ROMANIA -MINISTRY OF EDUCATION
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DOCTORAL SCHOOL

DOCTORAL THESIS
SUMMARY

RESEARCH ON INTEGRATING WIRELESS SENSOR NETWORKS WITH CLOUD INFRASTRUCTURES APPLICABLE TO AUTOMATIC MONITORING AND CONTROL SYSTEMS

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Introduction

It is a well-known fact that the operation of an automated system is based on the transmission and processing of information. The progress made in the field of automation equipment has marked continuous improvements in the nature of the information carrier signal, data storage availability and computing power.

After the ’90s, virtually all of the automation apparatus gradually took on important features of the fourth generation of computers as the use of circuits integrated on very large scale (*VLSI*) and connectivity.

This aggregation allowed the realization of complex systems through which the paradigm of *Calculation – Control – Communication – Knowledge* is implemented in practice.

Currently, technological developments in the fields of production, transmission and storage have brought to the fore the following technologies considered as a reference for further developments:

1. Wireless sensor networks;
2. Cloud infrastructure;
3. The Internet of Things.

This doctoral thesis has two main objectives, namely:

- ***OP1*** - Investigating the availability of the above technologies to be involved in performing the tasks of automated systems;
- ***OP2*** - Integrating the above technologies in order to achieve a hierarchical automatic monitoring system of a physical process.

Apart from these main objectives, the following secondary objectives were also associated with the doctoral thesis:

- ***OS1*** - Implementing methods to improve energy efficiency in a wireless sensor network;
- ***OS2*** - Investigating the prospects of modeling, simulating and controlling physical processes that will be used as support for the development of the hierarchical automatic monitoring system.
- ***OS3*** - Conducting statistical operations and generating predictions using acquired data.

The doctoral thesis is structured in five chapters, the content of which will be summarized below.

The first chapter details the foundations of wireless sensor networks, the protocols used, as well as the classification of wireless sensors. It also provides a brief description of the platforms used to form the nodes of wireless sensors. The chapter concludes with a contribution of the author in terms of using the random linear network coding for an increase in the performance of a *WiMAX* network.

The second chapter is devoted to investigations into the development and use of *Cloud* infrastructures, tackling several key aspects of *Cloud* infrastructures such as service models, deployment models, *Cloud* platform security and Cloud platform for Internet of Things presentation.

In the first two chapters, an identification of the current stage in the development of wireless sensor networks and *Cloud* infrastructures was carried out. The current stage of development offers premises to achieve complex automated systems based on these resources.

The third chapter treats the physical processes associated with accumulation of a liquid in a tank, transport and liquid blending. The three processes are described through three distinct perspectives: *dynamic modeling*, *simulation* and *control*. The last section of the chapter is the design, development and integration of algorithms intended for obtaining products containing several components specified by mixing recipes. The usefulness of algorithms is highlighted by implementing a real-time inventory analysis application.

Chapter Four is dedicated to integrating technologies based on wireless sensor networks, Cloud infrastructures, aiming at developing a hierarchical automatic system monitoring for the accumulation of a liquid. The hierarchical nature of the monitoring system is demonstrated by the existence of six distinct levels proposed by the author of the thesis. A special place in this chapter rests with the implementation of a function that generates predictions using the *Machine Learning* concept.

Chapter Five contains the general conclusions of the research, the author’s contributions, the dissemination of results and future research directions.

The doctoral thesis also contains a bibliographical section (133 titles), in which references are alphabetically ordered.

The last section of the doctoral thesis is represented by the 7 appendixes used to clarify issues as follows:

- Appendix 1 contains a detailed report generated by the real-time inventory analysis application.
- Appendix 2 presents the *Astank* research platform.
- Appendixes 3, 4 and 6 contain the technical specifications of the components of *Astank* platform studied in Chapter 4.
- Appendix 5 defines the decoding function implemented for data acquisition.
- Appendix 7 contains the rules used to generate predictions based on acquired data.

The doctoral thesis also contains lists of figures (210 figures) and tables (48 tables).

General conclusions, contributions, dissemination of results and future directions of research

General conclusions

As is apparent from the developments presented for the four chapters of the doctoral thesis, each of them ends with a subchapter in which the partial conclusions relating to that chapter are broadly presented.

A summary of the partial conclusions in conjunction with the objectives of the doctoral thesis, as defined in the section reserved for introduction, will be presented below.

A first general conclusion is that the objectives proposed and outlined in the introduction to the present doctoral thesis have been met.

Further conclusions of a general nature grouped for each objective (principal or secondary) will be presented below.

- With regard to the fulfillment of the first main objective (***OP1****- Investigation of the availability of wireless sensor networks and Cloud to be involved in performing the tasks of automated systems*), the following conclusions can be reached.
    - ***OP1_1*** – The fundamentals of wireless sensor networks with concrete reference to *topologies, radio frequencies, standards* and *protocols used* have been investigated and presented in Subchapters 1.1 and 1.2.
    - ***OP1_2*** – A comparative analysis of the current development platforms used in the implementation of wireless sensor nodes (Subchapter 1.3) was carried out. From this analysis, it was possible to use the Lopy platform for the implementation of wireless sensors, given the type of physical process

monitored (liquid accumulation process) and the features offered by this platform in terms of secure transmission at very long distances.

- ***OP1_3*** **–** An analysis of *Cloud* infrastructures with wireless sensor network components and services (Subchapters 2.3, 2.4 and 2.5) was conducted. The results of the analysis led to the choice of *The Things Network* infrastructure for managing the wireless nodes and *Amazon Web Services Cloud* infrastructure for available *IoT* components and services.

➢ Regarding the achievement of the second main objective (***OP2*** *- integrating technologies specific to wireless sensor networks and Cloud infrastructures in order to achieve a hierarchical automatic monitoring system for a physical process*), the following general conclusions can be drawn.

- ***OP2_1-*** The process of accumulating a liquid in a tank was investigated. The study assumed the mathematical modeling in the dynamic regime of this process and the development of simulators in the *Simulink*® Environment – Subchapter 3.2.
- ***OP2_2*** – Supplying quality data required the calibration of equipment (level transducer and execution element) related to the automation of the process of accumulating a liquid in a tank (implemented within the research platform *Astank* – Subchapter 4.2);
- ***OP2_3*** **–** A network of wireless sensors with LoRa technology intended for the acquisition of data from the process was implemented. The developed infrastructure assumed the use of *LoPy* microcontrollers – subchapter 4.3.
- ***OP2_4*** – A stage of the development of the *Hierarchical Automated Monitoring System (HAMS)* was the configuration of the management platform for network nodes (i.e. *The Things network* platform – Subchapter 4.4). The setup has required the resolution of several issues, among which: the configuration of client and Router nodes within the *TTN* platform; the identification of the signals that will be acquired and the transmission of the acquired data to the *TTN* platform.
- ***OP2_5*** **–** Integration of the *Cloud* infrastructure *with HAMS* required the replication of network nodes at the level of this infrastructure and the configuration of services specific to data processing and storage (for this

purpose, *Amazon WEB Services AWS IoT Infrastructure* was used – subchapter 4.5);

- ***OP2_6*** – To demonstrate the need of data from the *Cloud* an application for *statistical analysis* and *prediction generation* using the acquired datasets has been implemented (for the demonstration *Amazon SageMaker* Service was configured and used – Subchapter 4.6).

➢ The first secondary objective (***OS1*** *- implementing methods to improve energy efficiency in a wireless sensor network*) assumed the implementation of a *WiMAX* network in a simulated environment (*NS3*) in order to accurately retrieve the information transmitted between nodes. This network audit was necessary to study how it operates for both standard communication and communication in which packages were altered through the random linear network coding method (Subchapter 1.4). The reduction in energy consumption has been demonstrated by reducing the number of confirmation messages on the network.

➢ The second secondary objective (***OS2*** *- investigation from the perspective of modeling, simulating and controlling physical processes that will be used as support for the development of the Hierarchical Automatic Monitoring System*) required the description of three processes (accumulation of a liquid in a tank, transport and liquid blending) from three distinct perspectives, namely: dynamic modeling, simulation and control. For each investigated process simulations were performed in the Simulink® environment, based on generated dynamic mathematical models. Both the simulations of the time response of the accumulation, transport and blending processes, and those corresponding to the control of these processes, have presumed the achievement of a series of tests highlighting the dynamic evolution of the controlled variable of the process at step changes of the control variable or at the occurrence of disturbances (subchapters 3.2, 3.3 and 3.4).

➢ The third secondary objective (***OS3*** *- conducting statistical operations and generating predictions using acquired data*) assumed the use of data acquired from the *Astank* platform through the *LoRa network*. For this purpose, the components of the *Amazon SageMaker* service (J*upyter notebook* with *Python* libraries, Endpoint models and applications) were used for the selection of the dataset for the *Linear Learner* algorithm and predictions generation (subchapter 4.5).

To achieve the objectives, the developments in this doctoral thesis were based on:

- Bibliographical investigations;
- Analytical mathematical modeling of the processes of accumulation, transport and liquid blending;
- Simulation of processes modeled on the basis of simulators developed in the Simulink environment;
- Simulation validation based on simulators developed in the *Simulink* Environment of automatic control structures associated with accumulation, transport and blending processes;
- Elaboration and testing of algorithms associated with obtaining products containing several components specified by blending recipes;
- Experimental investigations within the *Astank* research platform in particular concerning the liquid accumulation process;
- Settings, implementations and tests of wireless sensor networks and communications with *Cloud* infrastructures;
- Research on integration into hierarchical systems of wireless sensor networks, *Astank* platform and *Cloud* infrastructures;
- Analyses of data acquired from the hierarchical system;
- Investigation of the possibility of generating predictions using the concept of *Machine Learning* to support data purchased and transferred to the *Cloud.*

Contributions

In this doctoral thesis, the author has developed an integration of technologies and standards comprising:

– *Physical level* (process apparatus, wireless sensor network, process data acquisition)

– *Logical level* (wireless network virtualization, the definition of data acquisition nodes in the Cloud, data processing, *Machine Learning* methods used to generate predictions based on processed data).

The original contributions are found in Chapters 1, 3, 4 and have been revealed in the afore-mentioned chapters. The contributions of special significance are summarized below.

1. A bibliographical study was conducted on the current state of wireless sensor networks. The main development platforms (microcontrollers) that can be used as nodes for wireless sensors have been identified and presented in this study.
2. Wireless networks have been deployed in a simulator (*Network Simulator 3*) to highlight the increase in the performance of a *WiMAX* network using random linear network coding.
3. A case study was conducted following which the author was able to choose the *Cloud* infrastructures used in the work.
4. A unified approach has been made in three perspectives: *mathematical modeling, simulation and automatic control* for the processes of accumulation, transport and liquid blending.
5. The *DCC* algorithm was proposed, designed and implemented – the algorithm used to calculate the needs of components in order to achieve the imposed quantities of the finished product.
6. The *ICP* algorithm was proposed, designed and implemented to calculate the maximum quantities of finished products made with all the quantities of available components.
7. The *ECP* algorithm was proposed, designed and implemented to calculate the optimum quantity of finished product achieved with all quantities of available components.
8. The RTSA application (real-time stock analysis) that integrates the three algorithms was developed in the C# environment.
9. The *Astank* research platform has been studied and configured for the process of accumulating a liquid in a tank.
10. The extension of the Chien Freuhauf criterion was proposed for the granting of the *PI* regulator parameters for the automatic level control system in a tank within the *Astank platform.*
11. L*oPy* wireless sensor nodes have been installed, configured and integrated into a *LoRa* network.
12. The connection of the local *LoRa network* to *the Things Network* (*TTN*) infrastructure for centralized node management and primary data processing was carried out.

13. The integration of the data from the accumulation process within the *Astank* platform with the *LoRa* Network and the *TTN* infrastructure (processing of physical signals from the process, data acquisition) was achieved.
14. Wireless sensor nodes from *TTN* (bidirectional communication, data storage in permanent databases, advanced data processing) have been defined and configured in *AWS* infrastructure.
15. The prediction generation module was configured using the *Linear Learner* algorithm within The *AWS SageMaker* service.
16. The integrative character of the work was demonstrated by testing the *Machine Learning* algorithm for a set of about 17,000 data (training and test) from the process of accumulating a liquid from the research platform *Astank*.

Dissemination of results

The results obtained in this doctoral thesis were disseminated in scientific works, the ones with a particular significance being highlighted below.

➢ Papers indexed Clarivate Analytics Web of Science (ISI)

1. **Zamfir F.**, Paraschiv N., Pricop E., *Performance Analysis in WiMAX networks using random linear network coding*, Proceedings of the 4th International Conference on Control, Decision And Information Technologies, Codit 2017, Barcelona, Spain, April 2017, page. 679-683, ISBN: 978-1-5090-6465-6, TWO: 10.1109/CoDIT. 2017.8102658.

2. Pricop E., Fattahi J., Paraschiv N., **Zamfir F.**, Ghayoula E., *Method for authentication of sensors connected on Modbus TCP*, Proceedings of the 4th International Conference on Control, Decision and Information Technologies, CODIT 2017, Barcelona, Spain, April 2017, page. 679-683, ISBN: 978-1-5090-6465-6, DOI: 10.1109/Codit. 2017.8102673.

3. Pricop E., Magesh SF, Paraschiv N., Fattahi J., **Zamfir F.**, *Considerations regarding security issues impact on systems availability*, Proceedings of the 8th International Conference on Electronics, Computers & Artificial Intelligence, ECAI 2016, June 2016, Ploiești, Romania, page. 1-6, ISBN: ISBN: 978-1-5090-2047-8 two: 10.1109/ECAI. 2016.7861110

4. Pricop E., **Zamfir F.**, Paraschiv N., *Feedback control system based on a remote-operated PID controller implemented using mbed NXP LPC1768 development board*,

Journal of Physics: Conference Series, Vol. 659, Proceedings of the 12th Advanced Control and Diagnosis Workshop, Pilsen, Cehia, 2015, Article number: 012028, IOP Publishing, 2015, DOI:10.1088/1742-6596/659/1/012028

➢ Papers accepted for publication

1. **Zamfir F.**, Paraschiv N., Pandey E., *Real-time stock analysis for blending recipes in industrial plants*, 23rd International Conference on System Theory, CONTROL AND Computing (ICSTCC) October 9-11, 2019, Sinaia, Romania

2. Paraschiv N., Pricop E., Fattahi J., **Zamfir F.**, *Towards A reliable approach on scaling in data acquisition,*23rd International Conference on System Theory, Control and Computing (ICSTCC) October 9-11, 2019, Sinaia, Romania

Future directions of research

One of the main objectives of the thesis consisted of integrating the accumulation process within the ASTANK research platform with *Cloud* infrastructures through wireless sensor networks. However, integration is the first step, as demonstrated in the thesis, since communication between the sensor network and *Cloud* infrastructures has had a unidirectional approach.

Based on the experience gained during the research, the results of which were presented in the doctoral thesis, four follow-up directions of the research were identified.

1. Implementing an algorithm for calculating the cost of the production of a finite product quantity for the stock analysis application.
2. Including disturbances in the prediction algorithm implemented through Machine Learning for the veracity of data relating to the control variable for the process of accumulating a liquid in a tank.
3. Identifying the possibility of automatically determining optimal values for the tuning parameters based on historical data acquired in the *Cloud*, depending on the changes in the reference and updating the new values within the *PLC*.
4. Making predictions for the control variable associated with the automatic control of the process of accumulating a liquid in a tank and generating real-time controls from the *Cloud*, in this manner the development of bidirectional data transmission.