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MONOCULAR VISUAL ODOMETRY FOR IN-PIPE INSPECTION ROBOT

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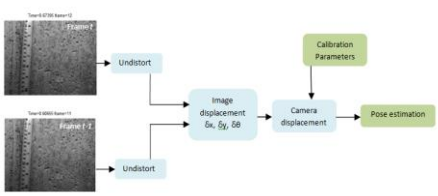
Graphical abstract



Abstract

This paper describes a monocular visual odometry technique for low texture environment localization. Estimating the pose of a robot in a small time interval is one of the challenging problems in robotics. Localization, mapping and motion planning are three fundamental problems which directly use the pose information of the robot to achieve their goal. In this work, we extract the pose information by processing image inside a concrete culvert which is taken by a camera attached to a mobile robot. We analyze different motion scenario using correlation based image to find displacement vector between two images. Real image data from the displacement of the robot are used to demonstrate the propose method. The experimental results show that the selected method proven efficient for the in-pipe inspection robot localization.

Keywords: Visual odometry, monocular, culverts, localize, image displacement

Abstrak

Kertas kerja ini menerangkan kaedah odometri visual monocular untuk lokalisasi persekitaran tekstur rendah. Menganggarkan orientasi robot dalam sela masa yang singkat ialah salah satu masalah yang mencabar dalam bidang robotik. Lokalisasi, pemetaan dan perancangan gerakan adalah tiga masalah asas yang secara langsungnya menggunakan maklumat orientasi robot untuk mencapai matlamat. Dalam kerja ini, kami ekstrak maklumat orientasi dengan memproses imej di dalam pembentung konkrit yang diambil daripada kamera yang disambung kepada robot mudah alih. Kami analisa scenario gerakan berbeza menggunakan imej berasaskan korelasi untuk mencari vektor sesaran antara dua imej. Data imej sebenar daripada searan robot digunakan untuk menunjukkan kaedah yang dicadangkan. Hasil eksperimen menunjukkan bahawa kaedah yang dipilih terbukti berkesan untuk lokalisasi robot ketika pemeriksaan dalam paip.

Kata kunci: Odometri visual, monocular, pembentung, penyetempatan, sesaran imej

1.0 INTRODUCTION

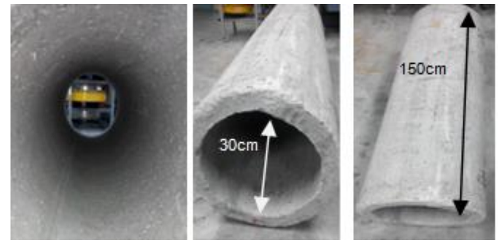
There is a special type of pipes that are placed beneath the roads in Malaysia to drain the water from the surface of the road. These pipes which are called culverts are a chain of 1.5 meter concrete segments and the diameter of each segment is about 30 cm. Maintenance is an important issue in the culverts since any damages on the culvert can cause the leakage of the water and collapsing the road surface. Finding the location of the damages is the first stage of the maintenance operation. The culvert inspection process is essentially visual in nature with all defects recorded manually and photographed. This procedure introduced the safety risk to the inspector due to steep embankments and loose surface material during the process [1]-[4]. One of the safe and reliable ways to achieve this goal is through a pipe inspection robot. The robot can be controlled manually from the outside.

The operator navigates the robot inside the pipe and inspects the wall of the culvert by the camera attached to the robot. Whenever the operator finds a damage on the wall, the location of the hazardous point must be reported for next actions. In other words, the robot should be able to localize itself inside the culvert and report its location to the operator. Pipe inspections robots are navigated inside a pipe and they commonly move slowly. Hence, the localization of the robot using wheel odometry, INS and GPS methods can be inaccurate. Therefore, by introducing visual odometry (VO) techniques to estimation ego motion of the mobile robot and provides more accurate trajectory estimates [5]-[10]. However, sufficient illumination in the culvert and enough texture to allow apparent motion to be extracted need to be considered.

2.0 PROPOSED METHOD

2.1 Camera Attachment

As it is mentioned before, the robot moves inside a concrete culvert with interior radius r = 150 mm. Even with perfectly perpendicular camera to the pipe, the pixel displacement vectors are not linear functions anymore. This is because the values of Z cam are not identical for different points on the wall the total derivative will be a nonlinear function. Suppose the camera is located at the center of the culvert (i.e. the height of the camera is 150 mm) and its optical axis is perpendicular to the ground of the culvert as shown in Figure 1. The z-axis is from the camera to ground and y-axis is from the camera to its right. Also, the x- axis is determined using by right hand rule.



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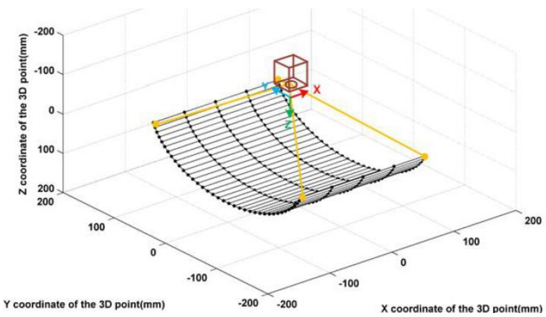


(b)

Figure 1 (a) Concrete culvert with interior radius r = 150 mm (b) Camera attachment

2.2 Pixel Displacement

Assume the robot is moved 15 mm and 5 mm along its x-axis and y-axis, respectively. This means that δX= 15, δY = 5 and δZ = 0. Now, suppose the 3D coordinate of a point of the grid are given in camera coordinate system. To obtain the pixel displacement vector of each 3D point, their total derivatives were calculated. Figure 2 indicates 3D points as well as their pixel displacement. Vector calculated for a camera with fx = fy = 800, a = 0:0004 and ki = 0. The x and y values for 3D points on with same X cam values, separately were shown in Figure 3. The field of view of the camera is 150o in this example. As the figure shows, the pixel displacement in center of the image is smaller than the displacement in the sides of the image. This is because of the division with squared value of Zcam. It should be noted that there is a significant difference of view. Therefore, the direct method of monocular visual odometry algorithm can be used to calculate the motion of the robot.

However, if the field of view of the camera is reduced to 30 and its height is increased to 230 mm, the total derivative of 3D points changes to the chart in Figure 4. As the results, by reducing the field of view the pixel difference between displacement vectors can be ignored. Therefore direct method of monocular visual odometry algorithms can be used to calculate the robot motion.

2.3 Monocular Visual Odometry

The pose estimation steps were performed using images captured by the monocular camera. The estimation of motion can be computed between the current image frame, t and the previous image frame, t-1. By linking all the single movements, the full trajectory can be obtained. In this work ,the position of the robot were represented by a 3-dimensional vector given by [X_{world} , Y_{world}, θ] where the X_{world} and Y_{world} are the position of the robot in world coordinate system and θ indicates the rotation of the robot around z-axis.

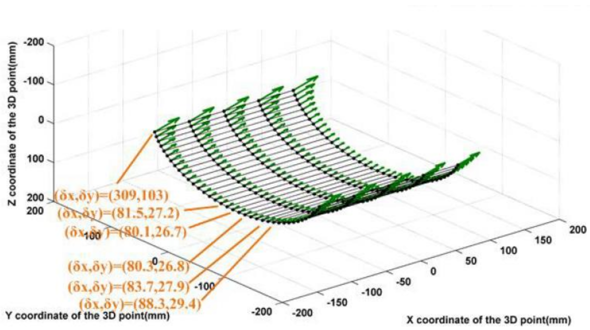


Figure 2 Pixel displacement

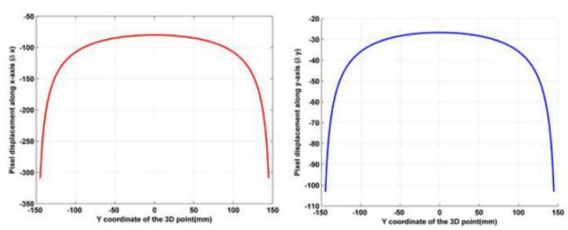


Figure 3 Total derivative of 3D points for field of view of the camera 30°

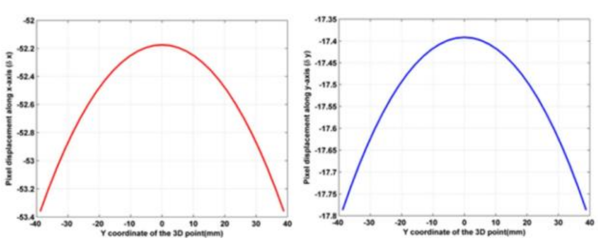


Figure 4 Total derivative of 3D points for field of view of the camera 30°

The visual odometry algorithm starts with finding the displacement vector between images frames which is represented by δx, δy, δθ then displacement of the camera is computed. Figure 5, shows the monocular visual odometry algorithms for calculating the motion of mobile robot. The phase correlation method were used to find the translation components. Using two images I_{t-1} and I_t and Fourier transforms F{I_{t-1}}and F{I}, phase correlation method finds these components by calculating following value for each pixel (x, y) on the image.

$$\mathcal{F}\{C_{xy}\} = \frac{\mathcal{F}\{I_{t-1}\}_{xy} \otimes \mathcal{F}^*\{I_t\}_{xy}}{\left|\mathcal{F}\{I_{t-1}\}_{xy} \otimes \mathcal{F}^*\{I_t\}_{xy}\right|} \quad (5)$$

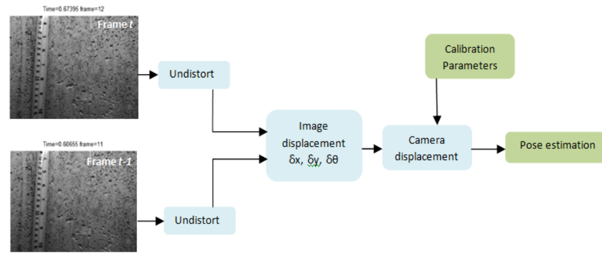


Figure 5 Visual odometry algorithms

In Equation (5), the F{.}xy and F* {.} xy indicates the value of Fourier transform and its conjugate at point (x, y), respectively. Also, ⊗ shows the member-wise product between two matrices. C indicate the complex matrix with the same size as the images. Based on this matrix, translation component can be calculated as follow:

$$c_{xy} = \mathcal{F}^{-1}\{C_{xy}\}$$
$$(\delta_x, \delta_y) = \arg \max_{x,y} c_{xy} \quad (6)$$

Here, $\mathcal{F}^{-1}$ indicates the inverse Fourier transform. The equation states that the translation components can be obtained by finding the location of the maximum value of matrix c. If there was no rotation between images, we could use the above method for finding the translation vector (δ_x, δ_y). Note that the phase correlation returns value $c_{\delta x \delta y} = 1$ with perfect matches, we can find the rotation component as follow:

$$\delta\theta = \arg\max_{\theta} \max\left(\mathcal{F}^{-1}\left(\frac{\mathcal{F}\{I^{\theta}_{t-1}\} \otimes \mathcal{F}^*\{I_t\}_{xy}}{\left|\mathcal{F}\{I^{\theta}_{t-1}\} \otimes \mathcal{F}^*\{I_t\}_{xy}\right|}\right)\right)$$
$$\forall\theta = -10 \ldots\ldots 10 \quad (7)$$

Using the above equation, it is possible to calculate the distance traveled in X and Y directions by image displacement vector and camera intrinsic parameters.

$$\frac{\delta Y_{cam}}{\delta t} = \frac{\delta_{y_{img}}}{\delta t}\frac{Z_{cam}}{f_y} \quad (8)$$

$$\frac{\delta X_{cam}}{\delta t} = \left(\frac{\delta_{x_{img}}}{\delta t} - \frac{\alpha}{Z_{cam}}\frac{\delta Y_{cam}}{\delta t}\right)\frac{Z_{cam}}{f_x} \quad (9)$$

3.0 RESULTS AND DISCUSSION

In this work, the proposed method was simulated using a simple platform. A camera mounted laptop is placed on an omni-directional chassis and the robots navigate inside the culvert and recorded different video form its motion.

3.1 Indoor Experiments

A camera mounted laptop is placed on an omni-directional chassis and several videos were recorded on a tiled surface. Figure 6 shows the trajectory of the robot for straight path videos. The thin (red) solid line at the trajectory indicates the heading direction of the robot. The videos are taken by moving the platform on the floor covered by 20 × 20 cm tiles. Over the training path, the robot was able to estimating position and orientation in a straight path. This suggest proposed method were able to remain localize with small effect of undistorted image effecting the error in pixel displacement.

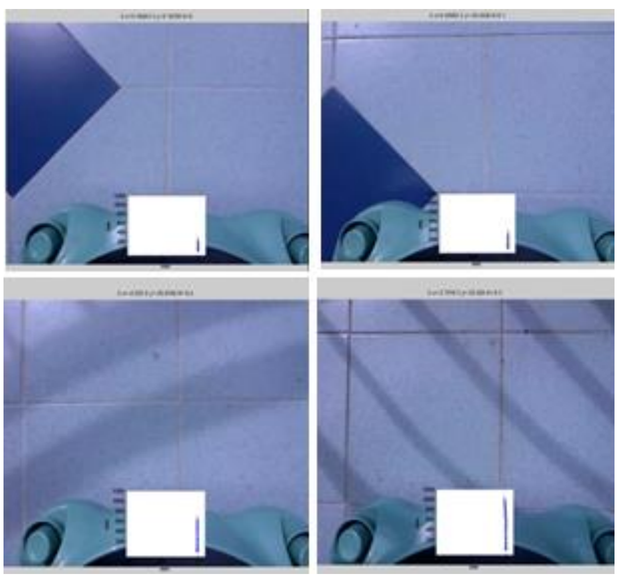
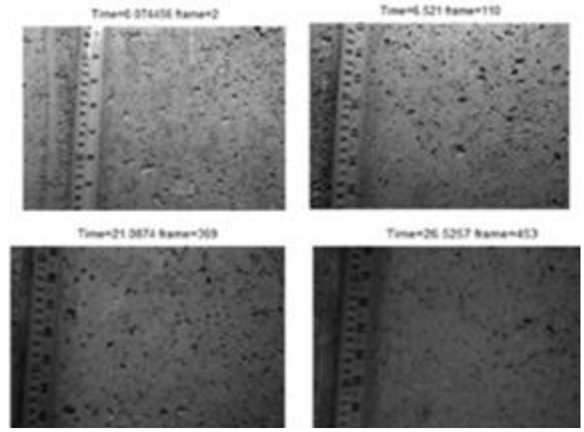


Figure 6 Screenshots of images from the indoor experiments for straight trajectory

3.1 Outdoor Experiments

In order to prove the concept, real culvert was used. Figure 7 shows the information about the robot navigation estimation produce by VO. In the figure, the pose estimation is shown in the graph with solid line. We can see that as the robot move deep inside the culvert, the image was affected by illumination. As the light condition become less, the estimation show slight error in the navigation path. Therefore, we conducted a series of experiments and evaluated the results. The robot inside the pipe for 4 times which is approximately equal to 6 meters. The results are shown in Figure 7



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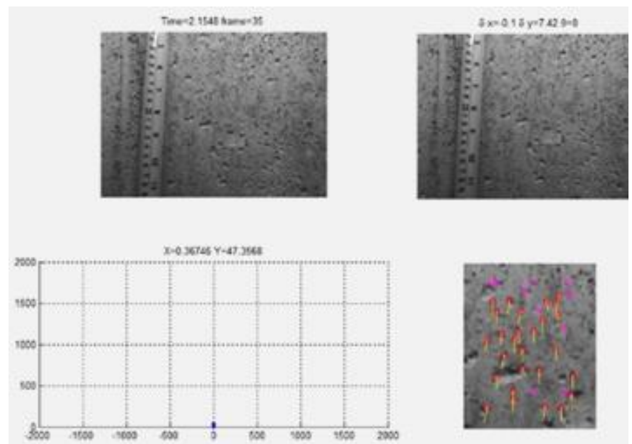

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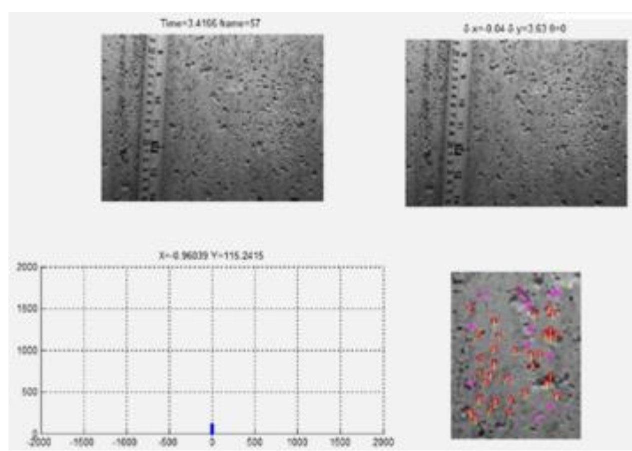

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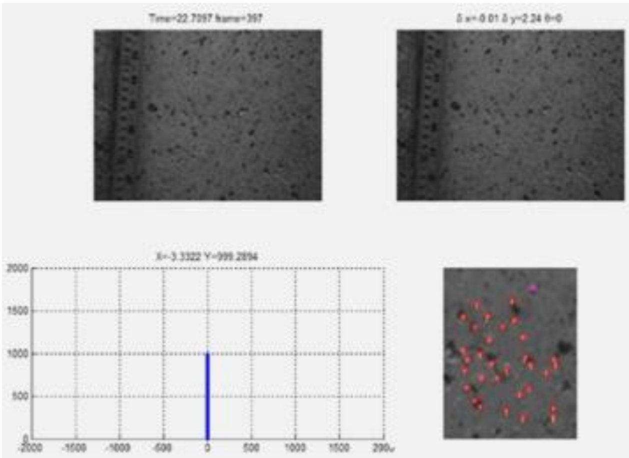

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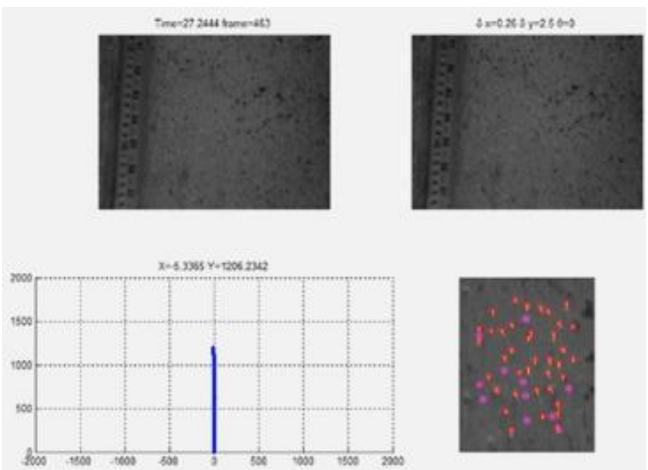
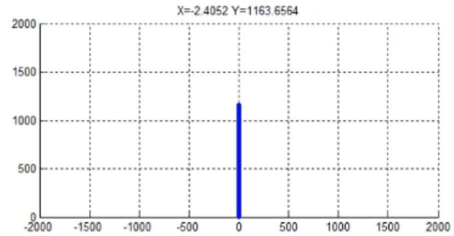


(e)

Figure 7 Visual odometry algorithms (a) Samples of image frame under different lighting condition (b)-(c) Robot pose under good lighting condition (d)-(e) Robot pose under low texture and lighting condition

3.2 Pose Estimation Error

Figure 8 and 9 shows the cumulative result of VO algorithms from of the recorded videos. It can be observed that, with low texture environment for features detection, the pose estimation error is acceptable. The error cause in the experiments is due to the camera. In some places, because of the shutter speed, the camera has taken blurry images and also effected by illumination. Therefore the effected the features detection and extraction which contribute to inaccurate robot trajectory. As can be observed that, the error displacement of experiment 1-4 shows very low error rate of standard deviation of 1.31 and variance of 1.7.



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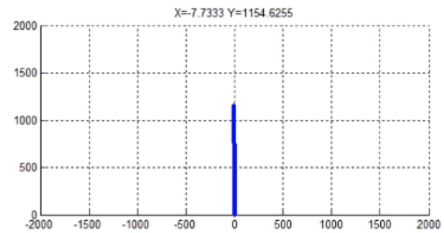

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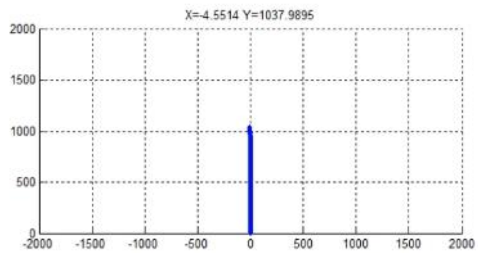

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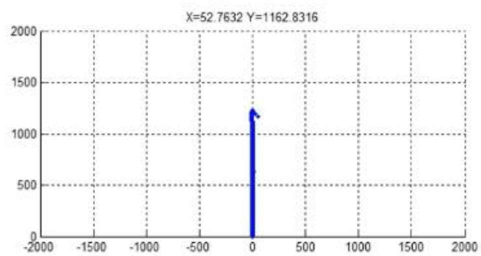

(d)

Figure 8 Sample of robot estimation path (a) experiment 1 (b) experiment 2 (c) experiment 3 (d) experiment 4

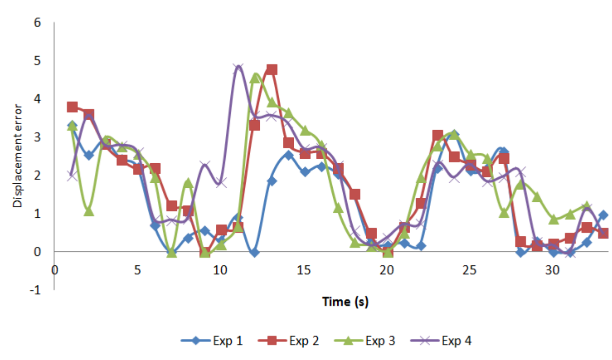

Figure 9 Error of displacement

4.0 CONCLUSION

In this paper, we have proposed method for In-pipe Inspection Robot using monocular VO, which can benefits culvert maintenance operation. The effectiveness of the proposed method is experimentally validated using real culvert concrete pipe. The experimental results demonstrated that the proposed method able to produce good localization estimation using the monocular camera with low texture environment and uneven lighting condition. Also extension of this idea to other platform can also be a potential future direction.

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