

Robust virtual encoder: Using ultrasound data for compensation of depth variations in camera-based odometry

Matheus F. Dário¹, Fernando H. R. Caetano¹, Daniel Santin¹, Henrique M. Guerra¹, Huriel A. dos Santos¹, Thiago E. Kalid¹, Tatiana de A. Prado¹, Gustavo P. Pires², and Thiago A. R. Passarin^{1,*}

¹ Universidade Tecnológica Federal do Paraná (UTFPR), Curitiba, Brasil. ² Centro de Pesquisa Leopoldo Américo Miguez de Mello (CENPES), Rio de Janeiro, Brasil.

*Corresponding author, E-Mail: passarin@utfpr.edu.br

1 Abstract

Ultrasonic inspection with mechanical movement requires accurate odometry to properly localize flaws. A camera-based odometry system (termed "virtual encoder") was recently proposed as a versatile solution to substitute mechanical encoders for 2-D and 3-D displacements. However, this solution assumes a fixed distance between the camera and the inspected specimen, making it less accurate when that distance varies. In this paper, we address this problem by leveraging the signals from available ultrasound inspections to improve the odometry system data. Our method utilizes the ultrasonic RF signal from an immersion test to estimate the distance, which is then used in a displacement compensation method. We compare the fixed-distance approach and the proposed method over a 25 mm to 40 mm distance range, and our model achieves an accuracy improvement of at least 84% in the evaluated cases.

Keywords: Visual-odometry; Motion estimation; Downward-facing camera; Non-destructive testing (NDT); Ultrasonic testing (UT).

2 Introduction

Ultrasonic inspections are widely used in non-destructive testing (NDT) due to their low cost and safe operation. Knowledge of the position of the transducer is necessary for image stitching and 3D reconstruction from ultrasound data. Mechanical encoders are usually employed to track the position of ultrasonic transducers in applications such as weld inspection, providing reliable odometry information. However, the use of this type of instrument in subsea environments is challenging, especially for inspecting equipment with complex geometries. The virtual encoder is a novel approach that estimates 2D position using visual odometry. Since it requires no mechanical contact between the odometer/encoder and the surface of the inspected part, it can be employed in ultrasonic inspections over arbitrary geometries [1]. This method uses a downward-facing miniature camera in a sealed enclosure. The camera feeds the visual odometry algorithm with a continuous sequence of images of the surface. The algorithm then employs Fourier-domain phase-correlation methods to estimate 2-D displacement between consecutive images.

Visual odometry methods using downward-facing cameras are independent of the travel mechanism and the presence of targets on the traveled path [2, 3]. However, the accuracy of position estimation relies on knowledge of the ground sampling distance (GSD) [4]. In ultrasonic inspections, the visual encoder distance corresponds to the underwater distance between the camera and the inspected part. This dependency makes the displacement estimate from the visual odometer highly sensitive to mechanical vibrations and changes in the water path — common occurrences during field inspections. The problem can be stated as follows: if the camera is farther from the surface than the nominal water path distance, the

detected displacements will be smaller (in pixels). Then, the pixel-to-mm conversion (which assumes nominal water path distance) will propagate this error to the estimated odometry.

To cope with this problem, we propose a method that uses ultrasound-based real-time water path measurement to correct the pixel-to-mm conversion, providing a robust solution to distance variations. This method consists of: (I) estimating the water path using ultrasound data acquired during a calibration experiment; (II) computing the displacement correction for different water paths; and (III) during inspection, the actual water path is estimated, and the previously computed compensation is applied to correct the displacement estimate.

3 Displacement Compensation Method

For ultrasonic inspections, where both ultrasound and odometry systems work in parallel, we developed a model independent of camera specifications. For this, the visual encoder must be coupled to the ultrasonic transducer, as shown in Fig. 1a. During post-processing, the water path distance (d_{wp}) is measured from the inspection ultrasound signals, and a compensation based on d_{wp} is applied to the odometry data. The compensation values are previously computed from calibration testing.

The distance traveled in the water can be measured using different ultrasonic acquisition modes, such as Full Matrix Capture (FMC), linear scanning, 0° plane wave, among others. In the envelope of a pulse-echo signal, as shown in Figure 1b, the time τ_{wp} of the first echo is converted into distance by making $d_{wp} = c_l \tau_{wp} / 2$, where c_l is the speed of sound in the coupling medium, usually water. To ensure accuracy, the time can be measured from the average of multiple echoes coming from the external surface.

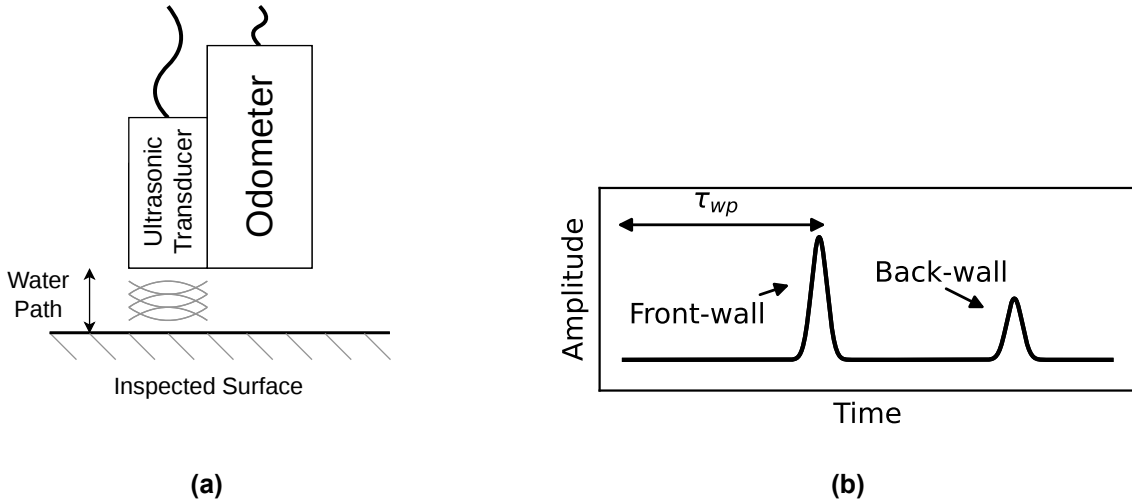


Fig. 1. Data acquisition procedure; (a) Diagram for the setup for data acquisition; (b) Distance measurement from expected ultrasound signal.

The calibration experiment consists of obtaining data from the virtual encoder at different d_{wp} , then estimating the pixel size, in millimeters, for each data set. Two methods can be used to measure GSD: circle detection and controlled movement. The circle detection method uses images captured from a standard reference in a static position. The standard reference consists of a white background with a filled black circle of known diameter, as shown in Fig. 2. Then, the size of the circle in the captured image is measured, in pixels, by the Hough gradient method [5], and the GSD (in millimeters/pixel) is calculated as the actual size of the circle (in millimeters) divided by the measured value (in pixels). In the controlled movement method, a predefined trajectory is traveled, and the controlled motion is recorded. Then, the GSD (in millimeters/pixel) is calculated by dividing the actual trajectory length (in

millimeters) by the estimated trajectory length (in pixels).

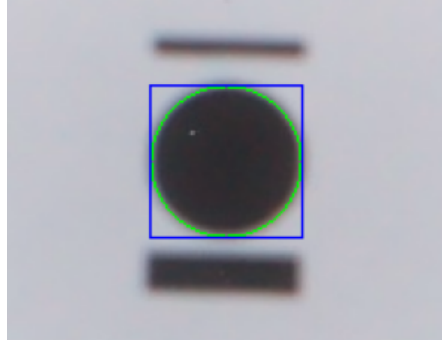


Fig. 2. Circle detection and measurement for a standard reference using the Hough gradient method. The detected circle (green) is used to find the corresponding bounding box (blue) and measure its size, in pixels.

Calibration generates discrete resolution values as a function of d_{wp} variation. Therefore, a function that approximates these points can be used to obtain continuous values. Since these points yield a curve, approximating it with a cubic function or a smoothing spline reduces the error between the measured points and the approximated curve.

For compensation, the GSD value corresponding to the distance measured from the ultrasound data is found on the calibration curve and multiplied by the odometry data.

4 Results and Discussion

The visual odometer video data was captured using a Pi Camera 2 with a 25 mm underwater focal length, enclosed in a waterproof case and supplemented with an external lighting system, as shown in Fig. 3a. The d_{wp} was manually adjusted for each sample considered in the calibration procedure. A phased array ultrasonic transducer (PAUT) 5LS64-A32 by Olympus® with a center frequency of 5 MHz and 64 channels was mechanically attached to the enclosure and used to measure the water path. The ultrasound data were acquired in a 0° plane waves using the Panther™ ultrasound system and Acquire software from Technologies™. Only the echo received by element 32 was used to measure the water path distance. The ultrasonic transducer and sealed camera were coupled in a robotic 2.5D positioning system as shown in Fig. 3b.

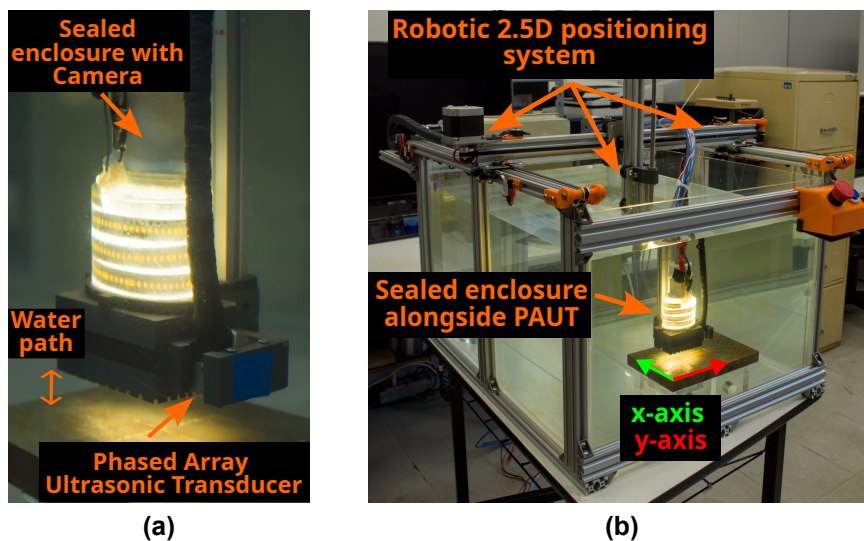


Fig. 3. Underwater tests to evaluate ground sampling distance for different water path lengths. (a) Close-up with the main components involved in the inspection; (b) Tap-water filled tank with robotic 2.5D positioning system.

To generate the compensation curves by controlled movement, a triangular-shaped trajectory was performed, varying the water path from approximately 25 mm to 40 mm in 1 mm increments. This range is typical in field inspections. Below 25 mm, the visual encoder itself does not work properly, resulting in erratic displacement measurements and rendering the correction impossible. For the circle detection method, images were captured in a similar range of water path. The target used has a diameter of 4 mm. Due to manual height adjustment, an adjustment error was expected. That way, the ultrasonic transducer measured the actual water path.

After estimating the GSD for a finite set of water paths using circle detection and controlled movement methods, we approximated the relationship between GSD and water path distance using smoothing splines [6]. The calibration process is needed once for each encircled camera used as a virtual encoder sensor. Fig. 4 shows the actual value of height, the GDS for each value, and the approximated function for each method.

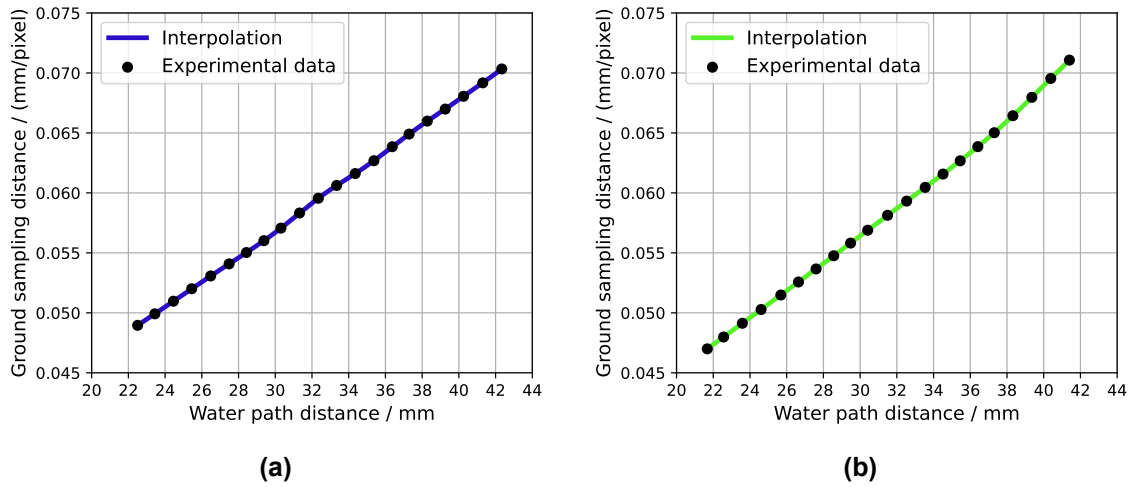


Fig. 4. Ground sampling distance for different water path distances from experimental results. (a) Evaluated with controlled movement; (b) Evaluated with circles detection.

To evaluate the proposed method, we performed five inspections with random values for the water path distances, and computed the relative error between the estimated and true trajectories as shown in Fig. 5a. Without compensation (yellow points), the error is greater than 6 % in all cases, whereas after compensation (orange and magenta points), the error is greatly reduced, achieving an accuracy improvement of at least 84%. It is also observed that compensation based on circle detection and controlled movement methods yields relative errors within the same range. However, the circle-detection method relies solely on water-path distance control and can be applied without the robotic 2.5D positioning system.

Fig. 5b shows an example of controlled movement with a water path of 37.67 mm. This trajectory was used to generate the GSD curve and to evaluate the compensation method. Overall, the compensated trajectory (green) was much closer to the actual (blue) trajectory, especially when compared to the uncorrected one (red). In this case, compensation based on the controlled motion method was applied. The resulting error was 22% for the uncompensated trajectory, while it reached 0.089% after compensation.

5 Conclusion

In this paper, we introduce a visual odometer that remains accurate despite variations in the water path distance during ultrasonic inspections. The GSD varies with water path distance, so if GSD is set to a fixed value, the trajectory estimation error increases. Experimental results show that our method adequately compensates for changes in water path

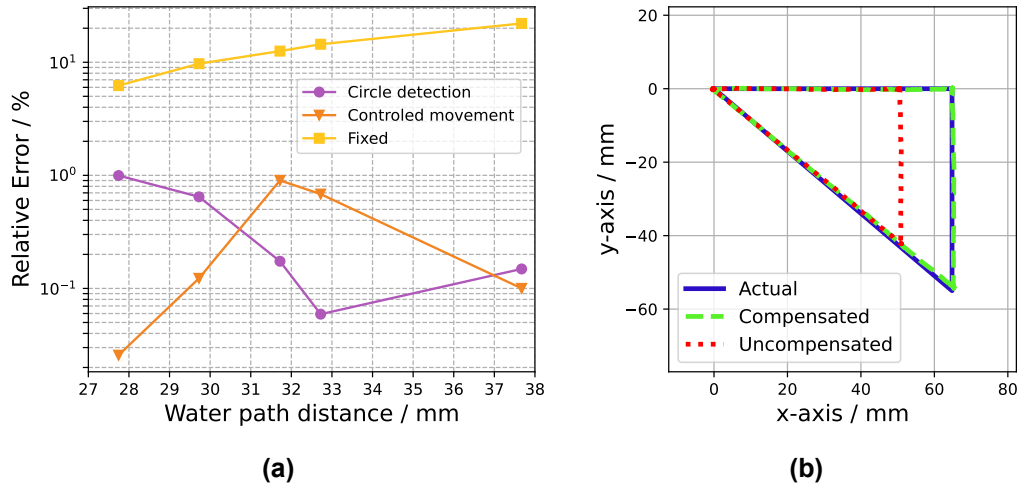


Fig. 5. Quantitative evaluation of the improvement resulting from the application of the proposed compensation method, in terms of the accuracy of estimation. (a) Relative error between the compensated trajectory and the actual trajectory in five water path distances for GDS by circle detection, GDS by controlled movement, and without compensation (fixed); (b) Compensated trajectory with 37.67 mm water column distance. Actual (blue) and odometry-based estimated trajectories, reconstructed with the proposed compensation (green) and without compensation (red).

distance by adjusting GSD, thus avoiding accuracy loss. Calibration is required only once for each specific set of inspection conditions, requiring minimal additional effort. In our test with random water path distance values from 25 to 40 mm, we achieved an accuracy improvement of at least 84%. The robust virtual encoder has proven to be a viable alternative due to its easy integration with scanning systems and its high accuracy, making it applicable to most visual odometry solutions for NDT immersion inspections.

Acknowledgements

This work was funded by Petrobras/CENPES through the R&D project AUSPEX2 (SIG-ITEC 2022/00436-2). The authors thank UTFPR, CAPES, Fundação Araucária, FINEP, and CNPq for the scholarships and additional funding.

References

1. Kalid, T. E., Jr, E. T., Prado, T. A., et al.: Virtual encoder: a two-dimension visual odometer for ndt, in] Proceedings of the 13th ECNDT (2023).
2. Birem, M., Kleihorst, R., El-Ghouti, N.: Visual odometry based on the fourier transform using a monocular ground-facing camera, *Journal of Real-Time Image Processing* **14**(3), 637–646 (2018).
3. Nagai, I., Watanabe, K.: Path tracking by a mobile robot equipped with only a downward facing camera, In: 2015 IEEE/RSJ international conference on intelligent robots and systems (IROS) (IEEE, 2015), pp. 6053–6058.
4. Utla, C., Dashora, A., Chandrasekhar Reddy, L., et al.: Analysis of ground sampling distance of convergent images for keypoints detection for close-range photogrammetry, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 93–98 (2022).
5. Yuen, H., Princen, J., Illingworth, J., et al.: Comparative study of hough transform methods for circle finding, *Image and vision computing* **8**(1), 71–77 (1990).
6. Schimek, M. G.: Smoothing and regression: approaches, computation, and application, John Wiley & Sons, (2013).