

# An Integrated Adaptive System for On-Pipe Landing and Adherence of Autonomous Inspection Drones

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**Abstract**—This video demonstration paper presents an integrated adaptive system for on-pipe landing and adherence of autonomous inspection drones. The system employs a dual-level adaptive method to address the challenges of the stable drone approach, landing, and adherence to pipes for performing subsequent close inspection. The first level, passive adaptation, is realized through morphologically computed double SOft Fin-ray landing gEAR (SOFEAR). It enables the drone to maintain and adhere to the pipe without significant control effort after landing. The second level, active adaptation, achieved via adaptive stability control, facilitates the precision approach and landing of the drone while compensating for external disturbances. The proposed system, incorporating both passive and active adaptation, demonstrates robust drone performance in the real world, including accurate pipe centering and approach, autonomous recovery from off-center landing attempts due to unexpected disturbances, soft landings, and steady on-pipe adherence.

## I. INTRODUCTION

Industrial inspections, particularly in oil and gas, refineries, and petrochemicals, are critical yet challenging due to extensive and complex pipeline networks [1]. These inspections must consider cost, safety, and environmental impact and often rely heavily on human involvement. Autonomous drones are now widely used for various tasks, including industrial pipeline inspection. Effective drone-based pipeline inspection requires several intelligent functions, such as trajectory planning, pipeline tracking and following, and visual information analysis to identify potential damage points [2]. These functions primarily support remote inspections, where drones capture essential data by flying above pipelines. This approach can be further enhanced with advanced detection equipment like thermal and high-resolution cameras. While drones can provide a bird's-eye view for overall inspection or pre-scanning to identify potential damage points, close-up inspections—requiring the drone to approach the pipe closely or land and adhere to the pipe for in-depth inspection—remain a challenging task [3], [4]. As a step toward addressing this challenge, this work introduces an integrated dual-level adaptive system for robust drone landing and adherence to pipes. The system is demonstrated in a real environment, showcasing the drone's ability to land precisely on the pipe, handle unexpected external perturbations, and maintain a stable position on the pipe after landing.

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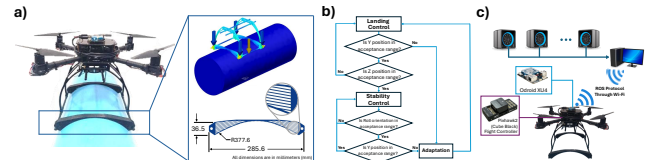


Fig. 1. a) A real drone with SOFEAR landing gear placed on the top surface of the pipe shows how the soft feet are designed and mounted with the landing gear, along with finite element analysis. b) Adaptive stability control. c) A system overview showing the OptiTrack motion capture system, which provides real-time positioning of the drone and pipe, as well as the drone components and their communication with the motion capture system.

## II. MATERIALS AND METHODS

In this study, we propose a dual-level adaptive system for drone landing and remaining on a pipe, featuring two-level adaptation mechanisms. One level is achieved through the morphological computation of 3D-printed double SOft Fin-ray landing gEAR (SOFEAR, Fig. 1(a)). This is considered a passive adaptation. The other level, referred to as active adaptation, is implemented through adaptive stability control (Fig. 1(b)). As a proof of concept, the system is demonstrated in an indoor environment using the OptiTrack motion capture system to locate the drone and target pipeline. The Robot Operating System (ROS) is used to interface between the OptiTrack system and the drone (see Fig. 1(c)).

### A. Drone Hardware Platform

A drone platform for testing the proposed integrated adaptive system is based on the X500 quadcopter frame, equipped with four Holybro 2216/880kV brushless motors, each paired with a 45A electronic speed controller (ESC) and 10-inch propellers. Key hardware components of the drone include a CubePilot (Cube Black) flight controller using the PX4 autopilot firmware, along with its accessories (remote control (RC), RC receiver module, and telemetry) and an Odroid XU4 onboard computer. The drone uses WiFi-based communication interfaces between the onboard computer and the OptiTrack motion capture system, utilizing the ROS protocol (see Fig. 1(c)). The landing gear for on-pipe landing and adherence is based on the F450 drone's landing gear measuring 190 x 265 x 330 mm and equipped with SOFEAR (see below and Fig. 1(a)).

### B. Double Soft Fin-Ray Landing Gear for Passive Adaptation

The base of the landing gear is equipped with two soft feet (SOFEAR), one at the front and the other at the back.

Each foot is based on a double fin-ray structure with a cross-beam angle of 10 degrees. This angle is optimally designed according to the structural analysis in [5]. It ensures proper stress distribution and a low-stress level (see finite element analysis in Fig. 1(a)). Each soft foot, scaled to a size of 36.5 x 285.6 x 20.0 mm, is 3D printed using the NinjaFlex flexible filament, a specially formulated thermoplastic polyurethane (TPU) material. The soft feet passively adapt their structure to follow the pipe curve (passive adaptation), creating a large contact area for easy drone adhesion (Fig. 1(a)). They also allow for spontaneous takeoff without requiring a release mechanism, unlike traditional methods [3]. With this foot size, the drone can stably adhere to pipes with diameters ranging from 168 to 325 mm (6 to 12 inches; see <https://www.manoonpong.com/SOFEAR/video.mp4>).

### C. Adaptive Stability Control for Active Adaptation

This control system ensures that the drone lands precisely at the center of the pipe's top surface by continuously monitoring the drone's position and orientation relative to the pipe's center, taking corrective action if either moves outside the control range (see Fig. 1(b)). The control process consists of three subcontrol mechanisms:

- **Landing control:** Controlling the drone's position to precisely land on the target pipe.
- **Stability control:** Controlling the drone's roll orientation (inclination level) to keep it within the acceptable range once the soft feet attach to the pipe's top surface.
- **Relocation control (adaptation):** Adapting the drone's position to ascend to a certain height above the target pipe if it starts to fall off due to external disturbance, and then switching to the landing control.

These position and orientation control modules rely on the low-level PID control system in the flight controller.

## III. EXPERIMENTS AND RESULTS

The performance of our approach was validated and demonstrated by conducting the landing on-pipe mission using a PVC pipe size of 12 inches as the target pipeline. The drone can successfully complete landing on the pipe. Additionally, it also shows robustness against unexpected external perturbation by performing relocation and landing back on the target pipe again (see Fig. 2). A demonstration video can be viewed at <https://www.manoonpong.com/SOFEAR/video.mp4>

## IV. CONCLUSION

An integrated adaptive system for on-pipe landing and adherence has been developed and validated on a real drone. The system exploits the passive adaptation of SOFEAR and the active adaptation of adaptive stability control based on a simple PID control method. This work demonstrates that the system enables softer landings on the pipe by leveraging the deformable properties of SOFEAR. It also ensures precise landings at the pipe's center, with the ability to adaptively reposition if the drone lands outside the acceptable range or encounters unexpected disturbances that push it off the

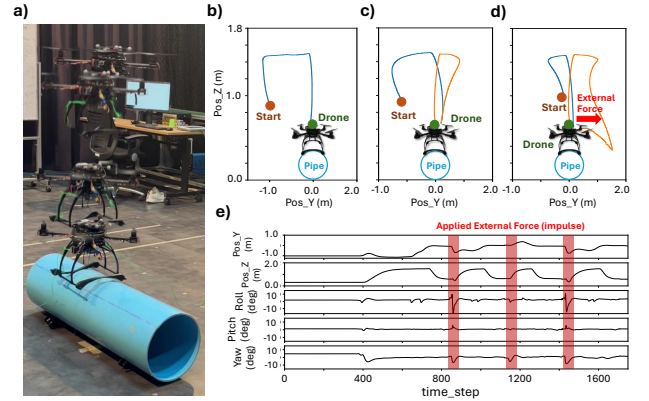


Fig. 2. a) A drone landing on the pipe experiment. b), c), and d) The flying trajectories of the drone during the landing on the pipe experiments in three different scenarios. In b), the drone successfully landed on the pipe (blue line). In c), the drone's landing on the pipe was unsuccessful due to misalignment with the center of the pipe (blue line). In this scenario, once the drone detected the imprecise landing, it switched to the adaptation control state, repositioned itself at a certain height above the pipe, and then attempted the landing again (orange line). In d), the drone's landing on the pipe was unsuccessful due to an external perturbation (an external impulse). In this case, when the drone was disturbed by the external impulse and moved away from the top surface of the pipe (blue line), it detected a position change that exceeded the limit, so it switched to the adaptation control state, repositioned itself at a certain height above the pipe, and then attempted the landing again (orange line). e) Monitored signals (in the experiment of d) when external perturbations (impulse) were applied (red block).

pipe. In the future, we will extend this work by incorporating a pipeline detection and alignment system based on visual feedback. Additionally, pipeline inspection sensors, such as ultrasonic testing (UT) devices, will be installed on the drone. This will enable the drone to autonomously perform on-pipe landings and UT inspections in outdoor environments.

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## REFERENCES

- [1] Parham Nooralishahi, Clemente Ibarra-Castanedo, Shakeb Deane, Fernando López, Shashank Pant, Marc Genest, Nicolas P. Avdelidis, and Xavier P. V. Maldague. Drone-based non-destructive inspection of industrial sites: A review and case studies. *Drones*, 5(4), 2021.
- [2] Sara Roos-Hoefgeest, Jonathan Cacace, Vincenzo Scognamiglio, Ignacio Álvarez, Rafael C. González, Fabio Ruggiero, and Vincenzo Lippiello. A vision-based approach for unmanned aerial vehicles to track industrial pipes for inspection tasks. In *ICUAS2023*, pages 1183–1190, 2023.
- [3] F. Javier Garcia Rubiales, Pablo Ramon Soria, Begoña C. Arrue, and Anibal Ollero. Soft-tentacle gripper for pipe crawling to inspect industrial facilities using uavs. *Sensors*, 21(12), 2021.
- [4] Marco A. Montes-Grova, Jaime Ortuño-Conde, David Tejero-Ruiz, Jesús Olmedo-Pradas, Francisco J. Pérez-Gran, Miguel A. Trujillo-Soto, and Antidio Viguria. Petrochemical industry aerial robotic inspection: A novel concept for landing and deploying robots on pipes. In *ICUAS 2024*, pages 1377–1384, 2024.
- [5] Poramate Manoonpong, Hamed Rajabi, Jørgen C. Larsen, Seyed S. Raoufi, Naris Asawalertsak, Jettanan Homchanthanakul, Halvor T. Tramsen, Abolfazl Darvizeh, and Stanislav N. Gorb. Fin ray crossbeam angles for efficient foot design for energy-efficient robot locomotion. *Advanced Intelligent Systems*, 4(1):2100133, 2022.