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Empirical Evaluation on the Localization Accuracy of Visual Odometry on the Gratings for PCV Internal Investigation

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As one part of the decommission tasks of Fukushima nuclear power plant, efficient and appropriate operation of removal of fuel debris requires essential information of distribution and characteristics of fuel debris. A robotic remote measurement system using an ultrasonic sensor called RhinoUS was developed to detect the distribution of the fuel debris and localize the unknown water leakages in the primary containment vessels (PCV) of the No.1 reactor. Experiments are carried out to evaluate the localization accuracy on the robot pose of the visual odometry method. The results turn out that we could acquire characteristics of the fuel debris and achieved localization error less than 15mm/1m in complex motion, and generate smooth grating map in bird view. We conclude that the visual odometry localization method might serve as a feasible solution to assist the robot localization on grating.

Key Words: Robot, Decommissioning, Visual SLAM, Fukushima Nuclear Power Plants

1. Introduction

The decommissioning task of the Fukushima nuclear power plants due to the great east Japan earthquake in 2011 has been of a high priority for current Japan. Due to meltdowns from the reactor core, large amounts of fuel debris spread into the underground floor of the reactor pressure vessels (RPV) and the primary containment vessels (PCV), while the distribution remains unknown.

As one part of the decommissioning of Fukushima nuclear power plants, these fuel debris should be accurately localized and properly removed. Such task requires preliminary survey on current situations of the reactors. In Mar. 2017, configuration changeable robot PMORPH developed by Hitachi-GE Nuclear Energy has successfully entered the PCV in the No.1 reactor [1], and captured photos of the fallen fuel debris. However, due to the poor visibility in the fluid, the recognizability of fuel debris from the photos was limited. The extreme radiation also restricted the available working period of cameras.

In order to overcome the difficulty of low visibility and radiation to the measuring sensor, a robotic remote measurement system with an ultrasonic measurement sensor named as RhinoUS was proposed in 2016 [2].

1.1 Overview of the robot

As the fig.1 shows, to localize the fuel debris distributed in the fluid of PCV in the No.1 reactor, the robot is moving on the grating floor above the fluid, with the ultrasonic sensor in the fluid for detection. At the center of the robot, a winch mechanism is installed to put the sensor into fluid through grating. In the front of the robot, a synchronized camera system is applied to acquire information of surroundings.

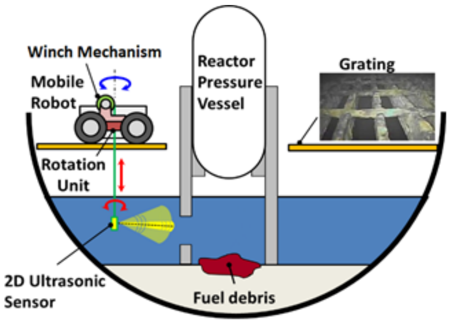

Fig.1 The basic concept of RhinoUS [3]

1.2 Localization of robot based on camera

To assist the localization of fuel debris, the localization of the robot itself when moving on grating is of importance. In the paper, we focused on the feasibility of the visual odometry localization method, and utilized an experimental method to estimate its localization performance in accuracy and map generating. As a result, we successfully generated continuous grating maps from bird view.

2. Proposal

2.1 Camera setting and transformation

In the situation of the PMORPH developed by Hitachi, a stereo camera system was utilized to estimate the position of the robot. A prismatic was applied to define the initialized coordinate system and serve as a landmark. The experiments showed that the images captured were inclined, while the angle was nearly horizontal, as Fig.2 shows.

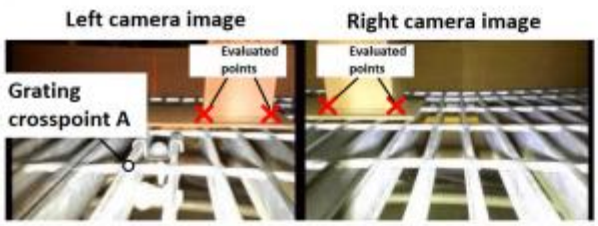

Fig.2 The view of the stereo cameras [4]

Compared with the proposal by Hitachi, we realized the localization of the robot using a monocular camera without landmark, and provided a more intuitive bird view of the grating. We applied a perspective transformation with an inclined camera, as fig.3 shows.

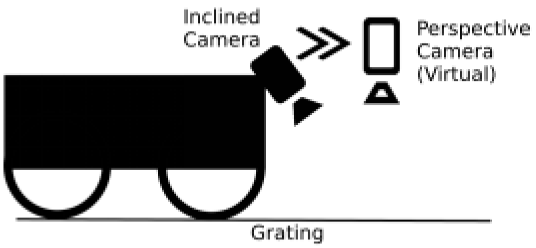

Fig.3 Perspective camera transformation

As fig.4 shows, we changed the original view of the inclined camera installed on the robot, to a vertical view from the virtual perspective camera. After the transformation, the grating in the vertical view will be planar so we can intuitively utilize its features.

2.2 Visual odometry method

Visual odometry is generally acknowledged as the front end of simultaneous localization and mapping (SLAM). We utilized the information of captured images to estimate the motion of robot, thus localizing the robot and generating map. We concluded the basic working procedures as below:

- Use a checkerboard to calibrate the semi-wide-angled camera with the calibration method by Zhengyou Zhang [5]. Calculate the homography matrix with the checkerboard for following perspective transformation.
- Perform a perspective transformation to transform the inclined camera view to the vertical view. Start the image processing when the robot starts moving. Extract the feature points in each frame using Oriented FAST and Rotated BRIEF (ORB) features.
- Use two adjacent frames as one segmentation. Try to match the feature points in one segmentation. Generate the group of the matched points containing the corresponding position relationships.
- Calculate the relative displacement between the matched feature points in the segmentation. Estimate the motion matrix of the camera based on the matched points group.
- Integrate relative motion of camera in each segmentation together, thus, update the instant 2-dimensional camera pose in the global coordinate system.
- Transform camera pose to robot pose.
- Combine the captured images according to estimated position of the camera at each frame to generate map.

2.3 Improvement strategy

In the localization situation, to improve the working performance of the method, we applied several improvement strategies listed as below:

- Use the estimated motion matrix of last segmentation when losing track of features
- Remove the motion component in Z axis due to vibration
- Make use of the number of grating lattices as reference

Losing track of features is one of the common problems for visual odometry. To reduce the influences of such problem, we supposed that the instant velocity of the robot in one segmentation of two frames will not change acutely based on the assumption of the smooth camera model from MonoSLAM [6]. So, we recorded the instant matrix of each segmentation, and used the matrix of last segmentation to replace the estimated motion matrix when losing track of features. Such strategy was proved to be effective to make the generated map more continuous.

Taking account of the motion characteristics of the robot, we could conclude that the robot is usually performing planar motion on the grating floor. Thus, the estimated motion matrix should only include the planar motion components. However, due to the vibration and noise during motion, the generated matrix often has tiny component in Z axis. Thus, we intently removed the component in Z axis trying to eliminating the influence by normalizing.

For the special case of planar localization on grating, we tried to make use of the grating lattices in the generated map. We used the known size and special shape to identify the grating that the robot passed so we could count the number to estimate the displacement of the robot. Such method can help limit the possible errors when the generated map is smooth and continuous.

3. Experiments

To evaluate the working performance of the visual odometry method, we would like to test the performance of the visual odometry method on two aspects. The 2-dimensional displacement and orientation localization accuracy, and the smoothness of the generated map under complex motion. We conducted several experiments and proposed an experimental method with an external 3D scanner to estimate the localization accuracy numerically.

To simulate the grating floor, we combined several grating blocks to form a grating plane of 2x2m for the robot to move on. For the planar motion of robot on grating, we concluded as 3 motion modes as translation, rotation, and combination of them as complex motion.

3.1 Accuracy estimating method

In the visual odometry method, we estimated the planar displacement and orientation of the robot based on the images captured. Thus, to study its accuracy, we would like to compare the estimated results with the actual displacement. Here we utilized an external 3D scanner to measure the displacement, and assumed that the measuring accuracy was good enough to serve reference. Thus, we compared the difference between the estimated results with the measured results to calculate the accuracy.

3.2 Map smoothness estimating method

Considering the situation where the generated map is formed with the grating floor, and the size of each grating has been known, we tried to identify all the recognizable grating features in the map using programs. Thus, we could roughly estimate the smoothness of the map. At the same time, the identified grating could also be utilized to estimate the displacement of robot.

3.3 Experiment results

In the experiments, we performed 3 motions with translation, rotation, and complex motion. When the robot stopped, we used the 3D scanner to acquire the measured position of robot. We compared the estimated and measured results in the table.1 as below:

Table 1: The comparison of estimated and measured motion

Type	X-direction	Y-direction	Orientation
Translation-VO	9.88mm	591.80 mm	-0.478 deg
Translation-Scan	7.92 mm	599.6 mm	-0.502 deg
Rotation-VO	6.92mm	-7.30mm	44.883 deg
Rotation-Scan	4.26mm	-5.34mm	45.021 deg
Complex-VO	727.99 mm	1247.87 mm	95.528 deg
Complex-Scan	718.38 mm	1256.06 mm	97.704 deg

For the smoothness of map, we counted the number of all the visible grating in the map, and compared with the number of the recognizable grating, using the ratio as the indicator. The results showed that all the ratios in three maps were over 95%. The generated maps with the estimated camera trajectory are shown with fig.4. The orange line indicates the X and Y direction, and the purple line stands for the orientation of the camera at the frame.

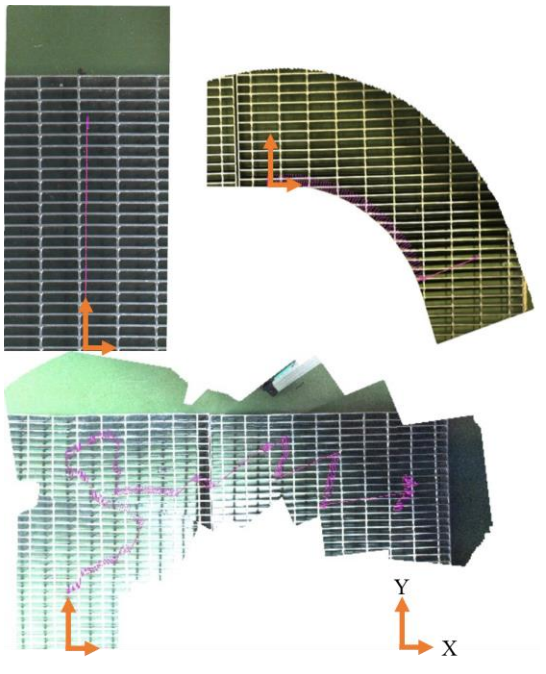

Fig.4 The generated maps

3.4 Discussions

Considering the accuracy of displacement, it's obvious that the error will increase with the moving distance increasing, due to the accumulating. So, we would like to calculate the ratio of the difference over the distance or angle passed. For the translation motion where mainly moving linearly in Y direction, the error ratio was about 13mm/1m; For the rotation motion, the angle error ratio was about 0.27 degree/90 degree. However, for the complex motion with both rotation and translation, the error ratio turned out to be: 13.37mm/1m in X direction, 6.52mm/1m in Y direction, and 2.00 degree/90 degree. We considered that the increasing error in complex motion could be explained with accumulating effect and pose transformation.

As we integrated the instant motion in each segmentation, correspondingly the calculating error in each segmentation will also accumulate when integrating. In simultaneous localization and mapping (SLAM) field, a good solution to such problem is the loop-closure detection method [7]. That requires the robot to judge the similarity between the pictures so that the robot can adjust the trajectory according to the positions that it has reached before.

In the pose transformation, since we defined the X direction vertical to the initial direction of robot facing. Thus, the displacement in X direction usually came with rotating motion. As we calculated the robot pose from the camera pose, the displacement between the camera view and the robot center formed a radius when the robot rotated. Taking it into account, we regarded that this radius would influence the error especially in X direction. Naturally, this radius should be concerned with the camera pose. We considered that we might reduce the error by adjusting the camera pose.

4. Conclusion

In the paper, we described the visual odometry method to help localize the robot on grating for decommissioning of Fukushima No.1 reactor. We successfully realized the planar localization with a monocular camera and generated intuitive map of bird view. We utilized some improvement strategies to improve its performance, and used experimental method to estimate the localization accuracy.

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