A Comparative Study of Vision Guided AUV Navigation Techniques for Pipeline/Cable Inspection

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Abstract

In the last few years exploitation of underwater gas and oil fields have increased. The produced oil and gas is transported mainly using pipelines which need to be inspected regularly. Submarine communication cables are laid on the sea floor for data communication across stretches of ocean. Due to earthquakes and other environmental changes these underwater cables and pipelines can get wear or get damaged. These damages need to be found and repaired quickly. Also the state of the pipelines and cables need to be constantly monitored. Currently inspection of underwater pipelines are done using Remotely Operated Vehicles (ROVs) which require human intervention. But this method is very risky. A more practical solution is to develop an intelligent vision based navigation and guidance system which involves efficient method for vision based target detection and tracking methods in underwater environment. AUVs used for survey missions in an underwater environment requires advanced precision navigation systems. Navigation usually requires high speed and high accuracy computation. Navigation is done through different techniques of which vision based navigation is the cheapest as it requires only a single camera. This paper presents a review on various AUV navigation techniques which uses vision sensor or any combination of vision sensor with any other sensor for navigation over the last decade.

Keywords— *Automatic Underwater Vehicle, Navigation, CCD camera, Vision, Optical Flow, Mean Shift Tracking, Segmentation*

I. INTRODUCTION

AUVs are Autonomous Underwater Vehicles are robots which can navigate through underwater environment without any human intervention. AUVs carry precision sensors as payload and are used mainly for survey missions, oceanographic mapping, and infrastructure inspection. As the duration of mission increases more advanced navigation systems are needed.

Navigation is the process of determining ones position i.e. localization and then discovering a path to advance further from the existing position. Underwater navigation poses further challenges due to the highly dynamic and complex environment. One of the most important aspects of navigation is the knowledge of the environment. And to get a knowledge of environment different types of sensing techniques are used. [1], [23]

1. Inertial navigation based on motion sensors or accelerometers and rotation sensors or gyroscopes. Using these sensors the position velocity and orientation of AUV can be calculated via dead reckoning.[1], [23]
2. Acoustic navigation based on acoustic transponder beacons. [1] During pipeline inspection acoustic sensors which act as microphones listen for sound generated when fluids under high pressure leak. [3]
3. Geophysical navigation based on estimating the location of the AUV using the environment surrounding the AUV.

Side scan sonars, magnetometers, sub-bottom profilers are some of the sensors used for pipeline cable inspection in underwater environment. For example, a magnetometer which can sense ferrous materials can be used to detect the existence of a pipeline. A sub-bottom profiler can be used to obtain images of buried objects in the ocean bed. Sub-bottom profilers can not only detect the existence of a buried pipeline but also can give information about the type and thickness of sediment above it. Side scan sonars together with a video camera can be used to inspect pipelines which usually project out of the ocean bed and they can make a good detection even in unclear water. [2] Once a pipeline/cable is detected different algorithms and high intensity computation are employed to calculate the orientation of the pipeline/cable and navigate along it. Hence the quality of navigation depends heavily on the accuracy of these sensors. Magnetometers have the disadvantage that they can detect only ferrous materials. Also they cannot give an idea of whether the object is buried or projecting out. Using side scan sonar is a costly option as use of sonar means mandatory use of companion equipment like transponders. Another condition is that these sensors should be able to adapt to the highly dynamic marine environment.

Vision sensors and the visual data captured by them provide a whole new way for autonomous underwater vehicles to perceive an environment. Vision sensor data analyzed using specialized computer vision algorithms can provide highly accurate information about the surrounding environment. Laser scans, fiber optics, ultrasonic and acoustic imaging are some of the methods employed for visual inspection currently. Advantages of using 3D imaging technique is that they can be used to detect and track pipelines/cable which are buried or projecting out of the sea bed.[2] But these techniques are pretty expensive. A cheaper and easier solution is to use a camera. Cameras are attractive in the sense that they offer richer information about the surrounding environment even though the detection range is limited in the poor visibility condition of the underwater environment. Hence for close range and high speed applications cameras are the best.

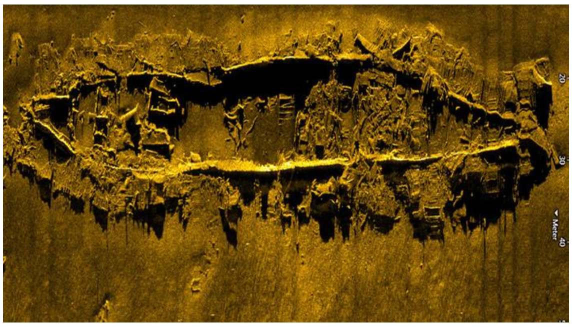

Fig 1. Side scan sonar image of a shipwreck [4].

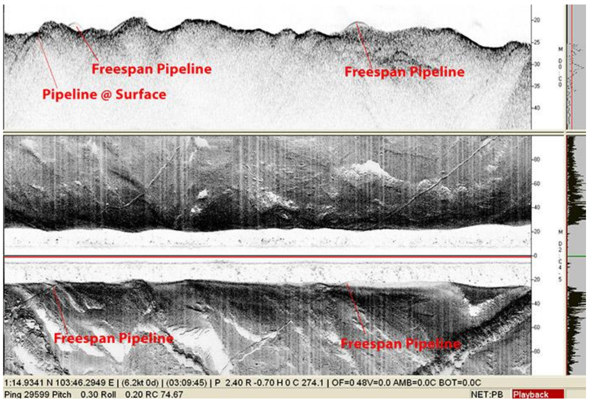

Fig 2. Image of a pipeline obtained using sub-bottom profiling technique [4]

Fig 3. Engine of titanic discovered underwater. Image taken using an underwater camera [5]

II. PIPELINE/CABLE TRACKING METHODS

In 1988 started the “ROV of 90s” program with an aim to build an automatic underwater vehicle for pipeline inspection. A pipeline can be characterized by it shape and uniform color but due to marine growth in underwater environment color may not be uniform. Hallset in his project titled PISCIS [6] does pipeline identification by detecting geometrical features of the pipeline from the data i.e. image frames captured by the vision sensor. And for edge geometrical feature extraction segmentation based on edge detection technique was performed on the vision sensor data. [6] For tracking purpose a CCD camera, echo sounder, and a compass was used. Hallset in [7] describes another pipeline tracking system using a model based recognition approach. Models which are basically geometric descriptions of the object to be detected was stored in a database. The best match between the captured 2D image data and the models in the database are found. The image processing operations employed were segmentation based on edge detection and rectangle matching.

In 1997 Balasuriya et al [8] developed an AUV that used a single CCD camera as vision sensor together with an acoustic sensor to locate an underwater cable and position the AUV accordingly. The navigation of AUV was based on the position of the cable relative to that of the AUV. Acoustic sensors were used to determine at what depth the cable lay with respect to the AUV. Using the depth information and the information obtained from the CCD camera the location of cable was determined in a 3D space. As the data from both vision sensor and acoustic sensor was taken for target localization the technique was called sensor fusion. Image processing operations were performed on the captured images degraded due to non-uniform lighting, sus-pended particles. Image processing algorithms utilized were Laplacian of Gaussian operation for noise filtering, edge detection and Hough transform to locate the cable in the captured image frame.

In 1998 Balasuriya and Ura [9] proposed another method for cable tracking which eliminated the use for an acoustic sensor completely. The vision sensor data was fused with other onboard sensors like inertial navigation system to de-rive the necessary parameters for navigation. In the image frames captured by the CCD camera geometric features are first labelled, then their location in the image extracted and then converted into parameters for navigation.

In the same year a robust real time pipeline detection and tracking algorithm was proposed by Zingaretti and Zanoli in [10]. The accuracy of this algorithm was enhanced by exploiting the temporal context in the image sequence. The disturbances on acquired images caused by motion was partially removed by Kalman filtering. Kalman filtering was used not only for the guidance and control of the ROV but also in creating a robust image-processing module. In the algorithm proposed by Zingaretti and Zanoli ROV is placed in such a position that the pipeline will be always viewed from the top. Only the brightest part of the image i.e. the center of the image is considered. First step is spatial filtering. Since the pipeline is viewed from the top, in the image plane the pipeline contour will be represented by two almost vertical straight lines.

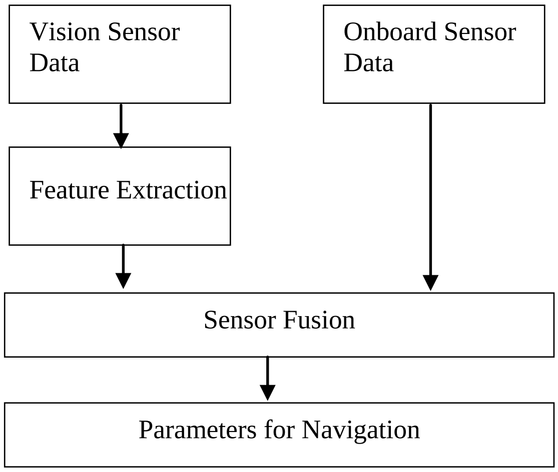

Fig 4. Cable tracking system proposed by Balasuriya and Ura [9]

Hence while doing edge detection only vertical edges are detected in each captured image frame. This reduces the computational complexity as only clusters of vertical edges are processed while ignoring high intensity isolated edge points. For tracking purpose data obtained from the previous images were used to estimate the position of the pipeline. The algorithm for target detection was insufficient in accuracy for pipeline contour detection. So Zingaretti and Zanoli proposed an enhanced vision system, the real time guidance and navigation of an ROV. The authors proposed an active vision system that will predict changes in the captured image frames and direct the computational resources to confirm expectations, by exploiting the temporal context in the image sequence and by dynamically adapting the processing mode. In the proposed system, the ROV guidance task is accomplished by the reconstruction of the relative position of the ROV with respect to the pipeline or equivalently the relative position of the camera fixed to the ROV. The active vision system made sure that the pipeline was always centered in a symmetrical position in the image frame

In 2000 yet another technique for cable tracking was proposed by Balasuriya and Ura in [11]. This work was an extension of their own previous works [8], [9]. Again sensor fusion technique which uses data from different type of sensors was proposed but this time they solved a practical problem. What to do when the cable is invisible and what to track when there are many cable like feature in the captured image. In the proposed method when the cable becomes invisible a 2D position model of the cable was used for AUV navigation. To construct the 2D position model, the position of different points on the cable contour is determined and this information is used for construction of a rough position model. Then this rough position model data is used to predict where in the captured image frame the cable is most likely to be present. Since only this predicted part of the image is processed, the amount of data to be processed reduces there by reducing the overall processing time. This work was further extended when the authors used a priori map of the cable for AUV navigation when the cable features are invisible in the predicted region in the image. [12]

In 2001 a vision system was tested by Antich and Ortiz [13] Image sequences for testing the system was obtained from videos taken by an ROV while tracking real cables. The frame rate of the video was higher than 25frames/second but still 90 percent average success rate was obtained. In [13] the necessary parameter required for navigation was not obtained from the processed image. The image was split into a grid of cells and each cell processed separately and then tried to locate the cable in every cell of the grid. For further processing only the cells with cable features were considered. This reduced the area to be processed to a small Region of Interest (ROI). This reduces the computation time considerably. The probability of false detection of cable like features appearing elsewhere in the image is also reduced. Once the cable was detected Kalman filtering was done to find its location and orientation. Using Kalman filter the present position and present orientation is computed and this information is used to predict the new position and orientation in the next image frame. Foresti in [14] proposed a system that uses a 3-D geometric model of the underwater environment and an Extended Kalman Filter (EKF) to estimate the AUV position and orientation in real-time.

In 2002 Ortiz et al [15] proposed a vision system. The system used only the output of a vision sensor i.e. camera and was able to detect and track a target, despite encountering the typical disadvantages of underwater environment like image blurring, light attenuation, non-uniform lighting, the object under consideration partially hidden by flora and fauna. For feature extraction from the captured data, segmentation step was implemented. In the resulting segments, orientation of pixels lying on the segment boundary were determined. Out of these contour pixels lying in a specific orientation were considered. If these pixels align up to form the contours of a cable i.e. the pixels are aligned in such a way that a large number of pixels form highly parallel straight lines running from bottom to top of the image, then the cable is considered to be located. Otherwise, the image is discarded and the next one in the sequence is analyzed. Once the cable is detected in one image frame, then the location and orientation of the cable in the next image frame are predicted by means of Kalman filter. Here instead of analyzing the entire captured frame only a portion of the image where there is a possibility of the object of interest being present i.e. a particular region of interest was only analyzed. Here also the number of pixels to be processed is reduced to a small ROI in the image. This in turn reduces the probability of system errors.

In 2004 Loung and Lim [16] designed a vision system for AUV. The basic idea was that the underwater track is detected within an image, if there exists at least one set of semi-parallel lines. The process of line extraction involved the use of a number of classical computer vision techniques. As a preprocessing step convolution of the image with a Gaussian filter was done to remove noisy pixels. The edge detection process used was a variation of the Canny Operator. The edge detection algorithm approximates the Canny Operator by convolving the input image with the first derivative of a Gaussian filter. This is a two-step process which first involves convolution of the image with a Gaussian filter, and then taking the difference between adjacent pixel intensities. The second step is achieved by convolving the image with Sobel Masks. Once the edges of the pipeline was detected the edges were extracted using Hough transform. Once the target was detected the vision system calculated the center of mass of the pipeline in relation to the AUV axis. These co-ordinates were then input to a control algorithm, for positioning the AUV over the track. The general aim was to keep the center of mass location within a small region about the center of the image, in order to keep the pipeline in the optimum field of view. After doing morphological operations on the image center of mass was calculated. This center of mass was aligned with the center region of the image. By calculating angle of Axis of minimum inertia orientation of the target is obtained and the AUV moves accordingly.

In 2006 Asif and Arshad [17] purposed a model based approach to detect and track underwater pipeline in complex marine environments. The authors implemented a vision guidance system for autonomous underwater pipeline tracking and navigation which was very different from the previous works. The purposed vision system used unconventional gray scale conversion technique to enhance the image and then Perona Malik filter was used to reduce the noise effect and enhance the features of underwater pipeline. To detect the pipeline boundary in an image, Hough transform was used. After detecting the pipeline in an image, parameterized curve or active contour was used to represent the underwater pipeline and for feature extraction. Based on the extracted feature, curve fitting was used to measure the current position and orientation of underwater pipeline. In order to track the pipeline in real time in a video, the tracking problem was expressed in terms of shape space model where the model is a mathematical relation used for describing the state of underwater pipeline or cable. The Kalman filter was used to track the pipeline boundary in the image sequences. The system efficiently track the pipeline when it is fully or partially covered by the sand or marine flora and even in clustering situations. The algorithm was implemented in Matlab environment.

In 2009 Narimani et al [18] also proposed converting the captured image frames into grayscale imaged to reduce the computation time. The authors claimed that 90 percent of the edges are same in both grayscale and color images. So by doing color to grayscale conversion only 10 percent of edges will be missed.

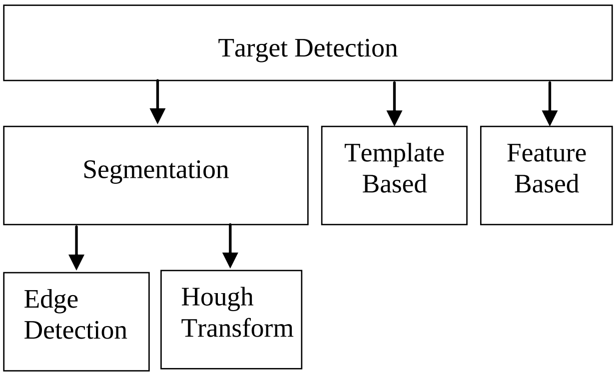

Fig 5. Different pipeline/cable detection techniques

In 2012 Cheng and Jian [19] proposed a technique which could detect pipelines even in harsh underwater condition like limited brightness, suspended matter, and incomplete pipeline contour. The proposed method first decomposes an image into foreground, background, and edges. Edge detection is achieved by a series of image processing techniques including opening and closing, the Gaussian mask, the Sobel filter, thinning, expanding, and Hough transform. Then prediction of the pipeline's location is done by the feature-based optical flow approach. Yet another method for detecting and tracking a pipeline when it becomes invisible was proposed by Drews et al [20]. The acquired images were first resized and converted to grayscale to reduce processing time. Then edge detection and Hough transform was done for line detection. Morphological operations were done before taking Hough transform. The method proposed was able to detect the target in different rotation, scale and displacement with minimum processing time. Once the algorithm has identified the target, the distance from the ROV to the target was estimated based on the target size in the captured image (number of pixels) and its actual size (already known). The disadvantage of this method is that the algorithm requires the knowledge of the width of the pipeline. Fei and Xinying [21] tried a different approach in which the shortcomings of the Kalman filter was overcome by using Particle filter.

Lee et al [22] studied in depth the vision based object detection and tracking techniques for underwater robots. In order to overcome the limitations of cameras and to make use of the full advantages of image data, a number of approaches were tested. This included color restoration algorithm for the degraded underwater images, detection and tracking methods for underwater target objects. For color image restoration the authors used Jaffe McGlamery image model. For target object detection two approaches were studied. Feature based and Template based approach. Template based approach was found to be better than feature based approach. For tracking optical flow tracking and mean shift tracking methods were studied.

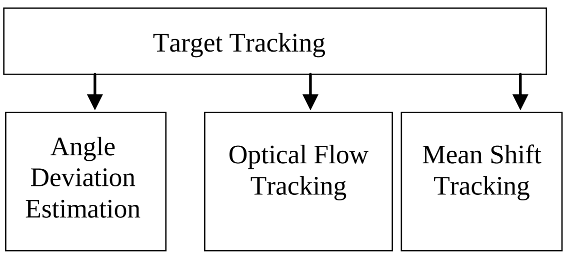

Fig 6. Different pipeline/cable tracking techniques

III.CONCLUSION

This paper presents a review on various AUV navigation techniques developed which uses a simple vision sensor like CCD camera for navigation over the last decade. Cameras offer cheaper solution compared to other vision sensing techniques for limited range applications like underwater surveying. To obtain useful information from CCD camera, the images captured will have to be subjected to image pro-cessing techniques. The most commonly used algorithm to detect an underwater pipeline or cable is to denoise the image and then perform edge detection and Hough transform to detect the pipeline contour. In order to reduce the processing time, image can be converted to grayscale. Another method is to analyse only a part of the image. Recently template matching techniques have also been proposed to detect pipeline/cable. For tracking Kalman filtering or Particle filtering approach can be used. Optical flow tracking and mean shift tracking methods have also been proposed.

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