ISA Transactions 53 (2014) 568–577

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Faulty measurement substitution and control reconfiguration by using a multivariate flow control loop

Sergio R.P. Perillo [a], Belle R. Upadhyaya [b,*], J. Wesley Hines [b]

[a] IPEN-CNEN/SP, Sao Paulo, Brazil
[b] Department of Nuclear Engineering, University of Tennessee, Knoxville, TN 37996-2300, USA

ARTICLE INFO

Article history:
Received 12 September 2012
Received in revised form
1 October 2013
Accepted 13 December 2013
Available online 8 January 2014
This paper was recommended for publication by Dr. Karlene Hoo

Keywords:
Measurement substitution
Control reconfiguration
Data-driven models
Fault-tolerant control
Sequential probability ratio test

ABSTRACT

A two-tank multivariate loop was designed and built to support research related to instrumentation and control, equipment and sensor monitoring. This test bed provides the framework necessary to investigate and test control strategies and fault detection methods applicable to sensors, equipment, and actuators, and was used to experimentally develop and demonstrate a fault-tolerant control strategy using six correlated variables in a single-tank configuration. This work shows the feasibility of using data-based empirical models to perform fault detection and substitute faulty measurements with predictions and to perform control reconfiguration in the presence of actuator failure in a real system. These experiments were particularly important because they offered the opportunity to prove that a system, such as the multivariate control loop, could survive degraded conditions, provided the empirical models used were accurate and representative of the process dynamics.

1. Introduction

Several techniques for on-line monitoring of equipment and systems in nuclear power plants are well established. Since the early 1970s, numerous efforts have been made to detect and identify anomalies and to provide alternative ways to measure critical and non-critical operating parameters in power plants, particularly reactor noise analysis which uses existing sensor signals to detect incipient faults, measure sensor response time, identify blockages in sensor lines, vibration of reactor internals, imbalance in rotating machinery, etc. In 1992 an MIT report [1] described the theoretical development and the evaluation via both experiment and simulation of digital methods for the closed-loop control. Signal validation and instrument fault detection was also used in this work by means of a numerical technique called “parity space approach” [2–5], which is based on simple algebraic projections and geometry. This method computes a residual vector that is zero when no fault is present and non-zero otherwise. The residual will also be different for different faults. In addition to validating sensor readings, this methodology performs instrument fault checks in which the weighting factor for each sensor is adjusted in proportion to the frequency with which its readings are judged to be valid. Thus, reliance on a failing sensor is gradually reduced, thereby assuring a “bumpless” transition when complete failure actually occurs. Examples of different techniques in the literature range from using Principal Components Analysis (PCA) [6–12] to Fuzzy Logic, Genetic Algorithm (GA) and Artificial Neural Networks (ANN) [6], to data clustering [8] and other residual generation approaches [13]. In many cases more than one approach were used, sometimes combining several of such approaches as tools to obtain residuals and/or control algorithms. In some works, techniques such as ANN and Group Method Data Handling (GMDH) were merged to form GMDH-Type Neural Network Algorithms [14–17] to help predict values based on historical data.

Such techniques evolved into on-line monitoring to track the vibration of reactor internals, measure reactor stability, verify overall plant thermal performance, leak detection, estimation of remaining useful life of equipment, and others. Early detection of the onset of equipment and instrument channel degradation and failure can improve plant safety, prevent loss of operational capability, reduce radiation exposure of plant personnel, enhance plant control, and minimize repair time [18].

The development of an on-line approach for monitoring and control with application to an experimental flow loop is described in this work, corroborating results available in the literature suggesting the applicability of such approach to operating plants with appropriate data acquisition and analytical redundancy. The approach uses empirical, data-based methods for characterizing the relationship among a set of measurements as data sets often

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[*] Corresponding author. Tel.: +1 865 974 7576; fax: +1 865 974 0668.
E-mail address: bupadhya@utk.edu (B.R. Upadhyaya).

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http://dx.doi.org/10.1016/j.isatra.2013.12.013

contain much more information than can be learned from just looking at plots of those data. Models based on observed input/output data can help us abstract and gain new information and understanding from these data sets. They can also serve as substitutes for more process-based models in applications where computational speed is critical or where the underlying relationships are poorly understood.

2. Description of the experimental flow control loop

The two-tank flow facility was constructed on a wheeled table-like steel frame structure seven-foot long, four-foot wide and six-foot high. This structure holds all sensors, piping, pump, sump tank, aircraft aluminum table top, cables, control valves, manual valves, connection boxes, power strips, and two tanks all of which can be repositioned. Since about 80% of the piping used to build the loop is made of Chlorinated Polyvinyl Chloride (CPVC) or PVC, union connections were strategically distributed so any maintenance or minor setup modification can easily be carried out. In Fig. 1 the final layout with both acrylic tanks is shown.

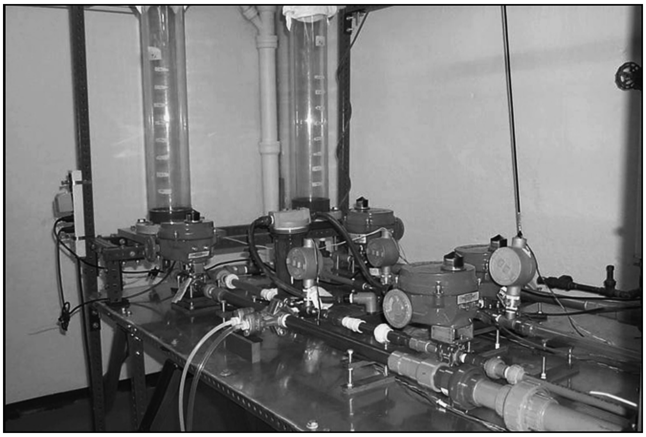
Fig. 1. Final layout of the control loop.

Level control experiments utilize two similar acrylic tanks, referred to as Tank 1 and Tank 2, respectively, and their dimensions are 146 mm in diameter and 1 m long. A 102-l stainless steel tank is installed underneath the table top to provide the necessary water for the circuit.

Several sensors for process measurement are installed in the loop: differential pressure transmitters, thermocouples, turbine flow meters, orifice meters and signal conditioners.

In order to manipulate the water flowing in the loop, five control valves are used: one at each tank inlet, one at each tank exit, and one connecting the piping between the tanks. These control valves have two components: an electric actuator and a 12.7 mm (½″) ball valve. Although not all five motor-operated valves (MOV) are actually used for control purposes, these actuators are manipulated via software and are responsible for opening and closing the ball valves to regulate the flow according to the experiment being carried out. The actuators are 120 VAC powered, with input and output of 2–10 VDC and can be locally or remotely operated, with a typical stroke time of 15 s (stroke time is the time needed to move the valve from the fully closed to fully open position, and conversely).

3. Description of the control loop devices and instrumentation

The two-tank loop was built primarily to provide the necessary framework to develop research related to instrumentation and control strategies, equipment and sensor monitoring, model-predictive control, and the demonstration of fault detection and fault-tolerant control strategy and reconfigurable control. With such objectives in mind, a set of sensors and actuators were placed in key positions throughout the loop to monitor and manipulate the water flow circulating in the loop. Fig. 2 depicts a schematic of this loop with low-pressure water circulation that is facilitated by a fractional horsepower motor-driven pump.

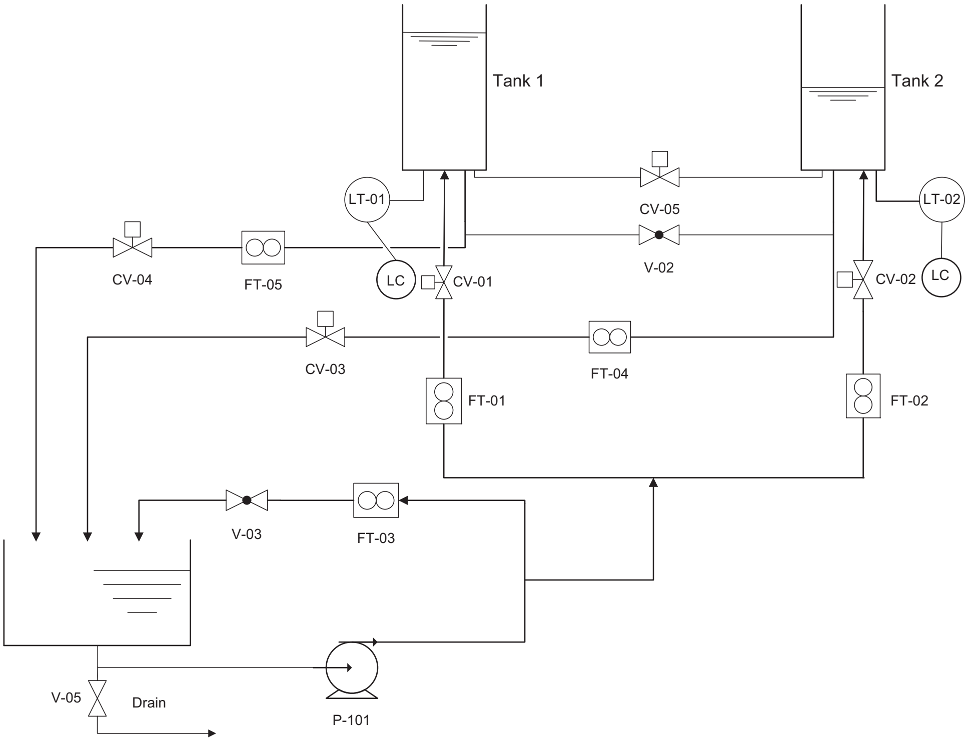

Fig. 2. Schematic of the two-tank experimental control loop.