Morphological Adaptation for Speed Control of Pipeline Inspection Gauges: From System Integration to Real-world Demonstration

Tachadol Suthisomboon[1,‡], Sujet Phodapol[1,‡], Thipawan Pairam[1,‡], Kitti Phongaksorn[1], Naris Asawalertsak[1], Pakpoom Kriengkomol[2], Tanapoom Jitnaknan[2], Petch Janbanjong[3], Poramate Manoonpong[1,*]

***Abstract*— This short paper with a video demonstration presents an add-on adaptive speed control module designed for pipeline inspection gauges (PIGs). The module integrates multiple sensors, a rotary valve unit with an actuator, and an embedded controller. The module's speed control is realized by adjusting the valve angle (morphological adaptation), which modulates bypass flow and, subsequently, moving speed. An Extended Kalman Filter (EKF) is utilized for sensor fusion and module speed estimation. Closed-loop Proportional–Derivative (PD) control automatically adjusts the valve angle or adapts the module morphology based on the difference between estimated and desired speeds, ensuring precise speed regulation. The module's performance is evaluated and demonstrated in an industrial pipeline environment under various fluid flow rates.**

***Index Terms*— Pipeline Inspection Gauge, Speed Control, Inspection Robot, Morphological Computation**

I. INTRODUCTION

Pipeline integrity is essential since the oil and gas sector heavily relies on pipelines for fluid transportation. PIGs have been used for routine inspection in order to clean and inspect pipelines. However, conventional PIGs often lack adaptive speed control and suffer from pressure fluctuation of the fluid in the pipeline, resulting in inaccurate data collection. Existing speed control concepts employing bypass valves, such as those presented in [1] and [2], are typically tailored for specific PIG designs. The development of a generic add-on module that can be retrofitted to conventional PIGs for speed control is an ongoing area of research with potential market benefits.

Building upon our previous work investigating morphological adaptation for speed control of an inspection tool through numerical simulations [3], this study advances by developing a generic, add-on adaptive speed control module with closed-loop control for PIGs, termed Morphological Adaptation for Speed Control of Pipeline Inspection Gauges (MC-PIG). MC-PIG is designed to be applicable across various PIGs and pipeline systems. The development of MC-PIG here focuses on robust hardware capable of withstanding real-world operational conditions and its system integration with adaptive state estimation and control algorithms.

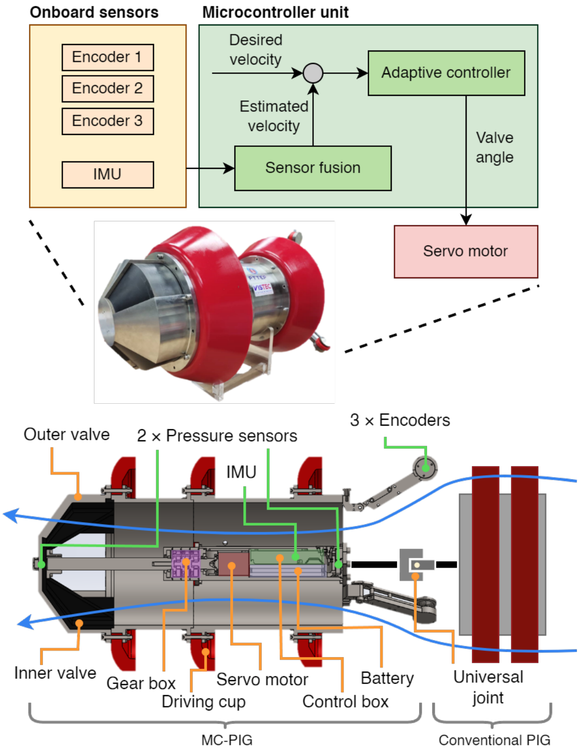

Fig. 1: A system overview of MC-PIG. The block diagram shows the EKF-based sensor fusion for speed estimation and adaptive PD control. The cross-section view demonstrates the key hardware components of MC-PIG. Blue arrows display the flow direction through MC-PIG.

II. MC-PIG INTEGRATED SYSTEM

A. Hardware System

The hardware design of MC-PIG is based on a modular concept that allows for attachment to conventional PIGs and operation in 8 to 12-inch pipelines (Fig. 1). Equipped with interchangeable driving cups, MC-PIG accommodates various pipeline sizes. Its compact speed control box houses a customized electronic system for state monitoring, a servo motor with a planetary gearbox for rotating the bypass valve, and a battery for powering the MC-PIG system.

Each MC-PIG body (i.e., body for 8-inch or 12-inch pipe) was designed to maximize the flow while maintaining the

[1]Bio-inspired Robotics and Neural Engineering Laboratory, School of Information Science and Technology, Vidyasirimedhi Institute of Science and Technology (VISTEC), Thailand (*Corresponding author: poramate.m@vistec.ac.th)

[2]AI and Robotics Ventures Company Limited (ARV), Thailand

[3]PTT Exploration and Production Public Company Limited (PTTEP), Thailand

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ability to travel in the sharp bend (the radius of the bend is at least five times the nominal diameter). The planetary gear was chosen, proving the capability to add more gear stages for the larger valve. Computational fluid dynamics (CFD) simulations were performed to optimize the valve structure, minimizing pressure drop when the bypass valve was fully open. This optimization also aimed to maximize MC-PIG's speed control range and determine the maximum torque required for servo and gearbox selection. The driving cups were designed to complement the bypass valve, providing sufficient friction to counteract fluid forces and enable speed control. Three odometer sensors (wheel encoders), two pressure sensors, and one inertial measurement unit (IMU) were installed (Fig. 1) and connected to the control board for data collection and speed control.

B. Adaptive Control Software System

To control MC-PIG's speed via the bypass valve, a state estimation system and an adaptive control system are required. The estimation system, employing an Extended Kalman Filter (EKF), predicts MC-PIG's position and speed by fusing data from the encoder and IMU sensors.

The adaptive control system regulates MC-PIG's speed by adjusting the valve angle to control fluid flow and pressure. Due to the complexity of directly calculating the optimal valve position, a closed-loop PD control algorithm was implemented. This controller increases or decreases the valve opening based on the difference between the desired and estimated speeds. Specifically, when the estimated speed falls below the desired speed, the controller reduces the valve opening to accelerate MC-PIG. Conversely, when the estimated speed exceeds the desired speed, the controller increases the valve opening to decelerate. The control law is expressed as:

$$\theta = \theta_{max} - (K_p e + K_d \dot{e}), \quad (1)$$

$$e = v_{des} - v_{est}, \quad (2)$$

where $\theta, \theta_{max}, e, v_{des}$ and v_{est} represent the target valve angle, maximum valve angle, speed error, desired speed (user-defined), and estimated speed (from EKF), respectively. The proportional K_p and derivative K_d gains were empirically set to 40 and 1.2, respectively.

III. EXPERIMENTS AND RESULTS

To develop and test the estimation and adaptive control systems, initial in-lab experiments were conducted on an acrylic pipeline to validate the state estimation technique. Subsequently, the adaptive control system was evaluated using a final MC-PIG design on an adjustable speed treadmill[1]. Finally, the field testing was carried out in a 12-inch diameter, 21-meter-long pipeline with a 15-meter operating section, as shown in Fig. 2. A pump maintained a constant water flow rate of approximately 60 m³/h during these tests. The primary goal of the field test was to demonstrate MC-PIG's adaptive bypass control. However, unexpected high pressure conditions caused a leak in the control box's electronic chamber, necessitating a modification of the test plan to fix the valve at different angles for different speed measurements.

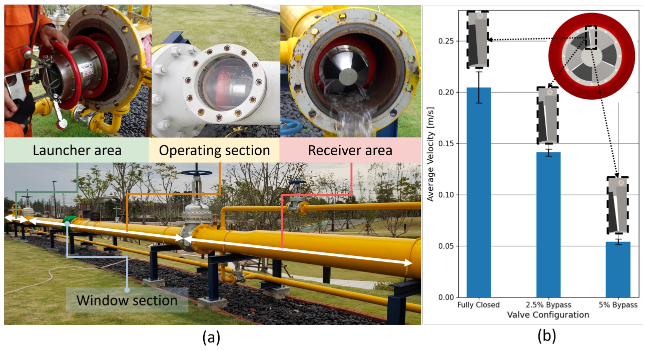

Fig. 2: (a) Field testing setup with a 12-inch diameter, 21-meter-long pipeline, with MC-PIG inserted via the pipe launcher, driven by the pressure difference in the pipe, and released at the receiver. (b) Comparison of MC-PIG's speed across different valve opening angles. A video of the tests can be viewed at https://www.manoonpong.com/MCPIG/video.mp4

Tests were conducted at various valve openings (0%, 2.5%, and 5%) three times per configuration. The percentage of the bypass was limited to 5% due to the maximum flow rate of the test setup. The results in Fig. 2 show a relationship between valve opening and MC-PIG's speed — a larger valve opening leads to a lower speed, and vice versa.

IV. CONCLUSIONS

This paper presents a speed control system for a pipeline inspection robot, employing onboard sensors and an adaptive control algorithm. The laboratory experimental results demonstrate the successful functional integration of our state estimation and adaptive controller. This system can adjust the module's morphology to regulate speed in response to sensory feedback or environmental changes. The performance of the module in the actual working condition was then validated in the field. In the future, we will enhance the module's waterproofing and test MC-PIG with the adaptive controller on different PIG systems and different pipe sizes.

[1]Due to space limitation, the results of the in-lab experiments can be viewed at https://www.manoonpong.com/MCPIG/video.mp4 .

REFERENCES

[1] T. T. Nguyen, H. R. Yoo, Y. W. Rho, and S. B. Kim, "Speed control of pig using bypass flow in natural gas pipeline," in *ISIE 2001. 2001 IEEE International Symposium on Industrial Electronics Proceedings (Cat. No.01TH8570)*, vol. 2, 2001, pp. 863–868 vol.2.

[2] J. Chen, X. Luo, L. He, H. Liu, L. Lu, Y. Lü, and D. Yang, "An improved solution to flow assurance in natural gas pipeline enabled by a novel self-regulated bypass pig prototype: An experimental and numerical study," *Journal of Natural Gas Science and Engineering*, vol. 107, p. 104776, 2022.

[3] S. Phodapol, T. Suthisomboon, P. Kosanunt, R. Vongasemjit, P. Janbanjong, and P. Manoonpong, "Morphological Adaptation for Speed Control of Pipeline Inspection Gauges MC-PIG," vol. Day 1 Mon, November 15, 2021, p. D011S025R004, 11 2021. [Online]. Available: https://doi.org/10.2118/207403-MS