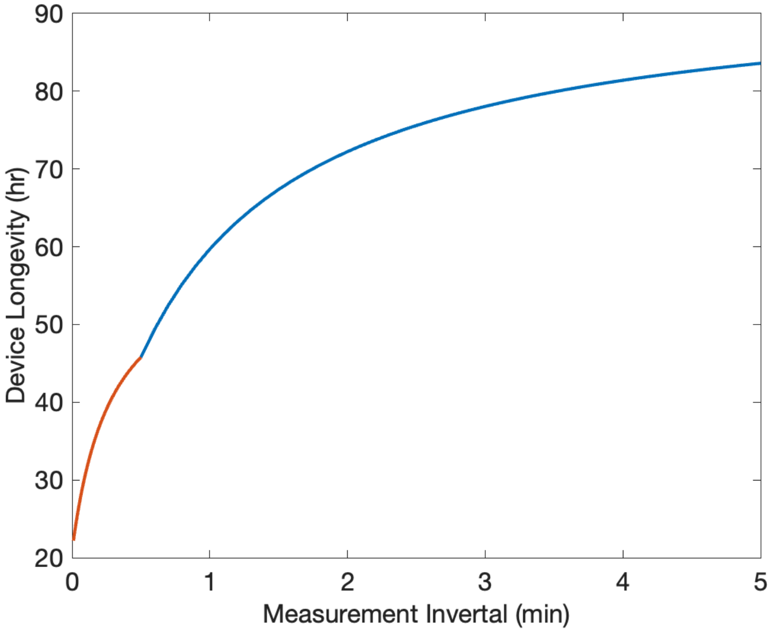


Figure 31. Final design estimated power consumption analysis. Due to mass limitations, the final design must have a much smaller battery than the build design. Even so, by removing some incompatibilities with build design breakout boards and selected power supplies, we anticipate slightly improved longevity.

Notably, the plot in **Figure 31** above is a very conservative estimate. The actual implemented PCB will likely be smaller than estimated. Without additional components, the total power consumption will likely be far less than measured with the current build design. Furthermore, the plot has a limiting longevity of ≈100 [hrs], as the microprocessor currently does not switch off. In a final design, this implementation would likely be changed, cycling the power of all components to save energy. With a very rough estimation of microprocessor duty cycle, the 90 [day] specification may be achievable with a sampling rate of 0.007 [Hz], or a 25 [min] interval between samples. Ultimately, we don't have sufficient information to accurately assess the final solution's ability to meet the 90 [day] specification at this time, although the preliminary results are very promising.

REFLECTION

Social Impact of Design

With the implementation of our product would come the accurate localization of Diamondback Terrapins. The highly accurate GPS module, coupled with a GSM transmission module, would allow for a system that would easily localize the terrapins over the full bay without requiring any maintenance. Hopefully, the gathering of this positional information about the terrapin populations would inform conservation efforts for the terrapins and other similar species. Conserving these indicator species would also indirectly preserve the health of the saltwater marshes, which are essential in saltwater filtration, fishing resources, and storm flood protection in nearby communities. Access to food, water, and safety directly concerns the public welfare in the St Joseph Bay area.

Our design itself also is relevant to the global marketplace for localization strategies. If our design were to succeed in localization and thus inform the conservation of Diamondback Terrapins, then our solution, or solutions inspired by ours, may be used for other animals of similar size. In other words, our system could go on to inform conservation efforts of other small land animals. Furthermore, the significant cost reduction in requiring no ground stations, due to the use of GSM, could possibly allow for more resources to be allocated to the localization market, which would in turn lead to more localization projects for animals.

The manufacture, use, and disposal of our design has certain social and economic impacts. Primarily, the use and disposal of our design are both involved in placing the system on Diamondback Terrapins and dispatching them into their habitat. However, leaving these tags on the animals, as previously discussed, could potentially harm their well-being. This is due to the large size and the potential for any battery leakages to pollute the area. Furthermore, once a terrapin is dispatched, it would not be recovered until after the study, if at all. This means that if any terrapins are lost, our design has contributed to littering the environment with plastics and toxic metals. The harm to the environment and any animals in it also manifests as a negative social impact, due to the previously discussed social and economic role saltwater marshes take. To weigh whether these potential concerns are large enough to pause development on the localization system, our team considered appeasing the primary stakeholders, including the USGS and the terrapins themselves. While our system may harm a handful of terrapins and some immediately surrounding wildlife in the short term, our system would also localize the general terrapin population as a whole, indirectly assisting in any conservation efforts for them.

The production of our GPS and GSM system in particular would eventually require PCB manufacturing, which involves printing a film of the design onto copper foil. Purification of this copper involves the release of sulfur dioxide and the usage of fossil fuels, a finite resource, to heat the required furnaces [35]. Aluminum, another vital metal in PCB production, is thought to require 6-8 [kW] per hour per pound in electricity to be produced [35]. The batteries providing constant electrical energy would also need fossil fuels to be produced. Our team has used Granta EduPack [36], a materials selection and eco-design software, to assess whether the life-cycle cost would be significant enough to consider no longer following through with our solution. Using this software, we've found that the life-cycle cost for our localization system is approximately $544.53, with manufacturing costs as the primary contributor. For reference, this life-cycle cost is much lower than the $5000 cost specification recommended by Dr. Lamont in **Appendix A**.

Inclusion and Equity

Cultural, privilege, identity, and stylistic similarities and differences between us team members have influenced the approaches that we took throughout the project, as well as the design processes and final design. Our differences allowed for a more robust design solution, since the differing viewpoints from our many backgrounds were utilized during the design process. Having multiple different viewpoints allowed for more ideas to be considered and tested. Our approach to general discussions was purposefully inclusive and collaborative in order to ensure that every team member's opinion was accounted for. Our similarities, particularly that we are all currently undergraduate students in engineering at the University of Michigan, has provided us with an advantage of having better understanding and communication, having completed the same curriculum and developed similar problem-solving skills. This made for discussion sessions, such as those during the concept generation and selection phases, to go smoother, since we were all nearly on the same page.

Due to our team's general shared level of experience, there were no significant power dynamics between the members of the team. This was an advantage, since the environment was kept stress-free, with everyone's opinions respected. There did exist notable dynamics between our team and the stakeholders. While we are familiar with signal processing and microcontrollers, we do not have extensive experience with using, testing, and designing localization tags. Meanwhile, Dr. Lamont has had experience with using localization tags with the USGS, studying similar animals to the terrapins. This difference in experience imposes a power dynamic between the team and the sponsor where we might have felt inclined to mostly listen to her ideas for requirements and design components, rather than coming up with our own. This can also be thought of as a cultural difference between us and the sponsor, changing our approach. Because we are all students, and have not been in the work field yet, we may have been more receptive to criticism and expectations that the sponsor had.

Additionally, there was a power dynamic between us and the diamondback terrapins. We, as human researchers, have an advantage over them in understanding what exact implications our solution may have on their own health and wellbeing. Therefore, it is our responsibility to prevent the design from having any potentially harmful effects. This relates back to the discussion of the animals in the St. Joseph Bay area as being stakeholders who could be negatively affected by the size of the device, litter, or any battery leakages.

Our team's identity and experiences, as compared to the end users of our product, has made us more methodical, since we were students who are developing the product ultimately with the expectation of a grade being assigned to us. Furthermore, because we have never worked in the field with Diamondback Terrapins as the USGS has, we were perhaps less aware of just how important the product would be.

Generally, stakeholders' and team members' viewpoints were all considered. In the concept generation process, every single design concept was recorded, and then filtered through plausibility filtration and a pugh chart. In terms of general criticism, the sponsor's opinions were considered as being of the highest priority, since they were who tasked us with this localization problem. The well-being of the terrapin as a stakeholder was also at the forefront, when considering solutions that may be too large in mass. In some cases, third party engineers' opinions helped shape our design choices. This occurred during our many design reviews held in front of other ME450 teams and professors. They would provide a useful outside perspective on whether all stakeholder needs are met, including range and accuracy. In particular, our team learned from them to prioritize the localization aspect of the problem, rescoping our design process. They also reinforced the importance of our GPS module having relatively low accuracy, which inspired us to consider more advanced GPS subsystems for future prototypes. Whenever there were multiple different viewpoints between the team members on a given design choice, a small vote typically took place in order to choose the best path forward. The team members holding each viewpoint were encouraged to explain why their proposed choice would work. Notably, this happened when our team was weighing whether to use VHF or GSM as transmission technologies. While VHF transmission had much more widespread historical usage in wildlife tracking, the team voted that GSM would more easily cover a large area without requiring external ground stations, which would impose a complexity and cost of their own.

Ethics in Design

In the design of our project, a primary ethical dilemma is that concerned with conducting the study on the actual Diamondback Terrapins. If our system is too big in mass, then it may hinder their movement or lifestyle, or even endanger them to predators. This ethical dilemma motivated our sponsor, Dr. Lamont, and us to define a requirement and specification based around it. If our system were to enter the marketplace, this same problem would take place on a much bigger scale. Currently, the USGS has stated that they would plan to study around 10 terrapins. However, having our system in the localization marketplace means that significantly more animals would be subjected to the extra weight and potential litter that our systems would create. Our team "managed" this concern by considering that our localization system should provide sufficient information about the terrapins to aid in the conservation of their entire species. This implies trade off between burdening a small fraction of the Diamondback Terrapins and potentially helping conserve the entire population.

Our team's personal ethics are largely aligned with those of the University of Michigan. However, our team would likely hold the well-being of the terrapins and nearby wildlife to a higher concern, whereas the university would likely prioritize adequately solving the sponsor's problem. A future employer, such as the USGS, may similarly prioritize solving the localization problem, since there are business obligations for them to fulfill as an earth mapping agency.

CONCLUSION

Saltwater marshes are vital ecosystems throughout the east coast of the United States. Recently, as a result of nearby coastal development, climate change, and declining water quality, these habitats are at risk. Diamondback Terrapins, through their role in feeding on potentially harmful snail populations, act as an indicator species for the health of the marshes. As such, the ability to track the movement of Diamondback Terrapins would be fundamental in informing saltwater marsh conservation strategies. In the past, this has been a challenging task, as most marine wildlife localization solutions are designed for larger animals and require less accurate measurements. This semester, our team attempted to solve this problem through an investigation of a variety of alternate localization methods for applications with Diamondback Terrapins.

We began by building an in-depth understanding of the problem. We researched localization technologies, read publications on previous studies, and interviewed stakeholders including the project sponsor, Dr. Lamont. The information gained in these steps was fundamental in constructing a cohesive list of requirements and specifications – guidelines that will help quantify how a successful solution should behave. Because this project originated as a result of the shortcomings of off-the-shelf solutions, many requirements are focused on improving these pitfalls including achieving high accuracy over a large range. More specifically, this project hopes to develop a strategy for Diamondback Terrapin localization around the 9.7 x 24 [km] St. Joseph Bay in Northern Florida.

Along the way, we also investigated off-the-shelf localization products including Argos, Motus, and SnapperGPS, and discovered none quite meet the needs of the project. As such, we moved on to researching localization technologies such as GPS, WiFi, and RFID, finding numerous promising solutions. With these as a starting point, our team brainstormed 60 unique localization strategies with potential to solve the design problem. From here, a functional decomposition was used to split the design problem into two distinct components: (1) localization and (2) data recovery. With additional solutions generated with the assistance of a morphological chart, a tiered filtering approach was used to down-select, leaving just 7 potential approaches. Finally, a pugh chart was used to select a GPS and GSM integrated strategy for additional development.

Leveraging the global range of GPS, this solution is intended to collect location data at set intervals whenever the Diamondback Terrapin is above the surface of the water. Further, the GSM (cellular networks) decision capitalizes on the coastal home-ranges of Diamondback Terrapins, which have widespread coverage in the St. Joseph Bay area. In practical use, the device will collect GPS data throughout the day, waiting to transmit data until it returns to GSM coverage. This solution is low-power, providing high accuracy and essentially global range without requiring additional infrastructure. For this semester, GPS and GSM breakout boards were used for rapid prototyping, and an Arduino Nano was used to control the device throughout the testing process.

By design, this solution meets range specifications, with global GPS range and adequate GSM coverage in St. Joseph Bay. Further, verification testing confirmed very reliable GSM data transmissions while under coverage. Notably, the accuracy specification of < 1 [m] was not met, with a calculated value of 8.17 [m]. While it's worth revisiting how this requirement was defined, if it is necessary to meet, future iterations may need to explore other localization technologies, such as GPS RTK. Finally, accelerated validation was also conducted on the same size scale as St. Joseph Bay, indicating the device can successfully provide a qualitative idea of where the device has traveled.

Beyond analyzing additional technologies to achieve higher accuracy, future work will primarily involve translating the technologies investigated this semester into a smaller form, on a single PCB. It's anticipated that device performance will be somewhat altered by this process, and new calculations will need to be conducted for accuracy, transmission reliability, and power consumption to inform battery selection and estimate longevity. While PCB design was out of the scope of this semester's project, it's absolutely necessary to achieve a product that can be implemented on Diamondback Terrapins. Ultimately, this semester we've been able to identify a solution to the design problem, construct a working prototype, and verify its ability to meet the defined specifications. We focused on laying the groundwork for future engineers, setting them up for success, and streamlining the processes they'll need to take to get the product to the finish line.

REFERENCES

[1] United States Environmental Protection Agency, “Southwest Florida Assess Salt Marsh Vulnerability to Sea Level Rise,” from https://www.epa.gov/arc-x/southwest-florida-assesses-salt-marsh-vulnerability-sea-level-rise

[2] Florida Department of Environmental Protection, “Salt Marshes,” from https://floridadep.gov/rcp/saltmarshes

[3] United States Geological Survey, “Satellite telemetry reveals space use of diamondback terrapins,” from https://www.usgs.gov/publications/satellite-telemetry-reveals-space-use-diamondback-terrapins

[4] GISGeography, “How GPS Receivers Work - Trilateration vs Triangulation,” from https://gisgeography.com/trilateration-triangulation-gps/

[5] Argos, “Argos User’s Manual,” from https://www.argos-system.org/wp-content/uploads/2023/01/CLS-Argos-System-User-Manual.pdf

[6] LABmaker, “ARGOS Horizon GPS Dev Board,” from https://www.labmaker.org/products/argos-horizon-gps-dev-board

[7] Mackenzie, “The Motus Wildlife Tracking System: working collaboratively to cover more ground,” from https://partnersinflight.org/the-motus-wildlife-tracking-system-working-collaboratively-to-cover-more-ground/

[8] Xeos, “A Comparison of Iridium vs Argos Technology in Xeos Location Beacons,” from https://xeostech.com/comparison-iridium-vs-argos-technology-xeos-location-beacons#:~:text=In%20Xeos%20Iridium%20products%2C%20the,frequencies%20that%20plague%20GPS%20systems

[9] ATS, “G5-L2A Iridium/GPS Tracker,” from https://atstrack.com/tracking-products/transmitters/G5L2A-Iridium-GPS-Tracker.aspx

[10] Adafruit, “SnapperGPS: a low-cost/power GNSS receiver for wildlife tracking,” from https://blog.adafruit.com/2023/10/03/snappergps-a-low-cost-power-gnss-receiver-for-wildlife-tracking-gps/#:~:text=Employs%20multiple%20satellite%20systems%20for,the%20temperature%20in%20addition%2C%20and

[11] iSiTech, “iSi-Tag from iSiTech: Real-time livestock and wildlife management,” from https://isitech.co.za/

[12] Learn, “Wifi-equipped Animals Can Improve Field Monitoring,” from https://wildlife.org/wifi-equipped-animals-can-improve-field-monitoring/

[13] Wynn and Clarkson, “Models of Designing”

[14] tractive, “GPS vs Bluetooth Trackers: What’s Best For Pets?” from https://tractive.com/blog/en/tech/pet-tracking-device-comparison-bluetooth-vs-gps-tracker

[15] inpixon, “Wi-Fi RTLS, Location Tracking & Positioning,” from https://www.inpixon.com/technology/standards/wifi

[16] O’Donohue, “How Accurate Is GPS,” from https://mapscaping.com/how-accurate-is-gps/#:~:text=With%20a%20clear%20view%20of,(33%20to%2066%20feet)

[17] Murray Associates, “World’s Smallest GPS Tracker,” from https://counterespionage.com/worlds-smallest-gps-tracker/

[18] Acácio, “Performance of GPS/GPRS tracking devices improves with increased fix interval and is not affected by animal deployment,” from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8966994/

[19] Fisher, “Locating large insects using automated VHF radio telemetry with a multi-antennae array,” from https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/2041-210X.13529

[20] Revathi et al., “Precise Positioning of GPS Receivers using Least Squares Method,” from https://www.serialsjournals.com/abstract/40748_ch_67_-_58._revathi-new.pdf

[21] BasuMallick, “What is GSM (Global System for Mobile Communications)? Meaning, Working, Architecture, and Applications,” from https://www.spiceworks.com/tech/networking/articles/what-is-gsm/

[22] Baddeley, “GPS - NMEA sentence information,” from https://aprs.gids.nl/nmea/

[23] Scadacore, “United States Cell Tower Map,” from https://www.scadacore.com/tools/rf-path/cell-tower-map-united-states/

[24] BasuMallick, “What is GSM (Global System for Mobile Communications)? Meaning, Working, Architecture, and Applications,” from https://www.spiceworks.com/tech/networking/articles/what-is-gsm/

[25] University of Michigan, “Bursley-Baits - Logistics, Transportation & Parking,” from https://ltp.umich.edu/campus-transit/routes-and-schedules/bursley-baits/

[26] u-blox, “Real-Time Kinematic (RTK),” from
https://www.u-blox.com/en/technologies/rtk-real-time-kinematic

[27] Wikipedia, “Dipole Antenna,” from https://en.wikipedia.org/wiki/Dipole_antenna

[28] Altium, “FR4 Dielectric Constant and Material Properties,” from
https://resources.altium.com/p/fr4

[29] Nist, “Time and Frequency from A to Z, G,” from
https://www.nist.gov/pml/time-and-frequency-division/popular-links/time-frequency-z/time-and-frequency-z-g#:~:text=All%20GPS%20satellites%20broadcast%20on,on%20L5%20at%201176%20MHz

[30] OurPCB, “Standard PCB Thickness - Determine the Right Standards,” from
https://www.ourpcb.com/standard-pcb-thickness.html#:~:text=The%20typical%20PCB%20thickness%20is,electronic%20devices%2C%20which%20included%20PCBs

[31] Peterson, “Build Your Own Patch Antenna for Your Next PCB,” from
https://resources.altium.com/p/build-your-own-patch-antenna-for-your-next-pcb

[32] Montoya, “Microstrip Antennas - Rectangular Patch,” from
http://montoya.sdsmt.edu/ee483_583/notes/rect_patch_tl.pdf

[33] EDCOR, “Printed Circuit Boards (PCB),” from
https://edcorusa.com/pages/printed-circuit-boards-pcb

[34] Zeta Energy, “Breakthrough Lithium-Sulfur Battery Technology,” from
https://zetaenergy.com/

[35] Design Life-Cycle, “Life Cycle of a Printed Circuit Board,” from
http://www.designlife-cycle.com/printed-circuit-board#:~:text=The%20most%20common%20gas%20released,the%20production%20of%20a%20PCB

[36] Ansys, “Granta EduPack”

[37] Barbara Brennessel et al., “Diamonds in the Marsh: A Natural History of the Diamondback Terrapin,” from https://muse.jhu.edu/book/84291/pdf

[38] Theresa Conant, “Diamondback Terrapin,” from
https://www.ncwildlife.org/portals/0/learning/documents/profiles/diamondback_091611.pdf

[39] BioMed Central, “Best practice recommendations for the use of fully implanted telemetry devices in pinnipeds,” from
https://animalbiotelemetry.biomedcentral.com/articles/10.1186/s40317-017-0128-9

APPENDIX

Appendix A. Additional Requirements & Specifications

Table A.1. Non Localization-Focused Requirements & Specifications

Requirement	Specification(s)	Source(s)	Measuring Strategies
Affix to average female Diamondback Terrapin without interfering with movement (maximum 5% mass)	Maximum length << 18 [cm] Combined equipment mass < 40 [g]	[3] [37] [38][39]	Measure with a ruler and electronic scale
Survives the movement patterns of Diamondback Terrapins	Can sustain > 6 [m] salt water depth for > 5 [hours]	[1] [3]	Prototype endurance testing at equivalent depth in pool
Device doesn't attempt to communicate while submerged	> 95 [%] confidence in submerged status	[1]	Blind testing submerged and unsubmerged
Costs less than comparable alternative solutions	< $5000 total cost if using GPS capabilities < $1500 total cost otherwise	Dr. Lamont	Market research and/or component cost breakdown

Appendix B. Concept Generation & Selection

CONCEPT GENERATION

To generate concept solutions we utilized two stages of concept divergence to expand our pool of possible ideas: brainstorming and a morphological chart. These concept generation stages are visualized on the left side of **Figure B1**.

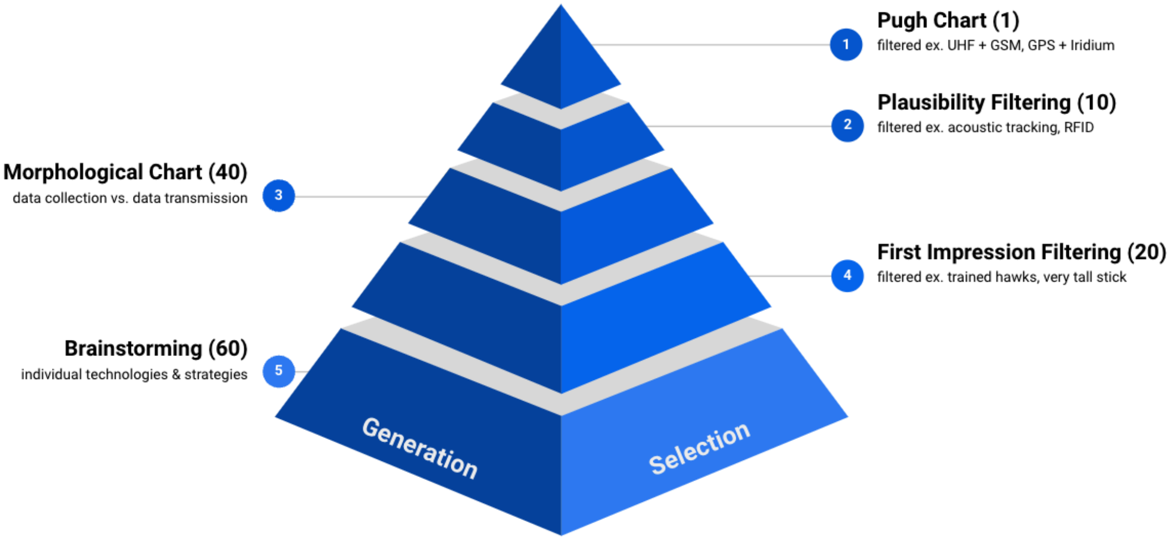


Figure B1. Concept Pyramid; concept generation processes on the left, selection processes on the right; processes in ascending chronological order. Number in parenthesis indicates the number of concepts at the end of the stage.

Brainstorming

Brainstorming was done by all four of our team members and consisted of an initial brainstorm of 20 unique ideas then a secondary step of iterating those ideas for 20 more ideas. Most of our iterations utilized the functional decomposition tool to expand on the original 20 ideas. Initial brainstorming led to a total of 60 unique ideas, as seen in **Table B1**, ranging from sonar buoys to fluorescent dyes. Sonar represented the more traditional and tried solutions of signal-based localization, being a common example of underwater signaling. Sonar signaling has been used in marine settings, but has a few drawbacks. Principally, it has limited range and exclusive underwater functionality for our semi-aquatic terrapins, but also could have environmental impacts on nearby marine life with sensitive hearing. On the other hand, solutions like fluorescent dyes imagined alternative approaches where specimens could be marked then combined with another solution for visually monitoring their locations. While this solution is minimally invasive and lightweight, it could increase the visibility of the terrapins to predators and also would require a form of intensive video surveillance to constantly monitor the locations.

Table B1: Unique Brainstorming Concepts

1. Reflective tags
2. Metal detectors
3. Fake snails
4. Dogs
5. GSM
6. Hire people
7. Turtle feeders
8. Radioactivity
9. Dead reckoning
10. Breadcrumb trail
11. Turtle train
12. Group turtle triangulation
13. Solar powered GPS
14. Shell-recognition
15. Biodegradable tags
16. Drones
17. Nest tracking
18. Boats with cameras
19. DNA sampling
20. 3d print the housing
21. ML predictive model
22. Buoy system
23. Ant tracking
24. Trained birds
25. Sonar
26. Bluetooth feeders
27. snailGPS
28. Argos
29. GPS
30. GPS + GSM
31. GPS + VHF
32. GPF + RFID
33. MOTUS
34. Bluetooth (fixed)
35. GPRS
36. Wifi drone
37. VHF
38. Ultrasound
39. IR
40. Implanted Trackers
41. Barcodes
42. Light up
43. Follow them
44. Train them to tell you
45. Footprints
46. Dye
47. UV fluorescent
48. Numbered tags
49. Sun and stars
50. Environmental variables
51. Iridium
52. Make them fly
53. GPS + dead reckoning
54. On top
55. On bottom
56. Drone triangulation
57. Balloons
58. Boats with collections
59. Dip it in epoxy
60. Waterproof case

Morphological Chart

For the next stage of concept generation, after first impression filtering (explained in the Concept Selection selection), we formally performed functional decomposition as a group to categorize the various functionalities addressed from the remaining ideas left. Our four initial functions were: Data Collection, Data Recovery, Data Storage, and Antennas, shown in **Table B2**. Data Collection consists of the various ways in which location of the specimen are determined, most of which were via visual markers or signal based. Data Recovery refers to the ways in which that location data was relayed back: again most commonly signal based, or visually through people, cameras, or drones. Data Storage referred to the processing units which would store location data if applicable. Finally, Antenna compared the strengths and weaknesses of various signal antennas. Ideas which met these functions were listed in a morphological chart in **Table B2**, and more solutions which met the functions were introduced. This stage added another 40 solutions as new combinations arose. Another section of note in the morphological chart is Auxiliary Components. Auxiliary components are ideas which compliment–rather than replace– the fundamental design concepts. For instance: environmental sensing or dead reckoning are easily included sensors which can add context and additional information in addition to a separate localization strategy. Salinity and depth sensing can be combined with localization to supplement the original research question and enlist the terrapins as data points on the conditions of the environment itself. Likewise, drones or buoys can serve as stationary or mobile signal stations to support low range signal strategies. Depending on the final solutions, signal stations may be necessary once other considerations have been weighed.

Table B2: Morphological Chart

Functionality	**Design Concepts**					**Auxiliary Components**		
Data Collection	GPS	VHF/UHF	Argos	RFID	Infrared	Acoustic	*Dead Reckoning*	*Environ. Sensing*
Data Recovery	GSM	Iridium	VHF/UHF	Argos	Manual	*Ground Stations*	*Drones*	*Boats/ Buoys*
Storage	SSD (SD card)	HDD (hard drive)	Cloud	Memory	None			
Antenna	Monopole	Standard Dipole	Broadband Dipole	Loop	Slot			

CONCEPT SELECTION

Filtration and Classification

The concept selection process for our team was largely intertwined with the concept generation process. In **Figure B1**, after our team initially brainstormed 60 total ideas, we filtered them down to 20 ideas through "First Impression Filtering". This largely involved judging at a second glance whether each design was realistic or blatantly impossible. For example, using an acoustic system to approximate the location of the terrapins would quickly be seen as insufficient since acoustic tags are not used for animals that spend a large amount of time on land or shallow waters - this idea was filtered out at this stage for that reason. Furthermore, the idea of having VHF transceiver birds fly over the area to collect position data was immediately dismissed due to the large cost and complexity of implementing that idea. After the amount of ideas was narrowed down to 20 this way, 20 more ideas were generated using the morphological chart, as previously discussed. At this time, we realized that it would be more efficient and simple to classify each design concept as being a unique combination of a data collection system and a data recovery system. This can be seen in **Figure B2** below.

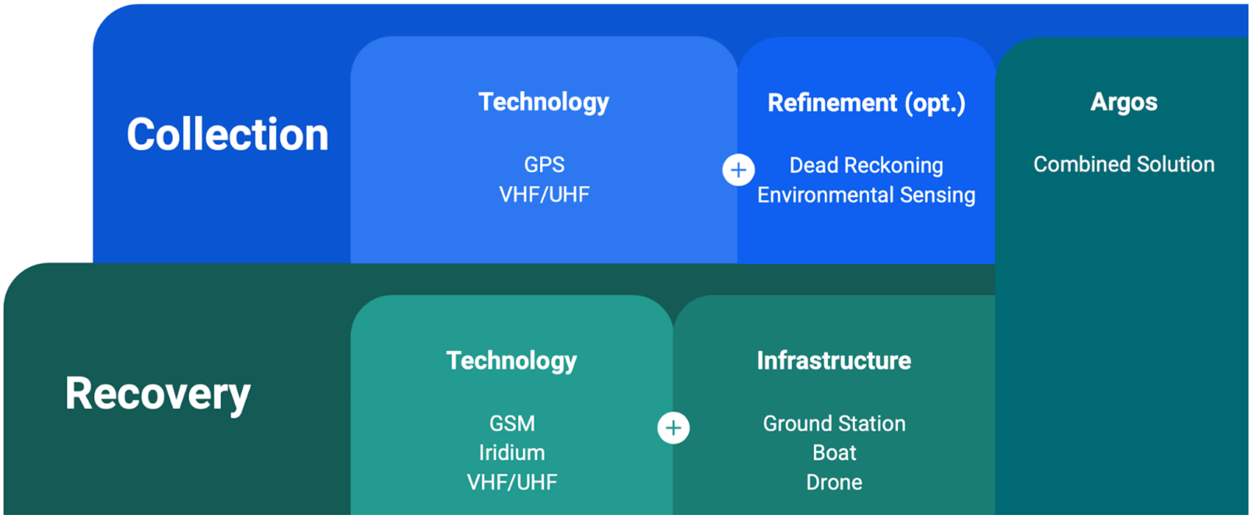


Figure B2. Visual of classification of designs as being a combination of a data collection and recovery system.

As seen from **Figure B2** above, each concept involved a collection and recovery system. For example, a GPS receiver tag with an Iridium tag would be one solution, while a GPS receiver tag with a VHF transmitter would be another. Both of these solutions may share the same collection system in GPS, but they have unique transmission systems. As an exception, Argos is a combined solution which handles both data collection and transmission. After concept generation via morphological chart, our 40 ideas were all classified this way, which allowed for easier (and more realistic) filtration and comparison between ideas.

We narrowed down the 40 ideas that remained to seven using “Plausibility Filtering”. This differs from the first method of filtration in that ideas were judged based on whether they would feasibly meet all of our defined requirements and specifications, as opposed to whether they would be realistic. For example, any solutions involving Wi-Fi or Bluetooth transmitters were eliminated since they did not easily meet the range requirement of 260 [km^2] without multiple receivers or access points. Using GPS alone as a data collection module while expecting the researchers to physically retrieve the terrapin in order to receive the data was eliminated at this time since this failed to meet the requirement of having an onboard data recovery subsystem.

Final Filtration of Best Concepts

Using the seven favorite ideas that remained from “Plausibility Filtering” we implemented Pugh chart filtration. We listed the most important criteria for accurate and feasible localization: accuracy, range, size, and equipment, and judged the seven ideas based on them. Specifically, we weighted each criterion on importance from a scale of 1 to 5, and multiplied those weightings by each solution’s ranking on how well they meet that criterion from a scale of -1 to 1. All of the resulting scores were added for each solution, and the solution with the highest score became the alpha design. This Pugh chart can be seen below in **Table B3**.

Table B3: Pugh Chart

Collection	*Recovery*	*Accuracy*	*Range*	*Size*	*Equipment*	*Score*	*Rank*
Argos [5]	Argos	-1	+1	+1	+1	+5	4
GPS [16]	**GSM [18]**	**+1**	**+1**	**+1**	**+1**	**+15**	**1**
	VHF/UHF	+1	0	+1	0	+9	2
	Iridium [8]	+1	+1	-1	+1	+7	3
VHF/UHF [19]	GSM	0	0	0	-1	-3	5
	VHF/UHF	0	-1	0	-1	-6	6
	Iridium	0	0	-1	-1	-7	7
Weight		5	3	4	3		

Accuracy and weight were chosen to be the most important criteria, following from interviews with our sponsor, Dr. Lamont. These parameters are vital in ensuring localization systems can provide useful data without harming test subjects. Range was considered slightly less important, since most of our remaining solutions involve satellite-level tags. Furthermore, the range of any system without satellite tags would be boosted with extra ground stations. This relates to the equipment aspect, which is a measure of how much extra ground stations or fixed receivers would need to be implemented and maintained. This mostly affects the total cost of the solution, rather than its ability to solve the localization problem.

Discussion of Best Concepts

The five best ideas in our filtration process were GPS & GSM, GPS & VHF, GPS & Iridium, Argos, and VHF & GSM. This subsection will provide a justification of why these ideas are the best while still highlighting the disadvantages of each.

Every concept meets the subfunction requirements of having a data collection system and a data recovery system. The GPS collection solutions all meet the ±1 [m] accuracy specification [16]. Iridium and GSM recovery solutions all allow for very high transmission range, being at least 35 [km], the range of cell towers typically compatible with GSM [18]. The VHF collection/recovery solutions would also technically facilitate a high range provided that they are coupled with enough ground stations. Therefore, these solutions all potentially allow for the entire 260 [km^2] area to be studied. Furthermore, all of these concepts involve components that can integrate together well into a system that has a microcontroller that receives the collected data and communicates to the recovery system to transmit that data.

GPS & GSM has a clear advantage of having a satellite-level collection system with a recovery system that reaches up to 35 [km]. This system would also allow for no additional equipment, since the data would be transmitted back to the researchers directly. Furthermore, the GPS and GSM modules themselves only weigh about 5-12 [g], which would allow for the total system to easily weigh under the required 40 [g] [18]. However, implementing the GSM module with a SIM identifier does add complexity in initial prototyping. This is not much more complicated than using a VHF or Iridium transmitter, however, since a microcontroller is needed to facilitate data transfer either way.

GPS & VHF allows for global data collection, which allows for the required accuracy and collection range specifications to be met. Furthermore, both the GPS receivers and VHF transmitters are around 5-12 [g] in size, which would allow for the size specification to be met. However, VHF transmitters only transmit up to 10 [km], and require fixed receivers in the field. While multiple of these ground stations would allow for the 260 [km^2] area to be studied, they would need to be paid for and regularly maintained, and provide a new level of complexity in themselves.

GPS & Iridium allows for both global collection and recovery, so the range and accuracy requirements are all perfectly met. Furthermore, no ground stations/field receivers would be required. However, the Iridium tags weigh approximately 30 [g], so it would be nearly impossible for the system to meet the size requirement of 40 [g] or less.

VHF & GSM would have good accuracy, at around ±15 [m], but this still is not enough to meet the defined specification of ±1 [m]. Furthermore, the range of a VHF signal is less than 15 [km]. Therefore, it would be difficult to study the entire bay without multiple ground stations. Furthermore, even more ground stations would be needed in this case in order to perform trilateration, since a VHF receiver on the terrapin is being used as the collection system. The recovery system still has a highly sufficient range, at about 35 [km]. A final disadvantage is that VHF receivers are typically heavier than the transmitters, being at about 20 [g]. This would make it more difficult to allow for the whole system to be within 40 [g].

The Argos solution, while being designed for wildlife tracking, does not nearly meet the accuracy requirement in this context, having an accuracy of ±500 [m] [5]. However, the collection and recovery systems are both satellite-level and require no ground stations or extra equipment. Furthermore, since the Argos system is a standalone system that is meant to work with itself to collect and transmit data, it arguably is the least complex of all solutions. Its mass is also satisfactory, being at around 5-12 [g] [6].

Comparison to Original Concepts

Two of the first concepts that occurred to our team when our project was initially assigned include an RFID tag and ground receiver system, as well as a GPS system that communicated through GSM with a SIM card.

The RFID system would work similarly to the VHF data collection systems in our Pugh chart; it has a low working range without multiple ground stations. RFID does heavily exist in the market, but mostly in contexts where a researcher would be nearby with a reader, rather than contexts of remote localization. The GPS & GSM system we initially thought of happens to be the same as our alpha design. While this would on the surface suggest fixation, our team did rigorous research on all localization modules, and the GPS & GSM solution happened to have the highest score on the Pugh chart and meet all the requirements. This similarity can be justified by the fact that, from the start, it was obvious that this solution would accurately localize the terrapins over the entire bay while remotely providing the researchers with the data without any extra equipment or infrastructure.

Appendix C. Bill of Materials (BOM)

Table C1. Build Design BOM

Component	Manufacturer	Part No.	Quantity	Cost ($)
Adafruit Ultimate GPS v3	Adafruit	746	1	$29.95
Arduino Nano	Arduino	A000005	1	$24.90
Adafruit FONA 3G Breakout	Adafruit	2687	1	$79.95
2000 [mAh] LiPo Battery	EEMP Battery	LP103454	1	$13.99
3G SIM Card	Speedtalk Mobile	N/A	1	$0.99 + $10.50/month
GSM Antenna	Adafruit	1991	1	$2.95
AA Batteries	Provided	Provided	6	Provided
Six-Way AA Battery Holder	Provided	Provided	1	Provided
Misc. Connectors	Provided	Provided	N/A	Provided
½ [in] Length 0-80 Standoff	McMaster-Carr	91115A815	4	$3.64/each
½ [in] Length 2-56 Standoff	McMaster-Carr	91115A816	4	$3.64/each
1 [in] Length 10-32 Standoff	McMaster-Carr	91115A153	4	$2.81/each
⅜ [in] Length 0-80 Screw	McMaster-Carr	92196A057	8 (100/pack)	$9.28/pack
⅜ [in] Length 2-56 Screw	McMaster-Carr	92196A079	8 (100/pack)	$8.72/pack
⅝ [in] Length 10-32 Screw	McMaster-Carr	91746A362	8	$3.86/each
6 x 6 x ¼ [in] Cast Acrylic	McMaster-Carr	8536K164	1	$16.84/each
1120 Protector Case	Pelican	1120-000-110	1	$49.95

Table C2. Verification BOM

Component	Manufacturer	Part No.	Quantity	Cost ($)
GPS Antenna - External Active	Adafruit	960	1	$19.95
Ultimate GPS GNSS with USB	Adafruit	4279	1	$29.95
2000 [mAh] LiPo Battery	EEMP Battery	LP103454	1	$13.99
Half-Size Breadboards (2)	Provided	Provided	2	Provided
Misc. Electronic Components	Provided	Provided	N/A	Provided

Appendix D. Team Biographies

Jack Evans

Jack is a senior Mechanical Engineering student from Arlington, Virginia. He decided to study mechanical engineering because he enjoys working with his hands, taking things apart, and learning how they function. In past summers, he's worked on engineering problems in the rail, energy, and aerospace industries. He's also enjoyed teaching introductory mechanical engineering concepts as an Instructional Assistant for thermodynamics. Following his graduation this semester, Jack will stay at the University of Michigan for an additional year to complete his master's degree in Mechanical Engineering. In his free time, Jack enjoys playing trumpet in the Michigan Marching Band and running outdoors.

Mobin Mazloomian

Mobin is a Michigan native growing up right next door to the University of Michigan down Washtenaw Avenue. He applied to engineering because he loves creative problem solving with a genuine curiosity of understanding the world. During his sophomore year, he joined BLUElab which applied real world engineering problems to address social inequality through sustainability and community co-design. That experience pushed him towards mechanical engineering as a broad, all-purpose field which could be applied to today's energy challenges like renewables and carbon neutrality. He also loves to play jazz and classical cello, also recently starting to play the drums.

Zane Seal

Zane is a senior student in mechanical engineering from Riverview, Michigan. He chose to study mechanical engineering because he is interested in learning about the practical tools that can be used to solve real world problems. He also generally enjoys learning how technical things work. Currently, Zane is a part of the University of Michigan Supermileage team, which creates a vehicle that focuses on making the fuel efficiency as high as possible. He is also currently doing research in designing MEMS gyroscopes. His anticipated career path is in the automotive industry, but he also plans on going to graduate school for engineering. As an interesting fact, Zane can play the trumpet.

Yichen Wang

Yichen is a junior student in mechanical engineering from Beijing China. She studies mechanical engineering to learn more about design and coming up with innovative solutions to real world problems. She works as an Instructional Aide for ENGR100.980 and 950, where students learn to design sensor systems for rocket and high altitude balloon systems. She is active in the Locomotor Systems Laboratory, where she helps improve exoskeleton and prosthesis systems. She hopes to continue her research in robotics, focusing on legged and walking robotics. In her free time, she plays the drums and competes with the Michigan Rifle Team.