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# Fault-Tolerant Control of an Advanced Nitrogen Removal Plant: A Data Pipeline from Raw Signal to Reliable Action

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**Abstract:** Efficient automation of wastewater treatment facilities is vital for enhancing nutrient removal, energy efficiency, and greenhouse gas emission reduction. However, sensor faults in Water Resource Recovery Facilities (WRRFs) present significant challenges to reliable operation. Fault-Tolerant Control (FTC) offers a solution to the occurrence of sensor faults by adapting control systems to manage the sensor malfunctions and maintain functionality. This study demonstrates the power of FTC by its implementation at an industrial-scale WRRF pilot plant, addressing sensor faults through a systematic approach involving data validation, fault detection, and control reconfiguration. Two experimental scenarios were studied: introducing a +1 mg/L bias and a -0.3 mg/L.h drift in dissolved oxygen (DO) sensors. FTC employs techniques like duplicate sensor data, historical patterns, and proportional control to mitigate faults and restore setpoints. Results confirmed that biased and drifted DO measurements initially disrupted aeration, nitrification, and ammonia removal. As soon as faults were detected, FTC actions restored operational stability by leveraging other, healthy sensors and adjusting the control strategies. Effluent analysis confirmed nearly identical results before and during experiments, confirming the FTC's ability to maintain performance despite sensor faults. This research highlights FTC's effectiveness in minimizing disruptions caused by sensor faults and provides insights into further developing fault management strategies.

**Keywords**: Fault-tolerant Control; Sensor Faults; Wastewater Treatment; AvN control

## Introduction

Efficient automation and control of wastewater treatment facilities are critical for enhancing nutrient removal and recovery, reducing energy consumption, and lowering greenhouse gas emissions. However, wastewater's variability, combined with the complex dynamics of WRRFs and low sensor reliability [1], hinders optimal control. Sensor malfunctions are inevitable in the harsh wastewater environments, posing challenges as they lead to faulty data [2]. This makes advanced WRRF control a vital yet challenging research area.

## FTC Overview

Faults in sensors, actuators, or processes can lead to system failures or plant shutdowns. Closed-loop control systems may even amplify faults, risking complete system failure. Preventing failures and maintaining system availability are key concerns in control engineering [3]. FTC addresses these issues by adapting control systems to manage sensor or actuator malfunctions. Effective FTC minimizes disruptions, allowing processes to continue with minor performance degradation [4].

An FTC system includes fault identification and controller reconfiguration. Fault identification detects faults and informs supervisory systems for corrective actions. The controller can be reconfigured by adjusting setpoints, modifying reference models, activating alternate controllers, or using soft sensors to mitigate fault effects [4-7].

## FTC Implementation

This study successfully demonstrated the feasibility of FTC in an industrial-scale WRRF pilot plant (pil*EAU*te, Figure 1) at Université Laval which aims to implement the AvN control for Anammox removal of nitrogen [8] by balancing the concentration of $NH_4$-N and $NO_x$-N (preferably $NO_2$-N) in the effluent. FTC implementation heavily relies on data reliability and effective fault detection. A systematic approach [9] using techniques such as sensor data validation with control charts [10], time series forecasting for gap-filling, outlier detection, noise smoothing, and fault detection [11] was applied to address common sensor faults like bias and drift.

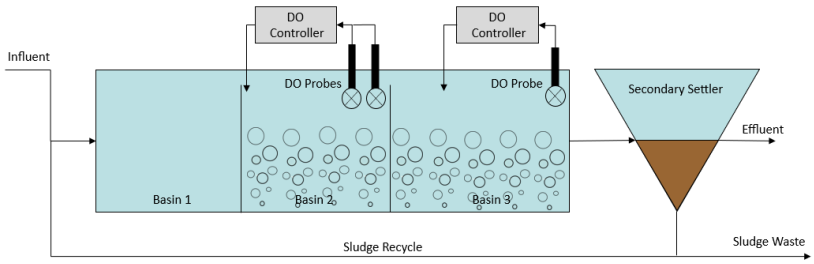


**Figure 1** Schematic of the WRRF pilot plant (pil*EAU*te) treating 12 $m^3$/day of municipal-like wastewater

## Scenario 1: Bias

In the first experiment, a sudden +1 mg/L bias was introduced to the DO sensor in Basin 2's aeration feedback control loop (Figure 1). As the fault was only detected after two hours, the biased DO measurement caused the aeration to decrease during this time, creating anoxic conditions in Basin 2, halting nitrification, and increasing the ammonia concentration. During this period, nitrite and nitrate concentrations dropped to zero.

Upon detecting the fault in the airflow rate signal, a Python script connected to a user interface modified the DO control strategy in Basin 2 via Programmable Logic Controller (PLC) ladder logic programming. The system compensated by using data from a duplicate DO sensor located in Basin 2.

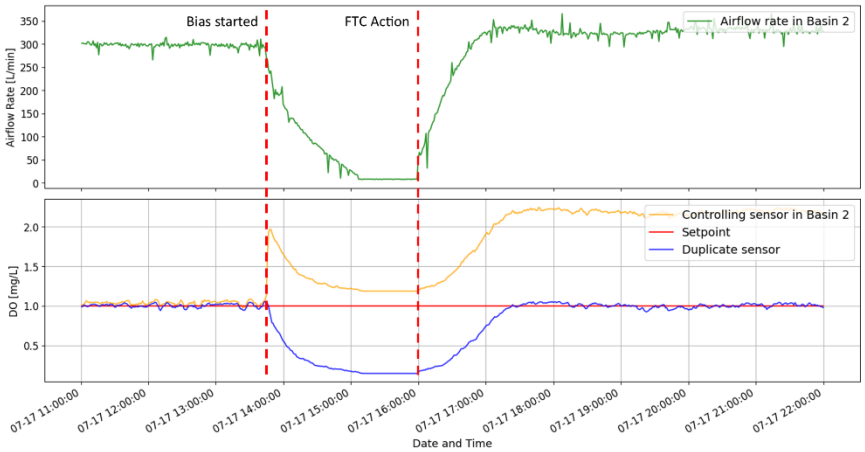


**Figure 2** Aeration and DO signals during the first FTC experiment of suddenly imposing a +1 mg/L bias on the controlling sensor in Basin 2

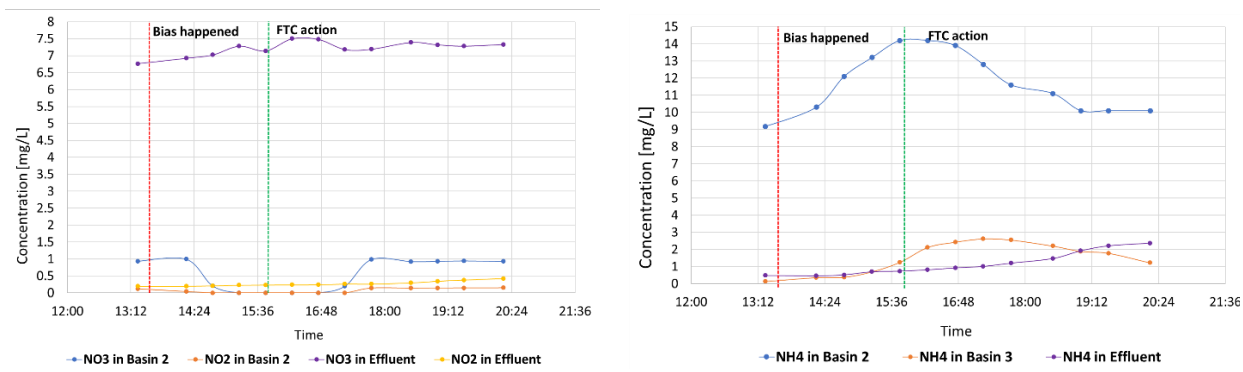


**Figure 3** Nitrate and nitrite in Basin 2 and effluent (right); ammonia in Basin 2, Basin 3, and effluent (left) during the first FTC experiment of imposing a +1 mg/L bias on the controlling DO sensor in Basin 2

Once the healthy sensor's data reflected the low DO levels, aeration increased, raising the DO concentration to the setpoint of 1 mg/L. This restored nitrification, reducing ammonia levels and increasing nitrite and nitrate concentrations, closing in on the desired AvN value. Analysis of 24-hour composite samples from the influent and effluent showed nearly identical operations before the fault and after reconfiguration, confirming the FTC's effectiveness in maintaining process performance despite the sensor fault.

**Scenario 2: Drift**

The second experiment introduced a -0.3 mg/L.h linear drift over five hours in Basin 2's DO sensor. After detecting the fault, the PLC reprogrammed Basin 2's controller to rely on Basin 3's aeration control actions. Based on historical airflow ratios between the two basins, a ratio controller with a ratio of 0.55 was used to obtain the desired airflow rate for Basin 2, accounting for differences in tank volumes, diffuser numbers, and pollutant loads.

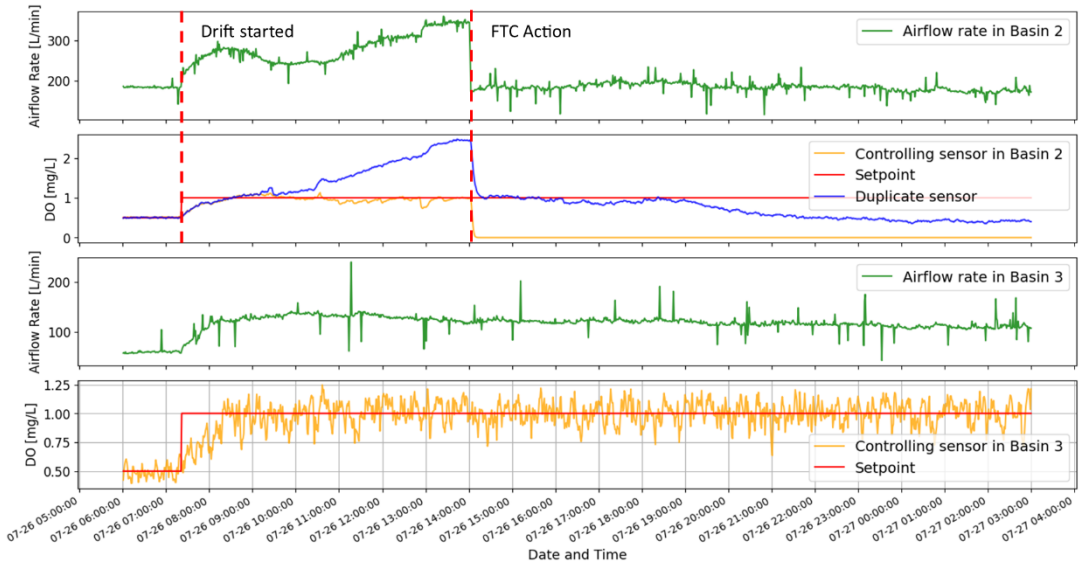


**Figure 4** Aeration and DO signals in Basin 2 (top 2 graphs) and Basin 3 (bottom 2 graphs) during the second FTC experiment of imposing a -0.3 mg/L.h drift over 5 hours on the controlling sensor in Basin 2

As the drift progressed (Figure 4), aeration increased, and the healthy duplicate sensor indicated the rising DO levels in Basin 2. This enhanced nitrification, gradually lowering ammonia levels in Basin 2, Basin 3, and the effluent (Figure 5). After fault detection and FTC action (controller reconfiguration), the aeration in Basin 2 dropped suddenly to the values calculated from the Basin 3 controller, aligning the DO levels quite well with the setpoint of 1 mg/L. Over several hours, the proportional airflow rates maintained the setpoint, but eventually a gradual decline in DO levels was observed, indicating the need to recalibrate the 0.55 ratio between Basin 2 and Basin 3 airflow rates in real time to account for pollutant load fluctuations.

Figure 5 illustrates that following fault identification and automated FTC action, the ammonia concentrations rose in Basins 2, 3, and the effluent after a two-hour delay. However, as DO levels stabilized at the setpoint, ammonia concentrations decreased. Nighttime sampling of the effluent showed that ammonia levels stabilized approximately 10 hours after FTC action, reflecting reduced nitrification under lower DO conditions. Despite a 10% higher influent load on the experiment day compared to the previous day, effluent conditions were nearly identical, demonstrating that FTC mitigated the fault's impact.

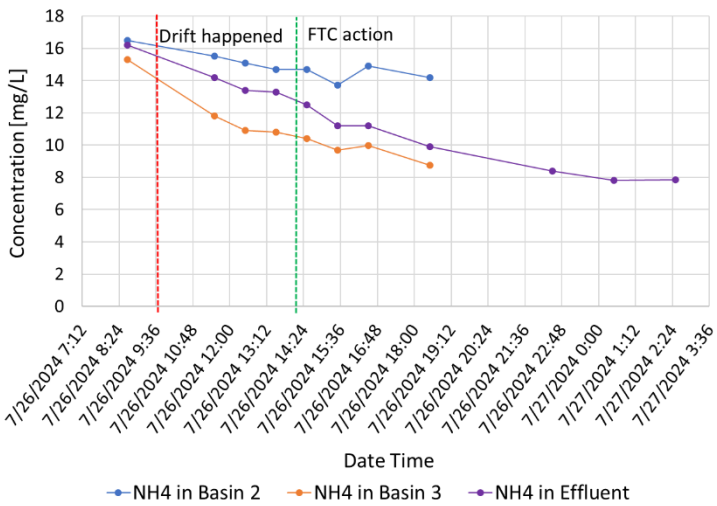


**Figure 5** Ammonia in Basin 2, Basin 3, and effluent during the second FTC experiment of imposing a – 0.3 mg/L.h drift over 5 hours on the controlling DO sensor in Basin 2

## Conclusion

This study demonstrated effectiveness of fault-tolerant control in maintaining system functionality despite sensor faults through two experimental scenarios. In both the sensor bias and drift cases, while the faults initially disrupted operations, FTC actions restored performance to acceptable levels. Analysis confirmed that the faults as dealt with by FTC did not significantly affect overall system performance. This study provides a foundation for further practical studies on control reconfiguration using soft sensors, analytical redundancy, and historical data patterns.

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