

# 論文の内容の要旨

## Dissertation Abstract

論文題目      Research and Development of Autonomous Underwater Vehicle  
Dissertation    for Non-contact Internal Inspection of In-service Water Pipelines  
Title            (利用中の水パイプラインを非接触内部検査する自律型水中ロボットの研究開発)

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### Introduction

Well functioning water networks are essential to the sustainability of a community. Large transmission and distribution water mains are often the most sensitive components of these networks since their failure can be catastrophic. Hence periodic inspection and maintenance of the pipelines is required. Since pipelines are enclosed and difficult to access, robots are ideal candidates for their inspection. During the PhD research, a new pipeline inspection AUV capable of visual inspection of the interiors of water pipelines without using a tether cable or contact with the pipe walls was proposed. The PICTAN-2 pipe inspection robot was developed as a prototype vehicle to demonstrate the proposed non-contact in-service pipe inspection technique.

A conical laser based navigation system was developed which uses feature matching technique to estimate position of a vehicle inside a pipe with four degrees of freedom [2]. The first version of the vehicle, PICTAN1 was developed by Yamada which used the developed conical laser vision based navigation technique.

### PICTAN-2 Hardware

The developed AUV has four tunnel thrusters for the lateral positioning inside the pipe. Tunnel thrusters are compact and do not protrude outside the body preventing any damage during launch and recovery through the pipeline small ports. Forward motion is achieved entirely by the flowing water in the pipe. The vehicle looks identical from the front and the rear and has identical fisheye cameras, LED lights and conical lasers on either ends. Lithium ion batteries provide power and two embedded computers are used for real time acquisition and processing of images. Compact and efficient image processing and control algorithms on the embedded system enable autonomous control of the thrusters and positioning of the vehicle inside the pipe.

Several enhancements were made to the existing vehicle to achieve robust tether-less control and accurate positioning. The problems in the thruster design were carefully studied and several problems were identified. Magnetic couplings were replaced with lighter non-magnetic ceramic ball bearings reducing the load on the motor. A new more efficient propeller was developed using the open-prop propeller design software and fabricated using 3D prototyping machine. The enhancement thrusters generated 0.24N thrust, 20% higher than the designed value. Reduced friction and

inertia in the mechanical system improved the speed of rotation (rpm) higher than the designed value of 2400rpm.

An accurate and visible cone-laser is essential for the proposed positioning and control system which produces a single thin beam of laser ray at the desired fan angle and generates no scattered rays. In the new design, point laser was directly used to shine on the cone mirror to reduce mechanical alignment errors. The outer cone mirror was precision machined to achieve a surface rms roughness of <16nm.

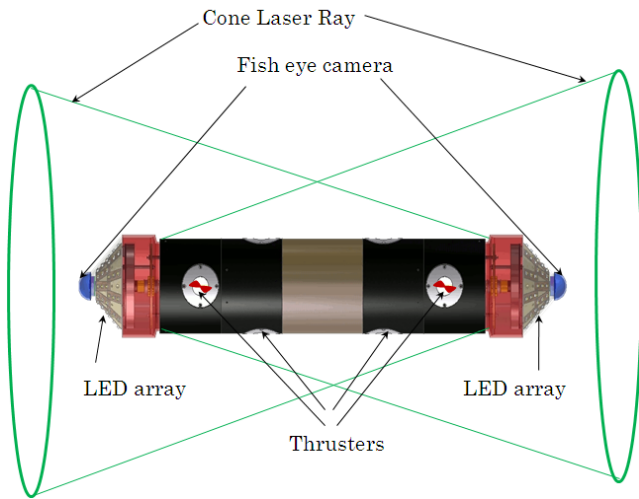


Figure 1: Schematic of PICTAN2 AUV

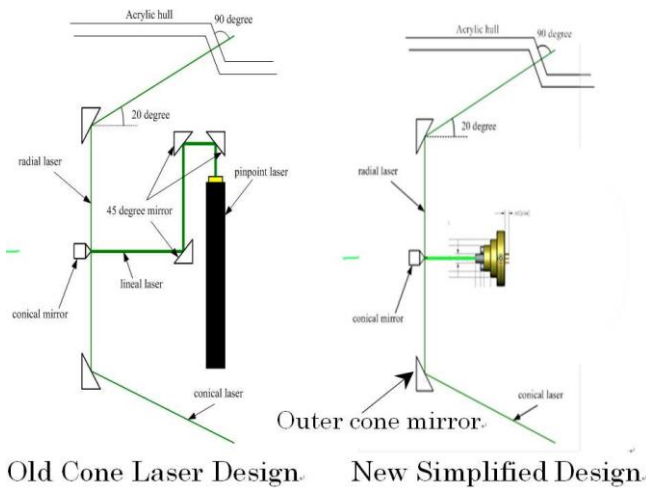


Figure 2: Cone laser design



Figure 3: Handmade 162 LED's Array

The vehicle uses two low power Marvel Xscale PXA270 microcontroller boards as the main CPUs. A compact and high-speed computer vision, PICOV, (Pipe Inspection Computer Vision) software had been developed which acquires images, processes it and performs real time control of the vehicle. A simplified flow chart of the program is given in figure 4.

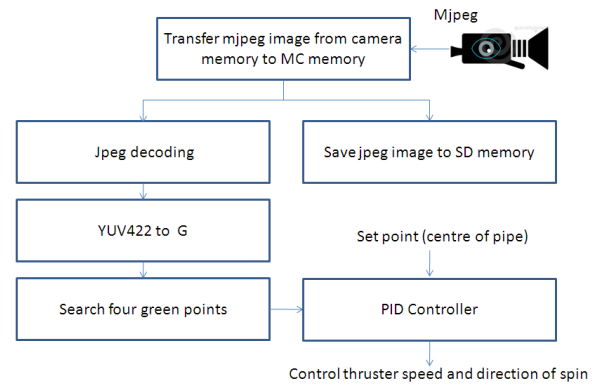


Figure 4:

Steps involved in image acquisition and control of vehicle

### Photogrammetric Position Estimation Algorithm

Position information is essential for generation of photo mosaics, 3D pipe wire frames, Ovality measurement etc. A novel position estimation algorithm, Photogrammetric, was developed to calculate the position of the vehicle in the pipe with 4-degrees of freedom namely Sway, Heave, Pitch and Yaw. Position is calculated using the camera model and trigonometric formulae.

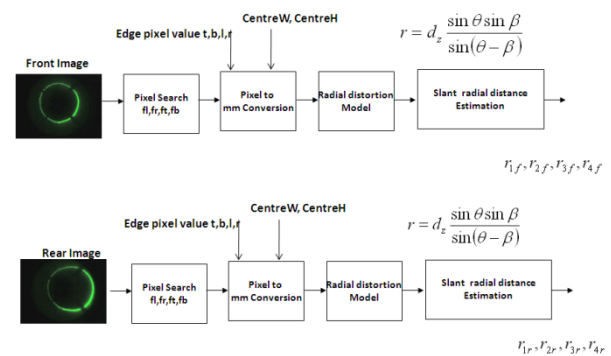


Figure 5: Algorithm

A cone laser of known fan angle is placed behind a fish eye camera at a fixed baseline distance. The primary axis of the laser and the projection axis of the camera are made collinear. The slant distance of the vehicle from the pipe wall can be calculated from the formulae. Once the slant distance is known, the pitch and yaw can be calculated by comparing the relative position shift between the front and rear side in their respective planes. The actual radial distance can then be computed by applying correction for the angular offset in the slant distance. For x plane yaw angle will be used and for y plane, the pitch angle. The position of the centre of the vehicle is finally obtained by using a straight line equation in parametric form.

A linear motion calibration bench with a rotary turn table was used to get ground truth image data. Heave displacements were simulated on the vehicle by using a lead screw. Ground truth images were used to calculate position using the position estimation algorithm and this output was compared to ground truth to visualize the position estimation accuracy. The accuracy of the positioning algorithm was later improved by treating the input images through image morphology algorithms and also by interpolating sections of the image where laser is not visible due to distance from camera, mirror frame shadow etc.

### Real time tether less Positioning tests

Real time positioning experiments were conducted in the freshwater pool test facility at the URA Laboratory. A 3m long 0.76m diameter polyethylene pipe with 0.4m long window in the middle was used for the experiment. The pipe was fully submerged in water. The vehicle was made slightly buoyant and placed in to the pipe through the window. Once the control was switched on, the vehicle controlled its thrusters to reach the set point, which was the centre of the pipe. The cone laser images collected by the front and the rear camera were

used to estimate the path the vehicle followed during the control action using the position estimation algorithm. The control system of the vehicle moved the vehicle successfully towards the set point taking about 60seconds for the vehicle to get aligned to the centre of the pipe.

### Real time Positioning test during motion

A simple experiment was conducted to test the control capability during motion. During this test, the vehicle was made to move slowly from one end to the other of a fully submerged 4m pipe by pulling it using a 0.5mm thin thread at a speed of 0.03m/s using speed controllable motor with pulley.

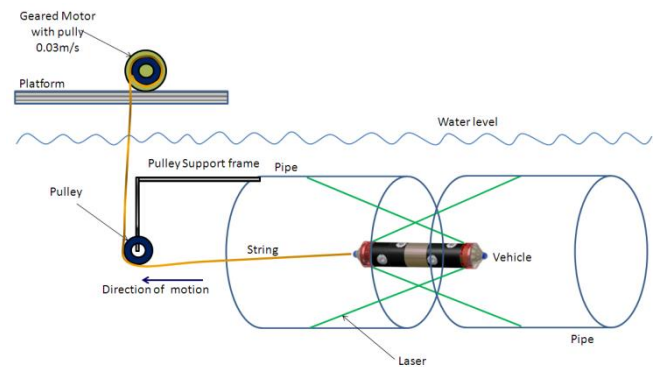


Figure 6: Schematic of Motion experiment  
The vehicle controlled itself to reach the centre of the pipe in less than 50 sec and dynamically positioned the vehicle towards the centre within  $\pm 20$ mm until the end of the pipe.

### Real time Positioning test with flow

The water channel experiment facility of Public Works Research Institute (Dobokukenkyujo) located at Tsukuba was chosen for the experiments with flow. The water channel has dimensions of 1m breadth, 1.3m height and

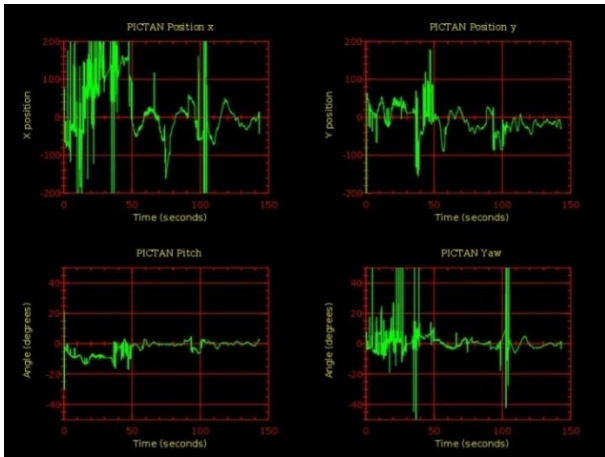


Figure 7: Position estimate during forward motion

15m length. Flow rates of 0.05m/sec to 0.3m/sec were generated. The vehicle was placed at one end of the pipe. The flow provided the forward motion to the vehicle in the pipe. During the motion the vehicle's controls system controlled the vehicle to reach the centre of the pipe. Similar to the still water experiments, vehicle position was estimated to verify the path of the vehicle.

#### Imaging tests and test in bent pipeline

An experiment was conducted to demonstrate the multitasking capability of the vehicles camera. The images captured were used to generate a photomosaic. Experiments were also conducted in a 90 degree bent section of pipe, successfully. The vertical 90 degree pitching capability of the vehicle was verified to prove that the vehicle can operate in vertical bents or vertical straight pipes.

#### Conclusion

A novel technique to inspect an in-service water pipeline without coming in contact with the pipe wall was developed through this research. A compact and efficient real time image processing program named PICOV has been developed. A new Photogrammetric position estimation algorithm was developed for estimating vehicle position with 4 degrees of freedom in the pipe by offline data analysis.

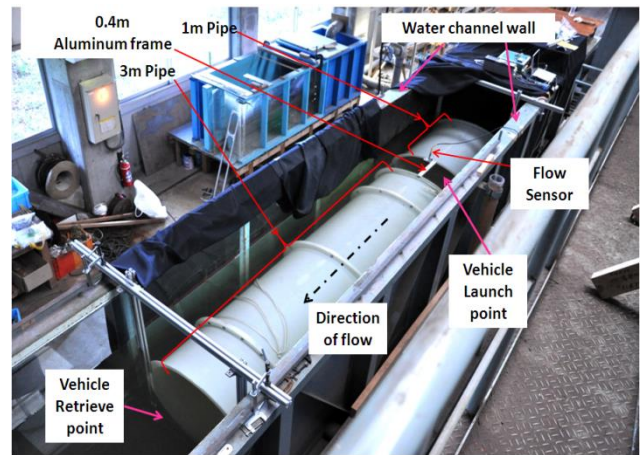


Figure 8: Experiment setup at Dobokukenyujo water channel

Experiments were conducted in still water, flowing water and to demonstrate the tether-less non-contact positioning capability of the vehicle as well as to test the position estimation algorithm.

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