USHRIS: A Subaquatic Hybrid Inspection and Visual Reconstruction System

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Abstract: Robotic inspection systems (RIS) have been a very stimulating robotic research and development area in this era ranging from the ocean to sky. In general, this inspection is done using a skilled professional. But it entails high skill and expense failing which it probabilistically will lead to huge devastation. Thus, came autonomous inspection systems where a robot is used to accomplish certain inspection tasks. Amongst all the structures to be inspected, subaquatic bridges have tended to be the most challenging, dangerous and expensive system to keep track of. Here in this research, we propose the **Unmanned Subaquatic Hybrid Robotic Inspection System (USHRIS)**, a RIS that can detect the defects (cracks) along with the dimensional analysis of the defect for the ease of monitoring. The design of the system is as follows: The Unmanned Surface Vehicle (USV) will be connected via an umbilical to the Remotely Operating Underwater Vehicle (ROUV) which will monitor inside aquatic regions using camera, sonar and instruments as such. The system is also designed to navigate in GPS prone surfaces without any turbulences. Also, changes in the edifice of the bridges are monitored using recurrent inspection as a result of mapping. Thus, encompassing all the above-mentioned facts into one controlling system we propose the 'USHRIS' in this research paper. The source code for the USHRIS can be acquired from https://github.com/USHRIS.

Keywords: Robotic Inspection, USV, ROUV, Hybrid Systems, Mapping, Pose Estimation.

I. INTRODUCTION

We have seen the application of robotics significantly influencing the quotidian mundane lifestyle of all more particularly in this era. Among several other applications of robotics, one very thought-provoking effect has been on there usage as robotic inspection systems (RIS) to detect faults and defects in big infrastructures. Most of the infrastructures tend to deteriorate over time. Thus, to prevent failing of these structures and causing accidents, effectual recurrent inspection is necessary. Inspection can happen in two ways: professionals who can visit the site and inspect; and robotic inspection systems. Inspecting small structures using professionals can be an ideal option but when it comes to dangerous and huge social infrastructures, professionals generally miss out some fault areas which might in future result in potential failures. Thus, considering the reliability and consistency of the inspection, it is best suitable to use robots for the task.

A study [1] shows that 5,75,000 bridges in the United States are built over streams and rivers. Amongst the five lakh bridges, 80 have collapsed over the last few years. Thus, the lack of inspection and physical constraints/ contributing to the ignorance of inspection in this system is a major concern. Some of the prime reasons highlighting the purposes of bridge inspection can be found in [3]. Thus, in this research, we are focusing solely on underwater inspection of bridge piers using the USV and ROUV hybrid system [2] equipped with perception algorithms and visual inertial SLAM adapted with it. Though our system 'USHRIS' can also be fused alongside other inspection systems like dam inspection, vessel inspection, etc. among various other systems.

II. RELATED WORKS

There have been tons of research on both bridge defect detection and using complex and robust systems like USV with ROUV by various other researchers. Some of the most interesting and effectual researches undertaken are shown in this section. Yeum et al [4] detected cracks near the bolts of the bridge structure using UAVs. Matni et al [5] uses a homography matrix for UAVs to navigate around the bridges inspecting and monitoring them. Optimizing the data acquisition for efficient inspection of bridges using a DJI Phantom and comparison with SDDOT data of bridge defects are done by Seo et al [6]. Shimono et al [7] proposed an inspection system particularly designed for dam using the hybrid USV and ROUV combination. Ellenrieder et al [8] surveyed on a lot of viable options for bridge inspection using USV.

III. PROBLEM DEFINITION

The paper presents USHRIS, an autonomous hybrid surface robotic inspection system enriched with the features mentioned below:

- To our best knowledge, USHRIS is the first completely open-sourced system which covers potentially everything from visualizing the defect and dimensional analysis of the cracks to the localization of the USV and monitoring changes in the structure over time and real-time comparing and enhancing using the ROUV.
- Enables navigation without instabilities in GPS-deprived locations that's maybe when the USV is under a bridge and the Satellite fails to capture its relative position.
- Dimensional Analysis of defects that's the crack for precise positioning and monitoring for future inspection. This ultimately helps to keep track of the change in the defect dimension over time for analysis and preventing failures of the structure.
- Remote perception in hazardous operation zones where humans can't be able to monitor regularly thereby preventing potential failures.
- Capturing change in the structure from recurrent inspection from the mapping techniques adapted by USHRIS. This will help monitoring of influencing defects in the structure.

In the remainder of the paper, related research proposed by various authors are put forth in Section II, the architecture of the entire USHRIS is proposed in Section III. In Section IV, the CNN approach of bridge defect detection and dimensional analysis is covered and in Section V the SLAM technique adapted to successfully accomplish the objectives mentioned above is shown. Finally, concluding remarks of the system and future works planned for enhancing the USHRIS is explained in Section VI.

IV. PROPOSED ARCHITECTURE

1. Mechanical Design

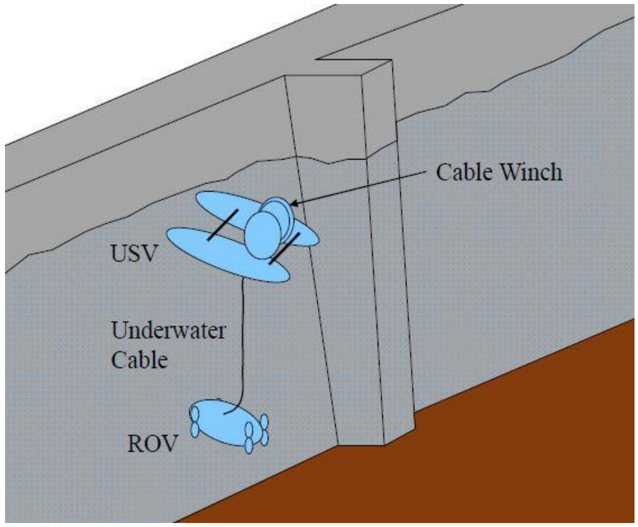


Figure 1. Overview of the system

As seen in figure 1, the overall system consists of the USV and ROV connected to the ROV by the umbilical cord which is used for data acquisition and power transmission. The cable wench is used to adjust the length of the umbilical cord or the underwater cable thereby making the ROV navigation in water more flexible and agile. The USV design has two thrusters for the horizontal navigation of the USV system. The power source and the central processing unit is placed in the USV which is less exposed to the water compared to the ROV. Thus, power and data are directly transmitted to the USV from the ROV since all the processing and the acquisition can happen only in the USV part of the entire system.

2. Electronic Subsystem

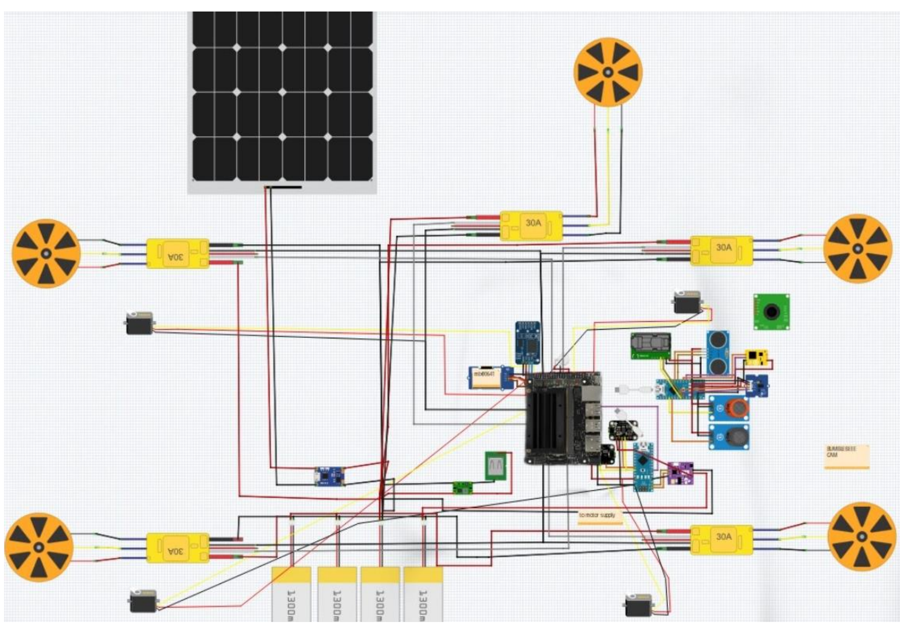


Figure 2. Overall Electronic Circuit

Combustion propulsion systems are very new and not yet reached its best usage with CO_2 and thus can't be used in environment which is rich in CO_2. Rocket propulsion systems are very heavy as they should have onboard propellants which will significantly impact the flight time. Thus, we are using electronic propulsion system. The figure 2, clearly depicts the overall circuit connection of the entire system we have proposed. This will be placed inside the USV and the black central part in the circuit shows the controller used for our system that's Jetson Nano.

The connection depicted in figure 2 is as follows: BLDC motors are connected to the ESCs, signals are sent through Pulse Width Modulation (PWM) as pulse signals. Jetson Nano is connected to a timer module that wakes and shuts the whole system down to increase efficiency when not necessary. Timer module is connected through the I2C protocol. I2C protocol is a communication protocol which is used by low power devices, especially sensors. Data is transferred bit by bit along the SDA line which ensures synchronization between various devices and assigns individual addresses to every device connected in the bus. For charging the battery, solar panel is used. Power output from solar panel is connected to battery using TP4056 module that regulates and protects battery from overcharging or over voltage. A voltage monitoring unit is connected to the battery to check the output to motors and Jetson. If there is an unusual voltage reading from the battery, the system will automatically disconnect thereby protecting the circuit. A buck converter is used to step down and regulate the voltage provided to the controller.

2.1. Motors

Selection of motors is directly dependent on the thrust required. Gearboxes were used along with the motors to attain low rotor speed requirement taking the slow speed of sound and the length into consideration.

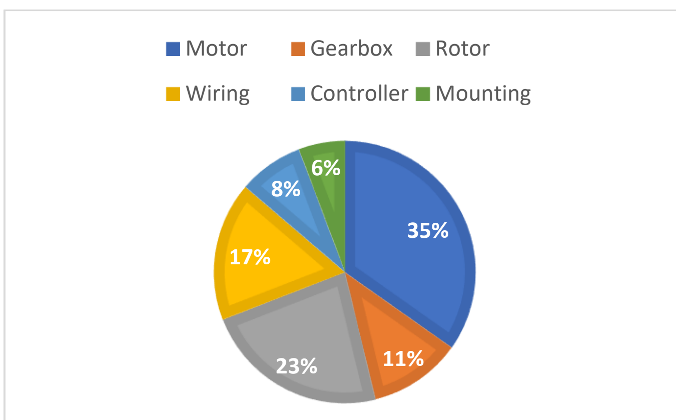


Figure 3. Propulsion System

3. Weatherproofing

A silicon conformal coating is used to prevent USHRIS from water splashes and corrosion preventing sprays. In addition, vibration motors are used to avoid sand in the internal components of the aerial vehicle. Thus, even if dust accumulates, the vibration motor can be triggered and dust can be removed.

4. Communication

For communication between USHRIS and the base station, Xbee communication is used which uses radio transceivers. In particular we are using 900 MHz Xbee-Pro Digi Long-range RF module which is designed by us to relay information over a distance of up to 15 miles or 24 kilometers. An ADF7023 transceiver is built in for analog signal transmissions, low power consumption and draws power less than 2.5uA. Thus, with a superior 15 miles of line of sight, XBee we are using takes 20% less current than the traditional modules of ZigBee.

5. Serviceability

- Power distribution boards are used to organize the distribution of power throughout the circuits.
- Emergency switches are inbuilt which can stop the functioning of the system with just a touch of button in times of malfunction.
- Power Source is completely isolated from the rest of the system to prevent total malfunction of the system. USHRIS also has external plugin for charging the systems.
- Additional IMU is built in as a safety to be used when data from one IMU is assorted.
- All the motors are positioned in-hub to prevent failures of propulsion system considering high sand and dust.
- Vibrating motors remove sand and dust present in USHRIS.

6. Software System

6.1. SLAM

The major tweaking in our proposed ORB3 system equipped in USHRIS lies in the visual odometry part of the architecture. ORB3 SLAM is heavy in nature of processing, but we have accelerated the process using CUDA making it scalable for our system. We have used the ORB Feature Extractors for extraction, FLANN for Feature Matching, KLT for Optical Flow, RANSAC for outlier removal along with Lowes's test and Efficient PnP for efficient estimation of the pose of USHRIS using Direct Linear Transformation and Levenberg Marquardt Algorithm in its backend. The architecture of Visual Odometry can be visualized in fig. 4.

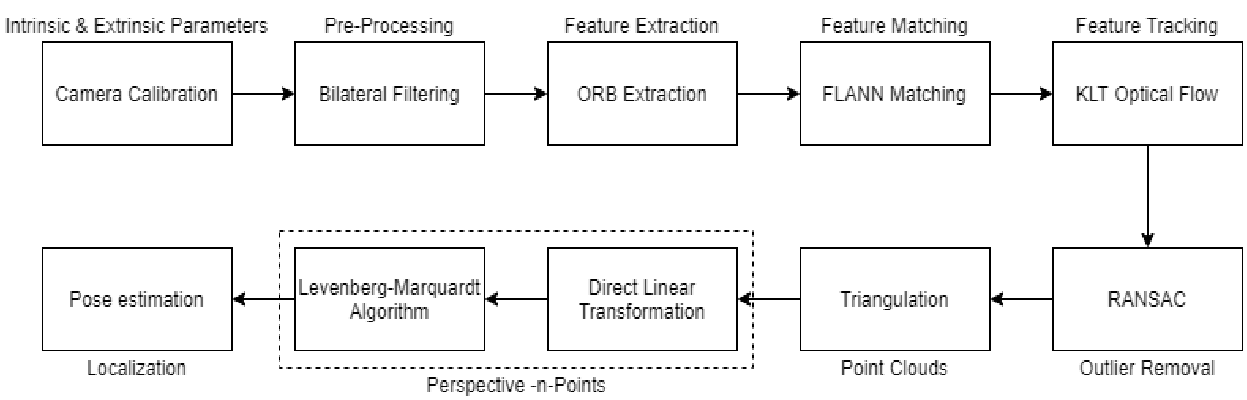


Figure 4. Architecture of the visual odometry

(a) (b)

Figure 5. ORB Feature Extraction

Fig. 5 depicts ORB based feature extraction in indoor and outdoor environment with a maximum feature threshold to be 1500. Fig. 6 shows FLANN based feature matching. FAST stands for Features from Accelerated Segment Test [5]. It is one of the fastest feature extraction technique. It is best for live real-time application point of view with efficient computation. The working of FAST is as follows: Corner detection by drawing the bresenham circle around the pixel p and labelling each of the circle from 1-16. Then intensity of N random pixels is compared.

$$S_p = \begin{cases} Ip \to x \leq Ip - T, \ darker \\ Ip - T \leq Ip \to x < Ip + T, \ similar \\ Ip + T \leq Ip \to x, \ brighter \end{cases} \quad (1)$$

Multiple interest points are cast off using the non-maximum suppression which is based on the difference in distance between subsequent keypoints.

Figure 6. FLANN-based Feature Matching

After feature extraction and matching, tracking of the feature points matched has to be done. We have used KLT Optical Flow approach to track the features from one frame to another which can be visualized for an outdoor environment in fig. 7. Apparent motion of pixels in a frame can be tracked using Lucas-Kanade Optical Flow algorithm, which is a method for detection for feature tracking. It assumes that neighboring local pixels have small (can be considered constant) flow and solves the general optical flow equation using least square criteria (error has a gaussian distribution of zero error). The image flow should always follow:

$$Ix\,(q1)Vx + Iy(q1)Vy = -It\,(q1) \tag{2}$$

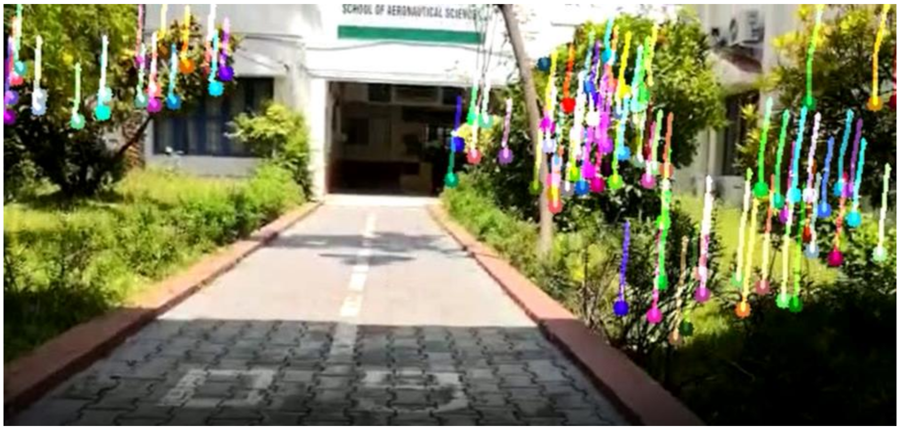


Figure 7. Feature Tracking using KLT

Equation (6) shows the camera projection matrix which will in turn be used to determine the rotational and translational vectors. From these matrices, the camera pose will be estimated and thus localization happens. Equation (7) is an expanded view of equation (6).

$$S \times p_c = K \times [R \mid T] \times p_W \tag{3}$$

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & \gamma & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \tag{4}$$

Here in equations (6) and (7),

S: Scaling Factor
P_c: Image Coordinates
P_W: World Coordinates
K: Camera Calibration Parameters
R: Rotational Vectors
T: Translational Vectors

6.2. Sensor Fusion

Sensor Fusion is combining many sensor data in a way that the system can understand better with less error ratios. Increase in the quality of the data by removing noises, increasing reliability and range are the major advantages of sensor fusion. We fuse sensor data using Extended Kalman Filter which is a nonlinear model to propagate the system state. It has three major steps- Predict; Measurement and Update.

Any sensor data always has an uncertainty in measurement associated to it. It's either in the form of disturbances due to noise or an error in sensor reading. These are rectified using filtering techniques to filter out the disturbance. The IMU data is fused with the stereo visual odometry to get a better and more reliable odometry data. The Global map from ORB Visual inertial SLAM is fused with the Local EKF localization using AMCL which stands for Anti-Monte Carlo Localization and EKF to get a better global frame. Hence using these sensor fusion and filtering techniques make our system more effective and failsafe making it better for Martian environment.

6.3. Path Planning

We are using a modified version of RRT path planning algorithm. The modifications are based on the necessity for robustness in 3D martian environment. RRT is a very fast algorithm designed to search an affine space and add it to its tree thereby building its tree. They are especially used in high dimensional large spaces with many obstacles and constraints. The algorithm is designed such a way that it will stop when a node is generated within the goal region. The architecture of the tweaked RRT path planning algorithm can be visualized in Fig. 8.

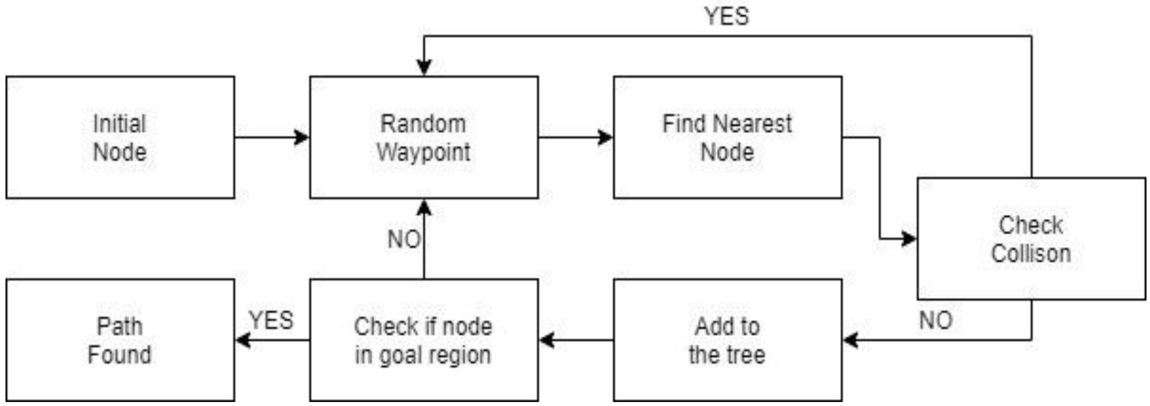


Figure 8: RRT Algorithm

6.4. Computer Vision

The major aim in computer vision was to determine the location of the defects accurately and faster. Thus, we devised our own algorithm with more accuracy and less computation cost. As seen in figure 9, we have done classification and precise detection of defects in steel (inclusion, cracking, patches, pitted surface, scratches and rolled in scale). We got a model with 96% precise matching and 0.066 loss factor.

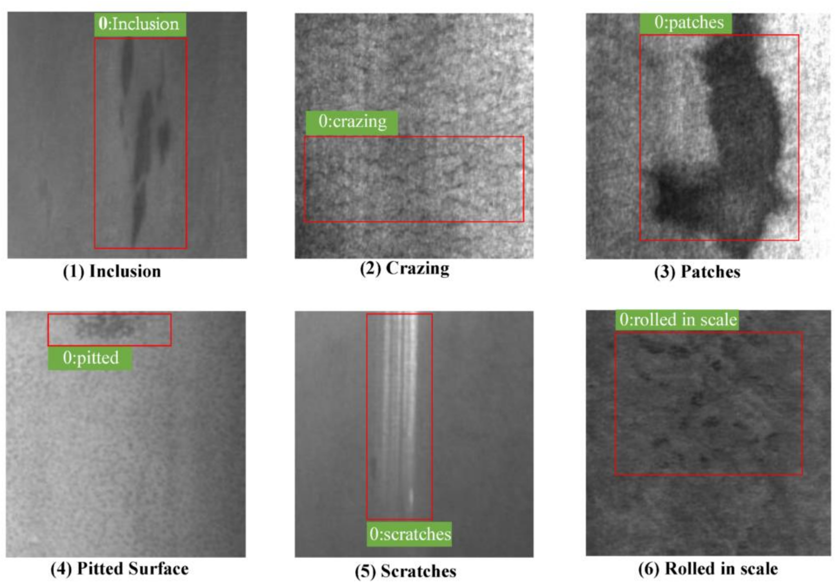


Figure 9. Steel Multi-Class Detection

6.5. Control Systems

In this section we will discuss all the types of controllers that can be equipped.

Proportional Controller (P only)- Stabilizes unstable process. It helps in reducing the steady state error in the operation. But this controller can't always eliminate the steady state error. Thus, we will check along with Derivative controller next.

$$output = K_p * error \quad (1)$$

Proportional Derivative Controller (PD only)- Increases the net stability of the operation. Derivative part of the control system helps in predicting the future errors of the systems based on its response. Thus, it helps in controlling the sudden shift of the operation.

$$output = K_p * error + K_d * (error - previous\ error) \quad (2)$$

Proportional-Integral-Derivative Controller (PID)- Thus, this is a very dynamic system equipped with zero state error, fast response, no oscillations and high stability. Here in equation 3, Iterm is incremented for every estimated error value in the system.

$$output = K_p*error + (Iterm + error) * K_i + K_d*(error - previous\ error) \quad (3)$$

We have used PID based control systems for the proposed system in fig. 1. The basic idea of PID is error of the system will be estimated based on setpoint (SP) values and the process variable (PV) value estimated. Thus, weights will be assigned and subsequent PWM values will be generated based on mathematical models and resulting speed of the rotors will be passed to the motors. This is the crux part of PID control system in general. We are using two PID modules in this work namely Altitude Controller (AC) and Position Controller (PC).

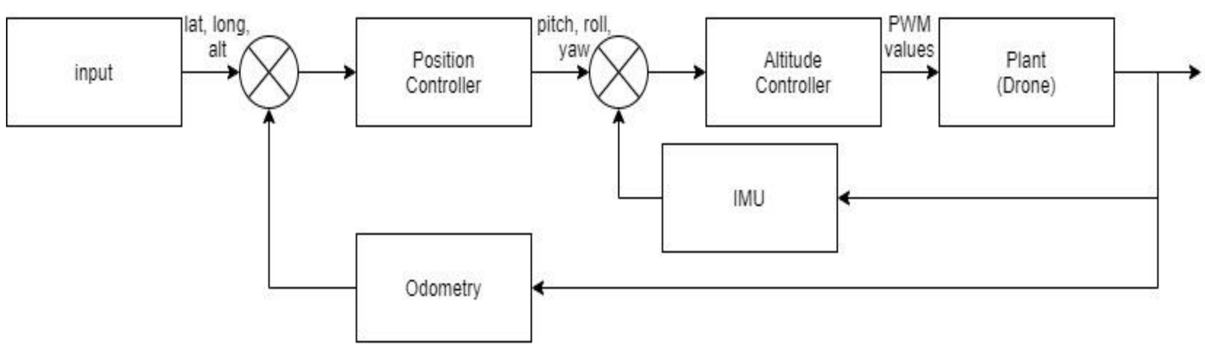


Figure 10. Control System for the Drone

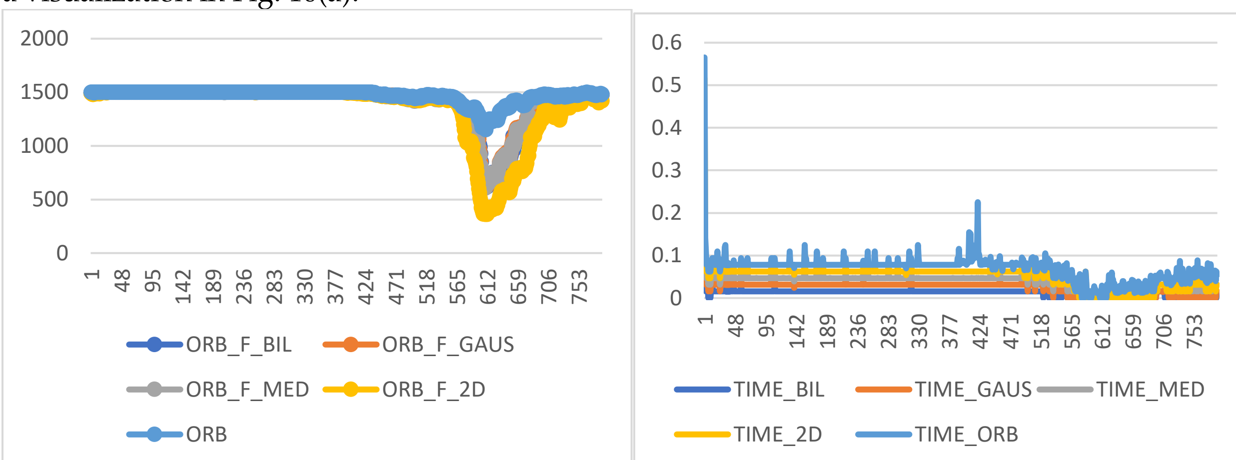
The **Altitude Controller** stabilizes the drone at the zero-error roll, yaw and pitch (R-P-Y) angles using a PID based control system. That's, stabilizing the orientation of the drone (R-P-Y) using PID is the aim of altitude controller. Then tuning of the proportional, integral and derivative function has been done to get the best suitable controller configuration.

The **Position Controller** takes in the target coordinates as setpoint values and calculates the R-P-Y angles to successfully move to the setpoint coordinates. That's position of the drone with respect to the environment is estimated using this controller. This controller will be in sequence with the altitude controller designed as mentioned in the previous paragraph.

This altitude and position controllers work in synchronization to autonomously navigate in the environment in a robust manner. From fig. 1, we can clearly understand the workflow, the position that's the latitude, longitude and altitude is passed through the position controller as input and then the output of the position controller being the R-P-Y values (orientation) which will act as input of the altitude controller. Thus, a dynamic position controller was designed so that instantaneous change in the latitude, longitude and altitude (position) can be altered and navigation can be established accordingly.

VI. EXPERIMENTS AND ANALYSIS

We have proved ORB extractors are best for visual odometry in our proposed system and made a visualization in Fig. 10(a).



(a) (b)

Figure 11. Smoothening techniques

Here in fig. 11,

F_BIL: Bilateral Filtering

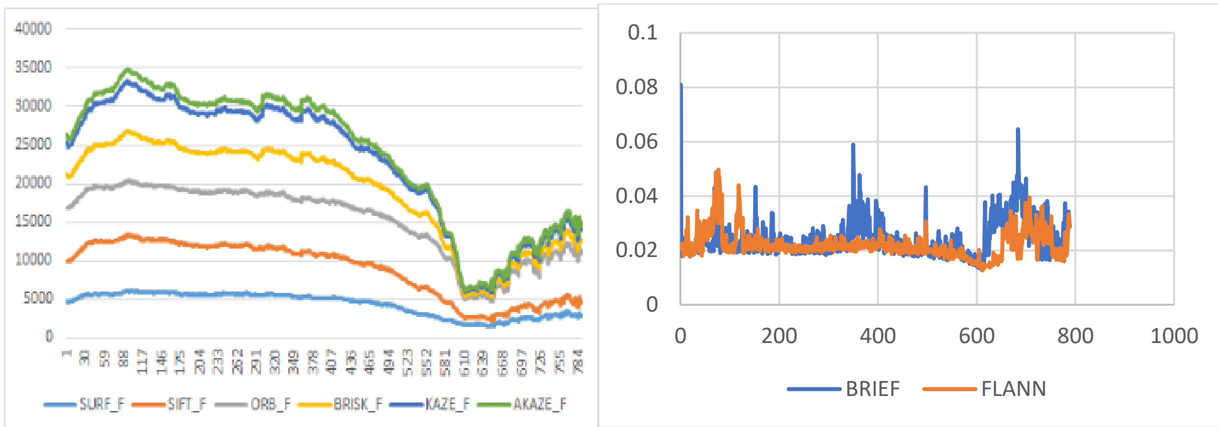
F_GAUS: Gaussian Filtering

ORB: Without pre-processing extraction

MED: Median Filtering

2D: 2D Image Filtering

We have used Bilateral filtering for postprocessing the frames obtained from the stereo camera and the reasons for choosing it over gaussian filtering, 2D filtering and median filtering can be visualized in Fig. 10 (a) and (b) representing the number of features extracted after smoothening per frame and the time taken for this extraction with respect to the frame, respectively.



(a) (b)

Figure 12. Comparison of various extractors and matchers

We have shown that FLANN based feature matching in Fig. 11(b). We have experimented our stereo visual odometry algorithm using KITTI dataset with its ground truth. The results can be observed in fig. 12. The red lines in the interface represents the ground truth and blue lines represent the estimated track obtained from our stereo visual odometry algorithms. KITTI dataset was used so that our estimated pose can be compared with its ground truth.

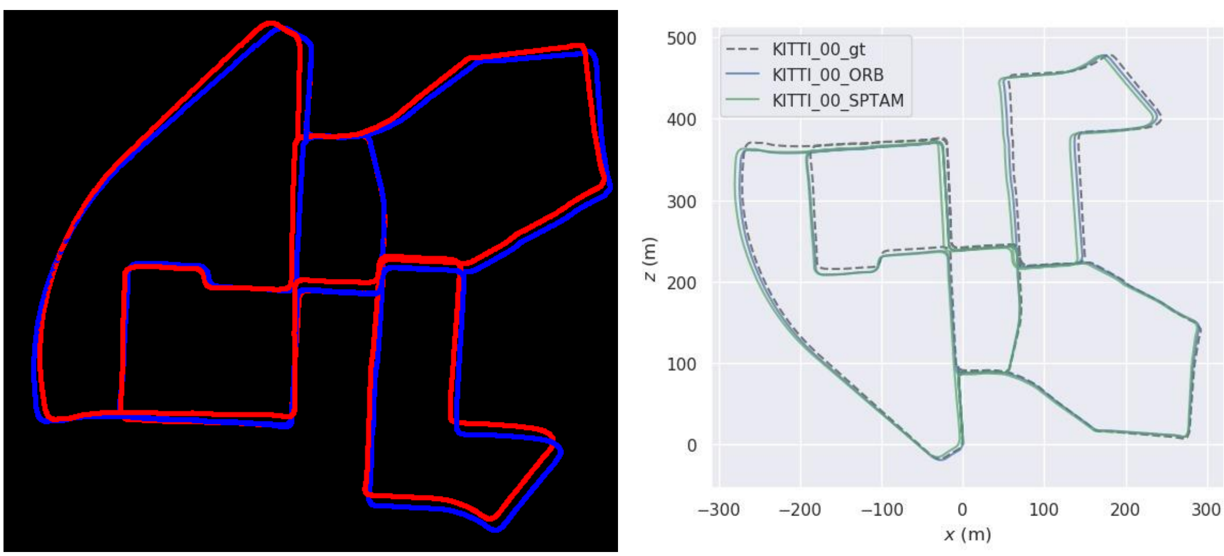


Figure 13. Trajectory of USHRIS in KITTI dataset

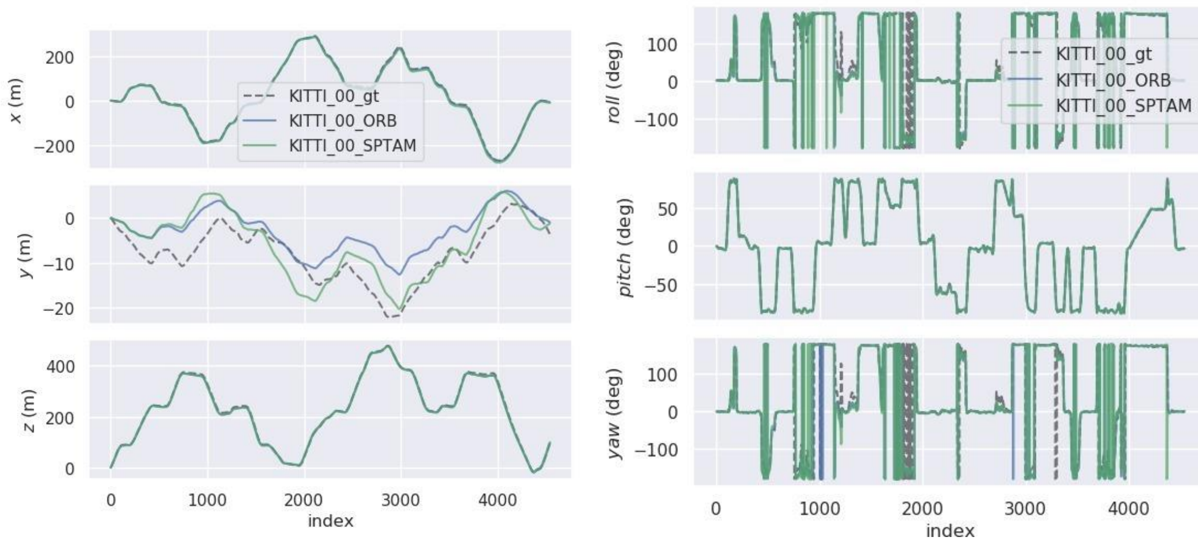


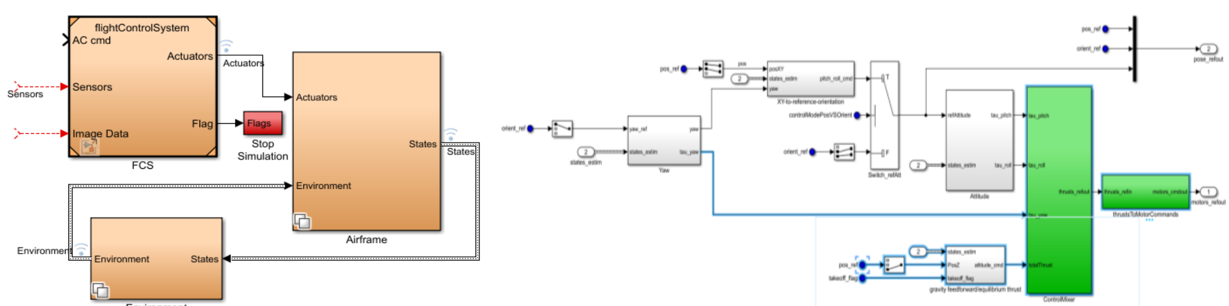
Figure 14. Evaluating the trajectory of the KITTI dataset

An aerospace blockset in MATLAB was used for the tuning of the drone motors PID gains. We have used proportional, integral and differential control gains for USHRIS. The physics and environmental setup were tuned to work in a similar environment as mars. Simulink graphical tuning was used to tune the PID gain values thereby reducing the overshoot, constant errors and proportional errors.

Table 1. Comparison with various networks

Method	Epoch	LR	Accuracy	Recall	Precision	F1-Score	Loss
SE-VGG	50	0.001	91.97%	0.900	0.987	0.941	0.1957
SE-Inception	50	0.001	94%	0.939	0.973	0.955	0.341
Our Network	50	0.001	96%	0.979	0.965	0.971	0.066

Table 1 shows our computer vision models accuracy when compared with other models proving how accurate our model is when compared to other.



(a) (b)

Figure 15. Simulation of Control System in Simulated environment using Simulink

Used EUROC Hall dataset for validation of the tweaked Vi-ORB SLAM technique. Fig. 15 visualizes stereo view of the approach adapted along with point clouds extracted in white, red line is the current pose and green is the trajectory in simulated environment.

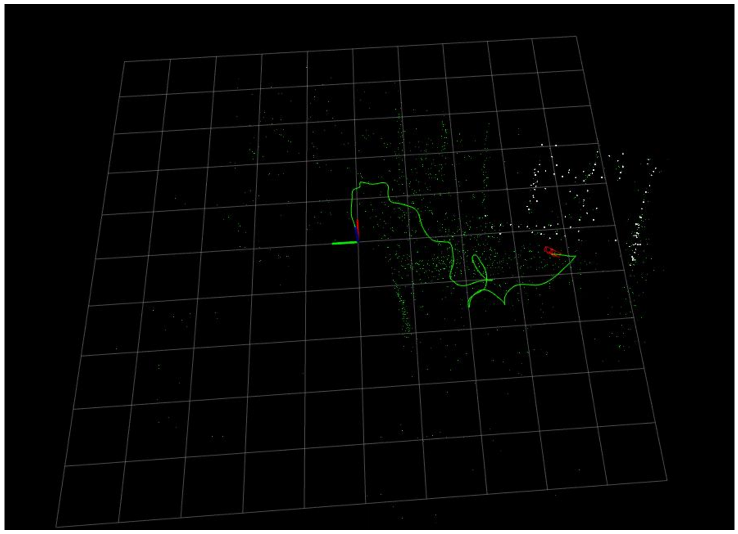


Figure 16. SLAM Implementation

VII. CONCLUSION

We have proposed a robust underwater system for inspection in this research explaining the reasons behind each and every subsystem chosen. The system is equipped to withstand heavy amount of water, float and traverse in water particularly built with the goal to inspect defects and cracks in bridges and dams in water surface. Once the defect is detected we will send communication to the base station where our system will automatically send a report stating the risk and the significant impact of the defect if any on the bridge/ dam/ infrastructure after which humans can decide on what has to be done after forth. Our system also has the ability to capture the structures posture on every surveillance which will be stored in the database and so will keep monitoring the change in the structure which also acts as a surveillance monitoring of the infrastructure. We have used PID control system to make the posture of the robot in place without any error and RRT Path Planning for choosing the most suitable path to be undertaken by the robot. Also, ORBv3 SLAM algorithm has been used in our USHRIS for autonomous navigation in GPS prone areas. Thus, a complete system has been proposed in this research proving the efficiency of the robustness of each sub-system.

We have also proposed a mono version of visual odometry in our proposed system. When it comes to feature extractors- ORB is most efficient, SIFT is most stable, SURF is faster than SIFT, Shi-Tomasi is fastest among all the extractors (considering the number of features extracted), FAST is second most efficient when compared to ORB in terms of accuracy and computation. When it comes to feature matchers, FLANN is more efficient than BF Matcher in terms of computation and insignificant change in accuracy. For outlier removal, RANSAC outperforms other techniques in determining the outliers more precisely than KNN or PROSAC. For Mono Visual Odometry, estimation matrix gave good results. Other possible option for mono would be testing with Kalman filters thereby estimating the state estimate distribution (planned for our future works). For Stereo Visual Odometry, EPnP outperforms PnP and MLPnP when tested with EVO evaluation of the trajectory using the R-P-Y and translational error rates. Thus, we have considered all environments and possible conditions and came up with conclusions that best suits for the stereo and mono visual odometry.

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