ANALYSIS AND DESIGN OF A MULTI-SENSOR PROTOTYPE FOR MEASURING THE LEVEL IN LARGE-SIZED TANKS

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Abstract

The purpose of this study is the definition and conception of a measurement system capable of continuously determining the level of carbon type bulk products, stored in a large-sized tank (mine shaft). This storage system has several supply circuits and a tapping circuit using motorized conveyor belts. The measurement system, associated with a data processing procedure, makes it possible to estimate the level in a relatively severe and hostile environment (near the working face, in particular).
The industrial prototype realized uses the principle of data redundancy using multi sensors. The redundant data coming from several data sources (ultrasonic sensors for tank height, flow rates on belts from ultrasonic measurement of product height, motor intensities, capacitive gauges for level measurement, etc.) is processed in order to make it coherent amongst them and to supply a reliable estimation of the level variable.

Key Words: *Level measurement, multi-variable sensors, data redundancy, ultrasonic sensors, laser range finder.*

INTRODUCTION

The study presented is the result of a three-sided collaboration between the Centre de Recherche en Automatic in Nancy, who contributed its know-how in data processing, the CEGELEC Company, a company in the electric sector who contributed to the realization of the industrial prototype and the HBL company, a company of the Lorraine Coal Basin who, other than making the sites available, participated in the realization of the specifications.

The purpose of this study was to define, among the various collaborators, a measurement system capable of continuously determining the level measurement for solid bulk products, such as coal, with a granulometry of 0 to 300 mm, stored in large-sized tanks.

Instrumentation associated with a data processing system makes it possible to estimate the measurement of the product height for tanks with varied constructions (vertical or slightly inclined) and large geometries (heights between 50 and 100 m, the width as large as 10 m).

Generally, the idea of a multi sensor is justified by the necessity of having measurements giving a pertinent image of the real functioning of a process. The presence of disturbance signals, which may come from sensor fault or nuisance parameters, can make the measurements from a sensor unusable. So, the measurement validation step is important and indispensable in order to generate data giving a reliable image of the physical value to be measured. This step is in theory extremely delicate since the sensor and the process to which it is attached are difficult to dissociate, the sensor delivering in fact data dependant of the transfer function of the process and also of the sensor.

Many validation techniques were considered. They can nevertheless be classified into two categories. The first one uses the principle of hardware redundancy and the second one analytical redundancy or the model principle. In one or the other case, the confrontation of various data makes it possible to validate the measurement according to a protocol having three main phases : detecting the presence of outliers, characterizing them and finally correcting the measurement in order to propose the most probable estimation of the actual value.

In our study, these two principles were used. Hardware redundancy is a priori the simplest to use and consists in using several "identical" sensors for measuring the same value. The comparison of data delivered by the various sensors allows validation. This principle uses the now well established technique of parity space. The second technique is more "constraining" since it uses one or several models linking different variables whose measurements have been tested. If the model linking these variables is assumed known and exact, any deviation from this model can be attributed to the measurements. The aptitude for isolating the suspect measurement(s) is closely linked to the number of models and the number of variables. The case of structurally exact linear models was largely exploited and in the case of dynamic systems, it is possible to refer to techniques known as generalized parity space.

The processing that a signal coming from a sensor may undergo are numerous. It may be classified in two hierarchy levels. The first one corresponds to a local processing level where the signal coming from each sensor is processed separately and the second one consists in joint processing of each signal. The local level makes it possible to detect and, in some cases, to isolate a certain number of events in a signal : isolated values with abnormally low or high amplitude, jump in mean, fast variation in frequency, variance,... However, if detection is often easy, interpretation of these events is delicate: is a jump in the mean in the signal due to a sensor defect or to a modification of the state of the process to which the sensor is attached ? So, it is necessary to give to this local level a certain amount of knowledge on the physical process, for example its dynamics.

Without pretending to have designed a smart sensor, according to its usual definition, the architecture that we propose uses several concepts. Please remember the minimal functionality that a smart sensor must have : to validate the measurements it supplies by eliminating undesirable data, to supply a confidence interval associated with the measurement. The proposed structure associates direct measurements (levels, flow rates, start-stop indicator, etc.) with indirect measurements, that is a mathematical model (estimation of a flow rate on a belt from a motor intensity measurement, etc.).

SPECIFICATION

Continuous and reliable knowledge of product height in the main tank of a coal exploitation unit, whose function is to play a buffer role between the bottom site (extraction) and the surface site (treatment), makes it possible to act automatically on production control. These controls intervene on the whole line, from the extraction machines to the treatment and classification plant, in order to optimize their functioning.

This level measurement, from which comes the volume of the stored product, is thus an important parameter for production. To date, no simple means exists, in terms of measurement, to make a direct measurement as soon as the measurement evolves in ranges located between 50 and 100 m.

Special requirements, concerning design and location of the data processing line, linked to the environment or exploitation, was imposed for this study, namely :

- To use a contactless measurement process. Indeed, traditional slope probe type systems must be forbidden because of their large measurement inertia (higher than one minute) and the risk of destruction by the product during filling.
- To allow easy and preventive maintenance. This point imposes that the system must have an easy access and it makes information available concerning its state of general functioning (state of communications, state of supply, etc.).

- To install the system in a risky zone. The system must be composed of equipment able to be exploited in an environment with a risk of explosion, zone type 0 (methane CH_4). This point implies that the components of the system must meet explosion proof and intrinsic safety standards.

- To respond to a high variation in the quality of products stored in bulk. Indeed, depending on the extraction site, product quality, granulometry, density, shape, color, etc. varies highly. All these parameters act directly or indirectly on measurements and thus they must be integrated and taken into account in the data processing line.

PROGRESSION OF THE STUDY

Introduction

It was thus decided to start with the concept of a multi-variable sensor. This concept makes it possible, through redundancy and the richness of knowledge acquired and processed, to estimate continuously the level measurement of the stocked product, whatever tank functioning might be (tapping, rest, filling, tapping and filling).

Pre-study

Upstream from the work, a study on the level measuring instrumentation made it possible to list the physical processes used for contactless measurement :

-Gamma ray measurement (gamma absorption sensor)
-Laser range finder measurement (laser distance meter)
-Ultrasonic wave measurement (ultrasound sensors)
-Pure acoustic measurement (acoustic ear)
-etc.

Each principle underwent laboratory and on-site tests in order to appreciate its behavior in multiple situations (study of its stability, its span, its reliability, its response time, etc.).

This first phase made it possible to choose among the existing measurement instruments and to select two measurement principles : measurement by ultrasounds and measurement by laser range finder. The other principles were not retained for the following reasons :

- Constraining use, especially for gamma rays that require special precautions

- Measurement signal having a low or non

representative dynamic, in particular for pure acoustics.
The two principles retained are satisfactory for measurements in low disturbance environments, but as soon as the site on which they intervene becomes hostile in the sense of measurement (high noise, high humidity, light absorbing product, low granulometry, dust, etc.), both of these principles become inefficient, but for different operating conditions.

The continuous estimation of the level measurement thus requires the association of different measurement principles.

Study

This association of multiple data taken in charge by a data processing system, whose measurement strategy resides in the principle of a choice of calculation algorithms from pre-defined scenarios, makes it possible to estimate reliably the level measurement.

The system associates a likelihood coefficient to this measurement, which qualifies the estimation quality as well as the measurements necessary for production (mass balance, energy balance, etc.) and maintenance (running time of equipment, number of equipment manoeuvres, etc.) management.

PROTOTYPE

Introduction

To realize the industrial prototype, following the study phase having resulted in its conception, a study site with all the necessary characteristics (57m high tank, hostile environment, granulometry of 0-250 mm, zone with risk of explosion) was made available to us in order to make tests.

These tests took place over several months with permanent experimentation in order to correct the algorithms making up the measurement strategy. In the same way, adjustment of the electronic running and control equipment could be refined, mainly on ultrasonic type measurements (response time, frequency of quartz oscillation, speed of sound propagation, etc.).

Installation instrumentation (figure 1)

a/ Level measurement

Direct measurement of the tank level is done using two sensors placed near the headbox. Each sensor has a different observation point in order to alleviate the non flatness of the free surface of the product (effects of humps and hollows). These two sensors are connected to joint processing electronics that delivers digital signals.

Associated with these level measurements H1 and H2, the processing electronics delivers several control parameters including a parameter making it possible to have an indication concerning the "confidence" to be accorded to these measurements (value included between 0 and 100).

Statistical analysis of the signal and the study of acoustic phenomena from the transducers intervene on this calculated parameter.

The capacitive sensors, placed on the whole span of the tank level, make it possible to obtain ranges where the free surface of the product is located. These sensors deliver a logic signal. There are 6 of them that determine 7 measurement ranges.

b/ Belt flow rate (input and output)

On each belt, an ultrasonic sensor makes it possible to know by differentiation the height of the transported product. This height associated with the belt speed makes it possible to determine its flow rate Qe and Qs.

c/ Tank output flow rate Qs'

A measurement of the product mass tapped from the tank is realized from a conveyor belt weigher under the discharge skip.

d/ Tank input flow rate Qe'

An indirect measurement of the input flow rate is realized from the drive motors of the belt. Indeed, it seems that the signal is characteristic of the belt load, with an acceptable precision (about 10 %).

Analytical and hardware data redundancy makes it possible, by cross checking and comparison, to validate the various measurements. For example, the tank level can be expressed by a simple equation using the input flow rate Qe and the output flow rate Qs, variables that can, themselves, be expressed by the combination of other measured values. Indeed, the input flow rate Qe' is a function of the motor intensities of the supply belt. In the same way, the mass of the evacuated product or the height of the product on the extraction belt makes it possible to deduce the output flow rate Qs'.

Functional architecture

A hardware architecture graded by level makes it possible to meet the processing needs of the prototype.

Level 0 corresponds to the sensors. These are placed near to the installation and are in liaison with the level 1 corresponding to the electronic measurement systems.

Level 1 elaborates the elementary calculations (compensation, filtering, etc.), the conversion into standardized and exploitable signals that are then passed on to level 2.

Level 2 is structured around a programmable controller whose main function is the acquisition and concentration of all the measurements of the installation. It elaborates the primary calculations (filter, mean, elimination of outliers, etc.) and reacts on the process for safety (installation stop in case of tank overflow, empty tank, etc.).

Level 2 exchanges data with level 3, structured around a PC type micro-computer equipped with peripheral equipment (graphic display, graphic printer, report printer). An exchange protocol makes it possible to guarantee the coherence of the transferred data. In our case, level 2 and level 3 are separated by more than 20 km since level 2 is located at 500 m from the surface and level 3 in the administrative offices of the exploitation unit.

The measurement strategy is installed in level 3 in order to estimate continuously the product level and its confidence interval. In addition to this determination, the calculated data is delivered. It is of two types :

- Surveillance type data :

* gradient of the level (tendency to rise or fall)
* alarm thresholds of acquired or calculated analogic values
* surveillance of motor intensities and their differences
* running times of the equipment with a view to their preventive maintenance

- Management type data :

* mass balance per shift, per day, etc.
* running and stopping times of the equipment
* etc.

All this data is made available to the operators in the form of real time data display, historic curves and data log books. A computer link was established between this system and the overall operation post of the exploitation unit in order to take into account the information in the same way as general information on the process.

ANALYSIS OF THE RESULTS

Figure 2 shows the direct measurements H1 and H2 of the product in the tank coming from the ultrasonic sensor as well as estimated measurement Hestim coming from the prototype.

The input flow rate Qe and the output flow rate Qs of the tank are represented on figure 3, and on graph 4 the number of the measurement strategy appears. For each of these figures, the x-axis bears the number of the temporal sample (sampling time of 5 seconds).

It may be noted that the values H1 and H2 are very disturbed, mainly when the tank is in the filling phase (Qe different from 0). This phenomenon is amplified when the product height is low. Indeed, disturbing acoustic resonance increases as the tank empties.

For each measurement strategy (11 in all), the processing system elaborates the calculation of the estimation from equations taking into account all or part of the collected or calculated data according to choice criteria coming from scenarios pre-recorded by simulation.

MEASUREMENT STRATEGY

General description

The strategy set up for elaborating level measurement estimation is organized in the form of a step-transition graph, with 4 steps and 4 transitions (figure 5).

The tank behavior (loading phase, emptying phase, empty state, stable state, etc.) and the state of its environment (noise level, product granulometry, rate of humidity, etc.) are described by 11 distinct states.
The main step (number II), called normal functioning, includes 8 of these states. The abnormal functioning step (number III) has 2 of them and one state is associated with each of the initialization and stopping steps.

The various steps

Step I : *Initialization*
It corresponds to the step during which the systems learns of the initial parameters (product density, belt width, the dynamics of each equipment, etc.) and configures itself.

As an indication, during configuration, there is determination of equations relative to the calculation of the product section on each belt in order to determine the flow rate of the transported product.
The transition making it possible to go to the following step corresponds to the stability of the tank (Qe=Qs=0), which makes it possible to obtain a reference height.

Step II : *Normal*
This step is the main step of the strategy. It is broken down into two steps that themselves include various states.

The sub step, called direct measurement, is a step where the level measurement is done by taking into account certain direct measurements, chosen with respect to the confidence accorded to it.

In the second sub-step, called estimation, the level comes from internal calculations, having models linking the various values intervene. In the same way as for the preceding sub-step, the criteria for selection concern either the measurements or the calculated values, making it possible to activate the best strategy. Passage from the normal step to the abnormal step is conditioned by "alarms".

Step III : *Abnormal*
This step concerns alarm processing. If the detected alarm does not concern the variables intervening on the strategy during processing, going back to the normal step is immediate. Otherwise, the system will make the estimation in deteriorated conditions, not taking into account the missing variable(s). Going back to the normal state takes place when the concerned alarm disappears.

CONCLUSION

The multi sensor prototype for level measurement in large-sized coal tanks, described above, has been in operation for a year on a production site of the Lorraine Coal Basin. It gave complete satisfaction during this test period. This continuous "measurement" of product height made it possible to optimize the whole production line : extraction, processing and classification. Please remember that, prior to the study and the conception of this prototype, the measurement means of this level were very precarious and the data, when it was available, corresponded more to an indication than to a real measurement.

Much of the data delivered by the prototype could not be exploited during this test period, the main goal being to obtain a reliable estimation of the level. The exploitation of multiple data should make it possible, if industrialization of this product is realized, to oversee the various values and thus contribute to the elaboration of a diagnosis for the functioning of the whole installation.

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