ROBOTICS FOR UNMANNED UNDERWATER VEHICLE FOR INVESTIGATION OF CORAL

DANIEL PETRO MRUMA
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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

Status of coral is changing due to disturbances in marine ecosystem by climate change, fishing activities and creation of beaches along the coastal areas. Probabilistic robotics using unmanned underwater vehicle can be the most promising method for collecting maximum information about the status of coral reef. Digitized map of coral around Klein Bonaire of 1985 and recent high resolution satellite images (4meter) of 2011 were integrated to give a priori information about current location, extent and distribution of coral reef. To develop and optimize routing for UUV based on robotics technology for acquiring maximum information about coral, we started by designing a straight forward trajectory for entire integrated layer from which the zigzag SLAM technique for optimal route was then proposed and evaluated for investigation in large and complex area with a given set of specification from start point to the target. The proposed zigzag SLAM technique shows that, a UUV can collect enough information for investigation purposes in underwater environment.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Motivation and problem statement

Corals are marine organisms that live in compact colonies of identical individuals. Most of them grow in shallow water where there are sufficient nutrients and light. Due to disturbances in marine ecosystem by fishing activities, land –based pollution and sea temperature increase due to climate change; the ability of coral to resist threat and to recover to its former state has decreased and causes coral bleaching (see Fig 1). To investigate the status of coral reef, different techniques are being implemented including the use of divers, of aerial photograph and of remote sensing images. Employing divers for data collection, however, is time consuming and dangerous especially in the presence of harmful fish. Investigations by using aerial photograph and remote sensing images techniques are limited to getting information of coral reef in shallow water. Robotics techniques might be useful to observe the status of coral under threat at reasonable time and at any depth. Robotics is a science that involves computer controlled devices for manipulating real world problems. It is mostly used for activities that are tedious, repetitive and dangerous to be done by humans. The progress of probabilistic robotics technique (Kaelbling, Littman, & Cassandra, 1998) went hand in hand with the deployment of physical robots.

Probabilistic robotic techniques pay attention to uncertainty in robot perception and action. Algorithms comprising information on probability distributions of robot position and movement need to be identified, then the robot determines its position relative to the environment. It is important for a robot to understand the surrounding environment when it is below the water surface as an unmanned underwater vehicle (UUV). Information extracted from an existing map integrated with a high resolution remote sensing images can serve as a basis for its localization. In real world problems, however, algorithms relying on maps to find out the position of a robot do not fully solve the simultaneous localization and mapping problem. The robot in fact has to do both: mapping the environment and localizing itself relative to this map. This is the so-called simultaneous localization and mapping (SLAM) approach. It is an extension of the robotics algorithms for a complex environment where both an initial map is absent as well as more specific robot position information (Dudek & Jenkin, 2010; Tovar et al., 2006).

A challenge in this research is to combine localization and mapping for a robot when collecting maximum information of the quality of coral by using a UUV. This requires integration of different orientation and mapping procedures. Prior information from previous digitized map and from a high resolution satellite image have to be integrated for a purpose of designing the optimal routing for a robot to collect maximum information of coral status. A camera on board this UUV will help in taking pictures of coral in the scene.

Such information will be correlated with our prior data to build a map of current environment. This map is then compared to previous map to give the current status of coral reefs.

Figure 1: Bleached coral (white foreground) and Healthy coral at background

(Source http://wikimedia.org/wikipedia/en/9/90/Keppelbleaching.jpg)

1.2. Research identification

Currently, robotics is applied together with super resolution satellite image for a range of applications, for example in the crop and weed status within agricultural fields(Slaughter, Giles, & Downey, 2008). Many other applications exist as well, such as robotics for mapping and surveying task (Fong. et al., 2008) and robotics for road construction activities (Bouvet, Froumentin, & Garcia, 2001). This study wants to extend the achievements from such studies to the mapping of coral. Geo-informatics technologies and robotics are to be used to optimize routing for investigation of coral reef. Studies of coral reef by using remote sensing satellite imagery and aerial photograph have been conducted by (Hochberg, Atkinson, & Andréfouët, 2003; Mumby et al., 2004; Yamano & Tamura, 2004). However, these methods become less effective to get coral information at lager water depth. By using a UUV we can investigate coral status at different depths, location and extent.

1.3. Research objectives

The main objective of this research is to develop the optimal routing for a UUV that includes robotics based localization and mapping of coral status. Information from digitized map and high resolution satellite images will be integrated with pictures taken by the UUV on route.

The main objective can be fulfilled by defining the following sub-objectives

i. To integrate information from a digitized existing map and a high resolution satellite image in order to help a UUV localize itself.
ii. To develop the optimal UUV routing for simultaneous localization and mapping of coral.
iii. To find the appropriate method for classification and mapping of coral from underwater images.

1.4. Research questions

i. How can information be integrated from different data sources to help a UUV localize itself and determine the optimal route?
ii. How different robotics based orientation and mapping procedures integrated to serve for coral mapping?
iii. How can the robot routing for localization and mapping be optimized for mapping the coral status?

1.5. Innovations aimed at

The innovations intended in this study are

i. To develop the optimal routing for a UUV based on robotics technology to acquire maximum information on coral status.
ii. To apply SLAM techniques for studying the status of the quality of coral reefs from pictures taken by a camera onboard the UUV and information obtained by integrating digitized an existing digitized map and a high remote sensing satellite image.
iii. To extend localization and mapping algorithms used in robotics toward a full use for a UUV.
iv. To clarify the appropriate method for mapping the coral status from underwater images taken by UUV.

1.6. Thesis Structure

The thesis presents a deep overview of optimal routing for a UUV that include robotics based localization and mapping of coral status by integrating prior information from digitized map and high resolution satellite image.

The thesis is divided into seven chapters.

Chapter 1 presents of motivation and problem statement, objective, research questions and innovations. **Chapter 2** is the literature review which contains overview of unmanned underwater vehicle, simultaneous localization and mapping problem for a UUV, particle filter method for SLAM problem and related works.

Chapter 3 is the description of study area and the datasets which were used in the research.

Chapter 4 describe in detail the methodology applied for the research.

Chapter 5 discusses the results

Chapter 6 elaborates the discussion from this study.

Chapter 7 will elaborate on the conclusions drawn from this research and recommendation for further study.

2. LITERATURE REVIEW

2.1. Historical overview of UUV

The first step to understand any technology is to understand why it exists. In case of UUV technology, it is a practically safe and economically feasible way to perform underwater exploration. Historically, humans have been doing everything by deploying divers to collect underwater information. This technique needs long time for data collection, involves high risk, and is not economically feasible. Human occupied vehicles (HOV) were introduced and appeared to be the solution for underwater exploration for longer periods of time. The problem was, they suffered same disadvantages as that of hyperbaric diving. HOVs require substantial dedicated support vessels and still put humans at risk for long underwater operation. They were also slow to launch and had limited bottom time which makes them economically ineffective. Remote operated underwater vehicle (ROV) was then introduced. ROVs are unoccupied, highly manoeuvrable and operated by a person aboard a vessel, linked to a group of cables carrying electrical power, camera and data signals back and forth between the operator and vehicle. Although this technology improved application for underwater exploration but it could not satisfy the human needs toward development of new technologies. The problem of continuous control and monitoring during the mission provides a challenge to researchers to invent technology that is autonomous. This idea brought the development of unmanned underwater vehicles (UUV).

2.2. Path planning for UUV

Path planning for a UUV is a determination of an optimal path for a robot to collect maximum information about the status of coral with a given set of input parameters from its start point to the target station. An optimal path for UUV can be done in *static* as well as *dynamic* environments. In static environment, the position of surrounding environments are fixed and do not change with time. However in dynamic environment, the position of surrounding environments changes with time. There are two types of optimal path planning, *global path planning and local path planning*. If the robot is given prior information of environment in advance, it is called global path planning and it is designed offline before the robot starts to move. If no prior information is available, the robot has to sense the environment and make its own decision while maintaining its internal belief to reach the target station. The second option is local path planning, this is done online when the robot moves in real time. The main advantages of optimal routing are to reduce running cost, such as time, distance and energy in a known or unknown environment.

2.3. Unmanned underwater vehicle

An unmanned underwater vehicle is a robotic device that is pre-programmed to follow certain trajectories in 3D at defined speed and depth from a start point to the target. To ensure its autonomy, two components must be taken into account; sensing the environment and reasoning. Sensing is provided by sensory on board UUV that gather information about the robot itself and the surrounding environment. Reasoning is accomplished by developing algorithms that exploit sensory information to generate appropriate commands for the UUV. Reasoning is based on a model or description of the environment. Since this model is not always available, the robot should have the means to build such a model over time as it explores its environments. Such a model is called mapping problem. Mapping and localization are interlinked problems, without a precise map the robot cannot localize itself using this map. On the other hand without precise knowledge of its spatial position and orientation, the robot cannot build a representation of its environment. The combinations of these two are so called simultaneous localization and mapping (SLAM) problem.

2.4. Position measurement for uuv

Position measurement is achieved by using Odometry technique or by using velocity motion model (Thrun., Burgar., & Fox., 2005). The UUV senses the environment by using sensors equipped on board, e.g. sonar sensor, range finder and camera. These sensors continuously sense the surrounding environment. The information from the sensors is called observations or measurements. Observations provide detail about the surrounding environment which is then used for state position estimates. Position measurement can be absolute or relative.

- Absolute position measurement provides a position estimate of UUV independent of the estimate of its previous state, it is purely depend on the current sensor information. Thus the position error does not grow over time. This kind of measurement is divided in two categories, one which make use of landmarks and other makes use of maps. Landmarks are the feature in the environment that can be detected by a robot. As the landmark is found it has to be compared against the given a priori information and hence the position of the robot is estimated based on the detected landmark information. There are two types of landmarks which are mostly used, active landmarks and passive landmarks. Active landmarks (Kleeman, 1992), are kind of landmarks that actively send out location information to the robot about its position. Passive landmarks do not send signal to the robot but the robot has to observe these landmarks to estimate its position.
- Relative position measurements are also called dead reckoning. This technique depends on speed, direction of travel and time passed with respect to previous measurement. Hence the position estimate is affected by measurement error which increases over time since the last known

position. Robotics probabilistic techniques are used to minimize uncertainty caused by measurements taken from the robot to reach a required accuracy.

2.5. Localization problem

The problem of UUV localization consists of answering the question ***Where am I***? from a robot's point of view. This means that the robot has to find out its location relative to the known or unknown real world environment. The term location is also known as pose, or position, refers to the (X, Y, θ) coordinates and the heading direction of UUV relative to world coordinate system. If the robot does not know where it is in the environment, it cannot be able to decide what to do. The general localization problem has a number of difficulties, if the initial position of UUV is known the robot will have to track the position based upon the navigation data provided. Techniques that solve this problem are known as position tracking or local techniques (Burgard, Fox., & Thrun.S., 1999). Global positioning problem is complicated and difficult to solve rather than position tracking, here the robot does not have any idea of its initial position and should localize itself from scratch. Techniques that are used to solve this problem are called global techniques (Burgard, et al., 1999).

2.6. Useful information for localization

During unmanned robot localization, the UUV can access several types of information so as to localize itself relative to the environment. One is prior information; this is type of information about the environment given in advance to the robot during its initialization phase. This information specifies certain features that are time invariant and can be useful to localize the robot. A priori information can be in the form of maps or feature relationships. Map of environment provide relevant information of the surrounding environment, it can be provided to the robot during initialization phase or obtained by the robot itself during exploration phase. The map can be in geometric or topological form(Singhal, 1997). A geometric map represents the surrounding environment in a metric format like the well-known normal map while a topological map describes the environment with specific characteristic of feature locations and they also give the information on how to move from starting point to the target station. The second type of information is the one acquired by robot itself about the surrounding environment and the robot has to localize relative to this information. This technique is called SLAM (Simultaneous localization and mapping).

2.7. Simultaneous localization and mapping

Simultaneous localization and mapping is process where by a robot acquire a map of its surrounding environment while simultaneously localize itself relative to this map. Different approaches have been developed to address SLAM problem for a UUV. The most famous techniques are SLAM with Extended Kalman Filters and Particle Filters algorithms (Thrun., et al., 2005).

2.7.1. Particle Filter method for SLAM problem

The particle filter technique of robot localization was initially introduced by (Gordon, Salmond, & Ewing, 1993) as a sequential Monte Carlo method for Bayesian filtering. Particle filters approximate the posterior states by a finite number of parameters which are different according to the way they were generated and populated in state space. These particles represent the posterior states by a set of random state samples drawn from a so called *proposal distribution*. The particles are propagated over time by Monte Carlo simulation to obtain new particles and their weights (Gordsill, Doucet, & Thrun.S., 2000); hence they form a series of probability density function approximation over time. The main objective of particle filter technique is to track a variable of interest over time by weighted sum of all the particles with non-gaussian Bayesian estimation. Particle filter algorithm is a recursive in nature and operates in two phases; *Prediction and update*. During the prediction stage each particle is modified according to the existing mode, include some amount of random noise in order to simulate the effect of noise on the variable of interest. In the update phase each particle is re-evaluated based on the most current sensory information available at that time. Finally the particles with small weights are eliminated leaving particles with high weights. The weight of a particle refers to the probability of a particle to be considered as a real position for a robot during localization and mapping (Ioannis & Rekleitis, 2003).

2.7.2. SLAM with Extended Kalman Filters

Extended Kalman Filter (EKF) algorithms are applied in an online SLAM using maximum likelihood data association. The algorithm uses non-linear models for process and observation stages contrary to previous Kalman Filter (KF) which uses linear models. In doing so, the EKF SLAM is subjected to a lot of approximation and limiting assumptions (Thrun., et al., 2005). EKF algorithm can be used by Odometry technique or by using a velocity motion model. Three-stage recursive are used for EKF position vector estimation $X(t)$ comprising prediction, observation and update steps. Prediction stage for a UUV is achieved by passing the last estimate through the non-linear model of the motion to estimate next position at instant t based on a control input $u(t)$ and previous instant $t-1$. In observation stage, measurements from onboard sensor at certain time t are incorporated into the position state vector $X(t)$. Finally an update is computed using an optimal gain matrix which provides a weighted sum of the prediction and observation from innovation covariance, state error covariance and gradient of the observation model.

2.8. Related work

Several authors have contributed in developing robotics methods and algorithms for simultaneous localization and mapping (SLAM) for unmanned underwater vehicle (UUV) and unmanned aerial vehicle (AUV). The paper by (Bildberg, Turner., Roy, Chappell., & Steven, 1991) elaborates an opportunity for a robot to have a communication policy, communication to the people, processor and building of robot perspective knowledge. The paper by (Slaughter, et al., 2008) describes a method of solving SLAM problems by using a feature based approach. This method uses multiple servo-mounted sonar sensors equipped on board of a robot to sense and build a map of geometric features in a surrounding environment. Localization is achieved by using estimated geometric features location in a map to determine the robot's position. Bouvet, et al., (2001) present a method for Real time localization system for compactors by using real time kinematic GPS for road construction activities. A compactor has to localize itself along all estimated position with the help of RTK GPS embedded. The paper by (Vu, Burlet, & Aycard, 2011) presents a grid-based localization and local mapping with moving object detection and tracking for solving SLAM problems from a moving mobile vehicle equipped with laser scanner, short-range radars and odometry. They introduced an incremental scan matching method for vehicle localization, the map surrounding the vehicle is updated incrementally and the moving objects are detected without a priori knowledge of the targets. The paper by (Stein, 2010) expresses localization based on an advanced image analysis in which the positions have to be well recorded. A graph formulation method for solving SLAM problem by using Aerial images as prior information was presented by (Kummerle et al., 2010). The method describes a feature-based algorithm and graph based approach (Berrabah, Bedkowski, Lubasinski, & Maslowski, 2008) to solve the SLAM problem for indoor and outdoor environment respectively.

The World Resources Institute (WRI) and partners have developed a detailed method for assessment of the threats status to the world's coral reefs, information intended for awareness about the location and severity of threats to coral reefs (http://www.wri.org/publication/reefs-at-risk-revisited). (Ninsawat & Tripathi, 2008) present Mapping of coral reefs by using remote sensing and GIS method for integrated coastal zone management. (Mumby, et al., 2004) presented a study of remote sensing of coral reef and their physical environment. IUCN, (2011) conducted a survey to assess the various resilience characteristics and bleaching threat of coral reefs in the Bonaire National Marine Park. In situ measurement methods were used in this study by divers who had to collect information by using measuring tape and a cage. Status of coral reef was then distinguished according to percentage of volume per square meter and width of the coral cover.

3. STUDY AREA AND DATA DESCRIPTION

3.1. Study area

The study area of this research is selected at the coastline of Klein Bonaire in Netherland Antilles. Klein Bonaire is an uninhabited islet in the west cost of Caribbean island of Bonaire located approximately in $12°09' N$ and $68°18' W$.

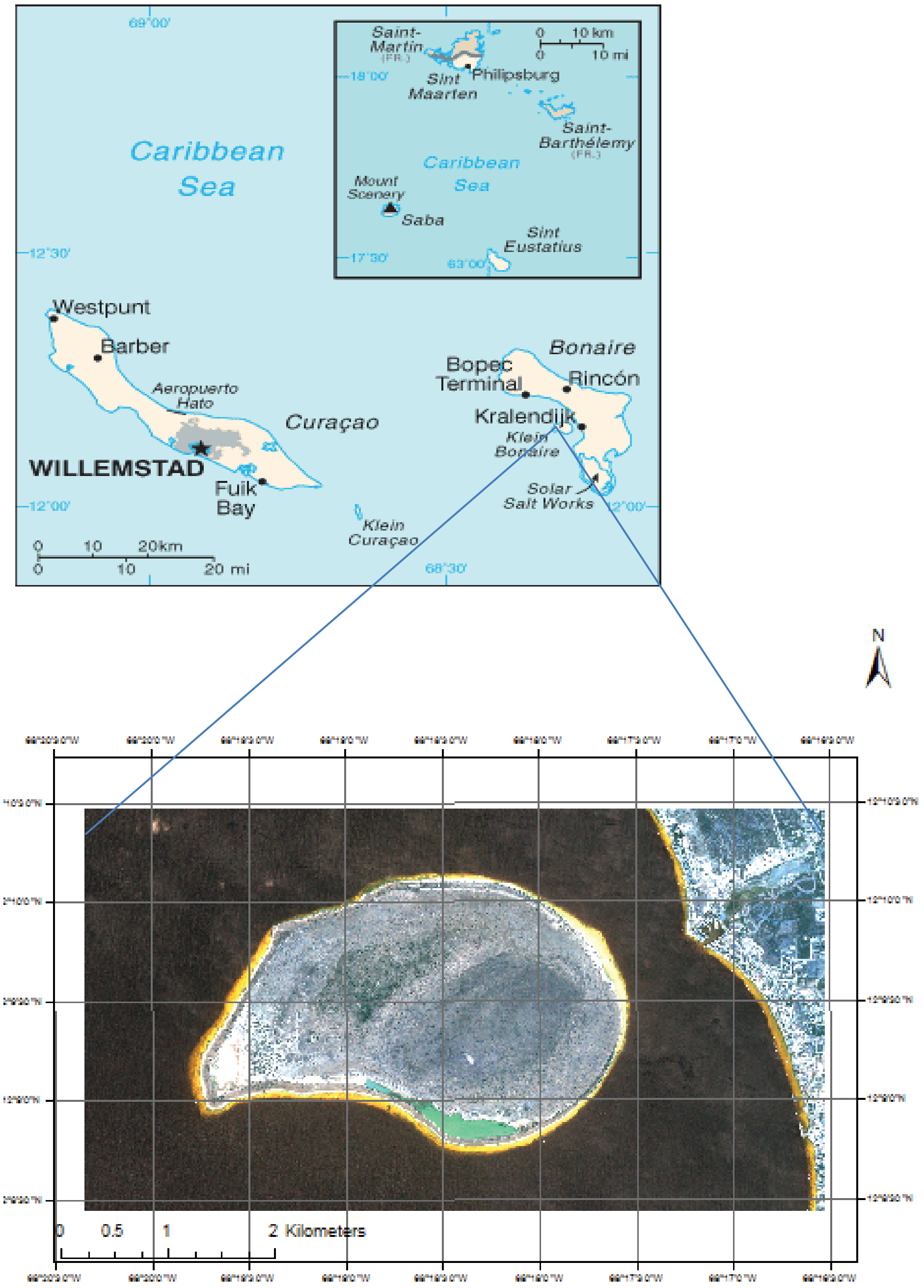

Figure 2: Map of Netherland Antilles shows the location of Klein Island

(http://.wikimedia.org/wikipedia/commons/b/b3/Netherlands_Antilles_before_1986.png)

3.2. Data description

3.2.1. Map of coral reefs

The overall coastline distance of Klein Bonaire is approximate 10,500 meters with diversity of hard and soft coral reef such as acropora palmata, acropora cervicornis, millepora, agaricia, madracis mirabilis, porites foliate, finger, rubble, head, sea fans and sea whips coral group. Klein Bonaire coral reefs were mapped in early 1980 by (Duyl, 1985). The atlas was made up from high resolution aerial photograph and ground truth from SCUBA diving.

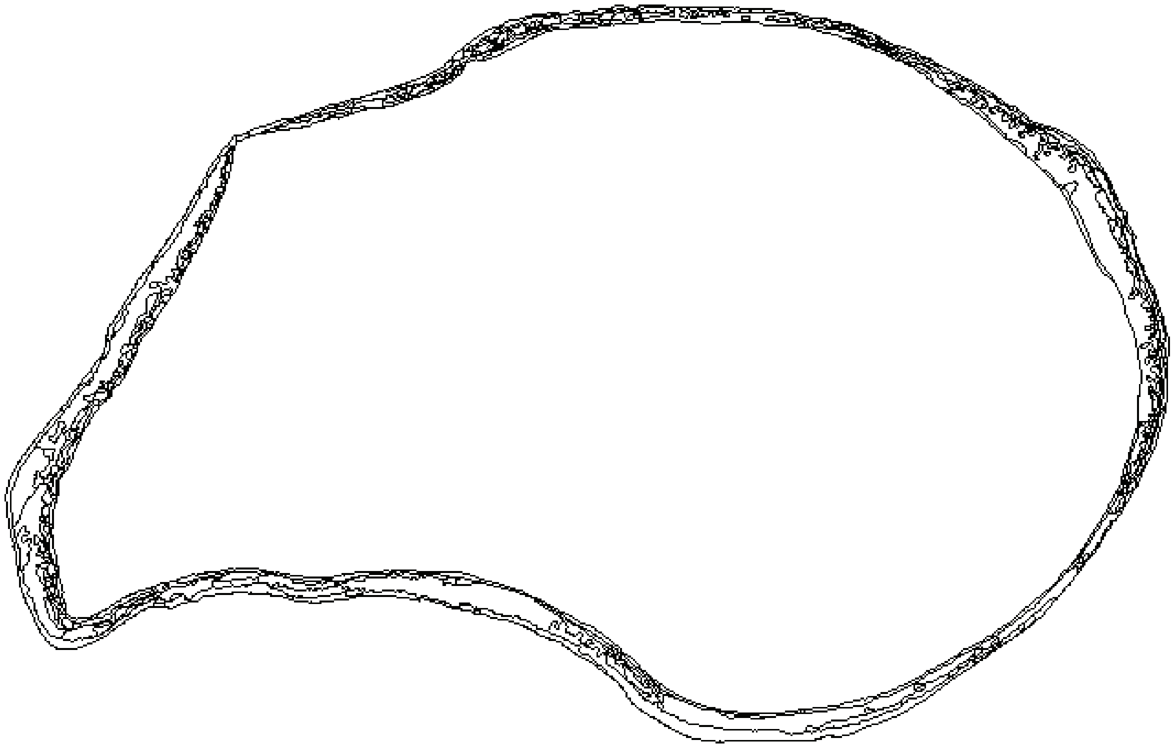

Figure 3: Klein Bonaire Island, from Atlas of Van Duyl (1985) showing distribution of coral

3.2.2. IKONOS satellite image

The IKONOS Satellite is a high-resolution satellite operated by GeoEye. It was launched on 24 September 1999 at Vandenberg Air Force in California USA. The IKONOS image of 11/11/2011 was used in this research with the following spatial and spectral resolution.

Table 1: Spectral and spatial resolution of the IKONOS satellite image as per metadata

Image	Spatial Resolution	Spectral Bands
Multispectral	4 meter	Band 1 (Blue): 445-516 nm Band 2 (Green): 506-595 nm Band 3 (Red): 632-698 Band4 (Infrared): 757-853 nm
Panchromatic	1 meter	450-900 nm

4. METHODOLOGY

The general workflow for this research is shown in Figure 4. Firstly, we extract information of coral reef from each data source. Secondly, the two data sources are integrated to fix the current position of coral reef from map and image. Finally, we design the optimal route for a UUV.

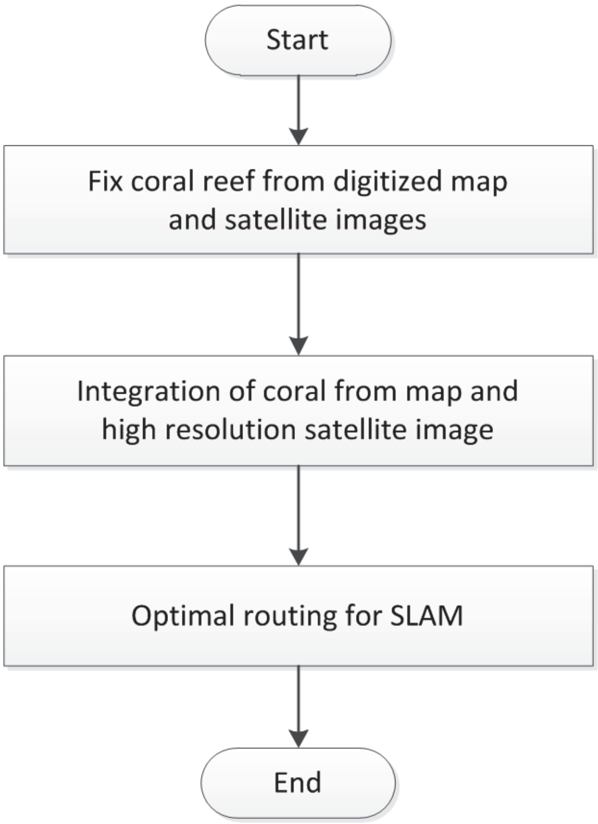

Figure 4: General framework of the research

4.1. Integration of data sources

4.1.1. Coral reef from map

The old digitized shape file of coral reef in 1985 had overall area of 1,033,923.518 m^2. This area did not include coral reefs alone but also marine plants, rubble hard bottom and sand. The coral reefs were divided into eight species, Acropora palmata, Acropora cervicornis, Millepora, Agaricia, Madracis mirabilis, Porites porites, Sea fans and sea whips. Each of the above species were further subdivided according the percentage of coral cover from 10-20%, 20-40% and >40%. Due to above subdivision of coral, the overall digitized map had 305 polygons covering the entire area. For the purpose of this research we grouped coral reef into two types. Predominant hard coral includes Acropora palmata, Acropora cervicornis, Head, Head/foliate and Foliate/finger coral. Soft corals included Sea fans, Sea whips and Head coral with sea whips. The summary of total area in digitized map is shown in Table 2.

Table 2: Distribution of coral reef from digitized map

No.	Types	Area in Square meter
1.	Predominant soft coral	172,977.88
2.	Predominant hard coral	312,689.13
3.	Rubble hard bottom, Sand and Marine plant	548,256.51

4.1.2. Coral reef from satellite image

The best available method for identification of coral reef from the satellite image is to perform image classification technique. Image classification can be done using supervised or unsupervised technique. Supervised technique can be done by selecting a training set for each class in the image. To develop the training sample, we need to have a proper understanding of the objects appearing on the image or to have an in-situ measurement as reference frame. In absence of the knowledge or baseline about the environment, unsupervised classification can be done for the same purpose.

4.1.2.3. Image classification

Delineation of coral reef information from the satellite image was done after performing image classification. We used unsupervised classification to split the whole image into 15 classes according to their spectral characteristic. After classification we were able to identify four homogeneous classes around our area of interest. Due to un-availability of in-situ data we were not able to group types of coral according to their species. The shore zone area was clearly identified as whitish area surrounding the costal. We used the knowledge about distribution of coral from previous digitized map to take decision about the observed classes. From the digitized map we saw that, the most abundance of coral was observed next to rubble hard bottom. By using this knowledge as prior information, we assigned the second class from the classified image as layer with coral reef. The first class was shore zone, sand as second class and rubble hard bottom as third class.

4.1.2.4. Extraction of coral reef layer from the image

Since our research aim was to investigate the status of coral reef, we had to extract the second class (coral reef) as a separate layer from classified image. The task started by converting the entire classified image from raster to vector format, the process known as vectorization. After vectorization, we clipped the area of interest and all the polygons delineated as coral reef in second class was selected and saved in a different layer. Selection of polygons with coral reefs was done by putting the classified image at the background of vectorized clipped layer. Hence by using editing tool we were able to identify and select all vectorized polygons in second class. Since the output vector polygons layer of coral from the image layer was very noisy with small polygons and sharp corners, further editing was done to smoothen and simplify the polygons. All the polygons below 16 m^2 were dissolved, sharp corners were smoothed by 4m tolerance. The parameters used here were selected according to the smallest feature which can be detected from the image (4 meter spatial resolution). Finally we achieved to get a layer of coral from the classified satellite image.

4.1.3. Integration of coral reef from map and image

Delineation of coral reefs from digitized map and a classified high resolution satellite image was integration to get the current spatial location and extent of coral reef. The two data sources were projected to the same projection system WGS_1984_UTM_Zone_19N. By using ArcGIS software we were able to overlay them in one layer. Since both data sets were now in vector format, we used an intersection tool to extract the polygons which appear in the recent image as well as in the older map.

4.2. Design of optimal routing for a UUV

An optimal routing for investigation of coral reef status is a determination of set of parameters which together can facilitate to minimize the total cost such as, time, distance and energy in known or unknown environment. The frame work will include path planning (Trajectory), zigzag SLAM technique for optimal routing and finally the overview method for identification of bleached coral.

4.2.1. Path planning for a UUV orientation

Path planning of Autonomous Underwater Vehicle (UUV) is a determination of a route for a robot to travel from stating point to the end. Since we have identified a best layer were we can get maximum information about status of coral, we used global path planning technique to determine our route. Global path planning is an offline technique for designing the route from available prior information about the environment. In our case the prior information available is the integrated layer showing polygons of coral reefs places. To get the best route, **we identified the midpoint of all the polygons**. With the help of ArcGIS tool we were able to design a path by obtaining a series of waypoints passing through each polygon. All the polygons were converted to point features (X, Y) representing the midpoints. The route was finally obtained by joining the line through all points for entire area.

4.2.2. ZIGZAG SLAM technique for optimal routing

In this research we proposed a **ZIGZAG SLAM** technique to optimize the process of localization and mapping for investigation of coral status. Since coral reef extends over a large area and is complex in shape, we need to have an optimal route which can optimize the distance and picture taken by a UUV but also leave no gaps between scanning lines. Since soft corals are more vulnerable for coral bleaching, these areas will be investigated using a proposed zigzag SLAM technique. For all other areas of hard coral, the UUV is expected to take pictures at a predefined trajectory.

In its original formulation, SLAM techniques did not require any prior information about the environment, the robot should have an accurate model to map the environment and use this map to localize itself. However, there are a certain scenarios in which one wants a robot to investigate at a specific location with a high probability. In this case a UUV has to be given prior information of the environment in advance for online optimization; otherwise for a given large area of soft coral, a UUV will need more than one route to investigate the entire area. For that purpose we see a zigzag SLAM technique to be optimal, since the process of investigating the status of coral reef will be done online. Prior information given to a robot are very essential since the robot decision and believes are accomplished by getting information from the sensors. For a robot to navigate from start to the target we also need to have a predefined path (Figure 16), this path is described by a list of landmarks to be encountered along the way. The landmarks define the distance and orientation to next point along the route so as to avoid the robot from kidnapping. Without having those landmarks, the robot cannot know which point to be followed after it has finished manoeuvring up and down along the path. The proposed zigzag SLAM technique will at the end minimize the total cost for investigating status of coral by minimizing the length of the route and number of picture taken.

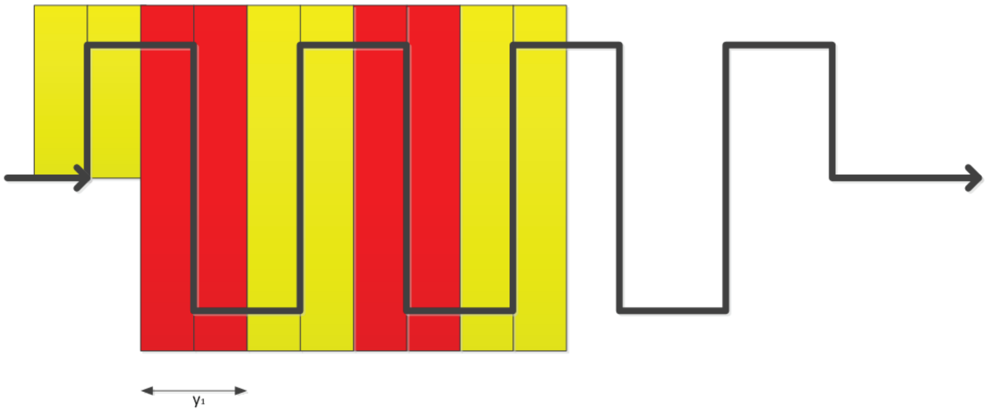

Figure 5: Proposed Zigzag technique for a UUV

The black line from figure 6 shows route undertaken when the UUV reaches the polygons with soft coral and y_1 show the swath width covered. The colour yellow and red depict up and down scan line.

To make sure we get maximum information about the coral status using a pinhole camera, we should be aware of geometry and mathematics behind it so as to calculate the size of the area to be mapped for optimal route. Since coral extends in 3D, standard Cartesian coordinate system translates the relationship between 3D world coordinates system to 2D image plane of the camera. If we know instantaneous field of view (IFOV) of the camera and the distance (x_1) from the camera to coral, the depth (y_1) occupied by single picture can be calculated from geometry relationship.

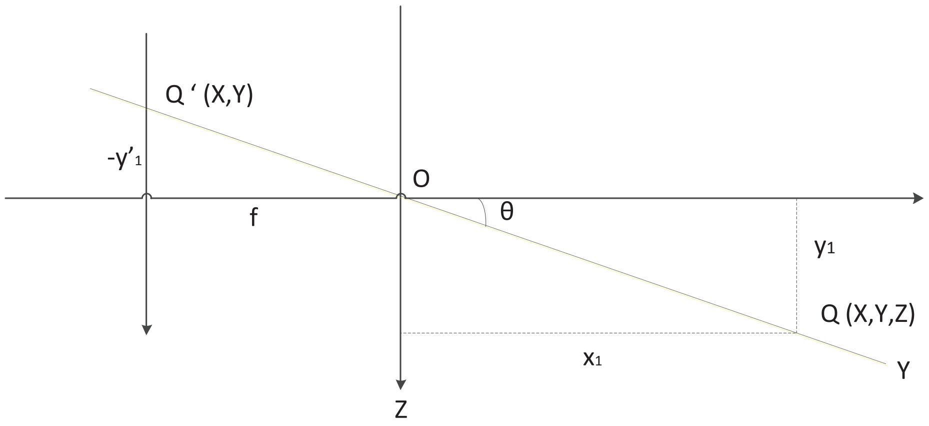

Figure 6: Geometric relationship between 3d space points with camera image plane

From figure 7, f denote focal length of the camera, θ is half of the viewing angle. X-axis is pointing toward the direction of principal axes; Y-axis is a horizontal distance perpendicular to X-axis and Z-axis is a line perpendicular to X and Y- axes. Both axes are intersecting at one point with coordinate o (X, Y, Z).

Width (y_1) taken by single picture can be calculated as

$$y_1 = x_1 tan\, \theta_i/2 \text{ ……………………………………………………………… (1)}$$

Total scanning width $y = 2(x_1 tan\, \theta_{i/2})$ …………………………………………..……... (2)

Total area covered per single frame $A = y^2$ ……………………………………………………….. (3)

If a robot total length is given by (l_R), the minimum number of picture (P_R) can be calculated as

$$P_R = l_R / y \text{ ………………………………………………………………….… . (4)}$$

Where the total length (l_R) is provided by odemetry on board the UUV

The final optimal routing should be the one which minimize total cost for a travelled distance (l_R) and picture taken (P_R).

4.3. Overview for ivestigation of bleached coral

The general technique for investigation of coral status is summarized in figure 5.

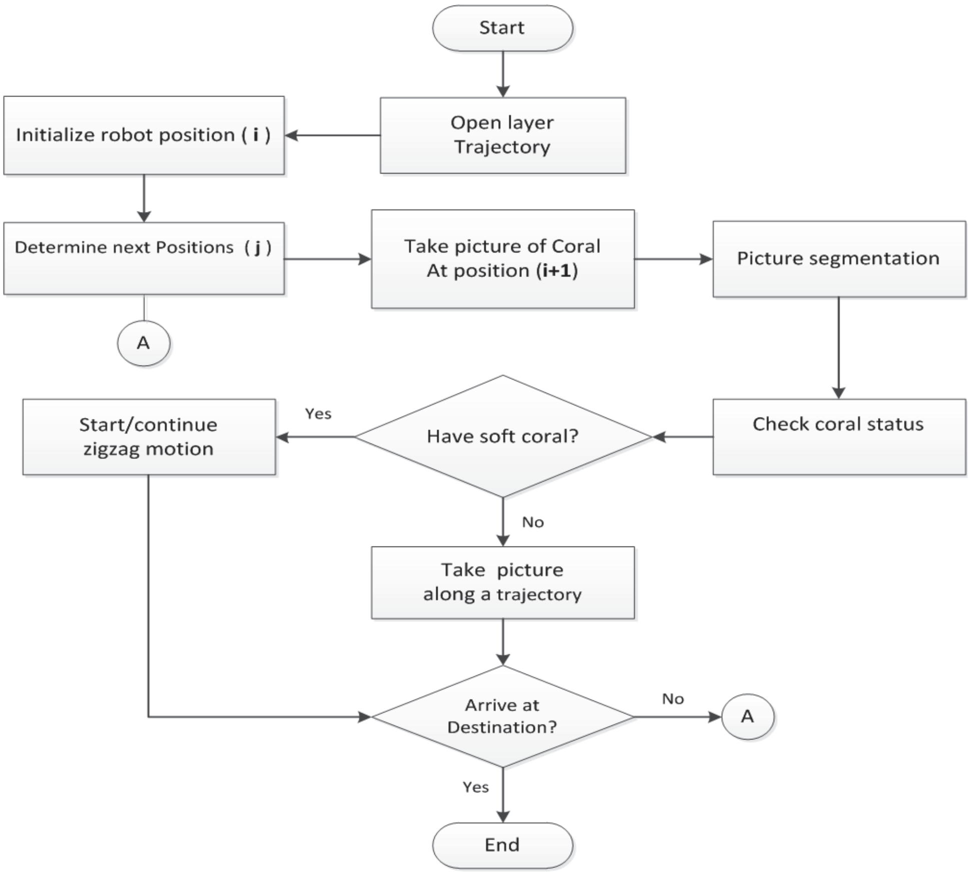

Figure 7: Proposed SLAM technique for a UUV

4.3.1. Initialization of robot position

For most SLAM system initializations, the robot has no specific knowledge about the surrounding environment when firstly switched on. It is necessary to define a coordinate frame work that the robot can use to estimate the positions and orientation toward the target while simultaneous taking pictures. The defined coordinate frame work is known as baseline or origin and can be in either local or global coordinate system. In our SLAM approach we aid the UUV with prior information, a technique known as local or position tracking. The available prior information is a set of points guide the robot trajectory from its start point to the end. We use Global Positioning System (GPS) to initialize the robot with known coordinate (X, Y, θ) in planar coordinate system, the robot is then tracking all the remaining points while simultaneous taking pictures until the end of its mission. The points which define our optimal route are now called landmarks, they define the entire trajectory. The UUV will start-up its mission with zero uncertainty in the original position. When it's moving toward the next landmark uncertainty start to increase due to sea current during the mission, the orientation and distance to the target needs to be updated every time the measurement is taken for modelling the uncertainty while maintaining its internal belief towards the target. In all our explanation we assume the robot motion is constant ($S = 1m/s$)

throughout, the bearing (θ) is not restricted at all. We will refer the robot position at time (t_i) as a state vector.

State vector $\beta(t_i) = [X_i, Y_i, \theta_i]$…………………………………………………………………… (5)

Where X_i, Y_i , represent $2D$ position in planar environment and θ is a bearing towards target

4.3.2. Prediction and update for a UUV

Before a UUV starts its mission, the prediction step in computed by calculating the distance and heading direction from initial position to the next landmark $(£, \theta)$, see Figure 8. Computation of initial distance and bearing to the next point is only to guide the initial belief of the robot towards the next landmark. However, the process of taking pictures continues between the two landmarks. After start up, the motion command μ given to a UUV will change the initial state vector to another position (Xi+1, Yi+1,θi+1). The uncertainty of vehicle pose and environment feature will affect our initial prediction towards the target and hence give a poor result. For that case, we incorporate measurement from odometry to model the uncertainty. Each time the picture is taken, the odometry provides the bearing and distance from last measurement, information which is now used to update the current position and orientation toward the landmark. The above procedure repeats for every time a new observation is done until all landmarks are mapped. The general formula for calculating distance and orientation to the next landmark can be written as.

Distance $£ = \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2}$ ………………………………………………….. (6)

Bearing $\theta = \tan^{-1}((Y_{i+1} - Y_i))/((X_{i+1} - X_i))$ ………..……….……………………….. (7)

We now introduced a motion model (see Figure 8) for by a UUV to predict next robot position based on old position. Given the UUV position $\beta_i = [X_i, Y_i, \theta_i]$, change in position of robot $\Delta\beta_i = [\Delta X_i, \Delta Y_i, \Delta\theta_i]$, where ΔX_i is the horizontal change in X_i- direction, ΔY_i is the horizontal change in Y_i- direction in the two-dimensional plane, , $\Delta\theta_i$ is the change in angle of the robot, then at k moment, the new UUV position $\beta_i(k)$ can be predicted.

$$\beta_i(k) = \begin{pmatrix} X_i(k) \\ Y_i(k) \\ \theta_i(k) \end{pmatrix} = \begin{pmatrix} X_i(k-1) + \Delta X_i cos\theta_i(k-1) - \Delta Y_i sin\theta_i(k-1) \\ Y_i(k-1) + \Delta X_i sin\theta_i(k-1) + \Delta Y_i cos\theta_i(k-1) \\ \theta_i(k-1) + \Delta\theta_i \end{pmatrix} \quad \text{……………………} (8)$$

For the purpose of this research, we identified the centres of each polygon to be the place where coral is abundant. These midpoints (X, Y) will also be used as landmarks for UUV orientation. The list of all landmarks is presented in the appendix A.

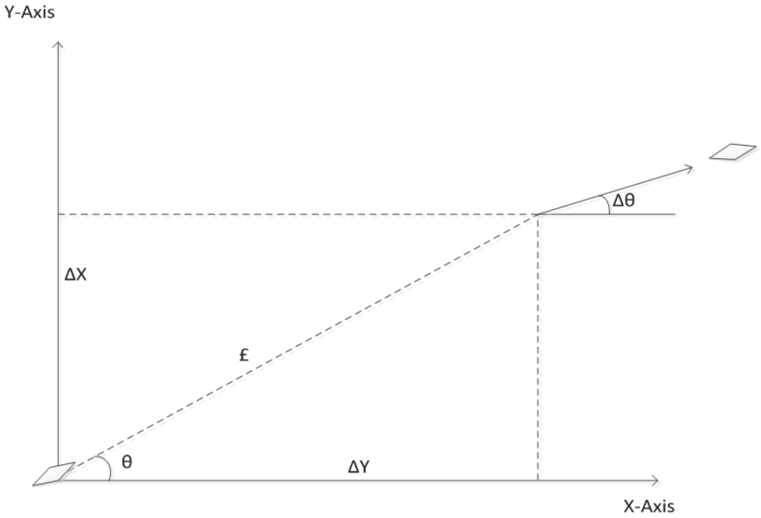

Figure 8: UUV motion model in 2D

4.3.3. Picture segmentation and detection of coral bleaching

Distinction between healthy and bleached coral is not a simple task as coral appears in different colours. Due to the dynamic nature of coral morphology, it is difficult to differentiate all types of coral with respect to colour. However, most of bleached coral tends to change from its original colour to whitish. Getting to know the status of coral in a particular area will help us as a basis for a UUV to distinguish between healthy and bleached coral. The research project conducted at the University of Queensland, Brisbane Australia proposed a technique of using the coral health chart (www.coralwatch.org). The colour charts are based on the actual colours of bleached and healthy corals. Each colour square corresponds to a concentration of symbionts contained in the coral tissue. The concentration of symbionts is directly linked to the health of the coral. What to do is matching the colour of the observed coral with one of the colours in the coral health monitoring chart to distinguish bleached from healthy coral.

In this research we decided to have two groups of coral, predominant hard and soft coral. We propose to develop a local coral healthy chart as a basis for a UUV to distinguish bleached and healthy coral (Table 1). Knowing the mean colour value for each group, a UUV can easily distinguish them from the segmented picture.

Table 3: Proposed mean colour value for a local coral health chart at Klein Bonaire

No	Type	Status	Mean colour value
1.	Soft coral	Healthy soft coral	HSC
		Bleached soft coral	BSC
2.	Hard coral	Healthy hard coral	HHC
		Bleached hard coral	BHC

Picture/image segmentation is a process of subdividing the image into regions or categories of homogeneous values or characteristics. In order to detect segments with bleached from segment with healthy coral, we use region based segmentation to split and merge the picture. Splitting will divide the whole image into sub-areas in quad tree fashion unless the homogeneity criterion is reached. Merging of the image follows by grouping together all adjacent regions which are not significantly different. After all the regions are partitioned in homogeneous segment, the algorithm computes the mean colour value for each segment. This value is compared to the coral healthy chart until the closest colour match.

5. RESULTS

This chapter shows the result obtained for integration of the old digitized map of 1985 and a recent high resolution satellite image. It also shows the result of path planning and landmarks for a UUV. Finally we show the zigzag SLAM technique as optimal routing for the investigation of coral status.

5.1. Integration of coral reef from map and sattelite image

Integration of coral reefs from digitized map and a classified high resolution satellite image was delineated to get the current spatial location and extent of coral reef from two data sources. We started by carried unsupervised classification of the whole image; total number of 15 classes was generated

Figure 9: Unsupervised classes of the satellite image

After unsupervised classification, we converted the resultant raster image to vector format so that we can extract a layer of coral reef from the image. Since we had a vector layer of whole image, we created a shape file layer (Figure 10) which will help us to clip the area of interest from which we can extract the second class.

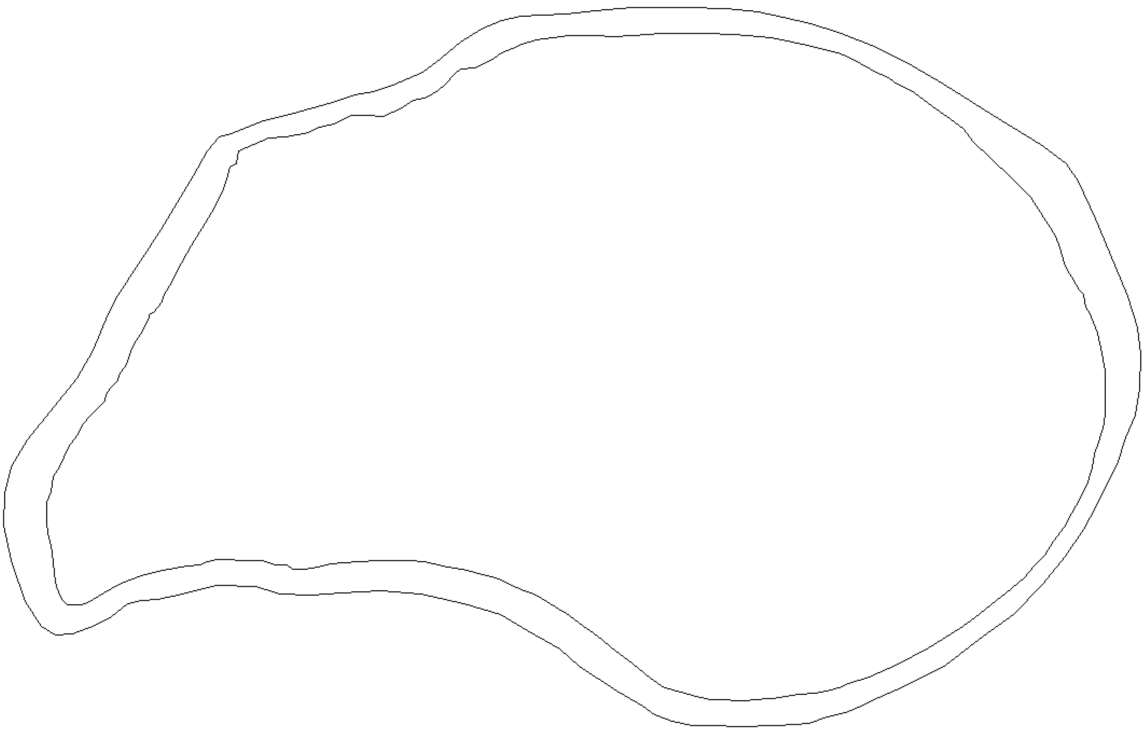

Figure 10: Shape file describing area of interest

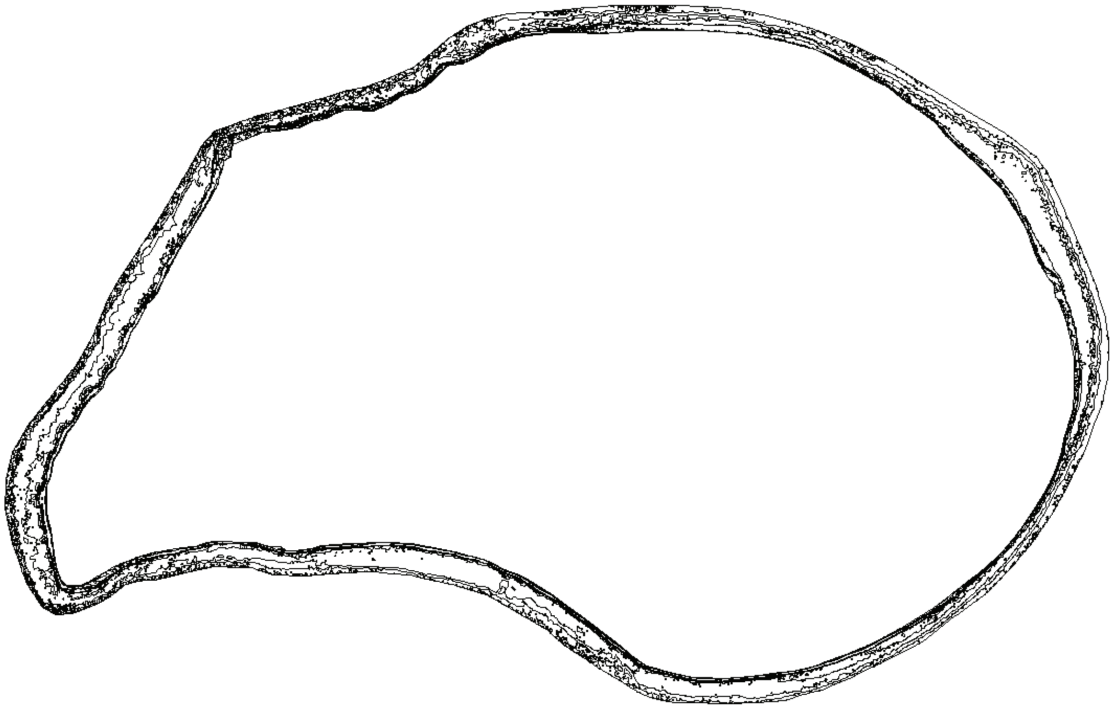

Figure 11: Clipped area of interest

By putting the classified image as background layer to the clipped vector layer we were able to select all polygons in second class as per figure 12.

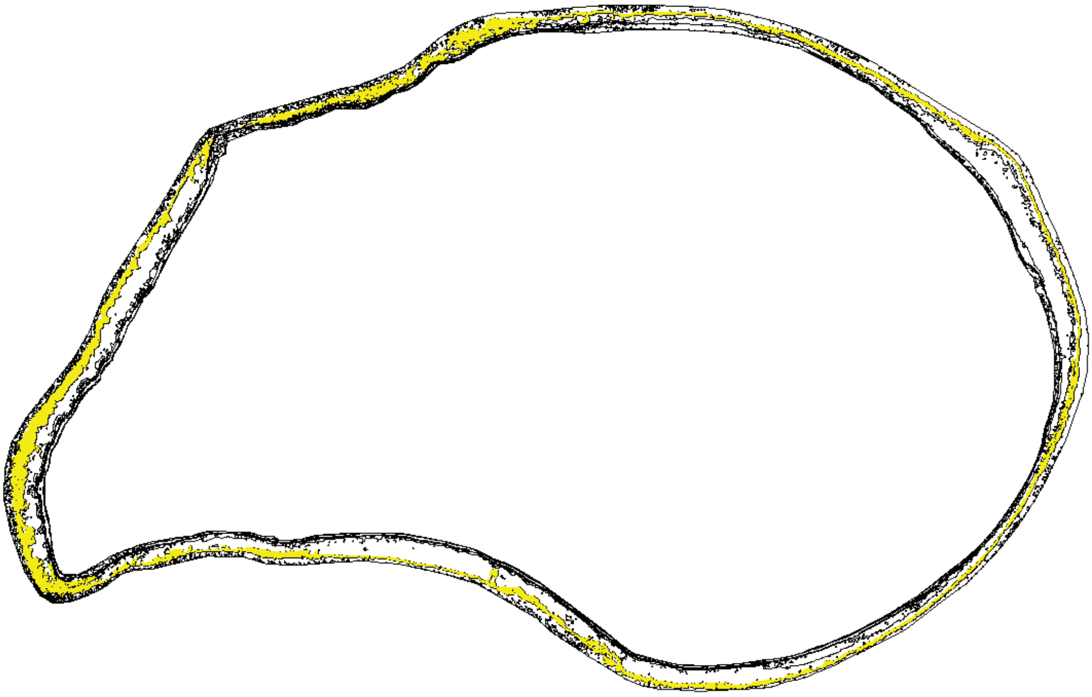

Figure 12: Identified coral reef layer from vector image

Hence the yellow layer was extracted separately as the layer representing coral from image. Finally we dissolved and simplify all polygons less than 16$m^2$and 4 m respectively.

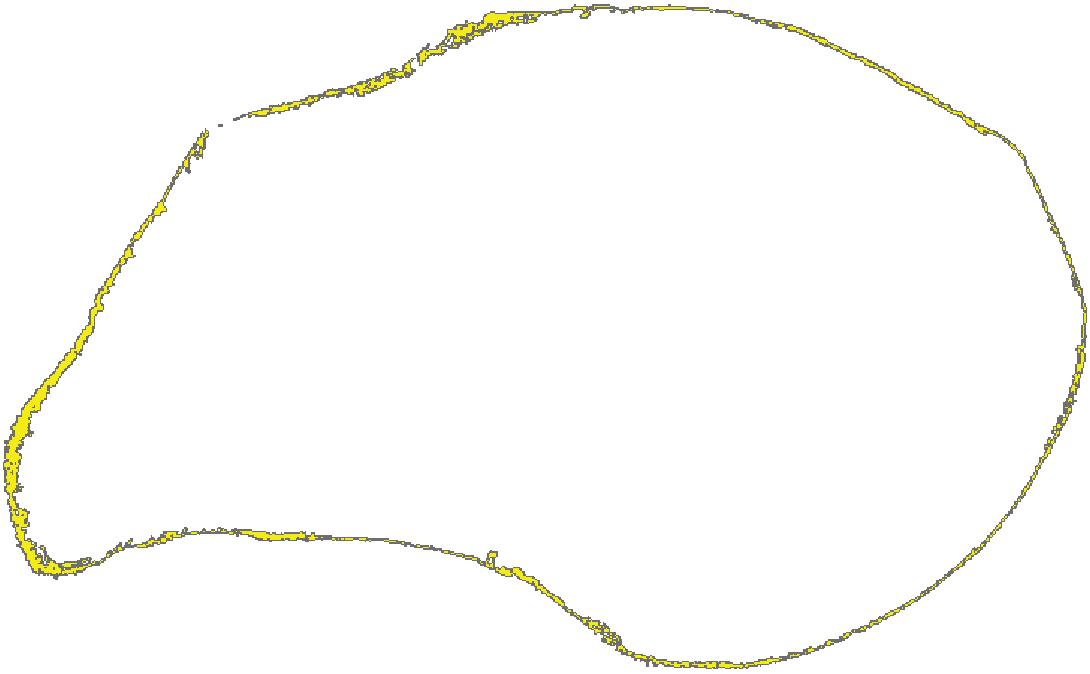

Figure 13: Coral reef from the Image

Finally the two data sources were projected to the same projection system WGS_1984_UTM_Zone_19N. By using ArcGIS software we were able to overlay them in one layer. Since both data sets were now in vector format, we used an intersection tool to extract the polygons which appears in recent image as well as in previous map as per figure 14.

Figure 14: Integrated layer of coral reef from map and image

5.2. Zigzag SLAM technique for optimal routing

In order to get an optimal routing, we started by designing a guided trajectory for a UUV. All the polygons in the integrated layer figure 14 were converted to point features (X, Y) representing the midpoints. The trajectory was obtained by joining the line through all points for entire area. Finally the result for zigzag SLAM technique is presented.

Figure 15: Midpoint developed from integrated layer

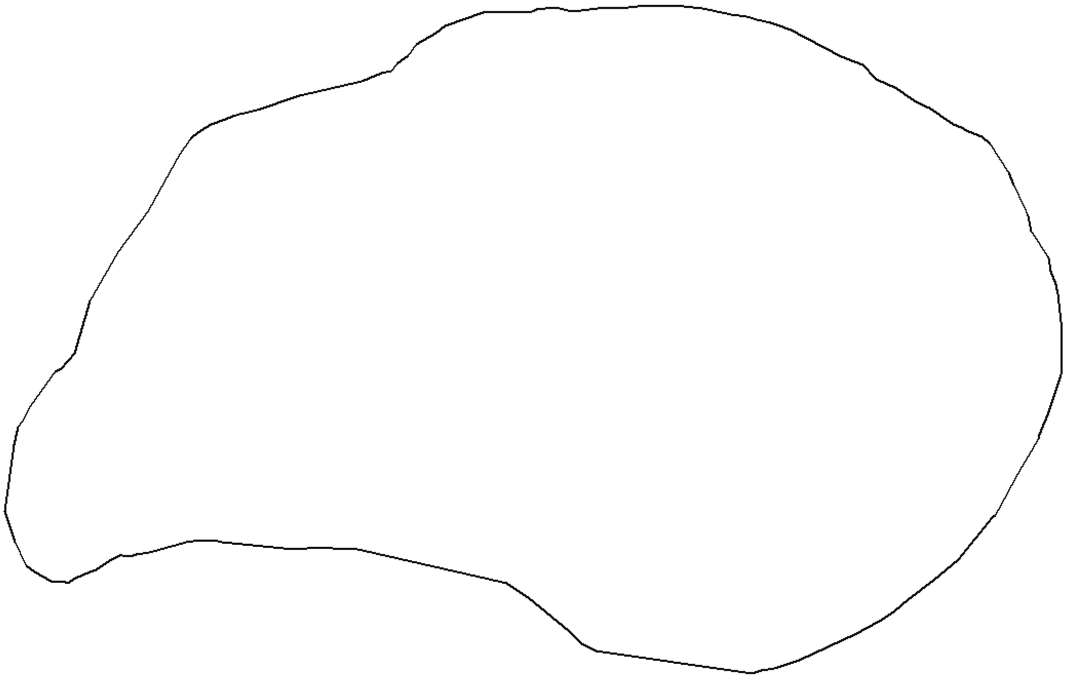

Figure 16: Designed trajectory for a UUV

A small section area of soft coral from the entire integrated layer was chosen to elaborate the result of zigzag SLAM technique for optimal routing (Figure 517). The red line show a trajectory to be followed if the robot was to have a single track, the soft coral is in green and hard coral in grey polygon. When a UUV come across polygons with soft coral it starts moving in zigzag way and come back to the original trajectory for all other polygons.

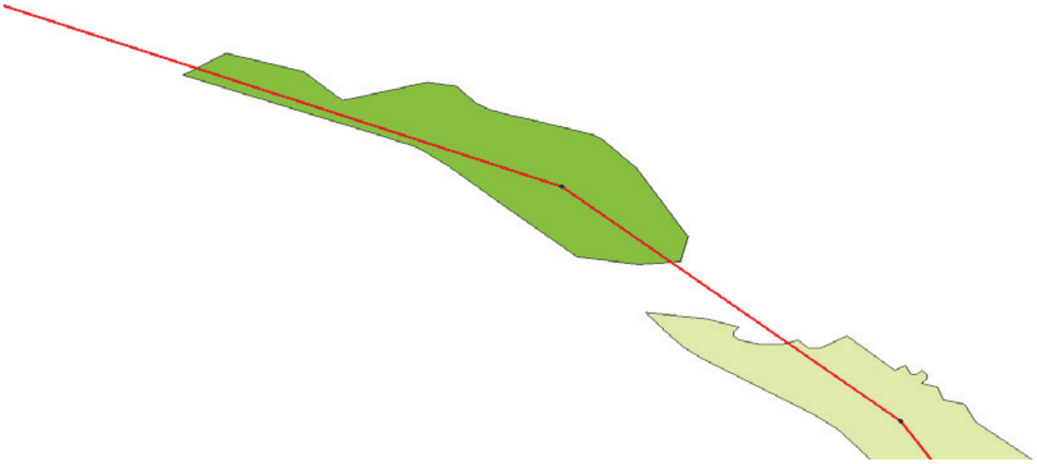

Figure 17: Sample area for soft coral polygon

The coral around Klein Bonaire are found at depth of 5 meter below the sea surface. The UUV is designed to navigate at a constant depth of 1 meter below the sea surface. A camera on-board of a UUV will be taking picture downward toward the coral reefs.

Let the camera instantaneous field of view = 60°.

Depth x → 5 – 1 = 4 meter

From equation 1 to 4 in section 4.2.2, area per single frame will be calculated as,

y_1 = 2.31 m

y = 4.62 m

Total area covered per single frame A = 21.34 m^2

For a UUV to live no gaps between two consecutive lines, we need a separation distance of 4 meter (Scanning width)

Overlapping distance → 4.62 – 4 = 0.62 m.

From figure 17 we get the following parameters.

Total length from a designed path across a soft coral polygon = 50.11m

Total width of polygon to be scanned = 15m

Shape area = 651.12 m^2

Number of picture which can be taken along this route

$P_R = l_R / y$

P_R = 12 pictures

Total area covered

$A_t = P_R * A$

A_t = 256.08 m^2

For a UUV to map the entire polygon we need more than one scanning line.

Zigzag SLAM technique maps the entire area with only one travelling route moving up and down. The UUV is turning around along the route every time it observes different information from the picture. For a soft coral, a UUV will move in a zigzag motion and come back to original route after the mission is completed.

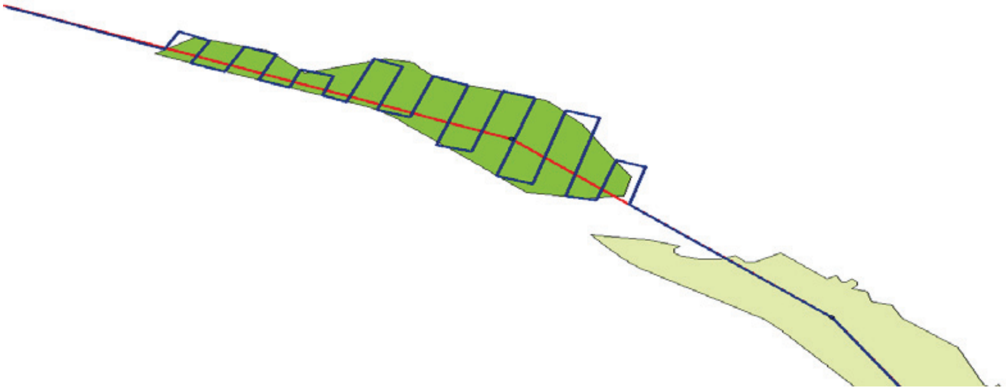

Figure 18: Practical implementation for zigzag SLAM

Entire traveling distance (l_R) = **155.93 meters**

Number of pictures

$P_R = l_R/y$

P_R = **39 pictures.**

Total area covered

$A_t = P_R * A$

A_t = 832.26 m^2

Table 4: Summary for optimal routing implementation

Method	Distance(m)	Number of picture	Area Covered (m^2)	% covered
Straight SLAM	50.11	12	256.08	39
Zigzag SLAM	155.93	39	832.26	128

6. DISCUSSION

In this study we started by integrating the data sources and finally we designed an optimal routing for investigation of coral reef status. Integration of data sources included a digitized map of coral reef as observed in 1985 and a recent high resolution satellite image (4 m). An optimal routing was then designed which can collect much information of coral status in a large at minimum cost with a given set of specification. The strength, assumptions, shortcomings and opportunities of the proposed methods are discussed in the following sections.

6.1. Proposed method for integration of data sourses

6.1.1. Strength of the integration method

The proposed method for integration of data sources provides a layer of coral reefs which is common to map as well as satellite image. The information on the old digitized map is well preserved in the final integrated layer. This information enables to set specification which should be followed by a UUV during the mission. The final integrated layer gives the basis for design the landmarks, trajectory and optimal routing for a UUV. This layer also contain information about the distribution of regions with soft and hard coral, which gives overview knowledge of the area which are most and not vulnerable for coral bleaching.

6.1.2. Shortcoming of the integrated layer

Though the developed method for integration of data sources provides a better result for investigating the status of coral but it has shortcomings. The extraction of information from satellite image does not provide unique types of coral reef. The spectral confusion occurs due to depth variation. The same type of coral can have different spectral reflectance due to variation in depth. Also, coral of different types can have same spectral characteristic within the same depth. For this case, you need to borrow information on how coral reefs are distribution from the shore zone toward deep water from other sources. The borrowed assumptions may lead to inaccurate result due to time difference (26 years) between the observations of two data sources.

6.1.3. Opportunities to improve integration process

Due to foreseen weakness in the method used there are some opportunities to refine the output. The image classification should start by including depth variation parameter and hence unsupervised classification replaced by supervised one. This will help to identify variation of coral reef types per depth.

6.2. Proposed method for optimal routing

6.2.1. Strength of the optimal routing

The proposed zigzag SLAM technique for optimal routing is more economically than tradition SLAM technique used for navigation purposes. For investigation activities in large area, the zigzag technique completes the mission with a single trajectory which covers the whole large area but also portray the shape of the area. In this study area the sample selected polygon has total area of 651.12 m^2. By employ a zigzag technique we were able to map 832.26 m^2 which is equivalent to 128% compare to straight forward method which cover only 39% of the entire area to be investigated. Though by looking at the summary table 4 for optimal routing, one may think the single track method is more optimal, but it is not giving sufficient information as their collected per single track which cannot be quantified for bleached area.

6.2.2. Weakness of the optimization method

The developed zigzag method was tasted on assumption that, the camera used was limited to IFOV of 60°,depth to coral was derived to 4m and the UUV is sailing at constant elevation of 1m below the sea surface. Other factors which may affect the precision of a UUV to manoeuvre such as sea waves, current and obstacles along the way did not be considered. Though we have seen that this technique provide much information for study the status of coral reefs but also result into an excess number of picture taken at the edges of polygon which increase the running cost for investigation purposes. Another weakness was lack of simulation software and codes to implement the result.

6.2.3. Opportunities to improve zigzag method for optimal routing

As discussed in the previous section for weakness resulting from this method but there are some opportunities to improve this method as it works well for investigation in underwater environment. The information about sea current and wave's direction can be included and simulated to decide whether the UUV can take a zigzag motion perpendicular or oblique to the designed trajectory. Simulation of the information can increase the precision for a UUV to manoeuvre with given prior information about the environment. The assumption made for constant depth to coral reef and sailing depth can be changed by including bathymetric information of the study area, this may increase the quality of the information collected especially for the areas which are more vulnerable for coral bleaching. Other methods such as concentric movement can be investigated and compared to zigzag technique. Addition sensors such as barometer, lighting system and sensor for measuring temperature have to be included in investigation. Side scan technique for taking picture from a UUV can also be investigated and compared with this technique of taking picture downward to the coral reef.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

The main objective of this research was to develop the optimal routing for a UUV that includes robotics based localization and mapping of coral status. Information from digitized map and high resolution satellite images was to be integrated with pictures taken by the UUV to design an optimal route.

The conclusions of this study are drawn by answering each research questions posed to achieve the research objectives.

1. How can information be integrated from different data sources to help a UUV localize itself and determine the optimal route?

The information of coral reef from old digitized map can be grouped to soft and hard coral by merging related coral species as described in section 4.1.1. Other polygons like shore zone, sand, rubble hard bottom and marine plant can deleted from the map. For the satellite image, you extract layers of interest from classified image after performing raster to vector conversion. The current spatial location and extent of coral reef is obtained by intersecting these data sources after projected to the same projection system.

2. How different robotics based orientation and mapping procedures integrated to serve for coral mapping?

SLAM technique is used to facilitate mapping of coral reef. A set of visual routing is used such that the UUV takes a picture of coral and localize itself relative to the observed picture. Information from the integrated data source is used to design landmarks for all identified polygon of coral reefs. A trajectory for a UUV based orientation is designed to pass through all landmarks for mapping processes. This information is also used as a basis for designing optimal path after including observation from the sensors.

3. How can the robot routing for localization and mapping be optimized for mapping the coral status?

Optimization is done by introducing a zigzag technique which can map a large area and get sufficient information about the status of coral reef. Zigzag SLAM technique was used and shows that, a UUV can collect information up to 128%.

7.2. Recommendations

From the experiences acquired by integrating old digitized map of 1985 and recent high resolution satellite image of 2011, and designing of an optimal routing for investigation of coral reef status. The followings can be recommended for further research.

a) The image classification of coral reef should including some depth variation parameter; this may enlarge the width of the classified area toward deep water. After including depth variation parameters, unsupervised classification should be replaced by supervised classification. This will help to quantify changes of coral reefs status per time before implementing a robot for practical investigation.

b) Designing of unmanned prototype robot for underwater environment such that, optimization of the route can be simulated by include other factors which may affect the precision of a UUV to manoeuvre within a given area such as sea waves, current and obstacles encountered along the way.

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Appendix A

List of landmarks for a UUV orientation purposes.

Point	Midpoint X	Midpoint Y	Group
1	-7604170.108	1364922.072	Hard coral
2	-7603649.634	1364913.458	Hard coral
3	-7604170.108	1364922.072	Hard coral
4	-7604004.156	1364910.099	Hard coral
5	-7603887.6	1364930.033	Hard coral
6	-7603649.634	1364913.458	Hard coral
7	-7604230.226	1364929.189	Hard coral
8	-7604170.108	1364922.072	Hard coral
9	-7604223.902	1364901	Hard coral
10	-7604347.857	1364903.339	Hard coral
11	-7604689.734	1364851.808	Hard coral
12	-7604749.238	1364814.791	Hard coral
13	-7604792.755	1364784.571	Hard coral
14	-7604845.687	1364729.116	Hard coral
15	-7604617.826	1364868.516	Hard coral
16	-7605531.29	1364498.021	Hard coral
17	-7604871.57	1364704.277	Hard coral
18	-7604902.991	1364672.745	Hard coral
19	-7604936.707	1364672.964	Hard coral
20	-7605019.913	1364635.226	Hard coral
21	-7605249.822	1364575.366	Hard coral
22	-7605531.29	1364498.021	Hard coral
23	-7605309.551	1364568.648	Hard coral
24	-7605531.29	1364498.021	Hard coral
25	-7605639.177	1364458.495	Soft coral
26	-7605674.021	1364432.833	Soft coral
27	-7605726.929	1364374.247	Soft coral
28	-7602865.567	1364600.692	Soft coral
29	-7603490.413	1364888.866	Hard coral
30	-7603318.749	1364832.157	Hard coral
31	-7603649.634	1364913.458	Hard coral
32	-7602299.99	1363340.804	Hard coral
33	-7602359.125	1363202.003	Hard coral
34	-7602376.857	1363145.948	Soft coral
35	-7602527.591	1362889.251	Soft coral
36	-7602274.363	1363396.518	Soft coral
37	-7602262.473	1363545.842	Soft coral
38	-7602474.778	1362947.973	Soft coral
39	-7602341.774	1363207.76	Soft coral
40	-7602415.429	1363086.572	Soft coral

41	-7603074.142	1364690.723	Hard coral
42	-7602982.979	1364630.812	Hard coral
43	-7602913.12	1364603.865	Hard coral
44	-7602840.94	1364554.988	Hard coral
45	-7602817.466	1364523.3	Hard coral
46	-7602792.726	1364528.355	Hard coral
47	-7602772.108	1364520.987	Hard coral
48	-7602671.146	1364437.313	Hard coral
49	-7602674.19	1364460.569	Soft coral
50	-7602624.354	1364413.855	Hard coral
51	-7602517.605	1364354.277	Hard coral
52	-7602494.257	1364292.695	Hard coral
53	-7602435.584	1364165.98	Hard coral
54	-7602398.392	1364130.87	Soft coral
55	-7602363.137	1364015.877	Soft coral
56	-7602380.154	1364028.321	Hard coral
57	-7602259.424	1363719.654	Soft coral
58	-7602267.707	1363681.141	Hard coral
59	-7602255.947	1363605.47	Soft coral
60	-7602262.966	1363582.604	Hard coral
61	-7602302.803	1363873.934	Soft coral
62	-7603209.233	1364783.091	Hard coral
63	-7602578.107	1364407.499	Soft coral
64	-7602279.995	1363810.648	Hard coral
65	-7603365.09	1364852.231	Hard coral
66	-7603446.672	1364875.29	Hard coral
67	-7603349.08	1364834.297	Hard coral
68	-7605716.063	1362799.128	Hard coral
69	-7605635.873	1362805.979	Soft coral
70	-7605697.33	1362764.611	Soft coral
71	-7605387.688	1362770.771	Soft coral
72	-7605227.383	1362766.782	Soft coral
73	-7605088.562	1362759.76	Soft coral
74	-7605343.152	1362745.876	Soft coral
75	-7606024.237	1362720.519	Soft coral
76	-7605716.063	1362799.128	Hard coral
77	-7605888.708	1362755.086	Hard coral
78	-7605842.892	1362778.962	Soft coral
79	-7605697.33	1362764.611	Soft coral
80	-7606024.237	1362720.519	Soft coral
81	-7605946.601	1362735.829	Hard coral
82	-7605088.562	1362759.76	Soft coral
84	-7606024.237	1362720.519	Soft coral
85	-7605726.929	1364374.247	Soft coral
86	-7605865.37	1364139.444	Soft coral

87	-7606056.523	1363851.055	Soft coral
88	-7606036.121	1363799.079	Hard coral
89	-7606090.08	1363769.605	Hard coral
90	-7606146.421	1363539.687	Hard coral
91	-7606204.795	1363492.043	Hard coral
92	-7606320.867	1363364.84	Hard coral
93	-7606352.453	1363285.968	Hard coral
94	-7606435.825	1363180.722	Soft coral
95	-7606393.995	1363187.907	Hard coral
96	-7606449.373	1362934.713	Hard coral
97	-7606401.553	1362898.457	Hard coral
98	-7606352.355	1362709.049	Hard coral
99	-7606319.21	1362673.622	Hard coral
100	-7606306.664	1362680.652	Hard coral
101	-7606252.659	1362645.729	Hard coral
102	-7606240.792	1362617.205	Hard coral
103	-7606166.865	1362654.732	Hard coral
104	-7606135.093	1362661.007	Hard coral
105	-7606154.629	1362635.035	Soft coral
106	-7603837.852	1362339.547	Soft coral
107	-7603256.349	1362348.278	Soft coral
108	-7602766.298	1362632.375	Soft coral
109	-7602810.968	1362591.663	Hard coral
110	-7602892.83	1362544.089	Soft coral
111	-7602681.241	1362698.355	Soft coral
112	-7603256.349	1362348.278	Soft coral
114	-7604360.623	1362579.77	Soft coral
115	-7604171.884	1362417.174	Hard coral
116	-7604170.502	1362395.307	Hard coral
117	-7604097.395	1362361.777	Hard coral
118	-7603837.852	1362339.547	Soft coral
119	-7603256.349	1362348.278	Soft coral
120	-7602270.888	1363470.846	Hard coral
121	-7602274.363	1363396.518	Soft coral
122	-7603256.349	1362348.278	Soft coral