DETECTION AND CLASSIFICATION MULTI-SENSOR SYSTEMS

IMPLEMENTATION OF IOT AND SYSTEMATIC DESIGN APPROACHES

Damian Dziak

Blekinge Institute of Technology
Doctoral Dissertation Series No. 2020:10

Department of Mathematics and Natural Sciences

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Applied Signal Processing

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'We are still confused now, but at a higher level'

WJK

Abstract

The detection and classification of features or properties, which characterize people, things or even events can be done in reliable way due to the development of new technologies such as Internet of Things (IoT), and also due to advances in Artificial Intelligence (AI) and machine learning algorithms. Interconnection of users with sensors and actuators have become everyday reality and IoT, an advanced notation of a Multi-sensor System, has become an integral part of systems for assessment of people's habits and skills as well as the evaluation of quality of things or events' performances. The assessment approach presented in this thesis could be understood as an evaluation of *multidimensional fuzzy quantities*, which lack standards or references.

The main objective of this thesis is systematical design of multi-sensor systems for *industrial* and *behavioral* applications. The systematization is based on User Oriented Design (UOD), the methodology where stakeholders and future users are actively involved in all steps of the development process. An impact of the application environment on design principles is quantitatively and qualitatively analysed. It shows different design approaches, which can be used for developing systems monitoring human activities or industrial processes.

The features identification approach applied in this thesis involves the extraction of the necessary data, which could be used for behavior classification or skills assessment. The data used for these purposes are vision or radio based localization and orientation combined with measurement data of speed, acceleration, execution time or the remaining energy level.

Background removal, colour segmentation, Canny filtering and Hough Transform are the algorithms used in vision applications presented in the thesis. In cases of radio based solutions the methods of angle of arrival, time difference of arrival and pedestrian dead reckoning were utilized. The applied classification and assessment methods were based on AI with algorithms such as decision trees, support vector machines and k-nearest neighborhood.

The thesis proposes a graphical methodology for visualization and assessment of multidimensional fuzzy quantities, which facilitate assessor's conceptualization of strengths and weaknesses in a person's skills or abilities. Moreover, the proposed method can be concluded as a single number or score useful for the evaluation of skills improvement during of training.

The thesis is divided into two parts. The first part, *Prolegomena*, shows the technical background, an overview of applied theories along with research and design methods related to systems for identification and classification of people's habits and skills as well as assessing the quality of things or performances. Moreover, this part shows relationships among the papers constituting the second part titled *Papers*, which includes six reformatted papers published in peer reviewed journals. All the papers concern the design of IoT systems for *industrial* and *behavioral* applications.

Keywords: Assessment; Behavior Recognition; Classification; Design Methodology; Detection; Indoor Localization; Internet of Things; Multi-Sensor System; Skills Assessment; Outdoor Localization; Wireless Sensor Network.

To my beloved Wife and Daughters

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Contents

List of Appended Papers

This thesis is based on the following research papers which are referred in the text by Roman numerals:

Paper I	D. Dziak, B. Jachimczyk, ”The Impact of Automatic Calibration on Positioning Vision System on Workpiece Localization Accuracy,” in The Scientific Papers of Poznan University of Technology, pp. 109-116, Poznań 2013.
Paper II	D. Dziak, B. Jachimczyk, W.J. Kulesza, "An Analysis of Uncertainty and Robustness of Waterjet Machine Positioning Vision System," in Elektronika Ir Elektrotechnika, vol.19, no.9, pp. 89-92, 2013, (ISI Journal)
Paper III	D. Dziak, B. Jachimczyk, W.J. Kulesza, "Wirelessly Interfacing Objects and Subjects of Healthcare System – IoT Approach," in Elektronika Ir Elektrotechnika, vol.22, no.3, pp. 66-73, 2016, (ISI Journal)
Paper IV	D. Dziak, B. Jachimczyk, W. J. Kulesza, “IoT-Based Information System for Healthcare Application - Design Methodology Approach”, Applied Sciences, vol.7, no.6, p. 596, Jun. 2017, (ISI Journal)
Paper V	D. Dziak, B. Jachimczyk, K. Bork-Ceszlak, T. Zydanowicz, and W. J. Kulesza, "Wireless Monitoring System for Fireman’s Competence Objective Assessment", Elektronika ir Elektrotechnika, vol.23, no.4, pp. 56–62, Jul. 2017. (ISI Journal)
Paper VI	B. Jachimczyk, D. Dziak, J. Czapla, P. Damps, and W. J. Kulesza, "IoT On-Board System for Driving Style Assessment", Sensors, vol.18, no.4, p. 1233, Apr. 2018. (ISI Journal)

Other publications related to the subject of the thesis produced during the doctoral studies:

Publication 1	B. Jachimczyk, D. Dziak, W.J. Kulesza, “Performance Analysis of an RFID-based 3D Indoor Positioning System Combining Scene Analysis and Neural Network Methods,” in The Scientific Papers of Faculty of Electrical and Control Engineering Gdansk University of Technology, vol.34, pp. 29–33, Sept. 2013.
Publication 2	W.J. Kulesza, B. Jachimczyk, D. Dziak, “E-Technologies in Teaching Research Methodology for Engineers – a Case Study of the Course for International Postgraduate Students,” in The Scientific Papers of Faculty of Electrical and Control Engineering Gdansk University of Technology, vol.37, pp. 27–32, Apr. 2014.
Publication 3	B. Jachimczyk, D. Dziak, W.J. Kulesza, "RFID - Hybrid Scene Analysis-Neural Network System for 3D Indoor Positioning – Optimal System Arrangement Approach” in IEEE International Conference on Instrumentation and Measurement Technology Conference, Montevideo, 2014.
Publication 4	B. Jachimczyk, D. Dziak, W.J. Kulesza, "Performance Improvement of NN Based RTLS by Customization of NN Structure – Heuristic Approach,” in The 9th International Conference on Sensing Technology, Auckland, 2015.
Publication 5	B. Jachimczyk, D. Dziak, and W. J. Kulesza, “Using the Fingerprinting Method to Customize RTLS Based on the AoA Ranging Technique,” in Sensors, vol.16, no.6, p. 876, Jun. 2016, (ISI Journal)
Publication 6	B. Jachimczyk, D. Dziak, and W. J. Kulesza, “Customization of UWB 3D-RTLS Based on the New Uncertainty Model of the AoA Ranging Technique,” Sensors, vol.17, no.2, p. 227, Jan. 2017, (ISI Journal).

Publication 7 D. Gradolewski, D. Masłowski, D. Dziak, B. Jachimczyk, S. Mundlamuri, C. Prakash, W. Kulesza, "A Distributed Computing Real-time Safety System of Collaborative Robot", Electronics ir electrotechnica., vol.26, no.2, pp. 4, Jun. 2020, (ISI Journal).

Part I

Prolegomena

1 Introduction

1.1 Background and motivation

The Internet of Things Internet of Things (IoT) is an advanced notation of a Multi-sensor System. Nowadays, due to its capabilities to easily interconnect users with many sensors and actuators, IoT has become a significant part of manufacturing [1], healthcare [2], along with education and training [3], as illustrated in Figure 1.1.

The IoT concept integrates both physical and virtual devices called things, such as distributed sensor nodes, actuators, mobiles and other devices, which are connected to the Internet. The Institute of Electrical and Electronics Engineers (IEEE) defines IoT as: “A network of items, each embedded with sensors, which are connected to the Internet” [4]. According to the Cisco, Internet Business Solutions Group [5], "IoT is simply the point in time when more *things* and *objects* are connected to the Internet than people, without requiring human-to-human or human-to-computer interaction."

The IoT approach is particularly relevant and often used in monitoring systems for detecting [6] things and objects and classifying them into different categories [7]. Even if detection is mostly recognised as identification of objects or events, it could be used for persons or features too. While classification is to be understood as a taxonomy of performance quality or assessment of person’s behaviour, skills or capacities.

As reported classification could concern the behavior of a monitored person [8], or assessing the quality of sleep but even image selection [9]. Many classification problems have to consider multiple variables and cannot be solved using linear models. Such new tools become more suitable for the following nonlinear models: Machine Learning (ML) [10] algorithms and methods, Neural Networks (NN) [11], Genetic Algorithms (GA) [12],

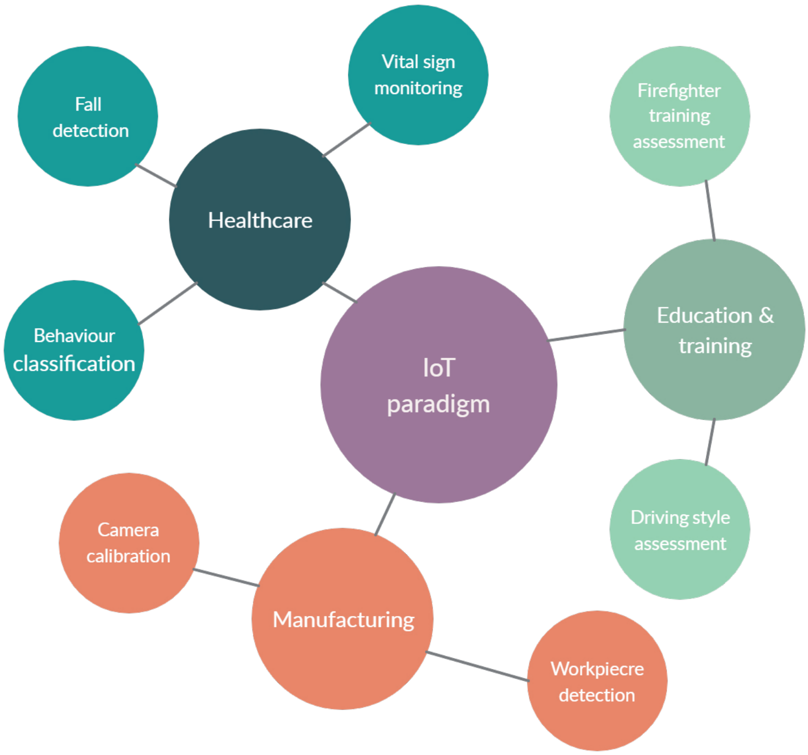


Figure 1.1: The IoT paradigm and its targets

Decision Trees (DT) [13] or Support Vector Machines (SVM) [14].

Selection of right technologies and algorithms for detection and classification in IoT systems is not a trivial task. The designer, who is usually also the developer of the entire product, needs to apply an appropriate design methodology to avoid unnecessary mistakes. Several approaches have been proposed such as the methodology used by S. A. Mengel et al., which consists of three stages: requirements, specification and implementation [15]. To improve the productivity of complex electronics system design, H. Eskelinen proposed to use two questionnaires to the traditional four-stage electronics system design, which were: system design, electronics design, mechanical design and design for manufacturing [16]. In turn, A. Saini and P. Yammiyavar chose the user as the focal point of their design of the m-health system [17]. They applied the object-oriented system design methodology, commonly used for software development. Then, they studied interactions and relationships between the system requirements and the components of user's needs and goals.

Although a variety of solutions were used in the IoT based detection and classifications system, a methodological approach to the design process had been missed and design and implementation processes needed to be systematized.

1.2 Thesis objectives and scope

The main objective of the papers included in this thesis was to design IoT based detection and classification multi-systems for two main applications fields: *industrial* and *behavioural*. Different design approaches needed to be used for solving problems related to human activities vs. industrial processes. This thesis covers two main applicational approaches: industrial and behavioral. Paper I and Paper II are embedded in the industrial environment while Paper III and Paper IV are dedicated to human activities. Whereas, Paper V and Paper VI apply both approaches with different proportions.

In this thesis, we focus on two functional approaches, which are *detection* or *identification* and *classification* or *assessment*. Paper I and Paper II deal with localisation and recognition, while the classification aspect is applied to quality assessment of the proposed solutions. Paper III and Paper IV included both identification and assessment approaches, however, Paper III focused more on the identification aspect. In turn, Paper IV mainly concerned the assessment of proposed Design Methodology (DM), along with an evaluation of applied methods and algorithms, but also classification of monitored person's behaviour, while the identification was just a means to obtaining data for the assessments and classifications. And finally, Paper V and Paper VI focused especially on the assessment aspects, nevertheless identification of suitable features was applied too.

The systematization of IoT system design became another objective of the thesis. The systematized design process is understood as using '*scientific principles, technical information and imagination in the definition of a structure, machine or system to perform pre-specified functions with the maximum economy and efficiency*' [18]. The engineering system design is to be performed in a systematic manner based on User Oriented Design (UOD) [19] principles and includes three engineering approach steps: *modelling*, *implementation* and *validation*. The aim of the proposed design method was to enhance the development of IoT applications.

1.3 Thesis outline

The whole thesis is divided into two parts. The first part, *Prolegomena*, shows the technical background, an overview of applied theories along with research and design methods related to detection systems localizing and monitoring people and things. The acquired data are used to classify the observation based on a behavioral or qualitative approach. Moreover, this part shows relations between the papers constituting the second part titled *Papers*. The second part consists of the six reformatted papers published in peer reviewed journals. All the papers concern design of IoT systems for identification and classification of people's habits and skills as well as assessing quality of things or performances. The systems were designed using a proposed design methodology. The concept of systematic design of IoT based systems for detection and classification is applied in all included papers, however, with different sensitivity and aims.

The overview of the included papers' contribution to the thesis is presented in Table 1.1 and illustrated in Figure 1.2. The thesis covers six key issues grouped into three approaches: *Methodological*, *Applicational* and *Functional*. *Design Methodology* and the *IoT* concept are parts of *Methodological Approaches*, while *Industrial* and *Behavioral* issues are accounted into *Applicational Approaches*. Finally, *Detection* and *Classification* subjects are included in *Functional Approaches*. Table 1.1 shows contribution of each of six papers to the whole thesis. The table consists of the estimated contribution of each itemized approach to the thesis. In Figure 1.2 each itemized approach is indicated by a different color and its length indicates its contribution to the paper. Moreover, each paper contribution to the thesis is depicted by the size of the dedicated wheel slice.

Table 1.1: The thesis key impact features of all included papers related to General and Itemized approaches, together with its contribution in the thesis.

Approach: General	Approach: Itemized	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI	Approach contribution
Methodological	Design Methodology	0.9%	1.9%	2.5%	5.6%	3.6%	1.8%	**16.3%**
	IoT Paradigm	0.3%	0.5%	7.4%	2.4%	1.6%	3.7%	**15.9%**
Applicational	Industrial	0.9%	1.9%	0.9%	1.5%	1.3%	1.1%	**7.6%**
	Behavioral	0.0%	0.0%	1.6%	4.1%	2.3%	0.7%	**8.7%**
Functional	Detection	3.2%	5.9%	2.2%	8.3%	2.9%	4.8%	**27.3%**
	Classification	0.0%	0.0%	2.0%	6.3%	5.8%	10.1%	**24.2%**
Paper contribution		**5.3%**	**10.2%**	**16.6%**	**28.2%**	**17.5%**	**22.2%**	**100%**

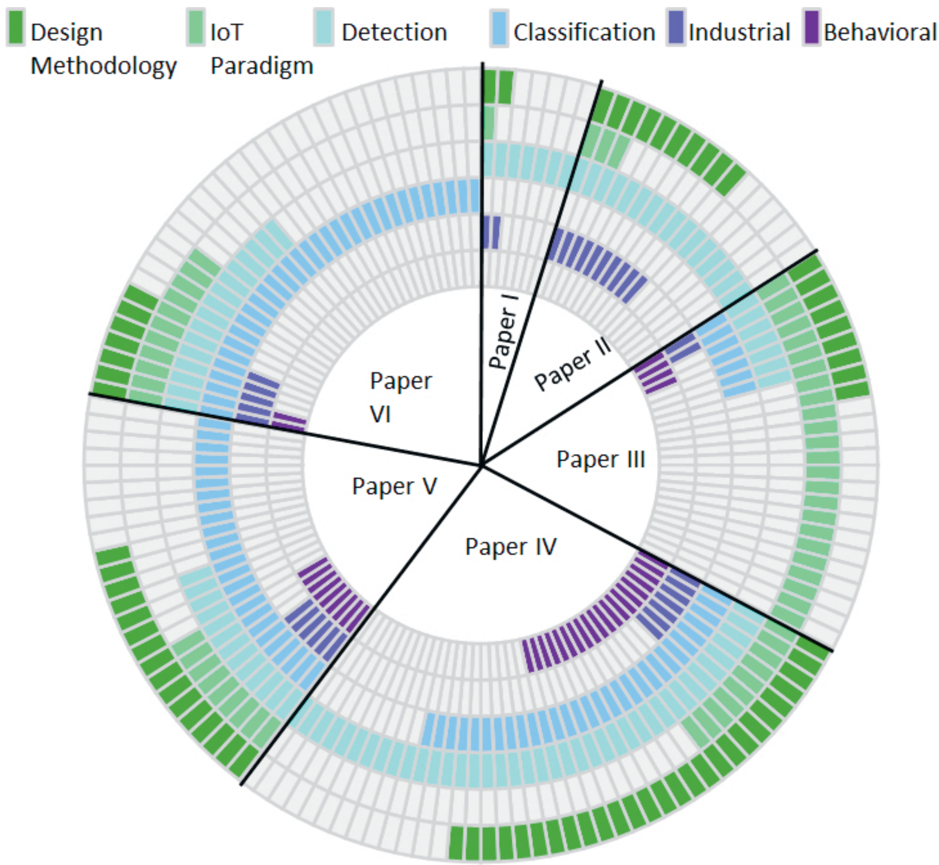


Figure 1.2: Table 1.1 related illustration of each paper's estimated contributions to the thesis. Each color corresponds to one of six specified thesis approaches while its length represents its significance in the paper.

Paper I deals with an industrial application when a lack of systematic design methodology was firstly noticed. This research introduces the Automatic Waterjet Positioning Vision System (AWPVS) for identification of the position of a workpiece placed on a waterjet machine table. Moreover, this work assesses the impact of a vision system calibration method on positioning accuracy. The proposed solution is based on two shelf cameras mounted on a machine requiring two-step calibration procedure, which uses a set of calibration markers in color contrasting to the background. The validation results show that the proposed method, despite demanding environmental conditions, ensures high accuracy positioning of the waterjet machine.

Paper II is a continuation of Industrial approach and study on AWPVS, where components of the workpiece positioning accuracy are assessed. Various image processing techniques are comprised to assure a required identification precision. To prove high identification quality, both synthetic and real images were examined under various conditions. The analysis indicates two main additive uncertainty components of AWPVS: a machine component, related to the precision of positioning the waterjet nozzle over the given coordinates, and a vision system component, related to corner identification accuracy. The evaluation of the vision system component is based on different sizes of image cropping frames and results show that for low and medium Gaussian or Salt and Pepper image noise level it is better to use cropping frame size 1000 pixel (px). In case of images distorted with high noise level, the cropping frame of 1500 px is used.

Paper III is a first attempt to systematize design of an IoT system dedicated for healthcare applications. The research proposes to analyze needs of the stakeholders, which later are used to define system functionalities and constraints. A presented case study concerns design of a Wireless Sensor Network (WSN) in the IoT concept from system lifetime perspective. Apart from proposing a system meeting the demands presented by stakeholders, a modified algorithm of a root node selection and an energy efficiency hierarchical routing technique are introduced and assessed in comparative studies.

Paper IV is a further extension on systematization of DM. It approaches the design target from a perspective of the stakeholders, contracting authorities, and potential users. It also concerns the IoT paradigm in a healthcare application. The proposed design methodology is used for developing a system dedicated to monitoring elderly people in their apartments along with a multi-story building, but even outside in the building's surroundings. The system's crucial functionalities consist of monitoring vital signs and posture recognition. The acquired data are used to detect and classify behaviors as *normal*, *suspicious* or *dangerous*. A solution is based on a 3-axial accelerometer and magnetometer, Pedestrian Dead Reckoning (PDR), thresholding and decision trees algorithm. The concept was validated with real life scenarios.

Paper V considers objective assessment of firefighter's skills during training. The features such as in-building behavior and tasks execution are analyzed based on data gathered with a wireless ultra-wideband Real Time Locating Systems (RTLS) and dedicated Inertial Measurement Unit (IMU). The assessment is based on the predefined required training tasks, comparison with expert's expertise and results of the firefighter trainee's test. As a visualization and data processing unit the Unity game engine is used. Moreover, the spider diagram is applied as a comprehensive final map of the trainee's skills and the single score method proposed as the conclusive statement. The proposed solution was verified experimentally in a real environment.

Finally Paper VI addresses the problem of the objective assessment of driving style. The proposed solution is based on eight indicators, which are associated with the vehicle's speed, acceleration, jerk, engine rotational speed and driving time. These measures are grouped into three driving style criteria: safety, economy, and comfort. The proposed solution is based on the systematically designed embedded IoT system. The data are acquired with the car diagnostic port—OBD-II—and from an accelerometer sensor and Global Positioning System (GPS) module. The proposed driving skills assessment method has been implemented and experimentally validated on a group of drivers. The obtained results proved the system's ability to quantitatively distinguish different driving styles and clearly confirmed the validity of proposed systematic design methodology.

Paper V and Paper VI confirmed that the DM proposed in Paper IV is valid. Moreover, these articles show that the proposed DM is applicable not only for Industrial and Healthcare approaches but also for more complex problems such as people's behavior and objective assessment of skills.

The main contributions of this dissertation cover two main application areas:

- Detection and classification for performance quality assurance, Paper I, Paper II and Paper III;
- Features detection and classification of people's behavior, skills or abilities Paper IV, Paper V and Paper VI.

The application environments where the research was conducted:

- Indoor environment: Paper I and Paper II dealt with harsh environment in limited space of a waterjet machine workspace; and Paper V dealt with in-building training facilities.
- Outdoor environment: Paper VI dealt with driving short rides in the city and a long route through the country.
- Both indoor and outdoor environments: Paper III dealt with monitoring in nursing home care both in-building and in the garden next to the building environments; and Paper IV dealt with monitoring in-apartment, in-building and even outdoors in the building's surroundings.

The technologies used for detection and classification:

- Vision systems were covered in Paper I and Paper II;
- Inertial Navigation Systems: where Paper III and Paper V used the accelerometer and gyroscope; Paper IV applied RTLS, accelerometer and gyroscope; Paper VI used GPS with accelerometer and gyroscope.

All proposed technologies and methods were validated by simulation tests and verified by physical experiments carried out within corresponding environments.

Chapter 1 of Part I, *Prolegomena* focuses on an overview of the thesis, explicitly its background, objectives, scope and content. Chapter 2 describes the research methodology applied for development of engineering systems, where the target was detection and identification of people or things and classifying or assessing their behaviour, performances or qualities. Chapter 3 presents the proposed Design Methodology and introduces extension of the IoT concept to multi-sensor systems. Chapter 4 presents applicational approaches of the thesis and their contributions to the research presented in each article. Chapter 5 concerns detection and assessment approaches in all of the included papers. The following Chapter 6 summarizes all included papers, concludes the thesis and presents future plans of the research.

2

Research Methodology

The classical Engineering Research Methodology applied in this thesis consists of three steps: *problem identification*, *problem solving* and *solution verification*, which can be found in each of the enclosed papers. A short summary of these steps, their exemplifications and possible methodological insufficiency in each paper are presented in this section.

2.1 Problem identification

A research begins with a question, which frames the previously unknown problem, as philosophy of science states. Also in each of the enclosed papers research questions were formulated.

In Paper I the problem concerned a calibration method of a vision system, used for positioning of the waterjet machine. In Paper II the problem was narrowed to precision improvement of workpiece corner localization and susceptibility of the previously designed algorithm to image noise. Moreover, positioning uncertainty components of the developed vision system was of research interest. Nevertheless, in both papers the problem formulation required several iterations and was time consuming, mostly due to varying views of the problems from perspectives of different contributors of the projects. The modification of a common approach to research problem identification concerned surveys with stakeholders and future users. As a result, the system price restriction, which was crucial for the stakeholders, was identified as a limitation of the possible solutions. Moreover, it turned out that difference between the users and stakeholders desirable system precision had to be compromised in formulation of the problem.

The problem identified in Paper III focuses on systematisation of the design process. A multi-sensor system for patient monitoring, based on WSN in the IoT paradigm, was a case study applied to validate the proposed DM. The issue of the design process was how to integrate various aspects of the design from the perspective of many contributors to the project, such as stakeholders, monitored persons and their relatives and even health service staff. Among many aspects, energy efficiency of information management was considered. The problem identification included analysis of the needs of the stakeholders and future users. Its impact can be noticed in the problem definition. In this paper, a case study was implemented to evaluate the methodology. Meanwhile the evaluation method became the research problem too, since it required a real implementation in the new field.

In Paper IV the problem was related to monitoring of elderly persons living alone with mobility difficulties or symptoms of dementia who still would prefer to live in their homes and surroundings. Paper IV searched for a methodological approach to the design process of such a system. As in most engineering researches, the problem formulation had to take into account a perspective of the stakeholders, contracting authorities, and potential users. Iterative problem formulation led to research questions, which included some requirements and constraints that framed a possible solution.

The research problem of Paper V was an objective assessment of firefighter training. The objective assessment of human skills is a complex issue and required a pre-study to find out which features of training should be considered. The results of the pre-study were needed to frame a solution to the problem. Moreover, after the pre-study a question was aroused how to present multidimensional data in a clear and user friendly manner.

The last of included papers, Paper VI, considers an IoT On-Board System for Driving Style Assessment. There is a similar approach as in Paper V of objective assessment of human skills required to answer the question, which driving quality criteria should be included in the assessment? The problem was how to estimate chosen criteria based on measurable data accessible in a large variety of cars. Moreover, the result presentation was important to show, in a comprehensive and educative way, all skills of the evaluated person compared to the test group or experts.

2.2 Problem solving and modeling

Finding solutions for engineering problems starts with hypothetical answers to the research question. Formulation of the hypothesis can vary between research fields, but in engineering science a model of the system can be a suitable answer. The model can be described mathematically or with a block diagram or flowchart.

In Paper I, the question about a calibration method was answered that "a two-stage calibration procedure of the positioning vision system based on detection of calibration markers in color contrasting with the waterjet machine workspace will ensure the required accuracy of the corner of the workpiece localization". The basic principle of the proposed calibration method was based on color segmentation of the image and thresholding methods.

In Paper II, corner identification accuracy was questioned, and the two main inquiries were stated. The first one concerned the optimal cropping frame and the second one referred to the relationship among the main uncertainty components of the automatic waterjet positioning vision system. It was hypothesized that the optimized size of a cropping frame led to better positioning vision system accuracy. Moreover, it was assumed that two main additive uncertainty components of AWPVS could be distinguished: a machine and a vision system.

Paper III asked about the monitoring system's functionalities and structure, which would increase safety of elderly or disabled people living alone. The proposed solution was based on the Wireless Body Area Network (WBAN) concept, where key components of the system were installed on a chest belt founded by the monitored person. Moreover, energy efficiency was in focus and solved by applying the modified algorithm of a root node selection and energy efficient cluster formation method.

In Paper IV a lack of a methodological approach to the design process of an IoT healthcare-monitoring system was interrogated. Furthermore, methods for recognition and classification of human behavior needed to be tailored to the specific application. As a solution, a systematic design procedure was modeled. The design methodology integrated perspectives of the stakeholders, the authority in charge and the potential users, as well as the view of the system developers. Moreover, the adapted recognition and classification methods were proposed for assessing current behaviour of the monitored person. Three classification categories and corresponding reactions were applied. For a *normal* class nothing should be done, for *suspicious* and *danger* classes the helping actions were defined.

Paper V points out a subjectivity problem of the assessment methods used for firefighter training. The solution to the problem was to measure five different training features by means of a wireless multi-sensor system using RTLS and IMU. In addition to this, the required method of data visualization and single grade assessment were introduced and modeled.

Paper VI deals with a problem of objective driving style assessment based on data acquired from a measurement system monitoring the car's dynamic driving parameters. The assumption stated was that driving style can be assessed based on the three driving quality criteria, which are determined based on eight indicators accessible in varied categories of cars. Moreover, similar to Paper V, data visualization and single grade assessment methods were introduced.

2.3 Solution implementation and verification

The final steps of engineering science are system implementation and validation and even, if possible, physical verification. Only validated hypotheses have meaning. The models of stated hypotheses and their implementations can be validated using simulations and emulations, but a real verification could be done on physical experiments. Often validation and verification methods have to be tailored to the solution or to a field of application. Therefore, these final steps of research also need new methods and have contributions to science.

In Paper I, the verification procedure was two-fold, using two approaches of the Global Camera (GC) and Local Camera (LC). The estimated coordinates of the workpiece corner were referred to the known coordinates. Already after the first measuring series, the localization accuracy met the assumed requirements. But, by adjusting the position of the calibration marker, localization uncertainty was so small that it could be neglected.

The verification of the solution proposed in Paper II was performed in three stages. Firstly, a set of synthetic images was applied to estimate an influence of the cropping frame size on the workpiece corner localization uncertainty. In the second stage, also using synthetic images, the algorithm robustness to different kinds and intensities of image noise was checked. In the last stage, the measurement from physical experiments verified precision of the workpiece corner localization method. These results along with previously estimated accuracy of the positioning vision system resulted in estimation of the waterjet machine accuracy components.

Verification of solutions proposed in Paper III was based on comparison of achieved results with the results of reference methods previously used for this purpose. Both of the designed methods outperformed exited solutions.

In Paper IV, the proposed solutions were verified with physical experiments. The test results proved that the accuracy of the proposed localization method is sufficient for room-level localization. The activity recognition method was tested while performing over 1300 different emulated activities. The results obtained matched the previously reported ones.

The verification of solution proposed in Paper V was based on experiments in a simulated environment. The tests should objectively assess basic skills of the firefighter trainee. The results of the full training performed by an expert were applied as reference. Results of the trainees proved validity of the proposed method, while showing which skills needed to be improved.

Two test routes in real environments verified the solution presented in Paper VI. The short route of 16 km in a city environment was performed by five different drivers and by an expert. The obtained results showed that based on chosen criterion's and indicators different driving styles were distinguishable. The long route of 325 km included typical types of roads like city roads, freeways and highways. The results confirmed usefulness of the proposed solution.

3

Methodological Approaches

Engineering is a synonym of technology, the word, which comes from two Greek words, transliterated *techne* - $\tau\epsilon\chi\upsilon\eta$ and *logos* - $\lambda o\gamma o\varsigma$. Where *techne* means *art*, and *logos* means *word by which inward thought is expressed*. Therefore, engineering can be defined as *the art* of applying *scientific principles*, *mathematical rules*, *experience*, *judgment*, and *common sense* to make **things that benefit people**. We, engineers create things to meet a specific human need, which distinguish us from nature scientists who try to understand how nature works. Therefore, an Engineering Design Methodology should be tailored for engineering science. The proposed systematization of developing IoT systems dedicated for identification and assessment is described in this section. Implementation of the IoT aspect into system development is also discussed.

3.1 Engineering System Design Methodology

This thesis applies a systematic design methodology understood as using "scientific principles, technical information and imagination in the definition of a structure, machine or system to perform pre-specified functions with the maximum economy and efficiency" [20]. The system design is based on general UOD principles, however, with modifications as shown in Figure 3.1. The developed DM, evolves in each of the papers included in the thesis. The essence of this process is described in the following section.

Needs identification and product conceptualisation are starting points of the design process when stakeholders introduce to the designers the general problem. It is important that the problem is defined together with the future users in order to include their desires. In this design stage, the project participants focus on general goals of the system, so that the designers can

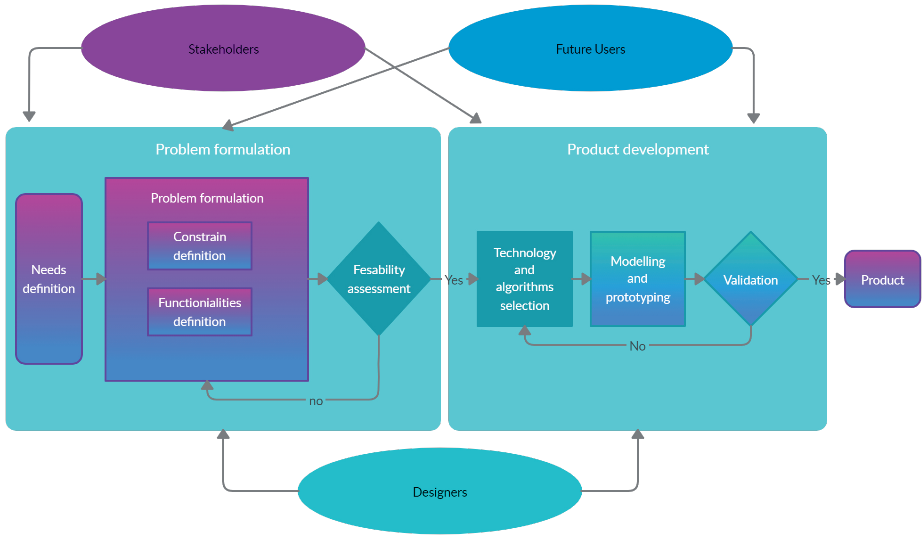


Figure 3.1: Design Methodology proposed in Paper IV

assess whether the problem is solvable with accessible resources.

The general needs in Paper I and Paper II concern functionality improvement of a waterjet machine. An automated identification of a workpiece position in a workspace of the waterjet machine was part of required improvement. A particular enhancement issue in Paper I is an automated calibration procedure on waterjet machine positioning and its impact on accuracy over the workpiece. The particular problem referred in Paper II concerns localization accuracy and its improvement.

In Paper III and Paper IV, the stakeholders and future users, who would be elderly people and their families, defined the need to increase their safety by means of modern technology. It concerns various aspects of the well-being of people living alone with limited ability to manage their life. The support should be yielded by means of an autonomous system monitoring the person's position, his vital signs, recognize different activities and classify his behavior.

Both Paper V and Paper VI considered the problem of an objective assessment of professional skills, competences and abilities. According to the stakeholders and future users reported in Paper V, the final score of the trainee's performance should be based on at least five features. While Paper VI concerned monitoring and assessing of motorists' driving style, to define driving skills and behind-wheel behavior. In both cases, assessment should be done and presented as comprehensively as possible.

Defining system functionalities and constraints and their feasibility assessment is the essential step of the proposed DM. At this design stage, the stakeholders and future users formulate the desired system's general and itemized functionalities. Furthermore, the constraints like costs, expected size, required lifetime and working environment are introduced as well. These functionalities and constraints constitute the design frame for the developer.

After reviewing the needs and requirements of the system, the designers have to assess the feasibility of the project. They have to consider whether the existing technologies or methods are able to solve the stated problems and state if the needs and requirements are realizable. If the designers encounter a difficulty in accomplishing the requirements, the stakeholders and future users would be asked to modify them. Otherwise, the designer has to consider development of new or modification of existing technologies or algorithms, in a way that requirements could be accomplished.

According to the stakeholders' desire in Paper I and Paper II, the designed calibration method should ensure the accuracy of the workpiece corner localization with tolerance of ± 0.5 mm. However, the accuracy desired by future users was higher around ± 0.1 mm. Moreover, required angular deflection uncertainty should not exceed 1°. The main constraints included the large workspace where the workpiece could be randomly placed, harsh environment with high humidity and limited spaces where the sensors could be installed. Due to working characteristics of the waterjet machine it was also expected that the designed system would be resistant for noise of salt and pepper type. Additional constraints concerned a price that should be as low as possible and used component accessibility, preferably off the shelf solutions.

The desired functionalities of the system presented in Paper III included localization, movement tracking and activity recognition of the patients in the home care facility. Moreover, wireless data transferring was desired, which would in no way restrict the ability of device mobility. Moreover, the device should be easily assembled and comfortable to wear. It was also required that the system should apply energy saving techniques to extend the operational time as long as possible. Another important constraint was preservation of patient privacy and integrity, understood as personal privacy as well as collected data security.

In Paper IV the functionalities desired by the stakeholders and future users, consisted of the localization of the monitored persons in their flats with up to four room-zone level accuracy, but also within a multi-story building, where the apartment was located, with a floor level accuracy. Furthermore, the person's positioning in the building's outdoor neighborhood with an accuracy of at least 10 m was desired. Moreover, the system should be able to monitor the target's vital signs and detect the person's fall. To recognize the required behavioral changes, in addition to the localization and fall detection, there was a need to distinguish the person's postures, like sitting, standing, walking or lying. It was even requested that the system should classify a current behavior into three categories: *normal*, *suspicious* or *dangerous*. In a case of unusual occurrences the people responsible for care should be notified. As general constraints the reliability, size, comfort of device-wearing, the subject's privacy assurance, and even a maximum price of 200 EUR was indicated. The itemized constraint concerned operational time of at least one week, high localization accuracy in the considered environments along with the high reliability of activities and fall recognition. Furthermore, real-time secure non-invasive measurements were crucial, in particular the constraints of vital signs' monitoring.

The desired functionalities of the system presented in Paper V included an objective assessment of firefighter skills. Furthermore, an educative and comprehensive visualization of results was required. The general requirements concerned a number of examined checkpoints, the examined area coverage, and a number of examined objects. The complementary requirements assumed that the system should be wearable and operate even under conditions of limited visibility.

The defined functionalities of the system presented in Paper VI included an objective assessment of driver's skills and his behavioral characteristics. The most relevant requirements of the system were its safety, economy and comfort. One of the constraints was its compatibility with as many types of cars as possible. It was also expected that the system would be easily implementable. Moreover, the assessment method should be comprehensive and straightforward.

In all of the included papers, the needs, functionalities and constraints presented by both stakeholders and future users were assessed as technically accomplishable and feasible. However, every solution had to be designed from the basis of and supplemented with new algorithms in cases where results were not satisfactory.

Technologies reviews, their applicability assessment and final selection is a stage when the designers propose technologies and algorithms, which are in line with the desired functionalities and constraints. However, if there are no suitable solutions accomplishing the requirements, or the solutions lack some of the functionalities or constraints, then the designers should propose and develop new solutions or adapt the existing ones.

In Paper I, to calibrate the GC, the basic image processing algorithm was needed and started with searching for objects of pre-defined color. A set of needed algorithms included the thresholding method to filter out noise and a Canny edge detection filter to extract the calibration markers' shape. To obtain a top view of images taken from an angle the metric rectification method [21] was selected. The Hough transformation [22] was chosen, which rectified images and detected approximate straight lines of the workpiece. Finally, to identify the intersection of the approximated lines, the decision algorithm defining the calibration marker corners was selected. The image processing algorithms used for the LC calibration were similar to GC except that the rectification method was not necessary because LC was mounted parallel to the waterjet machine workspace.

The image processing techniques used in Paper II also required a background removal method. Furthermore, the filtering part needed to be extended. To extract workpiece shape from the machine workspace, edge filtering was required. Corners of the workpiece had to be identified based on intersections of lines, and the Hough transform was found suitable for this task.

In Paper III from a set of applicable wireless technologies like Wi-Fi, ZigBee [23], Bluetooth Low Energy, BLE, [24] or RFID [25], Wi-Fi was chosen as matching best stated needs due to the range of the technology and easy access to infrastructure. Due to energy limitations along with restraints of processing and storage capabilities of designed WSN as a routing method, the algorithm of a root node selection was modified and implemented. For the same reason, the energy efficient cluster formation was selected. For localization the PDR method based on gyroscope and accelerometer measures was proposed. For vital signs monitoring, use of the heart rate monitor was suggested. Due to privacy constraints the information about heart rate was suggested to be sent only when abnormal situations occur.

In Paper IV, for indoor localization in an apartment at four room-zone level resolution, the PDR algorithm, based on three-axial accelerometer and magnetometer data, was chosen. The BarFi algorithm [26], which applies the Wi-Fi signal and fingerprints of atmospheric pressure measurements, was selected for indoor localization in a multi-story building with a floor level accuracy. The GPS and the PDR-based hybrid method introduced by Ch. Wu *et al.* [27] were chosen for the outdoor localization with an accuracy of at least 10 m. To detect a subject's fall, the three-axial accelerometer along with the thresholding method were applied. The same set of technologies was used for identification of the subject's different postures and activities. Due to lack of a suitable behavior classification method, one needed to be developed based on the decision trees algorithm. The water-resistant wireless Polar T34 heart rate monitor, mountable on the person's chest with an adjustable elastic strap to ensure comfort, fulfilled the requirements of noninvasive heart rate monitoring.

For the objective fireman training assessment, Paper V, the Ubisense RTLS, using Ultra Wide Band technology (UWB) technology outmatched other possible technologies. The localisation method was based on Angle of Arrival (AoA), Received Signal Strength (RSS) and Time Difference of Arrival (TDoA). A direction measurement system based on Adafruit's BNO055 absolute orientation sensor and pro trinket board, needed to be developed for checking which areas and objects in the training field were examined by the trainee. For data processing of the trainee's performance, the application built in the Unity3D game engine was chosen for use [28]. The spider diagram was selected for visualization of the results due to its user friendly and objective manner. This comprehensive visualisation method allowed the user to graphically analyse training aspects on a single diagram. With this method even comparative analysis with reference to the expert's or the average results of all trainees would be possible.

Vehicle location in Paper VI was to be done by the most common GPS technology. The easy accessible data of car speed and engine rotational speed could be obtained from car diagnostic port OBD-II. However, the deceleration and acceleration should be measured using the acquisition system developed for this purpose, including an accelerometer mounted on the car dashboard. The information about current speed limits could be obtained from a dedicated API with OpenStreetMap. All control functions could be performed by means of commonly used Raspberry Pi 3B+. Moreover, to objectively assess and visualize a multidimensional problem of driving style assessment, the spider diagram approach was chosen.

Solution modelling, prototyping and evaluation are iterative ways which the designers utilize during the product development phase. These tasks are time consuming and may involve experts of different fields. Furthermore, in user-oriented design, the models and prototypes have to be endorsed by both designers and future users. During this iterative process the designers evaluate the solution's performance, and the future users check if the functionalities and constraints defined by them are accomplished. The process continues until both contributors are satisfied. Then, the final outcome has to be validated.

The proposed solution of AWPVS presented in Paper I consists of two cameras: GC and LC and therefore the calibration procedure should be twofold. The calibration of GC was based on four reference markers of colors that could be easily extracted from the image background. The applied color segmentation was modeled mathematically. The flowchart of implemented image processing consists of image binarization, noise filtering and contour detection along with Hough transformation, where the lines are approximated and their intersections determine the corners of the workpiece. The transformation matrix of the camera coordinate system into the waterjet machine coordinate system is determined from the approximate workspace and rectification process.

Due to the required accuracy of workpiece localization, the LC was mounted next to the cutting nozzle of the waterjet machine. The LC calibration procedure utilizes one of the calibration markers of GC calibration. Based on LC calibration, the calibration vector is determined, by which the waterjet machine nozzle is moved so that it would be centered exactly above the designated corner. The calibration procedure was modelled using a flowchart, as it is shown in Figure 3.2.

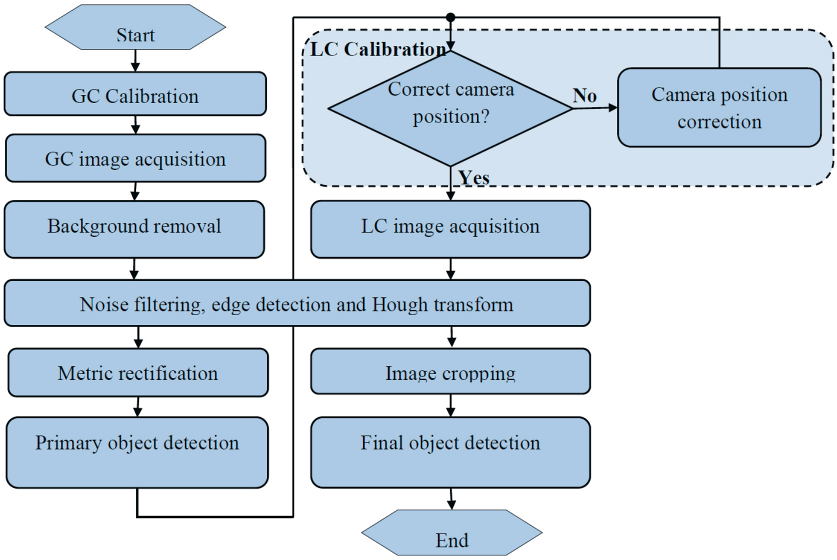


Figure 3.2: PVS algorithm block diagram

In Paper II, for an examination of the Positioning Vision System (PVS) accuracy, a set of synthetic images resembling the real operating conditions of the WJ were generated. The synthetic images imitate a part of the workpiece with one visible corner, and their resolution of 2592 px × 1944 px matches the resolution of images captured by the LC.

The implemented case study presented in Paper III consists of two parts. One is WBAN dedicated for nursing home care patient monitoring, and another one is related to improvement of energy efficiency of WSN. The prototyped monitoring system shown in Figure 3.3 consisted of an Arduino board, equipped with modules such as AltIMU-10 V4, GPS/GPRS/GSM V3.0, Polar T34 Heart Rate monitor and WiDo Wi-Fi IoT Node.

The energy efficiency problem of WSN was solved by implementing a modified algorithm of root node selection. The further extension of WSN energy problem was solved by using K-mean algorithm as a tool for defining the optimal distance between network nodes and the cluster head [29].

In Paper IV, for indoor localization, the PDR was developed and implemented. The 2D coordinates were estimated based on data about the previous position, number of steps, and their length and direction, which

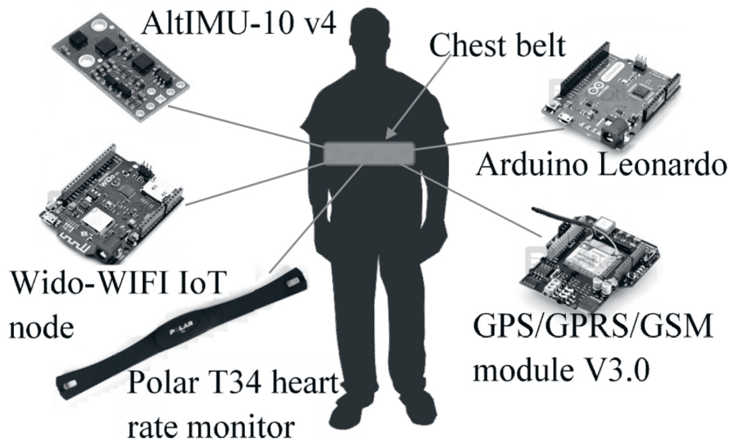


Figure 3.3: Components of the proposed WBAN system for patient monitoring in nursing home care.

were collected from a magnetometer and gyroscope. The person's position was estimated from:

$$\begin{bmatrix} \widehat{x}_k \\ \widehat{y}_k \end{bmatrix} = \begin{bmatrix} \widehat{x}_{k-1} \\ \widehat{y}_{k-1} \end{bmatrix} + M \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \tag{3.1}$$

where $\widehat{x}_k$ and $\widehat{y}_k$ are the coordinates of the estimated position, $\widehat{x}_{k-1}$ and $\widehat{y}_{k-1}$ are the coordinates of the previously estimated position, θ is the heading direction and M is the factor dependent on an individually defined step length.

The system developed for classification of five different activities: *lying*, *sitting*, *standing walking* and *falling* is presented in Paper IV. The activities were recognised based on data from the magnetometer and gyroscope. The purpose of the activities' identification was behaviour classification. The applied algorithms classified monitored behaviour into three classes: *normal*, *suspicious* and *dangerous*. The *normal* behaviour class was established based on longest time frame of the analysed monitored person's behaviour. The *suspicious* behaviours were defined when some activities took up to 150% of previously estimated *normal* behaviour time. All activities longer than 150% of *normal* timeframe were considered as *dangerous*. Moreover, some activities in an unusual place or time were also considered as *suspicious* or *dangerous* independently of their timeframe.

The system prototype presented in Paper V is used to support an assessment of firefighters' training. The system consists of two devices, one for the person's precise localization, and the other for monitoring head direction to follow the trainee's gaze. At the hardware layer, these two systems work independently. At the software layer, information from the systems were synchronized. The training evaluation consists of two phases: *online* and *offline*. At the online phase both systems were calibrated independently, and then they independently gathered and saved data, which could be synchronised based on timestamp labels that were established when the training started. After transferring the training data to the Unity application they were synchronised and analysed. To reduce trainee's path measurement noise the Chaikin algorithm was implemented [30].

For visualization of the training assessment, the spider diagram was proposed, see Figure 3.4, where assessed features were presented. The darker parts represent the trainee score and the lighter shows expert results or average results of all trainees. The proposed visualization method was used to calculate a single score T_s from the whole training, similar to [30]:

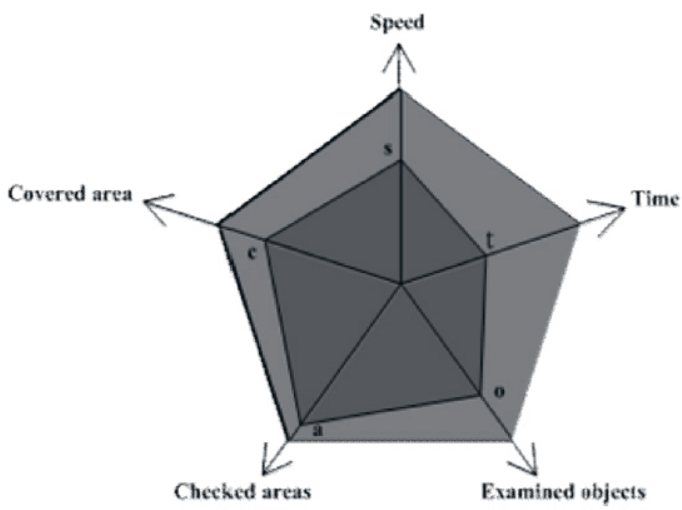


Figure 3.4: Spider diagram of trainee's performance.

$$T_s = \frac{1}{2} \times \sin 72^\circ * (st + to + oa + ac + cs) \quad (3.2)$$

where s, t, o, a and c represent scores of each key feature. This approach also allows the user to assess trainee results in comparison with the expert as:

$$F_s = \frac{T_s}{E_s} \times 100\% \tag{3.3}$$

where F_s is final score of a training and T_s and E_s are trainee's and expert's scores respectively.

Paper VI presents a system for an objective driving style assessment. It applied three driving criteria: *safety*, *economy* and *comfort*. Each criterion is quantified using various normalised indicators. Some of them are referred to as established regulation standards, and others to expert's ride and behavior measures. Eight different indicators were used: *de- and accelerating ratio*, jr_x; *bumping ratio*, jr_z; *cornering ratio*, jr_y; *driving time without rest ratio*, dtr; *car speeding ratio*, spr; *car speeding duration ratio*, $spdr$; *excessive engine rotational speed ratio*; rsr, and *excessive engine rotational speed duration ratio*, $rsdr$. Each of the indicators is related to specific information about driving aspects and they are used to assess each of the three driving criterion. The most crucial *safety* criterion, SAFC, is based on six of nine indicators: jr_x, jr_z, jr_y, dtr, spr and $spdr$. The *economy* criterion, ECOC, of driving style is assessed using jr_x, jr_y, rsr and $rsdr$. The final criterion, *comfort*, is measured using jr_x, jr_y, jr_z and dtr.

The visualisation and objective assessment, similarly as in Paper V, are based on the spider diagram. After analyzing the surface area of the resulting polygons, it was possible to depict the driver's style assessment. The *safety criterion* score, DSC_s can be calculated as a sum of six triangles from the formula:

$$\begin{aligned} DSC_s = \frac{1}{2} \times \sin 60^\circ \times (&jr_x \times jr_z + jr_z \times jr_y + jr_y \times dtr \\ &+dtr \times spr + spr \times spdr + spdr \times jr_x) \end{aligned} \tag{3.4}$$

The driver's DSC_s related to an expert safety criterion score, ESC_s forms the *normalized safety criterion* score, NSC_s.

By analogy, assessment methods for driver's *normalized economy criterion* and *normalized comfort criterion* scores, NEC_s, NCC_s were applied.

The proposed overall assessment score composed of all eight indicators, and the driver overall normalized final score NO_s is calculated as:

$$NO_s = \frac{DO_s}{EO_s} = (jr_x \times jr_z + jr_z \times jr_y + jr_y \times dtr + dtr \times spr \\ +spr \times spdr + spdr \times rsr + rsr \times rsdr + srdr \times jr_x)/8 \quad (3.5)$$

Verification and solution acceptance is the last stage when both stakeholders along with the designers have to verify whether the system's needs and requirements have been accomplished. In case of any discrepancy between the desired needs and requirements and these performed by the system prototype, the designers have to examine the proposed technologies and algorithms and come back to the initial stage of product development. Nevertheless, if both stakeholders and designers approve the results, the system is ready to be implemented and launched into service.

In Paper I by means of four calibration markers, it was possible to calibrate the GC with an accuracy of ±15 mm, which was four times better than the preliminary requirements. Moreover, the LC calibration resulted with accuracy around ±0.1 mm, which was five times better than required by the stakeholders.

From the results shown in Paper II, one could notice that the real accuracy of AWPVS was better than an algebraic sum of its components. Thus it could be concluded that the assumed worst case accuracy of the machine, 0.1 mm was too pessimistic and its real value is about 0.035 mm. Moreover, from the analysis of optimized cropping frame sizes it could be seen that a precision of corner localization with AWPVS is at the level of 0.063 mm with standard deviation of 0.015 mm. Such results pleased stakeholders, and the proposed solution was accepted.

The prototype of the designed system presented in Paper III was assessed as a suitable solution supporting patients in nursing home care. Moreover, the simulations results proved that modification of the LEACH routing protocol causes death of the first node later than in basic method and therefore the system lifetime was extended by 50%. What more, a residual energy after 300 rounds for second-order hierarchical structure surpasses the one with non-hierarchical structure, confirming longer operation time and superiority of hierarchical structure. Furthermore, K-mean cluster formation method resulted in death of the first node six times later and prolonged almost twice the system lifetime compared to the geographical method. The results fulfilled the requirements of energy management.

In Paper IV, the test outcome proved the proposed solution usefulness in monitoring of elder person. The high robustness of 98% step detection with proposed PDR fulfilled stakeholders' expectations. Moreover, the designed localization method met the room-zone accuracy requirement. The detection of falling using IMU and thresholding algorithms also showed sufficient reliability. The defined six-element behavior vector helped to classify activities as *normal*, *suspicious* or *dangerous*. All of these results proved that the system worked according to the required functionalities and constraints.

The study presented in Paper V proved that the wireless multi-sensor system, based on RTLS and IMU devices, yielded information about trainees' movement in the test-field in real-time and objectively assessed the trainees' skills. Furthermore, results visualisation provided a comprehensive map of their skill profile. The Unity game engine software along with the spider diagram have been appreciated as trainee results visualization. Moreover, the proposed single number score of a training, allowed for easy comparison of a larger group of trainees.

A system for assessing driving style skills of a person developed in Paper VI met the expectations of stakeholders. Usage of diagnostic port OBD-II made the system compatible with a wide number of cars, even those elder ones. The evaluation experiments conducted by five drivers on short and two drivers on long routes proved that the system facilitated differentiation and assessment of the person's driving style in terms of *safety*, *economy*, and *comfort* criteria.

3.2 IoT aspects of the systems

The IoT concept integrating different physical and virtual devices, such as distributed sensor nodes, actuators, mobiles and other devices called things is an additional link of all the papers presented in this thesis.

In Paper I and Paper II, the IoT approach was rather potential since, due to security reasons, there was not such a constraint from the stakeholders. Nevertheless, the designed system consisted of industrial *things*, and integrating the waterjet machine and its parts with sensors in the form of webcams and a closed internal network could be easily integrated with web or mobile app.

In Paper III, the IoT concept is extensively used and includes WSN, which constitutes a significant part of IoT paradigm, see Figure 3.5. The proposed WSN approach integrates WSN with users via Internet and base stations. The network nodes assemble and process information from the environment and then send it directly or indirectly to the base station and then to the Internet. The energy efficiency is an important issue of IoT concept, and the approach shown in Paper III proposed efficient Root Node Selection and Cluster Formation methods.

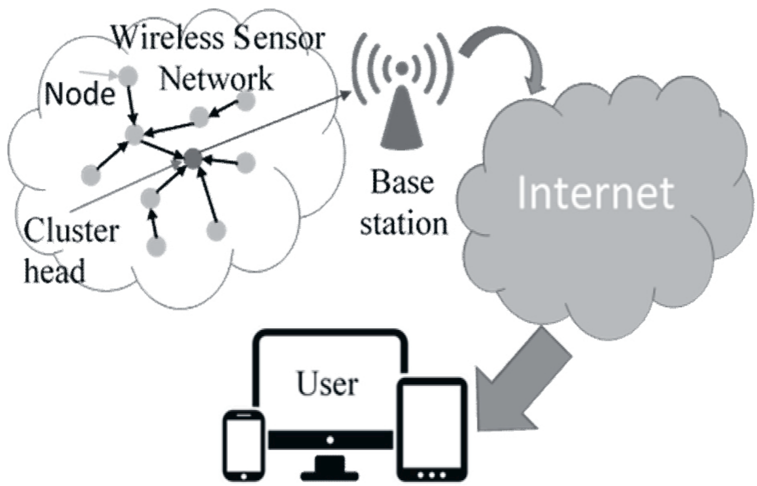


Figure 3.5: Illustration of WSN integration into IoT concept

Paper IV continues the WBAN approach, however, on smaller scale when a monitoring device is used by one person. But the designed device gathers data from different sensors, like pulsometer, accelerometer, gyroscope or GPS. The system application environment varies, and includes apartments, buildings and even outdoors. Gathered data are transferred via Wi-Fi or GSM. Data fusion, which is often of IoT concern, is used for longtime continuous behaviour analysis and assessment of monitored person.

The solution shown in Paper V, consists of a few interrogators located throughout the building and a small wearable device based on an Ubisence localization tag and Adafruit's IMU. For security reasons, firefighter localization data are transferred to the server via closed wireless network, and head orientation data are transferred to the server via USB after the training. Next, the obtained data are used for firefighter training assessment.

The IoT approach in Paper VI consists of the four functional layers: *sensing*-, *network*-, *application*-, and *business*-layer arranged in the structure as presented in Figure 3.6. The *sensing-layer* is responsible for data collection and pre-processing including filtering and edge computing. The *network-layer* is used for communication via a mobile network through GPRS, between *sensing*- and *application*-layers. In the *application-layer*, high-level data processing is performed and the cloud-level analysis and results visualization are realized. The final *business-layer* includes the management and decision-making functions, e.g. risk analysis or assessment of driving style required by a car rental or insurance company.

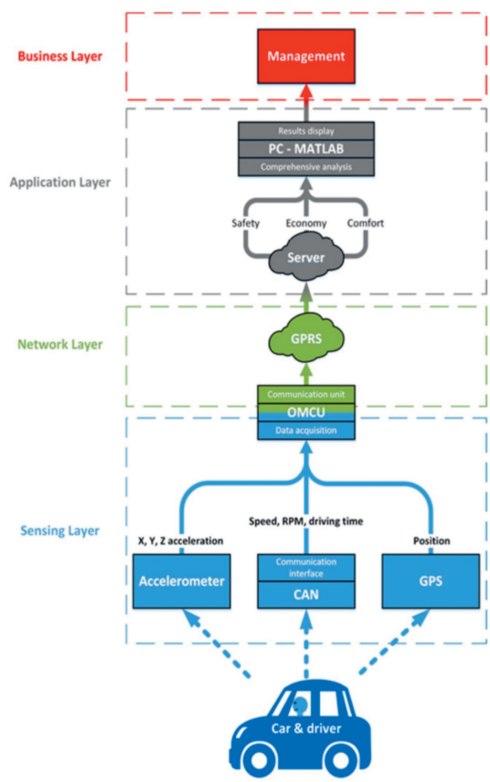


Figure 3.6: Architecture of the IoT-based driving style assessment system

Multi-sensor systems, which are concerns of this thesis match the IoT concept, not only because of sensing and communication approaches, but also because they work autonomously without human-to-human or human-to-computer interaction. However, this interaction is nor excluded if needed.

4 Applicational Approaches

Applicability and the application environment of the designed solutions have a key impact on design principles. Different approaches need to be used for systems involving human activities and industrial processes. This thesis covers two main applicational approaches *industrial* and *behavioral*. Paper I and Paper II are embedded in the industrial environment while Paper III and Paper IV are dedicated to human activities. Whereas, Paper V and Paper VI apply both approaches with different proportions.

In this section, the two approaches are scrutinised to show their differences and similarities in respect to engineering system design.

4.1 Industrial Approach

An exclusive industrial strategy is applied in Paper I and Paper II. Both papers concern the functionalities' improvement of a waterjet machine. The aim of the project was to shorten the time-consuming and imprecise manual process of defining a starting point for the cutting operation. The system design process needed to include environmental and working conditions constraints. One of the concerns was a low room where the waterjet machine was placed. It excluded a cheaper one camera solution, since its installation above the waterjet machine working table was not possible.

Paper V and Paper VI include both behavioral and industrial approaches but different strategies are used. Paper V deals with an objective assessment of firefighter skills and behaviour tested in training facilities. The industrial aspect of this paper concerns the environment of the training place, which is often located in industrial halls or office spaces. The challenge with this approach was to imitate a real environment for firefighter training. The problem was approached by defining some 3D features of a quasi industrial environment.

Paper VI focuses on objective driving style assessment by means of indicators based on measurements of a car's dynamic parameters. The assessment system was dedicated for an enterprise, and therefore the design required an industrial strategy. System flexibility was crucial to assure its applicability in wide ranges of cars, such as trucks or personal vehicles, even the older ones. Moreover, the proposed solution should be affordable, easy to install and should not be noticeable to the driver. It was proposed to use OBD-II interface, a common port installed in cars produced back in the late twentieth century [31]. Apart from parameters accessible using the interface, data from additive sensors such as accelerometer and GPS are used.

4.2 Behavioral Approach

The behavioral approach is included in papers from Paper III. Paper III made way for the IoT multi-sensor systems to assess elderly or disabled people's behaviour. For the assessment, the system localises the person's position, whether they are indoors or outdoors, identifies in which position they are and if a fall has occurred. The basic physiological characteristics such as heart rate are also monitored. The expected outcome provides behaviour analysis to anticipate possible progressing health or mental issues.

Applicational approach of Paper IV is also behavioral. The objective of the paper was to methodologically design an IoT-based system for monitoring people in their apartment, but also outdoor near the apartment. The proposed solution was based on the solution proposed in Paper III, however, the behavior analysis was extended greatly. In addition to localization and fall detection, the functional requirements were expanded to also recognize behavioral variations of the monitored person. It was also requested that the system should be able to classify the observed behaviors defined as normal, suspicious or dangerous. The decision system should define an action in a case of unusual occurrences, and notify the people responsible for the care. The applied technologies and solutions have also been chosen with respect to the monitored persons' integrity and privacy. The collected data are treated according to EU regulations.

In Paper V, the behavioural approach is applied for an objective fireman training assessment. The assessment is based on the five training indicators: a number of correctly examined checkpoints, the examined area coverage, a number of examined objects, the execution time and the average speed. The chosen features allow the user to assess both accuracy and efficiency of the performance. Analysis of the trainee's behaviour was carried out based on results of the expert's test. The proposed test result visualisation was designed to help coaches and trainees to observe training progress and to customise training to individual needs.

The last paper, Paper VI, proposes an objective assessment of drivers' skills and abilities based on monitoring of their behind the wheel behaviour. The assessment was based on eight measurable indicators. The indicators could be classified into two categories: 1) established regulation standards, 2) expert's scores and behavior measures. Among the standard indicators, the de- and accelerating ratios indicate a driver's tendency for aggressive driving. Also bumping ratio can indicate a driver's tendency to pass over speed-bumps or road holes with high speed. The aggressive driving style could also be indicated by a cornering ratio, which shows if corners are taken smoothly and calm or sharply and fast. To assess if the driver follows the rule of resting after a recommended driving time, another indicator was proposed. The car speeding ratio may indicate tendency of bad habits behind the wheel. The drivers' economical and environmental characteristics can be mapped by excessive engine rotational speed ratio and excessive engine rotational speed duration ratio. The extended number of indicators makes the assessment more objective and covers different types of driving skills and styles. The proposed result visualisation can be used as an individual assessment for drivers to understand how they can improve their driving skills.

5 Functional Approaches

The papers included in this thesis deal with different kinds of identification and classification technologies and algorithms. The functional approaches are presented in two sections. The first one shows methods to *detect* and *identify* different things or features. The second one presents ways how to *assess* or *classify* fuzzy quantities such as quality or persons' behavior and skills.

5.1 Detection and identification of features or things

The detection and identification approach in this thesis is applied in two ways. In Paper I, Paper II and Paper III, the main aim was to recognise some features. While, in Paper IV, Paper V and Paper VI, detection algorithms are auxiliary to provide data that are used to assess some properties, skills or changes in behaviors.

The identification issue raised in Paper I dealt with recognition and localisation of the lower left corner of a workpiece. The vision system presented in this paper applied two regular industrial cameras. Image processing algorithms assured required functionalities, which included color segmentation, image binarization, noise filtering and contour detection along with Hough transformation for line approximation of the detected calibration markers.

Those algorithms were used to solve the paper's main problem, which was performance of the AWPVS calibration method and evaluation of its impact on workpiece localization uncertainty. The calibration of GC was based on four reference markers of a color contrasting with the waterjet machine workspace, which needed to be recognised by the system. They were placed in the waterjet machine worktable corners to facilitate the detection. The verification test results showed that the proposed GC calibration ensures accuracy four times better than required, which guaranteed that the pre-located element would be placed in the LC field of view.

At the beginning of LC calibration, the machine nozzle is moved above the corner of the previously identified upper left marker so the corner could be localised. However, to centre the nozzle exactly above the corner a few iterations are needed. The entire calibration process is conducted until the detected corner is on the center of the image within precision of ±1 pixel. To estimate the impact of LC the calibration method on uncertainty of workpiece corner localization, four measurement series for different markers' positions were carried out. Figure 5.1 presents the results of measurements for each series. For the first test series, the uncertainty of the workpiece corner localization met initial assumption. However, further analysis showed that by adjusting the position of the calibration marker, it was possible to improve the accuracy. Measurements of the last test measurement series indicated the localization accuracy of the workpiece corner of ± 0.1 mm.

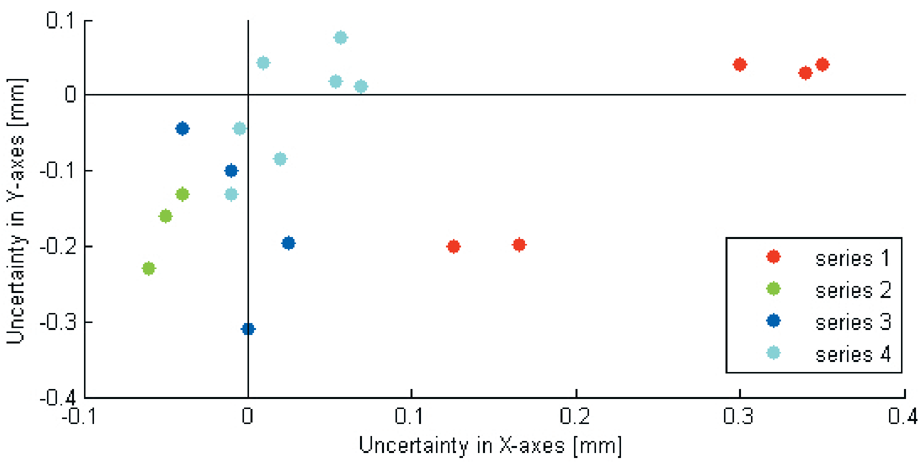


Figure 5.1: The localization uncertainty of workpiece corner detection with LC

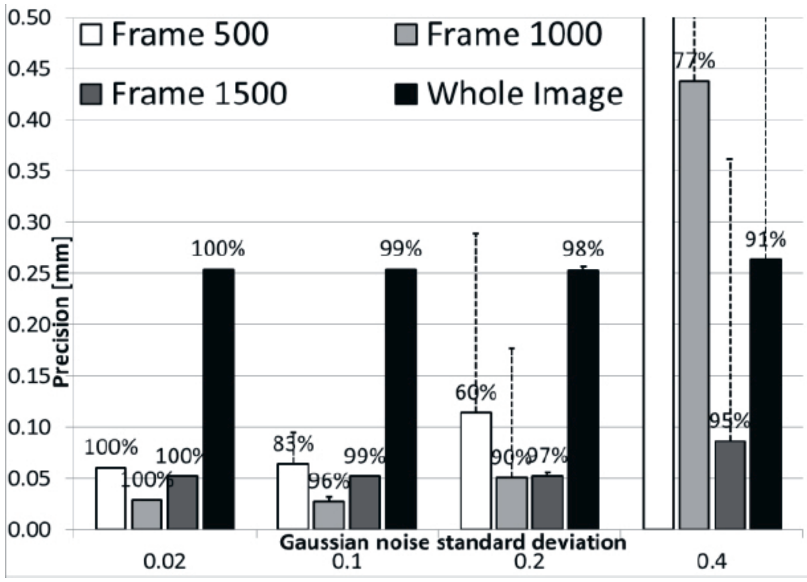
Research presented in Paper II continued with the AWPVS problem but from a perspective of harsh light conditions. Furthermore, in this paper, we intended to localize a corner of a square workpiece but randomly placed on the waterjet machine workspace. The applied image processing algorithms were similar as in Paper I with the difference being instead of the color segmentation method, background removal was used. In addition, the paper aimed for system optimisation in respect to the cropping frame size. For this purpose, impact of the cropping frame size on PVS algorithm robustness and localization uncertainty was for two common kinds of noises. The analysis was performed on two different types and different levels of image noises: Gaussian and salt and pepper noise. Results for the case of Gaussian noise are shown in Figure 5.2a and in Figure 5.2b for salt and pepper noise. For each test, the PVS algorithm was run 100 times. The corner localization uncertainty was measured as the distance between the defined corner coordinates of the image and the corner coordinates estimated by the PVS algorithm. If the distance was greater than accuracy required by the stakeholders, the PVS algorithm result was classified as unsuccessful. Above each bar, the corresponding positive detection rates are presented, which were calculated using formula (5.1):

$$D_R = \frac{C_D}{C_D + D_N} \times 100\% \tag{5.1}$$

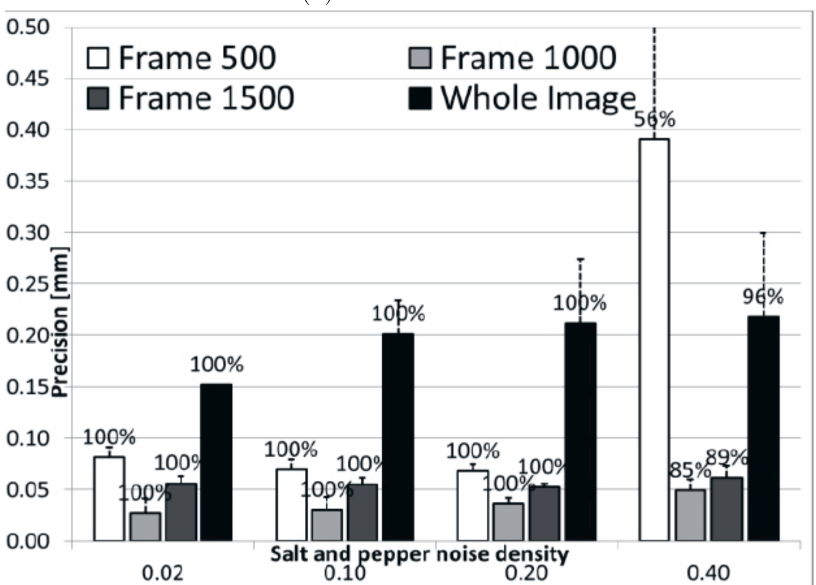
where D_R is the detection rate, C_D refers to the number of correctly detected corners and D_N refers to the number of failures.

The simulation results proved the sufficient robustness of the algorithm for Gaussian noise with standard deviation level up to 0.2, and for salt and pepper noise of density up to 0.2. As expected, the algorithm is slightly more robust for the salt and pepper noise, as the algorithm was aimed to filter out this kind of noise, which usually remains after the primary filtering and background subtraction. Moreover, it was concluded that the best results are achieved for (1000 × 1000) px and (1500 × 1500) px, depending on the noise level. The applied evaluation methods allowed one to find the trade-off between the cropping frame size and noise intensity and type. Based on those heuristic results the system was optimized.

The last stage of the identification approach in Paper II was to find out how Δ_{PVS}, the uncertainty of corner localization, and Δ_M the machine accuracy component contribute to Δ_{AWPVS}, the whole AWPVS. Based on experimental data, one could find that the average accuracy of AWPVS of less than 0.035 mm was better than the algebraic sum of its two components, which was the assumed worst case. The results shown that the precision of



(a) Gaussian noise



(b) salt and Pepper noise

Figure 5.2: Average precision of corner localization and positive detection rates for four sizes of cropping frame and two types of image noises (**a**) Gaussian and (**b**) Salt and Pepper

the whole AWPVS is at the level of 0.063 mm with standard deviation of 0.015 mm.

In Paper III, the identification challenge was to recognise the best cluster head in the large WSN from an energy efficiency perspective. The survey of related works showed that the WSN lifetime could be determined by the vigilance coefficient, which is the ratio of the sensor's active time to its idle time and the probability that the sensor is chosen as a cluster head or normal node [32]. To solve the optimisation problem, a modification of LEACH [33] routing protocol was proposed. The choice of the cluster head was based on statistical prediction of *energy consumption* in the next transmission round and minimizing the data *transmission path* to the base station. For validation of the modified root node selection algorithm, a simulation in Matlab environment was performed. 250 points were randomly distributed in three equal clusters with the area of 300 m $\times$ 300 m, corresponding to possible positions of monitored patients in a garden as illustrated in Figure 5.3. The proposed method was analysed in three different networks: *non-hierarchical*, as well as *hierarchical* of *first-* and *second-order*. The lifetime curves of each network structure are shown in Figure 5.4. The death of first node in the *first level hierarchical* network is observed ten times later than in the *non-hierarchical* one and the system is able to work almost 1.5 times longer. For the case of *second level hierarchical* network, death of the first node is observed 15 times later and the system was working almost three times longer than in the *non-hierarchical* case. However, it can be foreseen that increasing hierarchical levels could complicate the network too much.

The second extension of the WSN energy problem was optimisation of cluster formation. The solution proposed in Paper III was based on K-mean algorithm as a tool for defining the optimal distance between network nodes and the cluster head similarly as in [29]. To analyse the proposed solution, simulation of 100 nodes randomly distributed in an area of 90 $m \times 80$ m was performed. Each node had the same initial energy. Results of the simulation were compared with a commonly used method where clusters are formed geographically, see Figure 5.5. It could be denoted that even with a small number of nodes the death of first node with K-mean clustering method occurred six times later than in the case where clusters were formed geographically. The proposed system was able to work almost two times longer.

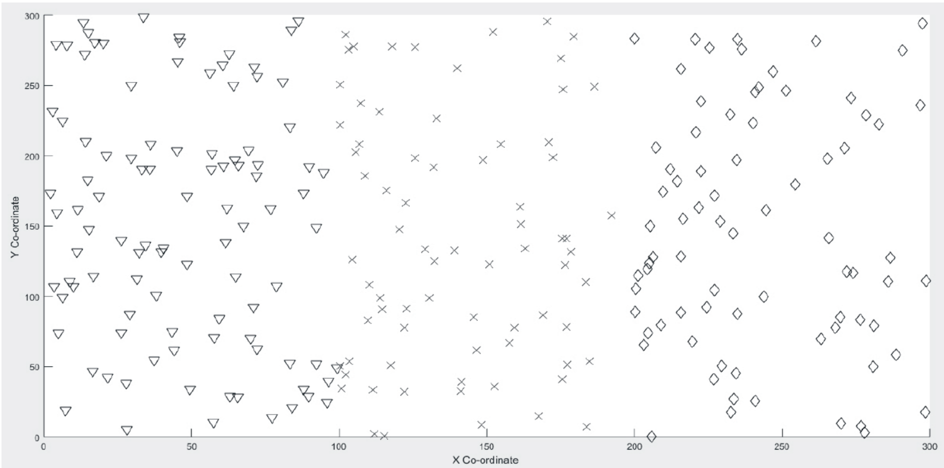


Figure 5.3: Example formation of nodes distributed in target environment where membership to each cluster is notified by different symbol.

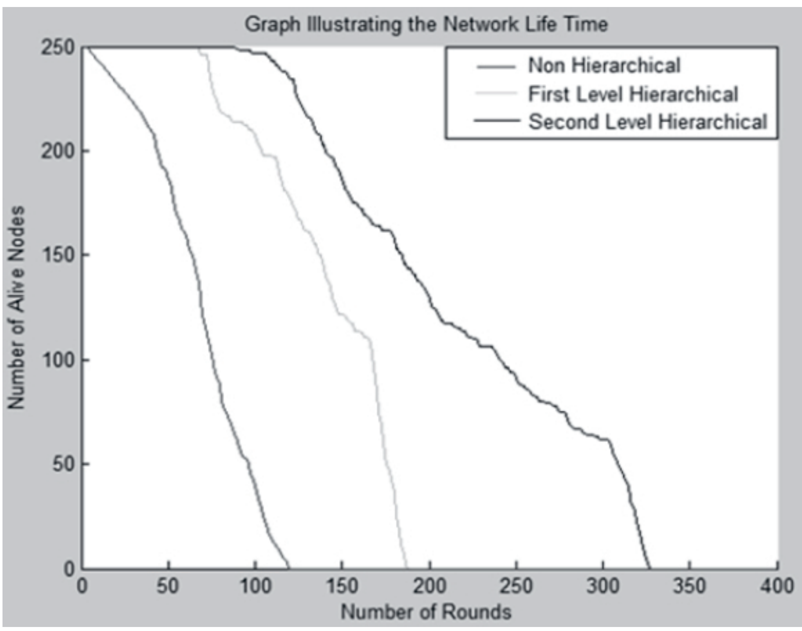


Figure 5.4: Comparison of network lifetime for different level hierarchical formations applying the proposed modification of the LEACH routing protocol.

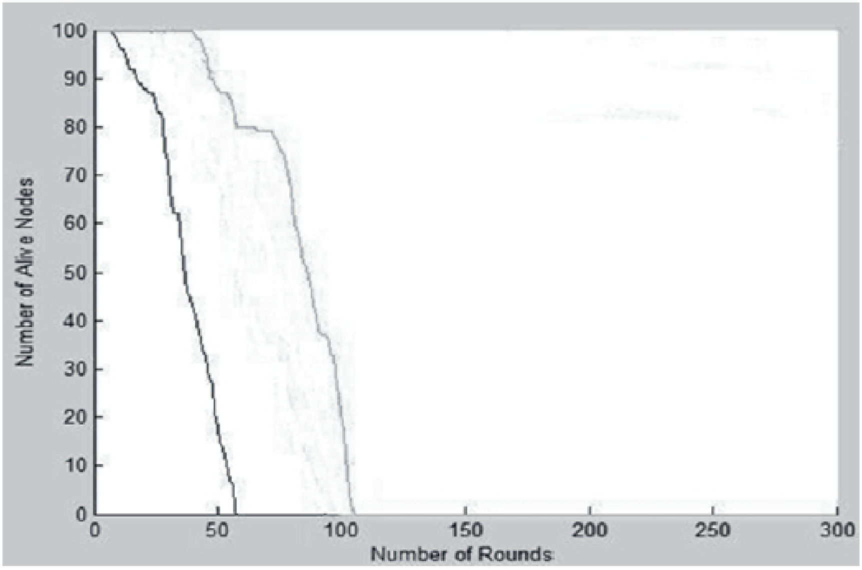


Figure 5.5: Comparison of node lifetime for second level hierarchical formations for two different clustering methods: geographical (the black line) and using K-mean method (the gray line).

The selected technologies determined solutions applied in Paper IV. Due to personal comfort, privacy and integrity we applied the solution based on technologies other than vision, e.g. accelerometer, pulsometer, Wi-Fi, and GPS. The included detection approach was related to multi-folded localisation.

For indoor localization the requirement was room level accuracy, which could be assured using the PDR method. The estimate of a person's position was based on information from several sources such as previous position, number of steps, their length and direction. However, to reduce accumulative drift of the PDR method, occasionally the system had to be re-calibrated in a known location of the apartment. It could be done while the person is sitting in a chair of fixed locus or while standing on a clearly marked place. Validation of the proposed solution started with analysis of step detection accuracy. The raw SMV readings of the accelerometer were fed to a Butterworth low-pass filter with a 2 Hz cutoff frequency, which assured the step detection with 98% validity for 1500 test steps. The evaluation of direction deviation showed a value of 1.33°, with standard deviation of

1.15° and the maximal error of 3.00°, which led to establishing a threshold of 6° to dump the system over sensitivity. With such a solution the mean localization error was measured up to 40 *cm* for a test walk of four-meters back and forth repeated three times.

The proposed PDR algorithm, based on results of step detection and direction estimation, was assessed in the tested environment of a walk back and forth repeated three times, shown in Figure 5.6. The test mean localization uncertainty was 33 cm with a standard deviation of 18 cm. The test results proved applicability of the proposed algorithm for the four room-zone level accuracy. However, long use could cause an accumulative drift. As a solution, the load sensor as a re-calibration point was proposed. The load sensors as in car seats could be mounted at the most frequently-used places, with fixed x and y coordinates. Moreover, this solution could be used for primary calibration of the system.

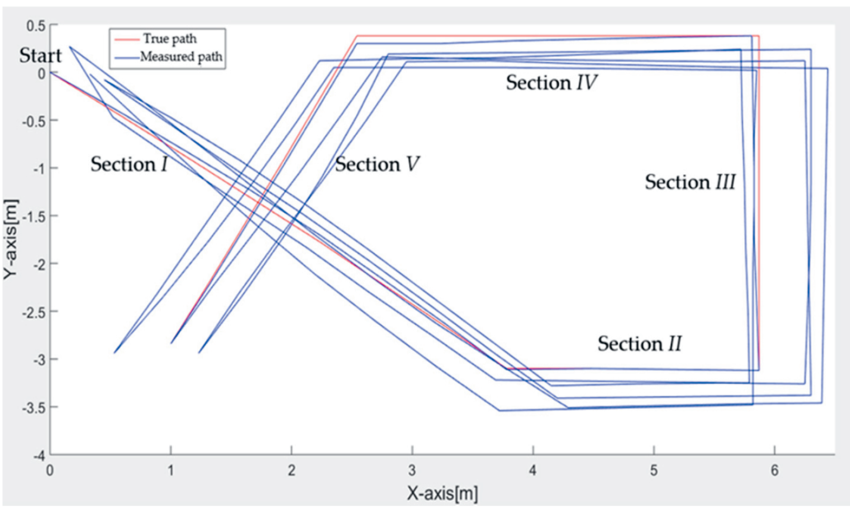


Figure 5.6: Localization results of PDR for periodical indoor test path.

The more complex identification issue presented in Paper IV was to recognise different activities of monitored persons, when due to their integrity a vision system was not applicable. Five different activities: *lying*, *sitting*, *standing*, *walking* and *falling* needed to be identified. Because of the risk level, the most crucial request of high reliability was *falling* detection, which in the case of an elderly person could be a serious life threat. To recognise the falling, we measured acceleration. Negative and positive acceleration peaks could correspond to the beginning of a fall and contact with the floor, as shown in Figure 5.7. However, fall detection was not as straightforward as expected since in some cases, for instance at rapid onset of walking, there are similar changes in acceleration readings. Fortunately, with older persons, such behavior is rarely seen. Nevertheless, to avoid false detection of falls, the auxiliary accelerometer measures in the x-, y- and z-axes were also included in the algorithm of fall detection.

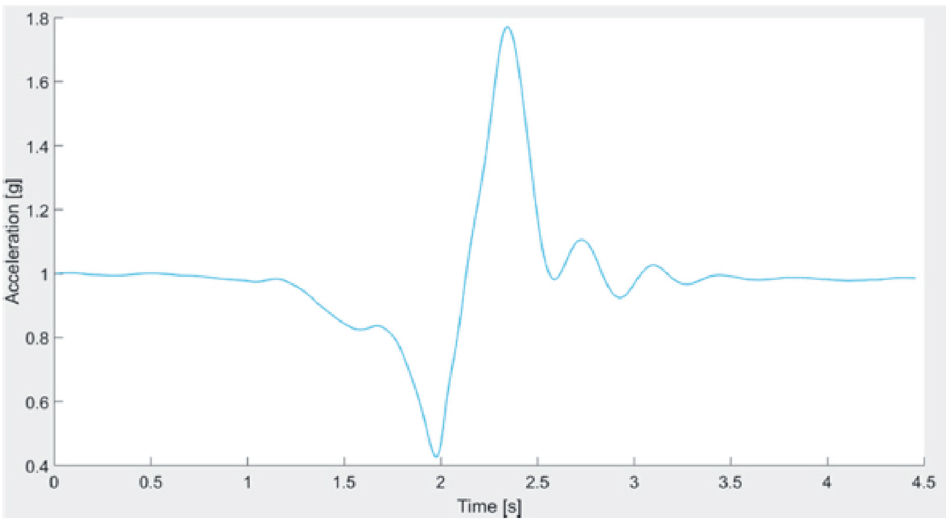


Figure 5.7: Exemplary acceleration characteristics for the fall test

The identification of *walking* was possible by means of the PDR algorithm. Whenever the accelerometer detected a step, a current activity state was changed to *walking*. The *lying* activity was distinguishable from acceleration z-component. Due to gravity affects this component dominated when *lying*. Whereas with other activities like *walking*, *standing* or *sitting*, the gravity influenced mostly the y-component. The most difficult activities to identify were *sitting* and *standing*, because the acceleration readings in both cases were very similar. Therefore, some additive measures were needed, for instance the change of posture. Analyzing the distinguishable changes of accelerations in the x-, y- and z-directions along with the SMV it was possible to clearly differentiate between *standing up* and *sitting down*, see Figure 5.8 and Figure 5.9.

Reliability of all activities detection was validated based on a series of measurements while performing different activities. The *fall* test consisted

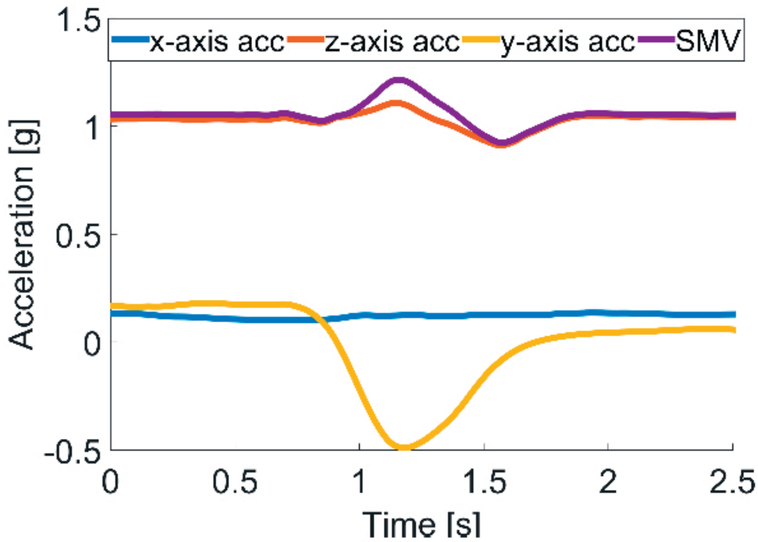


Figure 5.8: Acceleration in the x-, y-, z-axis and SMV readings while standing up activity

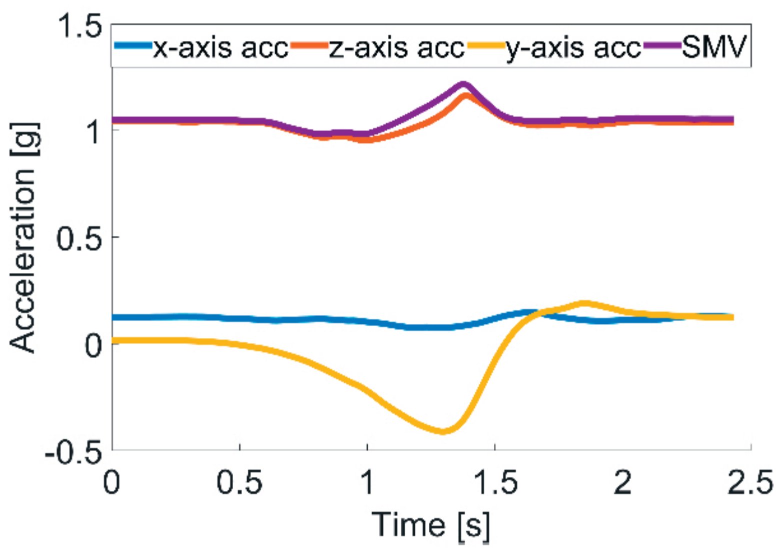


Figure 5.9: Acceleration in the x-, y-, z-axis and SMV readings while sitting down activity

of 350 falls including forward, backward, lateral, fainting and tumbling preceded by flexing the knees. Then 342 of them were identified correctly, which represents an efficiency of 98%. To assess other activities detection accuracy, volunteers performed lying down, standing up, sitting down, or walking, randomly 1000 times. The reliability of activity recognition was 95.5% where 2.5% of activities were recognized incorrectly, and only 2.0% were not detected.

The identification problem raised in Paper V was related to an objective assessment of firefighters' training. The assessment was based on five components, which were selected to be measured: *number of passed checkpoints*, *area coverage*, *number of examined objects*, *training time* and *average speed of the training*. Each of the measures evaluates some training feature. *A number of passed checkpoints* shows how thoroughly the trainee checked the training area. Usually, a single room is considered as a singular checkpoint. To assent an area as checked, the trainee had to enter it, which was verified from training localization data and known position of checkpoints. The *area coverage* indicates to what extent the room was combed out. It proves whether the trainee just entered the room or he/she also examined it carefully by looking around. The area coverage assessment was done by combining location and field of view data along with the colliders built in the Unity game engine. The third key feature of assessment concerned the *number of examined objects*, which simulates the cases when somebody hides in the closet or lies unconscious under the desk. It was assumed that the object is examined if at least 80 % of its area appears in the trainees' field of view for at least 0.5 second. The object examination principles are illustrated in Figure 5.10. The *training time* is measured to evaluate training efficiency. The final component of the assessment is *average speed*, which is estimated from training execution time and the length of the trainee's path. This feature gives the combined information about the ability to execute all tasks in the required time.

In Paper VI, a system for an objective driving style assessment was proposed. It applied three criteria of *safety*, *economy*, and *comfort*, which are based on eight indicators. The indicators are the objective measures of the driving skills. The measured data were collected from an OBD-II interface along with those from a developed device consisting of accelerometer, GPS receiver and Raspberry Pi 3 B+. The jr_x indicator is a measure of the car's dynamics represented by *mean jerks in x-axis*, where jerk is understood as

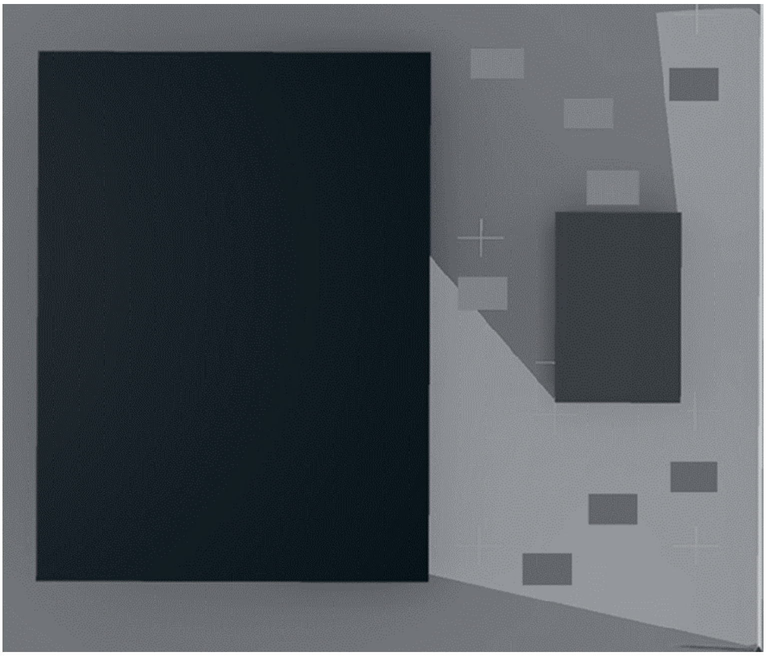


Figure 5.10: Example of recognition principles and FoV estimation. *The light grey colour indicates the estimated FoV, the darker rectangles are the objects, which are considered as properly examined and the lighter grey rectangles indicate objects, which are not checked*

the first derivative of the car's acceleration a_x in respect to time. To find out if a driver does not accelerate or decelerate too rapidly, it was normalised to respective mean of the expert's jerk $\overline{E_x}$. The indicator jr_z is estimated from the *mean jerk in z-axis* normalised to the mean expert's jerk $\overline{E_z}$. The indicator jr_y is measured as the *mean jerk in y-axis* normalised to the mean expert's jerk $\overline{E_y}$. The indicator dtr can be mapped from *engine uptime* information, which shows time of driving without stopping and is available using OBD-II interface. This indicator is reasonable for a ride, which takes more than two hours. Value of the spr indicator is calculated based on M samples of *current speed limit*, SL to the M samples of *current speed*, CS. However, to comprehensively assess the driver's style, the speeding distribution is more informative. Therefore, apart from the mean value, the normalized standard deviation σ_{spr} is also used. The $spdr$ indicator is estimated by relating the number of samples M of the *exceeding speed limit* to all N samples of the test ride. The rsr indicator is calculated based on

L samples of *engine rotational speed*, $RERS$, exceeding the recommended value related to the recommended value *EERS*. However, to comprehensively assess the rsr indicator, the excessive engine rotational speed distribution is needed. Therefore, apart from the mean value, the normalized standard deviation σ_{rsr} is also used. These measures are acquired via diagnostic ports. The last indicator $rsdr$ is a measure of how long *time engine rotational speed was exceeded* in comparison to the whole test drive time.

The features *identification* is a crucial part of the presented research as a means of obtaining necessary data, which then could be used for behaviour classification or skills assessment.

5.2 Behavior classification and skills assessment

The assessment and classification approaches could also be referred to as evaluation of fuzzy quantities, which lack standards or references [34]. In Paper III, it means to assess the validity of the proposed DM. In Paper IV, Paper V and Paper VI, which constituted a core of the research, the goals were to classify human behaviours and assess persons' professional skills.

The assessment approach presented in Paper III concerns validity of the proposed DM. The case study of WBAN dedicated for individual patients was used for the assessment. The solution was designed in cooperation with stakeholders and future users, both patients and care staff. Among other functionalities and constraints established during dialogue with all actors, there were low price, vital sign monitoring, wireless nature, user comfort along with privacy and integrity preservation. Especially the privacy preservation limited possible technologies, since use of a vision system was excluded. The designed and prototyped system consisted of small wearable devices, connected to a user friendly belt, which additionally provided monitoring of a patient's pulse. The proposed system was verified in a home care facility. The assessment of the Design Methodology was done by a survey, which showed full satisfaction of all contributors to the project and all users. The designers also confirmed usefulness and applicability of the Design Methodology.

Paper IV includes classification of monitored persons' behavior. In the proposed solution, three classes of behaviour were considered: *normal*, *suspicious* and *dangerous*. Figure 5.11 shows a flow chart of the proposed classification method. Data obtained from the sensors are combined with information about the occurrence, such as the time of day, section of apartment and its zone; then the current activity is defined and placed in the current activity map. The map is then compared with the pattern map of *normal* behavior and by means of the ML method, the behavior is classified.

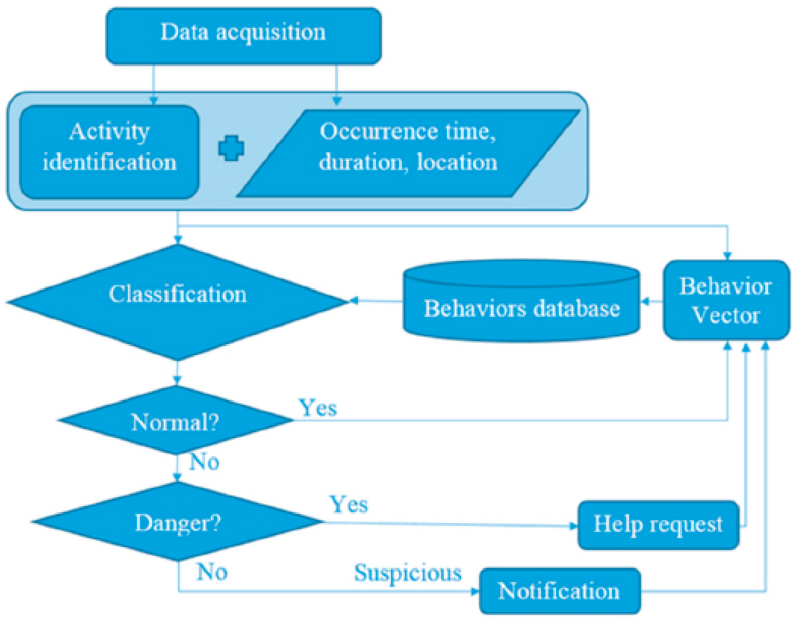


Figure 5.11: Behavior classification scheme

The behavior classification training-database consisted of more than 1200 situations of *normal*, *suspicious* and *dangerous* behaviors from the data gathered during monitoring tests of volunteers. The training database created was applied to six different ML techniques to establish the patterns of *normal*, *suspicious* and *dangerous* behaviors. The five-fold cross-validation method [35] was applied to evaluate chosen ML techniques, which were: *decision trees*, SVM, and *K-Nearest Neighbors (KNN)*, classifiers. Each of the methods were tested in two ways. The test of decision tree classifiers was done for two maximum possible numbers of splits, which were 20 and 100, respectively. The SVMs were tested for the linear and cubic kernel functions. In KNN method the Euclidean and cosine distance metric were used. Table 5.1 shows classification validity of chosen methods.

Table 5.1: Reliability of behaviour classification of validated ML techniques

Classifier	**Reliability of behaviour classification (%)**			
	Overall	Normal	Suspicious	Danger
Decision Tree I	82.4	92.8	92.9	74.1
Decision Tree II	94.8	93.7	93.8	96.5
SVM I	54.1	60.0	-	50.5
SVM II	85.1	87.2	75.2	86.8
KNN I	96.0	97.9	90.9	96.8
KNN II	95.8	97.6	89.9	97.1

Table 5.1 proved that Decision Tree II along with KNN I and KNN II achieved the highest classification validity. Therefore, they were chosen for further optimization by tuning their parameters. The tuning of KNN I and KNN II did not lead to improvement of their overall classification validity. However, increasing the number of splits up to 140, in the Decision Tree II classifier, enhances the overall classification validity up to 99.1%. The behavior classification validity for the tuned Decision Tree II classifier for *normal* behaviour was 99.1%. The *suspicious* behaviour was correctly classified in 98.4% of cases and *dangerous* in 99.5%. It is noteworthy to mention that only 0.25% (3 of 1200 test cases) of tested dangerous behaviors were classified as normal, which can be treated as a critical mistakes, and 0.3% (4 of 1200 test cases) of them were classified as suspicious, which is less critical since they should be checked anyway. For final verification the tuned Decision Tree II was fed with 50 different behaviors with randomly-chosen timeframes. The test resulted with overall classification accuracy at a level of 100%. All of the 25 *normal*, 7 of *suspicious* and 18 of *dangerous* behaviors were classified correctly.

The purpose of the system presented in Paper V was an objective assessment of firefighter training. This was done both *online* and *offline*. During the *online* phase, data from the designed system were gathered, while during the *offline* phase, synchronized data from measurement systems were processed, see Figure 5.12. Then the key features were extracted and compared with the expert's pattern.

For final verification of the proposed solution, the real test was conducted at a simulated training field. The chosen space was divided into six areas where five objects, which should be examined, were present. In addition, two artificial walls were added. In Table 5.2 an expert's and trainee's performance are compared.

Table 5.2: Performance assessment results

Evaluated factor	Expert	Trainee
A number of checkpoints	6/6	5/6
Area coverage [%]	100	80
Number of examined objects	4/4	3/4
Time [s]	27	31
Average speed [m/s]	1.8	1.3
Final relative score [%]	100.0	60.0

In Paper V a spider diagram was proposed as a graphical assessment method, as shown in Figure 5.13. This approach allows the assessor to easily observe the trainee's strengths and weaknesses. As one can see, time of a trainee's test run was similar to the expert's one. The trainee also checked almost all checkpoints and covered a substantial part of expected area. However, average speed was much lower than expected and the trainee missed some objects to be examined. Moreover, a required single score

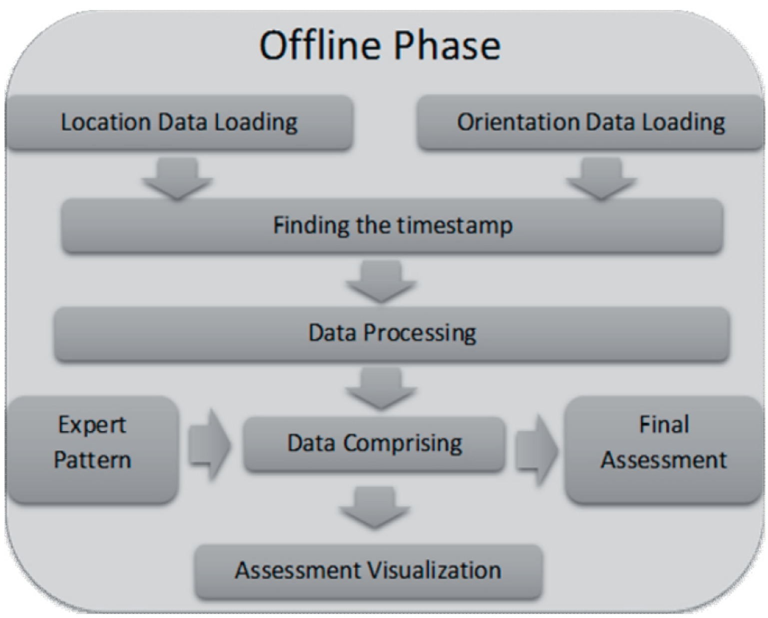


Figure 5.12: Flowchart of the system offline operations.

assessment of the person's multi-faceted training was possible by using formulas 3.2 and 3.3. In Paper V the trainee's final competence score was 60% of the expert's one. The proposed assessment method could help to compare achievements of all test participants. Furthermore, it may be used to monitor trainees' progress in their skills.

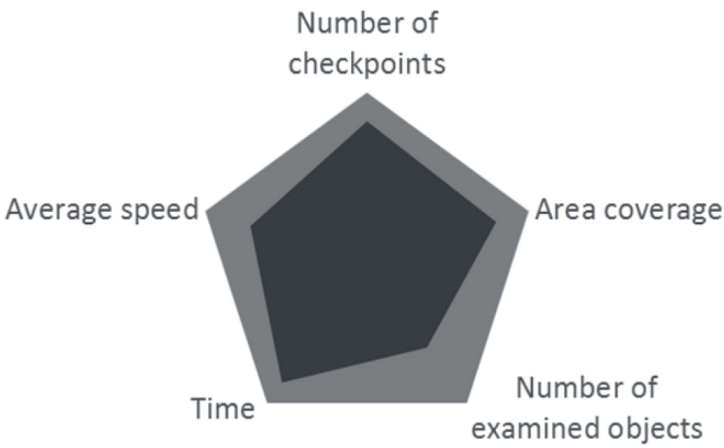


Figure 5.13: Visualization of expert's and trainee's performance.

Paper VI deals with a problem related to cognitive science and its aim was an assessment of driving style. An objective assessment of human behaviour is not a simple task and may have many implications, even ethical or mental health, especially when the results can be used for commercial purpose such as the insurance company's bonus system. Therefore, it was important to solve the problem in a transparent way that also respects human integrity. For this reason, the system does not refer directly to driver's character but to three driving criteria of *safety*, *economy*, and *comfort*, which to some extent may overlap each other. Nevertheless, those criteria could be seen as rather descriptive variables, lacking of any pattern, and could vary not only due to personal driver's attitude, but also environmental conditions such as weather or road quality. The spider diagram approach, similar as in Paper V was used to assess this multidimensional problem. The three criteria *safety*, *economy* and *comfort* illustrated respectively in Figure 5.14, Figure 5.15 and Figure 5.16 were analysed. Each color line represents one driver in respect to the expert who is treated as a reference. Moreover, on the diagrams each driver can be compared not only with the expert's results but also with other tested drivers. One can see that the *safety* criterion, which is the crucial one is the most multidimensional.

Apart from three driving criteria, which can be used to analyse driving styles, we aimed to give a comprehensive assessment that can be described as a combination of driving abilities and behind-the-wheel behavior. Driving abilities depend on the driver's knowledge, skills, and experience. The driver's behavior reflects driving abilities, developmental factors, personality, demographic factors, biological features, perceived environment and driving environment [36–38]. The following factors influence driving tendencies: speeding, unsafe passing, impaired driving, and tailgating [36]. Four driving styles are defined in Paper VI: *calm*, *ordinary*, *aggressive* and *unusual*, which are described in Table 5.3. From the Driving Style Description column one can relate driving styles to the measurable indicators. Nevertheless, we do not propose any final classification, which would label a driver. However, from the *Overall Score* diagram combining all criteria, one can find correlation between the score and the driving style, see Figure 5.17. Since each polygon vertex refers to an indicator normalised to the expert's, the surface covered by driver's lines shows how his driving style differs from the expert's one. The proposed overall assessment score composed of all eight indicators, and

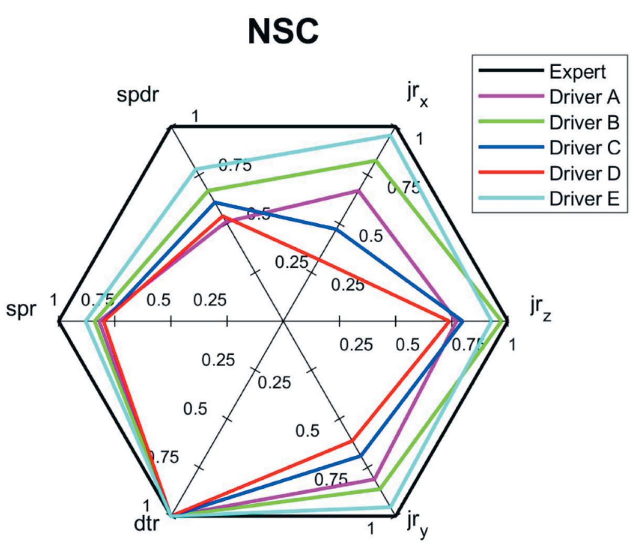


Figure 5.14: Spider diagram for *safety* criterion of short routes (*dtr* indicator is not distinct due to short time of the test).

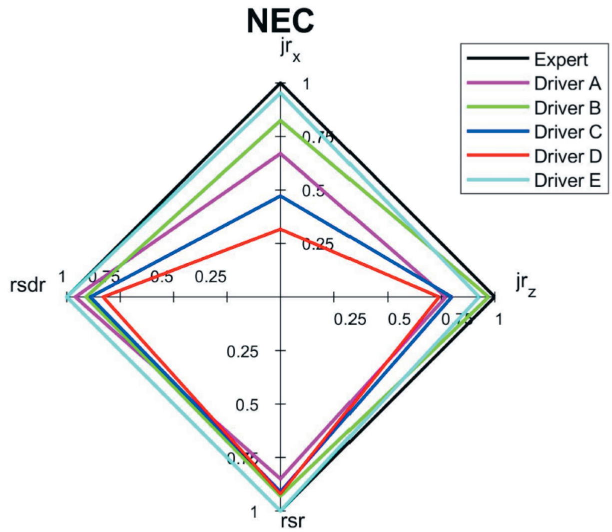


Figure 5.15: Spider diagram for *economy* criterion of short routes (*dtr* indicator is not distinct due to short time of the test).

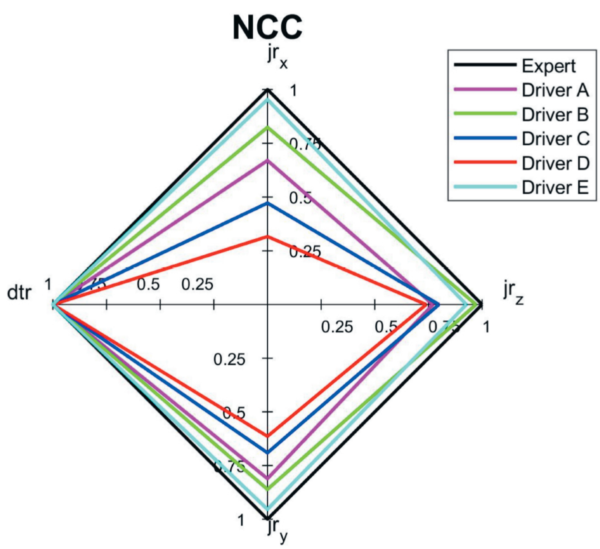


Figure 5.16: Spider diagram for *comfort* criterion of short routes (*dtr* indicator is not distinct due to short time of the test).

the driver overall normalized final score NO_s can be calculated as:

$$NO_s = \frac{DO_s}{EO_s} \tag{5.2}$$

where DO_s and EO_s are driver's and expert's overall score, respectively.

To make these assessments of driving style as transparent and objective as possible, they are based on eight measurable indicators described in the previous section. The measured data are collected from an OBD-II interface along with those from a developed device consisting of accelerometer, GPS receiver and Raspberry Pi 3 B+.

The proposed assessment method was verified by tests of multiple drivers on the same short route of 16 km. The drivers were asked to simulate drive style according to Table 5.3. Two drivers were asked to behave *Ordinary*, one *Aggressive*, another *Unusual* and one *Calm*. The short route tests included different road types, such as highways, ramps, and urban streets. Depending

Table 5.3: Driving styles and their descriptions

Driving Style	**Driving Style Description**
Ordinary	- driving in a common, ordinary way; - medium dynamic of braking; - accelerating and decelerating regularly; - not too many speeding events; - turning smoothly.
Aggressive	- driving fast and breaking sharply; - accelerating and decelerating rapidly; - many speeding incidents; - maintaining high speed while turning.
Unusual	- sickness or unnatural behavior; - braking unexpectedly; - accelerating and decelerating suddenly; - alternately low and high speed; - turning inconsistently and aggressively.
Calm	- driving calmly; - avoiding excessive braking; - accelerating and decelerating smoothly; - never exceed speed limits; - turning smoothly.

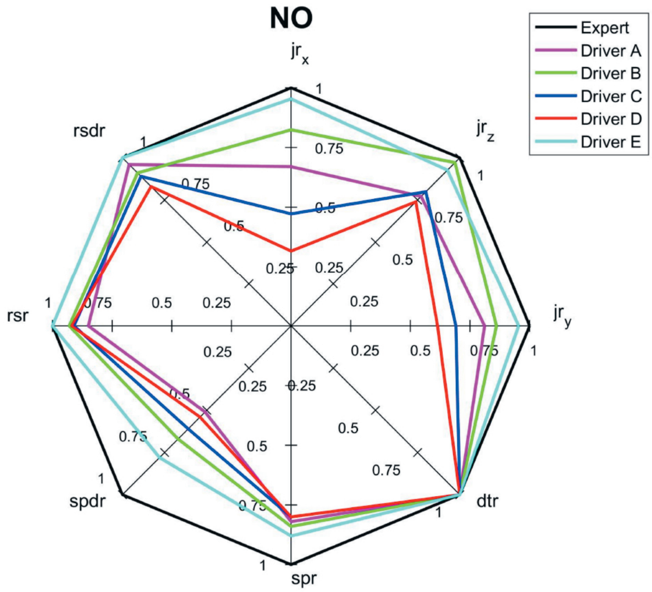


Figure 5.17: Spider diagram for *Overall Scores* (*dtr* indicator is not distinct due to short time of the test).

on the driver, each test lasted from 21 to 26 minutes. The test data were used to calculate all indicators apart from the *dtr*, which was set to the maximum score 1.0, since the tests were shorter than two hours and a rest was not required.

The test results proved worthiness of using the selected indicators in a sense that the diversities in scores among different driving styles are distinguishable. To map the expert's behavior, a professional driver took the same route. The test results, summarized in Table 5.4 show that by means of the chosen indicators, the driving styles could be clearly differentiated. As one can see *Aggressive* and *Unusual* drivers obtained the lowest values of all indicators, while the *Calm* driver almost reached the expert's level. The results also show significant difference in results for drivers who were asked to drive *Ordinary*. Comparing their results using Figure 5.17 one can see that first driver results are closer to *Aggressive*, while the second driver obtained similar results as *Calm* driver. The reason for such diversity could be that the test driver subjectively judged their driving styles.

Table 5.4: Indicator values for the test rides

Indicator	Ordinary	Ordinary	Aggressive	Unusual	Calm	Expert	Long-Route Test
jr_x	0.67	0.82	0.47	0.32	0.95	1.00	0.99
jr_z	0.77	0.97	0.80	0.74	0.93	1.00	0.69
jr_y	0.81	0.86	0.69	0.61	0.95	1.00	0.90
dtr	1.00	1.00	1.00	1.00	1.00	1.00	0.70
spr	0.82	0.84	0.80	0.80	0.88	1.00	0.85
(std)	(0.11)	(0.11)	(0.13)	(0.11)	(0.11)	(0.00)	(0.13)
$spdr$	0.51	0.66	0.61	0.54	0.77	1.00	0.67
rsr	0.85	0.93	0.91	0.92	1.00	1.00	0.84
(std)	(0.10)	(0.05)	(0.06)	(0.05)	(0.00)	(0.00)	(0.08)
$rsdr$	0.95	0.91	0.88	0.82	1.00	1.00	0.78

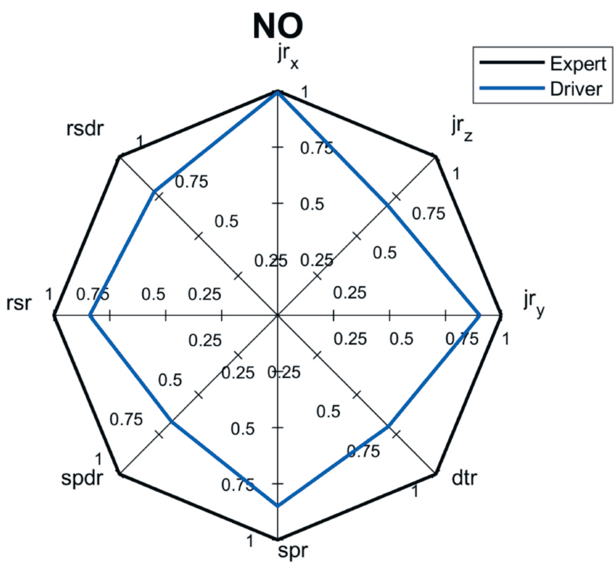


Figure 5.18: Spider diagram for overall score of long ride.

The designed system was also verified on the long-route test of 325 km with its majority on highways and freeways. The results displayed in the last column of Table 5.4 and on Figure 5.18, show that apart from deterioration of dtr, slight deterioration of $rsdr$ and improvement of jr_x, the other indicators were within the range of *Ordinary* driver short route tests.

The presented *assessment* approach was used both to show validity of the proposed solution and to mark persons' skills. The *assessment* approach applied in Paper III was meant for evaluation of proposed DM, which is treated here as non-standardised variable. While, in Paper IV the *classification* approach is applied to classify person's behaviour, which is defined based on statistical criteria. In Paper V the *assessment* of firefighter skills was based on five different objective features. However, each skill is visualized as a graph, which is a descriptive form of presentation. In Paper VI the driving skills were assessed based on eight objective indicators grouped into three criteria. The same visualization method used in Paper V provided possibility for descriptive assessment. Nevertheless, both Paper V and Paper VI propose final scores, which should not be treated as normative but as auxiliary.

6 Summary

The main objective of the papers included in this thesis was to design IoT based detection and classification of multi-sensor systems for two main applications fields: industrial and behavioural.

This chapter consists of a brief summary of all included papers. Next conclusions drawn from the work are shown. Finally, potential fields of application are proposed and future plans are presented.

6.1 Overview of the papers

6.1.1 Paper I - The Impact of Automatic Calibration on Positioning Vision System on Workpiece Localization Accuracy

In Paper I, to improve and automatise positioning of the cutting nozzle of a waterjet machine, the vision system is proposed. It is used to localise a workpiece randomly placed on a waterjet machine table. A calibration method of the vision system, ensuring the localization accuracy with tolerance of ± 0.5 mm, was the main research problem presented in the paper.

The proposed vision localisation system was based on two shelf cameras, global and local, which required a two-step calibration procedure. The proposed calibration method for the global camera used four calibration markers in color contrasting to the background. The local camera calibration utilized one of the four calibration markers. The result of local camera calibration was the correction vector, which improved positioning of the waterjet machine nozzle.

The verification of the global camera calibration method was based on real experiments, which proved all design assumptions. Experimental tests of the local camera calibration verification also confirmed that the localization accuracy met the stakeholders requirements. Moreover, the further analysis showed that by adjusting the calibration marker's position it was possible to perform the localization with almost perfect accuracy.

6.1.2 Paper II - An Analysis of Uncertainty and Robustness of Waterjet Machine Positioning Vision System

Paper II continued the study on Automatic Waterjet Positioning Vision System presented in Paper I. The accuracy components of workpiece positioning were assessed. Firstly, the corner localisation method's accuracy and its robustness to the different kinds of image noises were assessed. Finally, the relationship among the main uncertainty components were defined.

In this paper it was hypothesized that the optimized size of a cropping frame could improve the vision system positioning accuracy. Moreover, we assumed that it would be possible to distinguish between the two main additive uncertainty components: a machine and a vision system.

Analysis of the influence of cropping frame size on workpiece corner localization uncertainty was based on a set of synthetic images. The resistance of the localisation algorithm to different kinds and intensity of image noises was also evaluated using the synthetic images. As the result of simulation experiments, the design hypotheses were validated. Additionally, the results of real experiments verified the simulation results.

6.1.3 Paper III - Wirelessly Interfacing Objects and Subjects of Healthcare System – IoT Approach

In Paper III, the system dedicated to elderly persons for increasing their safety by means of monitoring systems is proposed. The expected functionalities of the system, for instance reminding them to take medicines in time or in case of a fall, alarming appropriate services and caregivers were proposed. In this paper, we proposed a new approach to the systematic design of an IoT system dedicated for healthcare applications. The User Driven Design based method included close cooperation with the stakeholders, who define system functionalities and constraints, and with future users, who might have their desires and requirements met.

The outcome of the implemented systematic design method was a concept of Wireless Body Area Network, where the key components of the system would be installed on a chest belt founded by the monitored person. Moreover, to improve information handling within WSN, in terms of energy efficiency, the modified algorithm of a root node Selection and energy efficient cluster formation method were proposed.

The methods were verified based on comparison tests of modeled solutions with the results of well known methods previously used for similar purposes. Both designed methods outperformed the exited solutions.

6.1.4 Paper IV - IoT-Based Information System for Healthcare Application: Design Methodology Approach

Paper IV consists of an extension of studies on a systematic design methodology. It approaches the design target from a perspective of the stakeholders, contracting authorities, and also future users. Moreover, it also concerns how the IoT healthcare paradigm could be integrated into the design. The case study of the proposed design methodology was for developing a monitoring system dedicated to elderly people in their multi-room apartments placed in a multi-story building. Even outdoors in the building's surroundings were included in the monitoring area. The system's functionalities consisted of monitoring vital signs, posture recognition and some other activities.

The monitoring system included a set of sensors along with AI based algorithms. Among others the 3-axial accelerometer and magnetometer, Pedestrian Dead Reckoning, thresholding and Decision Trees algorithms were applied. The system functionalities were verified with real experiments. The reliability of activity recognition was tested while performing over 1300 different activities. The obtained results do not differ from those reported by previous scientists. The acquired data were used to detect and classify different behaviors. Some of the behaviours classified as dangerous or suspicious would require to be reported to the health care service or relatives.

6.1.5 Paper V - Wireless Monitoring System for Fireman's Competence Objective Assessment

In Paper V the problem of subjectivity factor when assessing firefighter training is approached. To overcome the problem, the assessment is based on five different features of the training using a wireless multi-sensor system, based on RTLS, and IMU. The assessment is based on results of the firefighter trainee's test, which were normalised to the expert's results and expertise. Result visualization and data processing use the Unity game engine. The spider diagram is applied to comprehensively map the trainee's skills. The single score method was proposed as a conclusive statement.

A set of real experiments performed in a simulated environment verified the design assumptions and requirements. At the beginning the full trainings were performed by the expert and firefighter trainees.

Basically the same design methodology as proposed in Paper IV was applied here. The results proved that the proposed design methodology could be applied not only for industrial and healthcare approaches but also for complex problems, such as people behavior and objective assessment of skills.

6.1.6 Paper VI - IoT On-Board System for Driving Style Assessment

Paper VI addresses the problem of the objective assessment of persons' driving style. The preliminary questions were which driving quality criteria should be used for the assessment and how to measure criteria in a large variety number of car types. Moreover, it was required to show the results with a user friendly and comprehensive method.

The assessment was based on eight indicators, which are associated with the vehicle's speed, acceleration, jerk, engine rotational speed and driving time, which could be grouped into three driving style criteria: safety, economy, and comfort. The data were acquired with the car diagnostic port—OBD-II—and from a dedicated accelerometer sensor and GPS module.

The verification was performed during two kinds of test routes. The short route of 16 km in a city environment was performed by five different drivers and by an expert. Obtained results confirm that the chosen criterion's and indicators are suitable to differentiate four different driving styles. The single test of the long route at 325 km included typical types of roads like city roads, freeways and highways. Test results proved the usefulness of the proposed solution.

The solution developed in this article was also based on the systematic designed approach introduced in Paper IV, which confirmed its capability to be used in different engineering branches, especially the embedded IoT paradigm.

6.2 Conclusion

The presented research covers a wide scope of multi-sensor systems for broad application fields. Due to the PhD project time duration, but also due to changes in funding sources, one can see how research interests have evolved, from pure technical and industrial systems using vision technology and image processing tools, up to advanced multi-sensor systems for assessment of human behaviors by means of AI algorithms. However, it is still possible to find a common denominator for each part of the project since all of them were developed to meet human needs, and all of them combine hardware and software components. And last but not the least, all of them have been evaluated and verified on simulation or preferably real experiments.

Methodological design became an issue that arose when we identified a need to develop multi-sensor systems dedicated for identification and classification of complex fuzzy quantities, such as quality or behaviours. We could see that engineering approach saying *keep it simple stupid* would not be sufficient when one works for elders. Furthermore, developers have to respect desires of stakeholders and some other participants of the project such as medical staff, who would operate the systems. Therefore, using principles of User Oriented Design, we proposed our own interactive design schema, which has been successfully implemented on several presented case studies.

The gap in systematic approach in the design process was firstly recognized in Paper I and Paper II. There the design started on base of well-known research methodology: *stating the problem and formulating objectives and hypotheses*, then *modelling and implementing the solution*, and finally *solution evaluation and validation.* The research on systematization of design process and taking into the account clear definitions of the needs and requirements of stakeholders along with recognition of future users' desires, can be found in Paper III. However, in that paper an involvement of future users was still rather limited. The designer's role became very interactive, since apart from developing a new solution they have to take under consideration many aspects such as price, users characteristics, user friendly interface and even sustainability.

Then the research on DM was intensified, what can be seen in Paper IV. And as it is presented in this thesis, the stakeholders and future users were deeply involved in every stage of the design process with differentiating intensity. The proposed Design Methodology consisted of two main stages: Problem Formulation and Preduct development. Each of the stages is composed of three different steps. Problem Formulation consists of Needs Definition, Requirements Formulation and Feasibility Assessment; while Preduct development comprises of Technologies and Algorithms Selection, Modeling and Prototyping and Product Validation. The researches presented in Paper V and Paper VI validated the proposed DM. Both stakeholders and future users verified the solutions by expressing their appreciation.

Another key issue of the presented research is an IoT extension of multi-sensor system. In Paper I and Paper II using the Internet with its advantaged was just optional. However, in further papers the IoT concept was facilitated.This is especially seen in Paper IV where WSN, one of the fundamental technologies applied for IoT, was in focus of the research. Nevertheless, all papers, starting from Paper III extensively use the IoT concept.

The two kinds of applicational approaches, which covered two branches: *industry* and *applications of behavioral sciences*, needed different treatments in the applied DM. In Paper I and Paper II, the industrial environment is concerned, while Paper III and Paper IV are dedicated to human activities. Whereas, Paper V and Paper VI blend both approaches, however with different proportions.

The functional approaches could be divided into two categories: detection and identification of things or features along with assessment and classification of fuzzy quantities such quality or behavior. The first category could even be described using some synonyms, such as recognition, sensing or testing. In this thesis the approach is two-folded. In Paper I, Paper II and Paper III a core of the research is to detect some things, e.g. a marker, and to recognise which factors influence system performance in terms of accuracy. However, in Paper IV, Paper V and Paper VI identification meant to obtain data that were used to assess behaviour or skills.

The assessment approach used in this thesis was also two-folded, related to several functionalities and could be described using other terms, such as classification or rating, and therefore related to some kind of taxonomy. In Paper IV, Paper V and Paper VI a rating, which requires making decisions constituted a core of the research. The goals were to assess behaviour, training or driving skills of a person. Behavior or skills are some kind of fuzzy quantities, since they can be multidimensional and lack of standards; therefore, they require some references, e.g. expert's or average scores [34]. Furthermore, to grade a score of multidimensional quantity, which combines several quantities of fuzzy nature, is a challenge in many cases.

As one can see, due to variety and complexity of the IoTs systems their design and implementation for identification and classification processes needed to be systematized. However, it was important to present them with a clear methodology, which could be understood and applied by developers.

6.3 Future work

Modern technology shows its pros and cons especially using AI for assessment of human behavior, which could be controversial [39]. Therefore, designers' responsibility becomes multifarious, not just limited to the development of new technologically sophisticated systems. Including future users and other authorities into the design process needs to be extended, which could reduce a misuse of technology capacities. The use of AI should be especially considered in assessing systems like in [40] regarding an implemented Social Credit System.

Power of the IoT concept causes new systems and ideas to flourish everyday. Unfortunately, the commercial approach of many R&D activities forces fast execution of a product without interactive design and therefore may lead to creating a perfectly useless product. That is why every task has to be approached systematically despite the pressure that would require proper R&D management and searching for funding.

The Design Methodology presented in this research was targeted for quality assurance of things and people behavioural assessment. However, it can be applied in other engineering fields. An area where the proposed system may by implemented is robotization, especially in Intelligent Assist Device (IAD) [41] like collaborative robots, where robots or manipulators are placed in workspaces shared with humans [42]. However, in such cases it seems reasonable to add an additional aspect of *safety* during the requirement formulation phase.

Another potential field of application of developed DM is environmental studies. In systems where engineers work together with naturalists, as Bioseco does with ornithologists on the Bird Protection System [43], a dialogue is particularly important but also challenging due to participants' different backgrounds and research methods. In such case while in the Problem Formulation phase, proper formulation of expected functionalities and related constraints may save time, efforts, misunderstandings and reduce a number of mistakes in the Preduct development phase.

Proposed DM may be introduced to the teaching canon of engineers in courses like Research Methodology or Engineering Methods and Tools [44]. With such approach, a new generation of engineers and researchers will learn the advantages of methodological approach to systems design. In the future such an approach may result in better systems fitted for users' requirements.

The research field where the proposed DM can be successfully implemented is Artificial Intelligence. A multitude of currently available methods and algorithms and their complexity, require a methodological approach to deliver the right quality product. The work of Balakrishna et al. [45] shows that first steps in this direction have been taken.

We hope that this work showing the importance of the Design Methodology in Engineering Science will inspire a new ideas into paradigm shift [46], and other researchers dealing with design problem include proposed approach in their Engineering Code of Ethic.

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Part II

Papers

Paper I

The Impact of Automatic Calibration on Positioning Vision System on Workpiece Localization Accuracy

Paper I

The Impact of Automatic Calibration on Positioning Vision System on Workpiece Localization Accuracy

D. DZIAK, B. JACHIMCZYK

Abstract

This paper presents the structure and operational principles of the Automatic Waterjet Positioning Vision System (PVS), which was implemented on the WaterJet (WJ) machine. Moreover, it presents an impact of calibration method on PVS performance. Two webcams mounted on the industrial WJ, form a basis of the system, and constitute its characteristics features. Together with the identification algorithm, the PVS was aimed for high accuracy positioning of the WJ machine. For this purpose, the two-step calibration procedure that uses a set of specific calibration color markers contrasted to the background, has been developed. The results analysis shows that, despite demanding environmental conditions, the proposed method enables reliable high accuracy positioning of the WJ machine.

1 Introduction

Most of the solutions of Computer Numerical Control (CNC) requires an operator to manually define a starting point before the cutting process. However, this is a time-consuming process, furthermore due to the limited accuracy, it results in material losses [1]. The proposed Positioning Vision System (PVS) installed on a WaterJet (WJ) machine reduces time of the positioning process and at the same time increases the accuracy of the workpiece location.

This article presents the PVS implemented on the industrial WJ in Swedish Waterjet Lab in Ronneby [2]. The article concerns the analysis of the system calibration method, and its impact on the precision of positioning system.

The obtained results show a significant improvement in accuracy of the localization of the elements in the workspace of the WJ machine when using the proposed method of Automatic Calibration (AC) of PVS. It was also proved that the proposed AC of the PVS enables positioning accuracy exceeding precision of the human eye.

Aranda Penaranda et. al used a vision system for inspection and optimization of the cutting process using WJ technique [3]. They applied a vision system based on a camera with servo-operated zoom lens. The calibration of the system was based on a chessboard as a calibration standard. In addition, to compensate the optical aberrations of camera, the authors used an algorithm defining the correction matrix, which depended on the lens focal length.

In [4], a vision system consisting of a series of linear cameras for monitoring operation of the WJ machine, was calibrated by mean of the calibration block with fixed reference markers. As a procedure result, a correction vectors are defined, which are used to transform the camera's coordinate system into the corresponding machine coordinate system.

2 Research Problem

The key of the PVS calibration process is to determine the precise relationship between the camera coordinate system and the corresponding coordinates system of WJ machine. The precision of this relationship is limited by the structure of workspace (lattice), environmental conditions (e.g. abrasive, water, residue of cut materials) and the level of lighting. Therefore, the development of a reliable calibration procedure that is robust to the mentioned inferences is an interesting research problem from both engineering and scientific point of view.

According to the user's requirements, the relevant calibration problem was defined as follow: which calibration method of a vision system used for positioning of the WJ in real conditions, ensures the accuracy of the workpiece corner localization with tolerance of ± 0.5 mm? The general problem formulated in this way leads to two further questions. First question is how to calibrate the Global Camera (GC) to be able to estimate the exact position of the workpiece by means of the Local Camera (LC)? Second question is how the performance of LC calibration affects accuracy of the workpiece localization?

Considering the construction of a two-camera vision system, the structure of the WJ machine workspace and complex environmental conditions, it can be assumed that a two-stage calibration procedure of the PVS based on detection of calibration markers in color contrasting with the WJ machine workspace, could ensure the required accuracy of the workpiece localization.

A method applying four calibration markers, which define the real workspace of the WJ machine, will ensure the localization uncertainty of the GC, which does not exceed ±60 mm. Therefore, the correct location of the corner of the workpiece by means of a LC will be possible. The correct assembly of the LC reference markers, assures an accuracy of PVS localization with uncertainty ±0.5 mm.

3 Positioning Vision System

The purpose of the presented PVS is localization of the workpiece and then automatic positioning of the WJ machine nozzle over a workpiece left corner. By estimating localization of WJ manipulator in the workspace, the system can determine the transformation matrix of the coordinate system providing a required accuracy. The prototype of the PVS consists of two off the shelf webcams. One, a GC mounted above the machine, is used to approximately localize the workpiece. To determine the exact position of the workpiece corner and to estimate the rotation of the WJ manipulator, the LC is attached to the cutting head. To provide an in situ calibration, four reference markers are placed in the corners of WJ machine worktable, which allow to determine the actual workspace of the machine. A PC controlling the PVS is connected to the Sinumeric 840d sl control system, which directly supervises the operation of the WJ machine.

The workpiece identification algorithm, which estimates the workpiece corner's accurate coordinates and its angular deviation, is shown in Fig. 10. An initial filtering is applied to extract an treated workpiece from the WJ machine workspace helping to find out its characteristics features. The pre-processing is a necessary part of the algorithm, to enable the system performance in a typical lighting conditions with high level background light interferences in the workspace. In the following algorithm step, the image beforehand subjected to the binarization process, is transformed by a Canny edge detector. As a result, the contours of the workpiece in the WJ machine workspace are determined. Afterwards, the Hough transformation[5] is used. This algorithm operating on the contours of detected workpiece, approximates straight lines onto the image. By identifying the intersection of the approximated lines, the decision algorithm of PVS defines the workpiece corners.

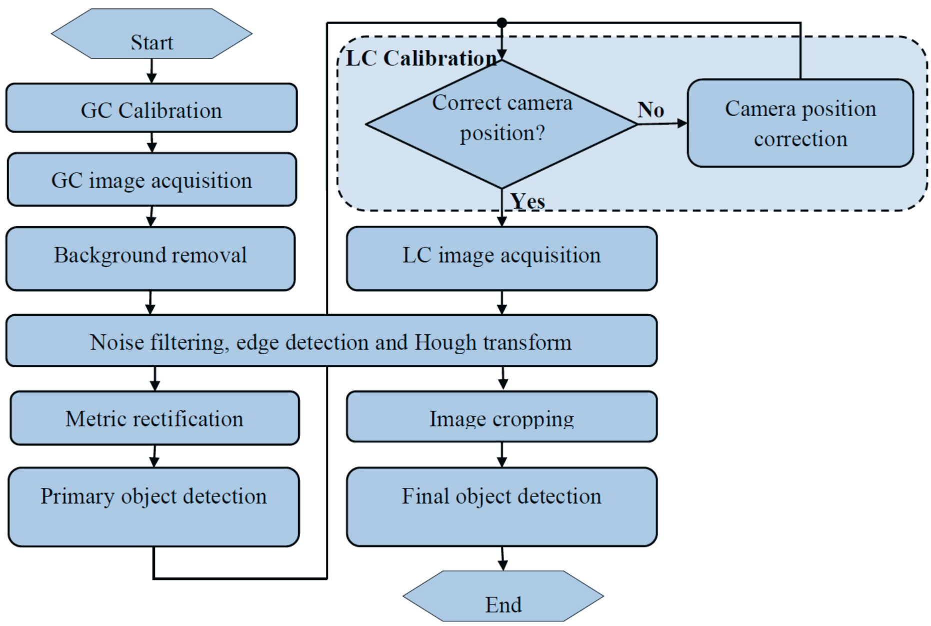

Figure 1: PVS algorithm block diagram

4 PVS Calibration

In situ calibration of the proposed PVS is a key part of an algorithm enabling the integration of PVS and WJ machine coordinate systems. To reach the required localization accuracy of ±0.5 mm, the manual calibration is insufficient. Therefore, it was necessary to develop an automatic calibration procedure.

For this purpose, a set of four reference markers of a color contrasting

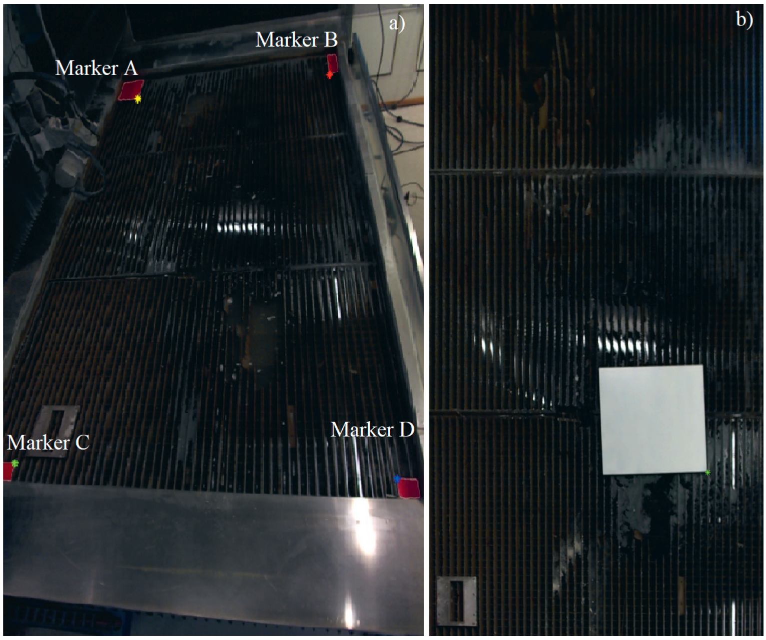

Figure 2: a) Calibration markers placement of WJ machine worktable, b) Image after rectification

with the WJ machine workspace are used. The markers are used for both GC and LC calibration. The procedure determining the relationship between WJ machine and camera coordinate systems is divided into two stages: first GC calibration, then LC calibration

4.1 Calibration of the Global Camera

For the calibration of the GC, four calibration markers of a color contrasting to the background are used so that they can be easy extracted on the histogram. The markers placed in the WJ machine worktable corners, see Fig. 6a, determine the actual workspace of the WJ machine, see Fig. 6b.

At the first calibration stage, the markers are extracted from the background of the image by means of color segmentation using thresholding defined as follow:

$$g(x,y) = \begin{cases} 0, \text{ where } f(x,y) < K_1 \\ f(x,y), \text{ where } K_1 < f(x,y) < K_2 \\ 0, \text{ where } f(x,y) < K_2 \end{cases} \quad (1)$$

where $g(x, y)$ is a matrix of the processed image; $f(x, y)$ is a matrix of the segmented image; K_1, K_2 are color threshold vectors determined empirically on the basis of the image histogram.

In the next calibration phase, the following steps are made: image binarization, noise filtering and contour detection. Then, by use of the Hough transformation, the lines are approximated and their intersections determines the corners of the workpiece. The calibration markers corners closest to the center of the image determine the approximate workspace of the WJ machine. Based on the coordinates of points determining workspace of the WJ machine, by applying the rectification process, the transformation matrix of the camera coordinate system into the WJ machine coordinate system is determined. In Fig.6b, the image of the working space after rectification is shown.

4.2 Calibration of the Local Camera

Due to the required accuracy of the workpiece localization and because of a lack of an additional lens, the LC was mounted next to cutting nozzle of the WJ machine. For this purpose, a fastening element has been produced, which could be easy disassembled. The images obtained from LC are used for both precise detection of the workpiece corners as well as in the calibration process of the camera itself.

The LC calibration procedure applies one of the calibration markers, which was exploited during the GC calibration. Due to area restrictions, the operation of the machine and the method of mounting LC, the marker A was chosen, see Fig.6a. The purpose of LC calibration is to determine the calibration vector, see Fig.7. On its basis, the distance by which the WJ machine nozzle should be moved is calculated so that it would be centered exactly above the designated corner.

The calibration process begins with moving the machine nozzle to the default position, which takes place, when the center of the LC sensor is above the corner of the calibration marker A. Then, analogously to GC calibration, the corner localization of workpiece calibration marker is done. After the correction of WJ machine position, the precision of the corner central placement at the image is determined. The entire calibration process is repeated until the detected corner is on the center of the image within precision of ± 1 pixel, which corresponds to 0.1278 mm if the mounting

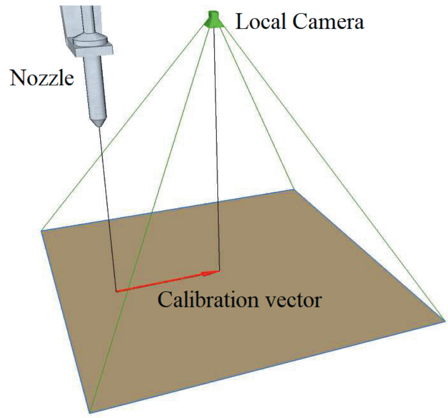

Figure 3: Graphical interpretation of calibration vector

height of the LC and its resolution are taking into account.

The estimated coordinates of the WJ machine nozzle position are subtracted from the known coordinates of the corner of calibration marker. In such a way, a calibration vector is calculated, by which the cutting nozzle has to be moved so that it would be located over the corner of the workpiece, with an accuracy of ±0.5 mm. The graphical interpretation of the calibration vector is shown in Fig. 7.

Based on the conducted tests, it can be concluded that two iterations are sufficient to obtain the required calibration accuracy. The case when more iteration would be needed may indicate that the camera is mounted incorrectly and that it is impossible to determine the corner of calibration marker position with the required accuracy.

5 The Assessment of an Impact of Calibration on a Workpiece Localization

To determine the impact of PVS calibration on the workpiece localization accuracy, a two-stage assessing process was carried out. In the first stage, the impact of calibration on workpiece localization accuracy of the GC was analysed. In the second stage, the impact of LC calibration on workpiece localization accuracy is assessed.

The GC is used for initial approximate localization of the workpiece

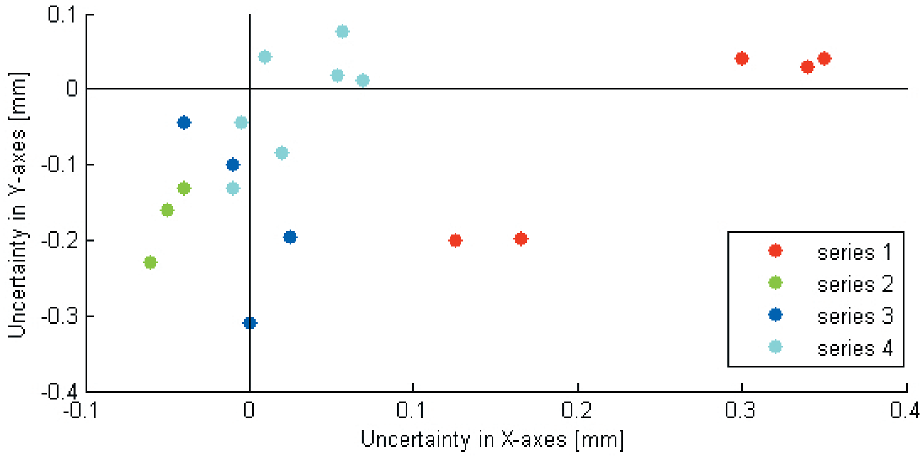

Figure 4: The localization uncertainty of workpiece corner detection with LC

placed on the WJ machine workplace. The coordinates determined during that process are used by the software designed for precise detection of workpiece corner by means of LC. A required accuracy of element location by means GC was ±60 mm. This value results from the limitation of LC's field of view. In a case of GC location accuracy less than ±60 mm, the workpiece could be placed out of the LC field of view.

The accuracy of the GC calibration is estimated by comparison of detected workpiece corner coordinates with the coordinates of workpiece corner detected by calibrated LC. Considering the mounting of the GC, the calibration marker *A* was located furthest away from the camera, see Fig. 6a, which results with the potentially largest inaccuracy of the workpiece location.

During the GC location accuracy tests, a set of 15 measurements was made. The average localization uncertainty of the corner calibration marker A by means of GC was 14.55 mm, and a standard deviation of 1.10 mm. The measurements results show that the proposed calibration method ensures accuracy four times better than the required one, which guarantees that the pre-located element will be placed in the LC field of view.

To estimate the accuracy of the LC calibration process, an assessment has been carried out of four measurement series. Fig.8 presents the results of measurements for each series.

For the first test series, the localization accuracy of the workpiece corner met the design requirements. However, further analysis showed that by adjusting the position of the calibration marker, it was possible to reach even greater accuracy. Measurements of the last fourth series indicated the localization accuracy of the workpiece corner of ±0.1 mm. Further exertions with the marker resulted with measurement uncertainties around the value of ±0.1 mm. Considering the positioning limitations of the WJ machine and the accuracy of the PVS the calibration inaccuracy was close to zero.

6 Conclusions

The purpose of this article was to present the proposed method of automatic calibration of the PVS installed on an industrial WJ machine.

Using four calibration markers of a color contrasting to the workspace, it was possible to calibrate the GC with an accuracy of ±15 mm, which was four times better than the design requirements. Such accuracy ensured that the corner of the workpiece was detected by a LC in each attempt. Moreover, by means of LC calibration resulting with appropriate calibration vector, the inaccuracy of workpiece corner detection can be reduced to values close to zero. Such accurate calibration in combination with PVS, ensured the detection of the workpiece corner at the accuracy level of ±0.1 mm, which is five times better than required by the stakeholders.

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Paper II

An Analysis of Uncertainty and Robustness of Waterjet Machine Positioning Vision System

Paper II

An Analysis of Uncertainty and Robustness of Waterjet Machine Positioning Vision System

D. DZIAK, B. JACHIMCZYK, W. J. KULESZA

Abstract

The paper presents a new Automatic Waterjet Positioning Vision System (AWPVS) and investigates components of workpiece positioning accuracy. The main purpose of AWPVS is to precisely identify the position and rotation of a workpiece placed on a waterjet machine table. Two webcams form a basis for the system, and constitute its characteristics. The proposed algorithm comprises various image processing techniques to assure a required identification precision. To validate the PVS identification quality, synthetic images were applied under various conditions. The analysis ascertains dependence of an object detection rate and accuracy on a size of cropping frame. Experimental results of the proposed PVS prototype prove that a combination of the vision algorithm and webcams is an alternative to dedicated expensive industrial vision systems. The two main components of AWPVS uncertainty, a machine component and PSV component are discerned and estimated.

Index Terms—Image cropping, object detection, vision system, waterjet machine, web camera.

1 Introduction

Nowadays, most cutting techniques require an operator who manually determines the starting point of the cutting process. The procedure is time consuming and imprecise, and causes unnecessary material loss [1]. A solution to this problem is automation by applying a vision system which shortens the positioning time and improves the cutting process accuracy. An application of vision system in Waterjet (WJ) technology has not yet been investigated extensively.

This paper is related to a previous work [1], where a new Automatic Waterjet Positioning Vision System (AWPVS) was presented. Here the uncertainty of the Positioning Vision System (PVS) is examined and factors of the uncertainty are analyzed. The focus of the paper is on workpiece corner detection and its accuracy analysis under various experimental conditions. The article demonstrates how cropping frame size affects the accuracy of corner localization and the manner of adjusting it to improve the PVS performance.

The presented results show a relationship between two components of AWPVS accuracy, mainly waterjet machine precision and the accuracy of PVS.

2 Survey Of Related Works

Attempts to utilize vision systems in WJ technology refer mainly to control of a cutting process [2]. Using a set of line scan cameras, a vision system is used to monitor the cutting process of planar objects placed randomly on a cutting table. To assure an appropriate lightening level, this system is equipped with an extra illumination unit; additional halogens were installed on the ceiling. Such mounting causes machine shadows on the workspace, which introduces an additional uncertainty in some areas. Uncertainties in edge detection caused by material height variations are corrected by a laser measuring device mounted on the machine. The calibration procedure uses a reference bar manufactured with high accuracy.

Another attempt to automate a WJ cutting process by means of a vision system requires equipping the main camera with servo-controlled lens located perpendicularly to the WJ workspace [3]. A system combining an inspection camera, central processing unit and a vision algorithm is used for quality inspection and optimization.

In case of AWPVS, the accuracy of workpiece corner detection constitutes a crucial issue. An image gradient analysis forms a basis for novel corner detection methods, such as MIC, SUSAN, Harris [4, 5]. However, the methods do not extract directly a corner position with subpixel accuracy. In order to obtain sub-pixel precision, the method based on Hough transform is proposed [6].

Cropping is a technique used to reduce an amount of irrelevant information in image processing, thereby to decrease computational complexity. This approach is widely used as an image enhancement tool as well as it may be adopted in optimization problems. Using a combination of artificial intelligence techniques with auto cropping methods, it is possible to simultaneously solve an optimization problem by maximizing an objective function and extract characteristic features [7].

3 Problem Statement And Main Contribution

From the review of related works one can observe that the WJ cutting process, which is a modern technique of separation and cutting of many types of materials, has not yet been fully automated. Among other issues, there is a need to automate the identification of a workpiece position in a workspace. Furthermore, a camera calibration and the ability to accurately specify the initial coordinates of the machine is a critical problem for any Computer Numerically Controlled (CNC) cutting technology [8]. On the basis of study of the vision algorithm, a problem related to system accuracy and its verification has arisen. The applied verification process relied on distance measurement between the estimated corner position of an element and the real one. It validated the whole AWPVS process. To determine the algorithm performance, further experiments are required.

Considering a verification problem of corner identification accuracy, the two main inquiries can be stated. The first one concerns the optimal cropping frame. The second issue refers to the relationship among the main uncertainty components of AWPVS.

Considering the first inquiry it was also hypothesized that the optimized size of a cropping frame leads to better PVS accuracy, however, it depends on image quality. Regarding the second query, it was assumed that it is possible to distinguish two main additive uncertainty components of AWPVS: a machine component and a vision system component. A machine uncertainty component can be computed from an estimated accuracy of the whole AWPVS and from a vision system accuracy component, which can be found from simulations.

The main contribution of this paper is the AWPVS accuracy analysis, verification and the procedure implementation in Matlab. To determine the relationship between the AWPVS components, estimation of the workpiece corner position was performed, using sets of synthetic images. Additionally, the influence of cropping frame size was tested for different noise levels.

4 Positioning Vision System

The main purpose of the PVS design was to identify with the required accuracy, the position and rotation of a white workpiece placed on the machine table [1]. The required identification accuracy of position was defined by the user as 0.5 mm. The required accuracy of rotation was defined in accordance with the workpiece size, and for instance, for a workpiece of 1 m the required angular deflection uncertainty should not exceed 1° [1]. To follow another design constraint, which was a system price, the system had to be made up of webcams.

4.1 Structure of the PVS algorithm [1]

According to the requirements, two webcams form a basis for the PVS where the first global camera (GC) is used to roughly detect a workpiece; the second local camera (LC) finds a workpiece corner with required precision.

The proposed PVS algorithm, consists of various image processing techniques Fig. 10. The object recognition process extracting the edges and corners of the workpiece, applies a background removal technique, an edge detection algorithm and the Hough transform. Auxiliary algorithms and functions, such as the metric rectification method, are used to obtain a top view of the workspace from laterally installed cameras, and to merge an image with waterjet machine coordinate systems. To complete the automation process, the in situ calibration procedures for both webcams are applied.

4.2 Implementation [1]

The PVS algorithm was implemented in MATLAB ver. R2012a and interacts with the machine control unit Simens Smnumeric 840d SL. The main program recalls all the vision application functions. The precise coordinates of the initial workpiece corner and angular deflection are the algorithm outputs.

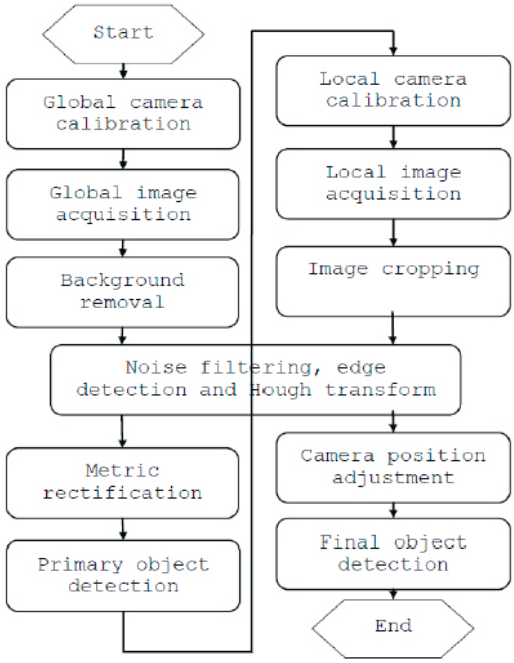

Figure 5: PVS algorithm block diagram

The vision system consists of two web cameras equipped with high definition 5 megapixel sensors with 24-bits true color depth. The sensor has a resolution of 2592 px $\times$ 1944px.

The used calibration markers are cut out of a stainless steel plate and painted in a color contrasting with the background. The markers have a rectangular shape and are fixed to ribs of the machine table. The corners of the markers, which are closest to the workspace center, indicate workspace corners.

5 Uncertainty Of Corner Detection Using Positioning Vision System

To examine the PVS accuracy, a set of synthetic images resembling the real operation conditions of the WJ was generated. The synthetic images show a part of workpiece with one visible corner. The image resolution of 2592 px $\times$ 1944px matches the resolution of images captured by the LC.

Figure 6: Images used for verification; a) image captured by the LC; b) synthetic picture.

Fig. 6 presents two images, a real image obtained by the LC, and a synthetic image.

To analyze robustness of the PVS corner detection algorithm the test images were contaminated with two different types of noise: a white Gaussian noise with mean value equal to 0 and varying standard deviation levels; and salt and pepper noise of various noise density.

To investigate an influence of image size on the detection uncertainty, the simulations for the whole image and for different sizes of cropping frame were run.

For each test, the PVS algorithm was run 100 times in order to identify the corner coordinates. The precision of the corner detection was measured as a distance between the defined corner coordinates of the synthetic image and the corner coordinates estimated by the PVS algorithm. If the distance was greater than required accuracy, the PVS algorithm result was classified as unsuccessful.

Cropping frame optimization. Cropping, a widely used image processing technique, enhances an image subject matter by removing outer areas from an image. As the size of an image affects the length of detected edges, the influence of the size of cropping frame on the PVS performance has to be investigated. The cropping frame is defined as a square with a specified length of side and intersection of diagonals indicating the identified workpiece corner.

To investigate how the cropping frame size affects the corner detection accuracy for different image qualities, simulations were performed for:

- Four different frame sizes: the whole image, 1500 px, 1000 px and 500 px;
- Two different types of noise: Gaussian and salt and pepper noise;
- Four different levels of noise.

Results within the required accuracy range for 100 simulations are presented in Fig. 7 and Fig. 8. Each bar group shows a mean value of uncertainty of corner identification for a given noise level. Each bar in the group corresponds to a different frame size. The uncertainty standard deviation for each case is depicted as a thin dashed line. Above each bar, the correct detection rate is presented, which is calculated using the following equation [4]

$$D_R = \frac{C_D}{C_D + C_N} x100\% \tag{2}$$

where D_R is a detection rate, C_D refers to a number of correctly detected corners and C_N refers to a number of failures.

Tests showed that differences in precision for distortion level below 0.02 are negligible; therefore results for not disturbed images are omitted.

The results prove that to optimize the performance of PVS, it is recommended to adjust a cropping frame size and the best results are achieved for 1000 px and 1500 px, depending on the noise level. Figure 9 shows the results for the two optimal cropping frame sizes. For low and medium noise levels the use of frame size 1000 px brings better results. The average uncertainty is about 0.03 mm, and standard deviation up to 0.015 mm. In these cases, the corner detection rate is higher than 96 %. However, for a relatively higher noise level, the recommended size of a cropping frame is 1500 px with the efficiency of more than 90 %, although the corner precision accuracy is the worst, it still fulfills the system requirements.

The simulation results show the robustness of the algorithm on Gaussian noise of standard deviation level up to 0.2 and also on salt and pepper noise of density up to 0.2. However, the algorithm is more robust for the salt and paper noise, because it was designed to filter out the kind of noise which remains after the primary filtering and background subtraction.

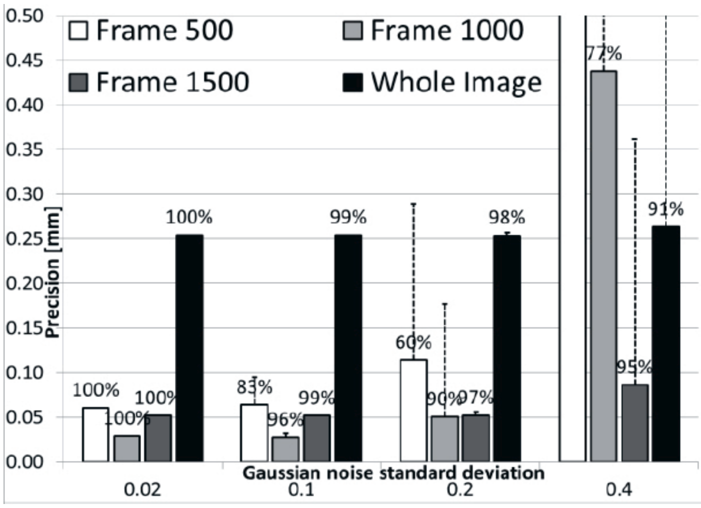

Figure 7: Precision of corner localization and detection rate for synthetic image distorted with Gaussian noise.

As for the smallest examined cropping frame of 500 px in all cases, the detection accuracy and corner localization rate are considerably worse than for bigger cropping frames. For the bigger cropping frame, a greater noise influence is compensated by longer edges used for corner detection [1].

6 Verification Of PVS Accuracy Analysis

In order to verify the accuracy of PVS one can find the relationship between the accuracy components of the AWPVS. The verification process was performed in two stages. Firstly, the PVS algorithm was tested using a set of synthetic images shown in Fig. 6(b). As the result of the test, the PVS accuracy has been estimated. The second stage required experimental discovery of the corner detection precision of the AWPVS and its comparison with the machine uncertainty. The corner detection accuracy of the whole AWPVS, Δ_{AWPVS} can be defined using

$$\Delta_{AWPVS} = \Delta_M + \Delta_{PVS}, \tag{3}$$

where Δ_{PVS} represents the PVS accuracy, Δ_M depicts the machine accuracy component.

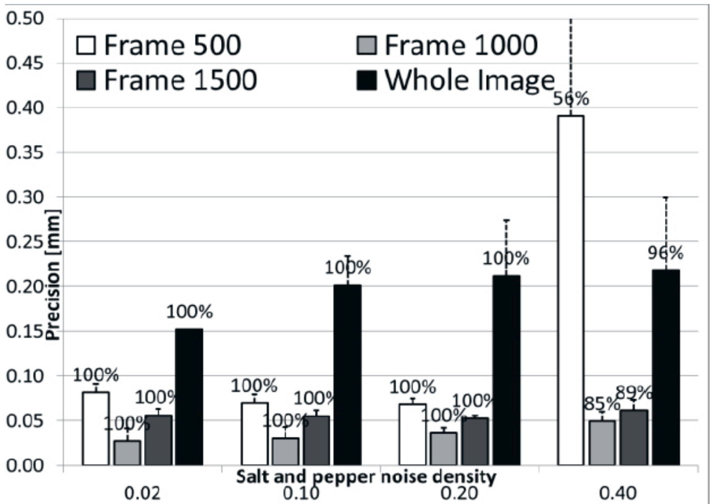

Figure 8: Precision of corner localization and detection rate for synthetic image distorted with salt and pepper noise.

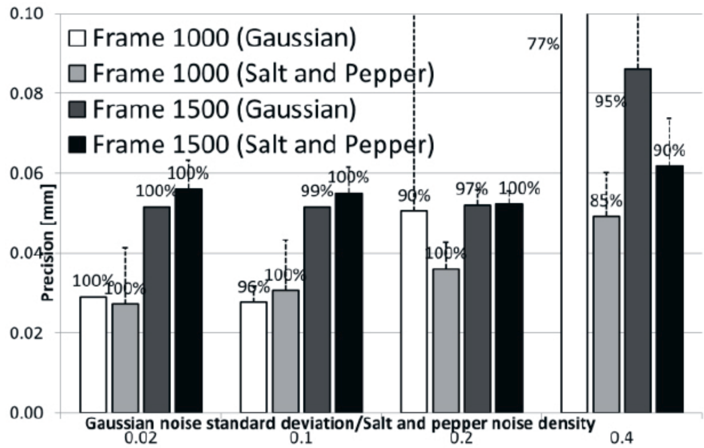

Figure 9: Optimal cropping frames for both Gaussian and salt and pepper noises.

From the waterjet machine specification it is known that the machine uncertainty during common operation mode is below 0.1 mm.

The experimentally proved accuracy of the AWPVS for cropping frame 500 px was also below 0.1 mm [1]. The used cropping frame of 500 px was chosen due to its best computational complexity within acceptable accuracy range. The result was proved using two independent methods. The PVS accuracy estimated using a synthetic image for the cropping frame of 500 px is represented by white bars in Fig. 7 and Fig. 8. It demonstrates that for the cropping frame, the accuracy of corner localization using the PVS is about 0.065 mm with a standard deviation 0.01 mm.

Applying experimental data to 3, one can notice that the real accuracy of AWPVS is higher than an algebraic sum of its components. Thus it can be concluded that the assumed worst case accuracy of the machine was too pessimistic and its real value is about 0.035 mm. It matches operators' opinions about the Waterjet machine precision.

From the results for optimized cropping frame sizes and the estimated precision of Waterjet machine, one can see that a possible precision of whole AWPVS can be at the level of 0.063 mm with standard deviation 0.015 mm.

7 Conclusions

The aim of this paper was to present the positioning vision system, intended for accurate positioning of waterjet machine, based on two webcams. Furthermore, the paper aimed to show a relationship between main uncertainty components of corner detection and investigate whether a size of cropping frame influences the accuracy of workpiece corner localization.

The experimental results summarized in Table I show that the PVS algorithm provides good results of corner detection estimation for different types of noise, without compromising detection efficiency.

Test results prove that due to its structure, the detection algorithm is characterized by a high resistance especially to high level of salt and pepper noise.

The results of the PVS accuracy verification confirmed that a determined machine accuracy component is 0.035 mm which confirms the waterjet machine operators' experiences.

The influence of square cropping frame size on the PVS performance was examined using synthetic images. From results, it can be stated that selecting the optimal cropping square size increases the PVS accuracy of corner localization.

For image distorted by Gaussian noise, the optimized accuracy is 0.3

Table 1: Average PVS Accuracy For Three Different Levels Of Noise

Frame [px]	**Mean value [mm]**		**SD [mm]**	
	S&P	Gaussian	S&P	Gaussian
500	0.07	0.08	0.01	0.07
1000	0.03	0.04	0.01	0.04
1500	0.05	0.05	0.01	0.00
Whole image	0.19	0.25	0.02	0.00

mm with 100 % detection efficiency. In case of salt and pepper distortion, the estimated accuracy of corner localization was about 0.04 mm with the same 100 % detection rate.

For a low and medium noise level it is better to use cropping frame size 1000 px. In case of images distorted with high level noise, the cropping frame of 1500 px is preferable.

Further development of the presented PVS may concern a survey of uncertainty and robustness of angular deflection estimation of an element. PVS can be adapted to industrial environment by being equipped with cameras with protective covers. The PVS algorithm can be developed to detect elements other than white or made of transparent materials. Moreover, the system may be developed for cutting optimization or workpiece material identification purposes.

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Paper III

Wirelessly Interfacing Objects and Subjects of Healthcare System – IoT Approach

Paper III

Wirelessly Interfacing Objects and Subjects of Healthcare System –IoT Approach

D. DZIAK, B. JACHIMCZYK, W. J. KULESZA

Abstract

Wireless sensor networks, WSN, for which development has begun by military applications, are nowadays applied to all human activities; e.g. in medicine for patience monitoring or to reduce the effects of disasters. Therefore, the WSNs area has been also one of the emerging and fast growing scientific fields. Increasing interest of WSNs is even caused by equally intense growth of interest in the Internet of Things domain, IoT, in which WSNs constitute a significant part. These reasons have brought about developing low cost, low- power and multi-function sensor nodes. However, the major fact that sensor nodes run quickly out of energy has been an issue and many energy efficient routing protocols have been proposed to solve this problem. Case study presented in this paper concern design of WSN in IoT concept from system lifetime perspective. A hierarchical routing technique, which shows energy efficiency, has been validated. Simulation results show that chosen technique prolongs the lifetime of the WSN compared to other investigated clustering schemes. The advantages of this method are validated by comparative studies.

Index Terms—Energy efficiency; Internet of Things, routing protocol; wireless sensor networks

1 Introduction

World Health Organization research [1] shows that over the last 25 years life expectancy was extended significantly, e.g. in Poland life lengthened by six years from 71 to 77 years. However the life expectancy between man and women differs eight years, what causes that elder population lives alone. Some of those people have mobility difficulties, symptoms of dementia or other health problems. In such cases there is a need to increase their safety by using monitoring systems, which could e.g. help them to take medicines in time, or in a case of fall, inform appropriate services and caregivers. Therefore, modern technology provides a variety of solutions among them there is a new promising approach concerning Internet of Things, IoT. This paradigm employs among others Wireless Sensor Networks, WSN, the technology, which is essential for this paper approach.

The IoT concept [2] integrates many different physical and virtual devices, such as distributed sensor nodes, actuators, mobiles and other devices called things [3], [4]. It has to be emphasised that WSN constitutes a significant part of IoT [5], [6] because this technology is feasible in many areas of everyday life, industry and science, including infrastructure protection [3], diagnostics, industrial measurements, and also environmental and health monitoring [7],[8],[9].

Fig. 10 illustrates how healthcare applications benefit from combining WSN technology into IoT paradigm. The WSN consists of network nodes where each node assembles and processes information from the environment and then sends it directly or indirectly to the base station and then to Internet. Such solutions could be used e.g. for tracking or monitoring vital signs of patients.

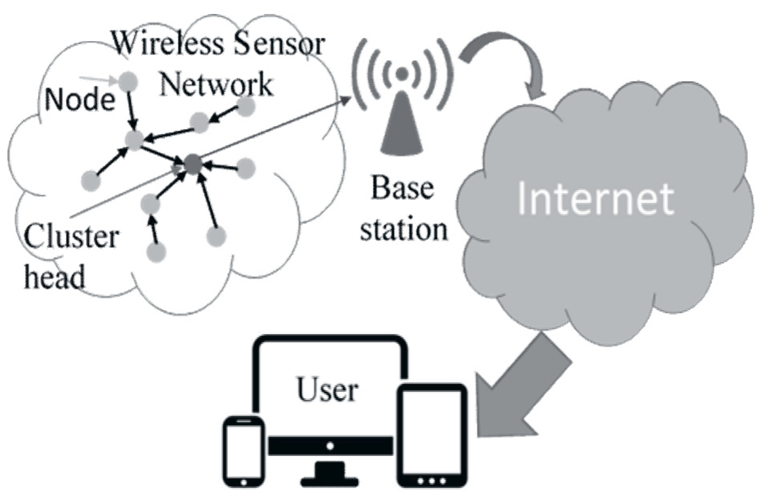

Figure 10: Example integration of WSN in IoT.

Most of nodes constituting WSN in IoT applications are battery-powered, then the energy issue becomes one of constraints limiting the whole network lifetime and thereby its applicability for healthcare purposes. Since sending information from a node requires most of energy, the way in which information is sent within the network and its quantity are essential for system lifetime [10].

Moreover, while designing a WSN based healthcare system in IoT paradigm, it is necessary to consider organization and structure of the network, which also affect its lifetime. The structure in turn determines the type of possible transmission protocols, which depends on the node location method and the required security [11].

The advantages of WSN combined within IoT paradigm facilitates design of an energy efficient healthcare system for patient monitoring. The paper focuses on the design process of a multi-sensor system for patient monitoring based on WSN in IoT paradigm, and considers the various aspects of the design, from the healthcare perspective. A case study of design of Wireless Body Area Network, WBAN, including an aspect of system lifetime in the design process is presented.

2 Related Work

The advantages and variety of wireless sensor networks make this technology suitable for IoT application in healthcare sensing systems. Among others the adaptability of smart wireless sensor node, which can adjust both its internal and external conditions is the crucial advantage. Due to this the entire network is scalable, reconfigurable and capable to auto-adapt in a case when some of the network components fail or degrade, or if networks' tasks or requirements change [5].

The driver of wide range of applications of WSN in IoT domain is development and technological capability of Micro-Electro-Mechanical Systems, MEMS, which constitute WSN sensors. Through this technology the miniaturized, high performance sensors have become cheaper and therefore widely available and commonly used [12], [13].

W.-Y. Chung, S.-C. Lee, and S.-H. Toh in [14] use advantages of wireless electrocardiography, ECG, and blood pressure sensors and combine them with cellular phone sending information to a hospital server when any suspected or unknown pattern of signals is detected. G. Bakul, D. Singh, and D. Kim [15] apply wireless Ultra-Wide Band, UWB, in an ECG monitoring system, which can be used at the same time by many patients in hospitals or other healthcare facilities. Data are gathered by wireless nodes, sent to an access point and then upload on a remote server via Internet. For wireless oxygen saturation and heart rate monitoring C. Rotariu and V. Manta [16] use Micro Power Oximeter Board from Smiths Medical and Texas Instruments module.

Many healthcare applications require to know actual position of either patient or equipment. A popular indoor localization approach is based on receiving signal strength, RSS, measurement. In this methods the localization is performed based on strength of Wi-Fi [17] or RFID [18] radio signal. A. Dobîrcău, *et al.* [19] in order to fit their system to IoT paradigm use low powered Wi-Fi RFID active devices, which send gathered information to an access point coupled to Internet. An interesting concept presented by Matteo Faraone, *et al.* allows to localize patient inside a room without a need to wear any device just by analysing RSS disturbance between sensor rows, evenly distributed on each wall of the room [20].

The localization methods for indoor purposes frequently are based on accelerometer, compass and gyroscope data e.g. Pedestrian Dead Reckoning method, PDR [21]. Superiority of these solutions is because they allow not only to localize a patient in a building with accuracy about one meter, but also the same data can be used for other purposes such as tumble detection [22] and even posture recognition [23].

Though in the most healthcare applications, just indoor localization is sufficient, sometime there is a need to track a person outdoor. In such a case wireless sensor nodes are equipped with a Global Positioning System, GPS, module. Today's GPS assures localization accuracy in city environment of about 6 m [24]. However, Chenshu Wu *at al.* show that by combination of GPS with PDR based on accelerometer, it is possible to increase localization accuracy up to 4 m.

Advantages and diversity of wireless sensor nodes and their applicability in IoT paradigm justify healthcare related applications called Wireless Body Area Networks, WBAN. Using several different sensor nodes, S.-L. Tan, J. Garcia- Guzman, and F. Villa-Lopez designed system for body temperature, heart beat rate, blood oxygen saturation and blood pressure measurements which using Wi-Fi transmits gathered data to a base station [25]. Moreover, they use accelerometers for posture and falls detection.

J. Wannenburg and R. Malekianc also developed the mobile health device for monitoring blood pressure, heart rate, oxygen saturation and skin temperature [26].They apply Bluetooth technology to transmit data to a smartphone.

Capabilities of WSN based IoT systems enable comprehensive recognition of patient behaviour. Systems, recognizing patient behaviour and classifying it as typical, abnormal or dangerous are helpful for patients at first stages of dementia or elderly people living alone, and even in caregiving facilities. L. Sun *et al.* use mobile phone with embedded accelerometer and Support Vector Machine, SVM based classifier to recognize different activities like walking, running, bicycling and others [27]. Liang Wang, *et al.* [28] designed a WBAN consisting of accelerometers and coin size RFID readers mounted on each hand of supervised people, and one additional accelerometer mounted on their waist. Furthermore, they apply passive RFID tags for labelling the equipment related to patient's different activities e.g. iron, mug, computer, etc. Using such system they recognize 25 different activities by matching current accelerometer data with the pre-defined activity set and identified RFID tags. M. Henar, *et al.* [29] use a Google Nexus S accelerometer, gyroscope, magnetometer, light and proximity sensor applied to fuzzy classifier to recognise body position and other activities.

Clifton Phua *et al.* [30], gather information from pressure, infrared and video sensors, accelerometer, RFID tags and compare them with 2-layer erroneous-plan recognition system which classifies behaviours based on blacklist, whitelist and naïve Bayesian classifier. The disadvantage of this method is that most of sensors do not operate wirelessly.

Another important aspect of WSN based IoT monitoring systems is patient's privacy. Most solutions using WSN in IoT domain do not apply a global addressing scheme [31]. Data gathered by an ad hoc established network are aggregated inside the network and then sent by cluster heads to the base station, which has its own IP address and is able to transmit information via Internet to the final user. Such solutions however can suffer of data security problem, due to vulnerability on attacks like: sinkhole attack, sniffing or energy drain [32]. Authors of [33] and [34] propose secure communication in WSN based on pairing identity encryption and pairing based cryptography over an elliptic curve respectively. Nevertheless, scalability of WSN using such data security methods is limited due to required additional power supplies for cluster heads.

Secure solutions for easy scalable networks was proposed by Md Mizanur Rahman et al. for WSN using identity-based encryption and pairing based cryptography [35]. For WBAN, Rghioui, L'aarje, Elouaai and Bouhorma [36], and Li, Lou and Ren [37] apply symmetric cryptography with a session key management system and a node authentication model with a special ID and attribute-based encryption access control respectively.

As it was mentioned, considering a WSN for healthcare application in IoT domain it is necessary to concern energy issue. As the transceiver consumes the most power of wireless sensor [38], an adequate communication technique has to ensure the energy conservation. This could be obtained with clustering technique [39]. The amount of consumed energy depends on the cluster size, smaller clusters consume less energy for internal communication but such a solution requires more energy for the external communication. Therefore, for this approach it is necessary to find out a trade-off between the cluster size and a number of clusters in the network [40]. Bandyopadhyay and Coyle [41] apply K-means cluster tree framework, in which the K value is optimal from the point of view of energy needed for communication within a cluster. The parameter K determines the maximum number of hops needed that information from any network node can reach the base station. The parameter also determines the maximum delay needed to send the data to the base station.

3 WSN Based IOT – Perspective Of Healthcare Application

As the survey of related work shows, a number of nowadays solutions of IoT sensing systems is based on WSN and many of them are designed for healthcare purposes. Due to system complexity, the design process of such system requires a comprehensive approach. Fig. 11 shows a flow of design process and interrelationships among different features and actors of the process, which are described in the following sections.

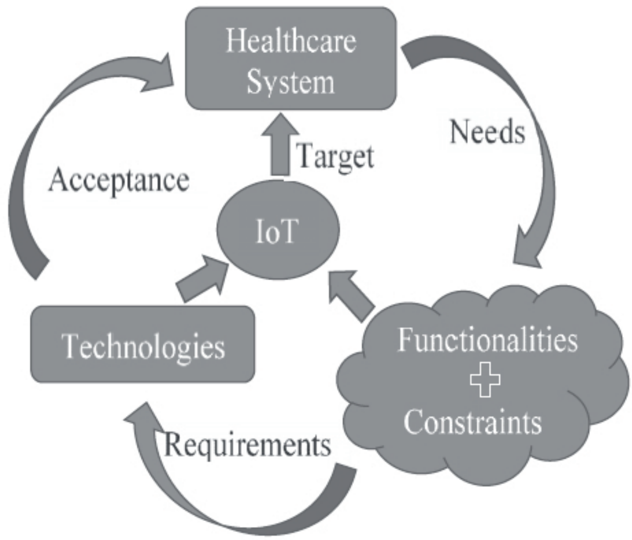

Figure 11: Healthcare application features and relationship among them in system design process

3.1 Healthcare System Target

The system contractor and/or service provider define the target and related needs, which define system functionalities and constraints. This way, the stockholders indirectly affect system final structure. A precisely defined system target is essential since systems even in the same application domain e.g. healthcare, could differ in many ways. The target, functionalities and system constrains together constitute design requirements.

This stage of the design is crucial for the final solution and requires cooperation of multidisciplinary team consisting of medical experts and investors, but even the future users who may have their wishes and limitations.

3.2 Functionalities and Constrains

An example of the system constrains expected from healthcare application is user's comfort. MEMS based WSN nodes without compromising prices and social aspects of the product, can satisfy comfort requirements and provide sensors that can be placed on patients, monitor their life parameters, tracking movement, analyse behaviour and even call for help while life threatening situations.

One of crucial functionalities of healthcare application is monitoring of patient's vital signs. Survey of related works indicates that wireless sensors facilitate monitoring among others ECG, blood pressure, oxygen saturation, and body temperature.

Features, which are especially valuable in healthcare applications with mobile patients, are their localization and movement tracking. In IoT domain, Wi-Fi or RFID technologies are most convenient for indoor localisation and tracking. Other useful technologies are accelerometers, compasses and gyroscopes, which not only allow patient's localization, but could be also used for posture recognition or tumble detection. When patients are allowed to stay outdoors, then localization data are supported by GPS.

In a case of serious diseases such as dementia the healthcare application may require analysing patient's behaviour or its changes, and reporting caregivers when current behaviour deviates from standard one.

Since most of wireless sensor nodes use batteries, system lifetime demands techniques saving energy and it is an important system constrains, which each designer of IoT healthcare application has to focus on. Discrete measurement methods belong to the energy saving solutions because the sensors are active just for short sampling instants. However, this sampling strategy is applicable just for slowly changing phenomena e.g. temperature or humidity. Detection of instantaneous, rapidly changing phenomena such as an acoustic pulse is considerably more complex. Another problem of measuring unsteady phenomena can be solved by means of its rarely sampling in node's sleep mode and awakening at an instant when a specific event occurs [12], [32].

WSN lifetime is determined by the *vigilance coefficient*, which is the ratio of the sensor's active time to its sleep time and the probability that the sensor is chosen as a cluster head or as a normal node. If *P(c)* is the probability that the sensor is a cluster head and *P(n)* denotes the probability that the sensor is an ordinary node in an active state then the current consumed by a sensor node can be estimated by [13]

$$I_c = P(c) \times I_a + (1 - P(c)) \times (P(n) \times I_a + (1 - P(n)) \times I_s), \quad (4)$$

where I_a and I_s are the maximum currents (in mA) of sensors in active and asleep states respectively, assuming that there is no other activity in the sensor node. Then the sensor's lifetime can be calculated using 4.

The lifetime constrain can be also approached from perspective of optimal design of WBAN, by studying the joint data routing and relay positioning problem [42].

Another constrain expected from good healthcare applications is preservation of patient privacy, understood as personal privacy as well also as collected data security. Wireless sensor networks are suited for both of these cases.

3.3 Technologies of WSN Healthcare Application in IoT

Presented functionalities and constraints defined by the system target together with IoT constraints constitute requirements for technologies, which could be used. For example, the healthcare target of designed system together with requests of WSN in IoT domain, constitute requirements for applicable technologies considering only wireless communication standards [30] like Wi-Fi, ZigBee [43], Bluetooth Low Energy, BLE, [44] or RFID [45].

Concerning energy limitations along with restraints of processing and storage capabilities of WSN in IoT domain, the functionalities and requirements of designed system determine a framework of routing methods and algorithms. The main types of routing algorithms are:

- data-oriented e.g. Sensor Protocol for Information via Negotiation, SPIN [46],
- hierarchical e.g. Low Energy Adaptive Clustering Hierarchy, LEACH [47],
- location-based e.g. Minimum Energy Communication Network, MECN, [48],
- based on Particle Swarm Optimization technique [49],
- Multi-Criteria Decision Analysis and Entropy Weights,EMCR, [50].

To assure an efficient and reliable transmission from network nodes to the base station and then via Internet to final user, the network should be properly organized. Clustering based on nodes' neighbourhood is one of the effective hierarchical sensor network organizations. In this method, each node, after identifying a base station, transmits data via head nodes of intermediate clusters to the base station. The method assures bandwidth and energy efficiencies by decreasing transmissions between clusters, optimizing transmission path and data fusion, which is in line with the system requirements and functionalities.

The conducted survey reveals several basic techniques of cluster forming e.g. Random Competition based Clustering, RCC [51], which applies a random timer. The registration of nodes to each cluster is based on a rule called First Declaration Wins, FDW [52]. According to the rule, the governing function is assigned to the node, which the first declares to become a cluster head.

Another important issue of cluster formation is a transmission method. There are two possible transmission methods: direct- and multi-hop–broadcasting, [39]. In a network with the direct transmission, a request initiating a cluster is randomly sent by a node. Direct transmission method is easy to implement but is not energy efficient, since it requires sending information to all network nodes. Even nodes located far away from the head node receive a call with no chance of its acceptance. In multi-hop transmission there are specified cluster ranges where the nodes are invited to participate in. The disadvantage of this method is a significant transmission delay compared to the direct technique. The delay is caused by data processing at each of the nodes along the multi-hop transmission path.

When the cluster is formed the selected head node governs the cluster. This node is responsible for data aggregation and control of transmission algorithms from each cluster node to the base station. In the case of a cluster with many nodes, load of the head node is greater in order to properly receive, aggregate and re-transmit the data. Since the role of the cluster head requires much energy, hence the rotation of the cluster head can lengthen the cluster life.

The cluster head can be chosen randomly or pre-defined by the network designer. Random assignment of the heading functions is based on the probability that the new selected node has never been the cluster head. This rotating assignment leads to reduction of the load on the heading node.

If selection of the cluster head is based on a power residuum, then the heading role is taken by a node having the most energy. The roles can change after the end of the cycle when it is noticed that heading node energy falls below the average energy of all clusters. This method of selecting the heading node significantly lengthens the network life [53].

Another way of allocation of cluster heading function is based on the principle of minimizing the total distance from the cluster head to all nodes in the cluster. Since the transmission energy depends on the distance to the receiver the alternative minimum transmission path reduces power consumption in the cluster [54]. Hamed extended this approach with unequal size clustering formation, where clusters closer to the base station, which have to re-transmit data even from farther clusters, have fewer nodes than clusters far from base station [55].

Further constrain for WSN healthcare application in IoT paradigm is a hardware matching. In a case when sensors are worn by a human, the proposed device cannot cause any discomfort and should be as light as possible and of compact size. They should also be compatible with chosen communication technologies and allow adding extra sensors and/or remove these unnecessary. Such capabilities, are provided, inter alia by an Arduino platform [56].

The presented analysis justifies the use of IoT technologies for healthcare application, however, the design process should be a well-planned, because beside the target there must also be considered functionalities and constrains which constitute the important requirements of designed system.

4 A Case Study Of Design A Multi-Sensor Healthcare Application In IoT Paradigm

Considering the target of design application as a patient monitoring in nursing home care and defined earlier requirements and technologies, some design aspects need to be considered and verified as it is exemplified in this section.

The case study presented in this chapter consists of two approaches. Section 4.1 concerns design of WBAN dedicated for nursing home care patient monitoring. The second approach deals with energy efficient root node selection [57] and cluster formation method [58], [59] presented in sections 4.2 and 4.3 respectively.

4.1 Design of Arduino based Wireless Body Area Network

One of possible technologies matching mentioned targets is Arduino solution, a commonly available electronics prototyping platform, which is inexpensive, open-source, easy programing with availability of many extensions, actuators and sensors.

An Arduino board, equipped with modules such as AltIMU-10 V4, GPS/GPRS/GSM V3.0, Polar T34 Heart Rate monitor and WiDo Wi-Fi IoT Node, is designed and prototyped allowing monitoring patients in nursing home care, see Fig. 12.

AltIMU-10 v4 module with gyroscope, accelerometer and magnetometer and using PDR method are applied to localize a patient inside the nursing home care building. Moreover, accelerometer and altimeter data are used for tumble detection and posture recognition. In a case of localization outside the building GPS/GPRS/GSM V3.0 module is employed.

Data form Polar T34 heart rate monitor are exploited as additional assessment supporting decision if abnormal situations like a tumble actually occurred, because during such situation heart pulse of monitored person is higher than in normal position. Moreover, the system reports to caregivers if low or high heart rate has lasted for a longer time.

WiDo WIFI IoT node operates for communication with the base station, which aggregates and sends data via Internet to the caregivers in nursing home care. Wi-Fi standard is used to facilitate internal communication among other nodes, constituting WSN.

Mentioned modules are designed to be mounted on a chest belt and are managed with the Arduino Leonardo board.

4.2 Modified Algorithm of a Root Node Selection

As the IoT paradigm requires reliable access to things, then to assure the system reliability, its lifetime becomes the crucial system parameter.

In the proposed modification of the LEACH routing protocol, the choice of the cluster head is based on prediction of energy consumption in the next transmission round and minimizing the data transmission path to the base station. The proposed algorithm consists of four stages:

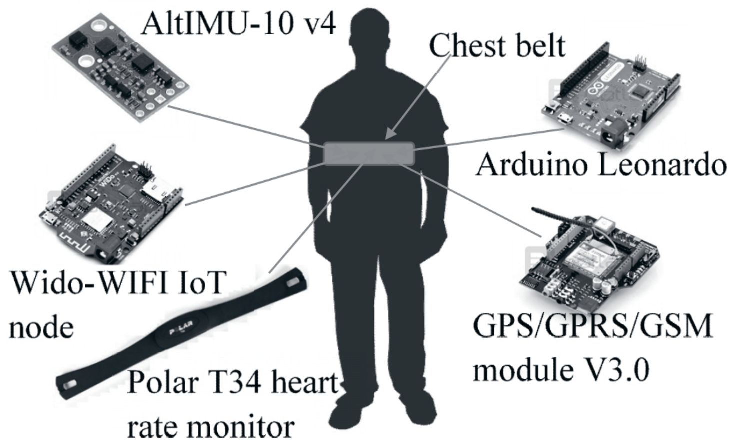

Figure 12: Components of the proposed WBAN system for patient monitoring in nursing home care.

- dynamic formation of clusters based on the geographic principle,
- selection of all cluster heads,
- in each cluster, aggregation of data from all cluster nodes in the cluster head,
- data transmission to the base station or to the cluster head located closer to the base station.

The procedure of selecting the cluster heads starts from a clusters closest to the base station. Initial energy E_{in}, of each cluster node and its distance d to the base station are estimated. Then the energy required for transmission k bytes from any potential cluster head to the base station is calculated using the relationship: $E_{amp} \times k \times d^2$ and then based on the relationship: $E_{in} = E_{amp} \times k \times d^2$, a node which has the largest energy residuum is appointed to be the cluster head. The same procedure is repeated successively to the next clusters further from the base station using estimated distance d to the head of the cluster closer to the base station.

The procedure was implemented in Matlab and simulated using parameters listed in Table 2.

250 points are randomly distributed in three equal clusters of the area of 300 m300 m, corresponding to possible positions of monitored patients in a

Table 2: Simulation Parameters

Parameters	Symbol	Unit	Value
Number of nodes	N	-	250
Initial energy of each node	E_{in}	J	200
Transmission packet size	K	byte	100
Energy consumption per bit to run the transmitter	$Eelect$	nJ/byte	50
Energy consumption per bit to send signal into the open space	E_{amp}	pJ/bit	100
Network area	S	m*m	300×300
Coordinates of the base station	x,y	-	(0,0)

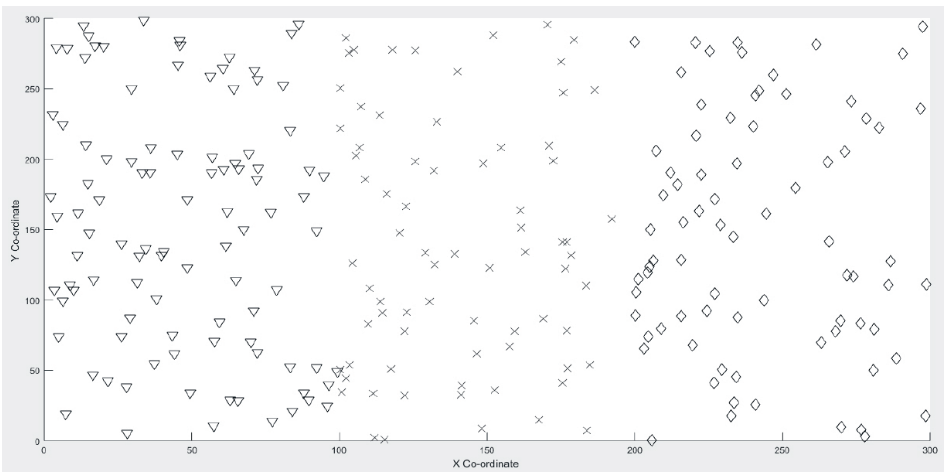

Figure 13: Second level hierarchical formation with differentiated shape indicating the three clusters where membership to each cluster is notified by different symbol.

garden what is illustrated in Fig. 13. Lifetime curves of the proposed system for three different network structures: non-hierarchical, and hierarchical of first- and second-order are shown in Fig. 14.

The nodes lifetime curves prove the advantage of hierarchical structures. The death of first node in the first level hierarchical case is observed ten times later than in the non-hierarchical case and the system is able to work almost 1.5 times longer.

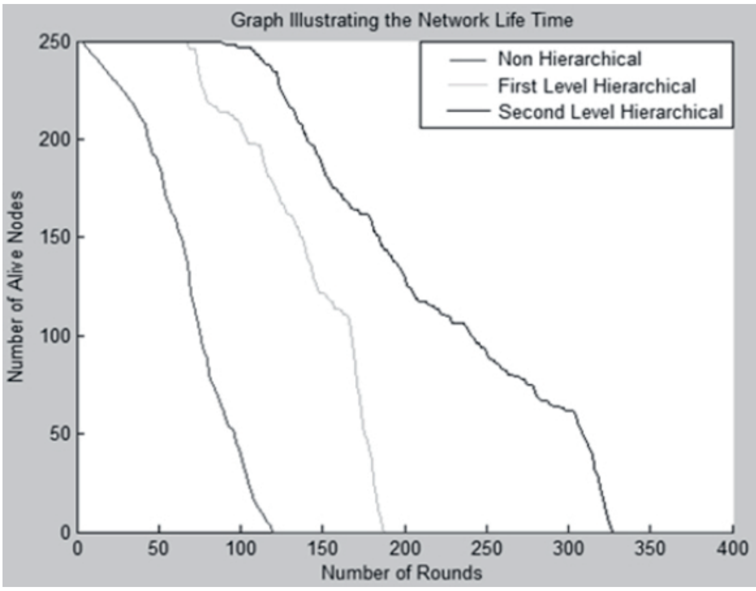

Figure 14: Comparison of network lifetime for different level hierarchical formations applying the proposed modification of the LEACH routing protocol.

Moreover, Fig. 15 shows histogram of the residual energy after 300 rounds for non-hierarchical and hierarchical of first and second-order structures. As one can see the amount of residual energy remaining in the network with non- hierarchical structure is much smaller than both first- and second-order hierarchical cases, what means much longer operation time of hierarchical network.

It could be also observed that the higher hierarchy level and a greater amount of clusters improve the network lifetime. However, it can be foreseen that the number of clusters and their populations have to match each other to optimise the network lifetime.

4.3 Energy Efficient Cluster Formation Method

Further extension of the WSN lifetime is possible due to appropriate cluster formation method. We propose using the K-mean algorithm to define the optimal distance between network nodes and the cluster head [60]. The proposed algorithm consists of five steps:

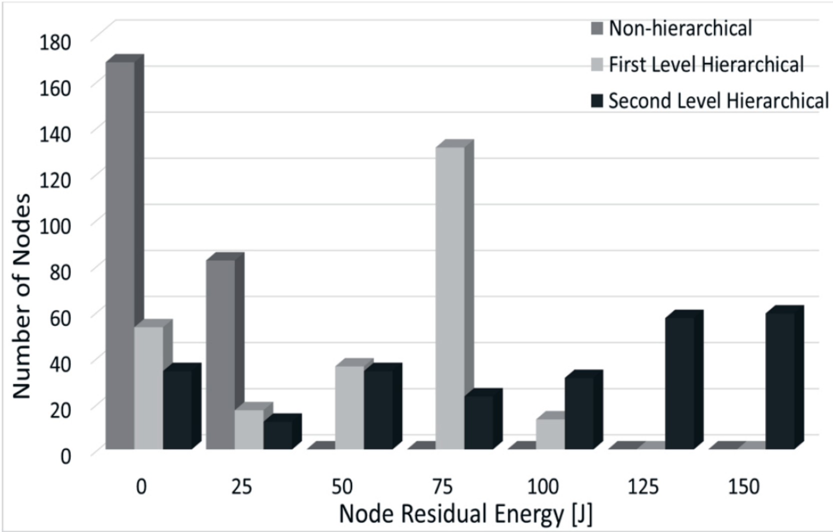

Figure 15: Histogram of residual energy for different level hierarchical formations after 300 rounds.

1. Defining a number of clusters,
2. Selecting an initial cluster headings in each cluster,
3. Estimating the distance from each node to all initial cluster headings,
4. Assigning each node to the nearest heading initiator,
5. Formation of clusters consisting of nodes placed closest to the heading initiators.

To analyse the proposed solution a case of nursing care home has been implemented and simulated in Matlab. 100 patients are randomly positioned in a garden of area 90 m × 80 m. Each patient is equipped with a node, with the same initial energy. The simulation results are shown in Fig. 16.

The simulation results are compared with the results of the method when clusters are formed geographically. It could be denoted that even with a small number of nodes the death of first node with K-mean clustering method occurred six times later than in case where clusters were formed geographically. Moreover, the proposed system was able to work almost two times longer.

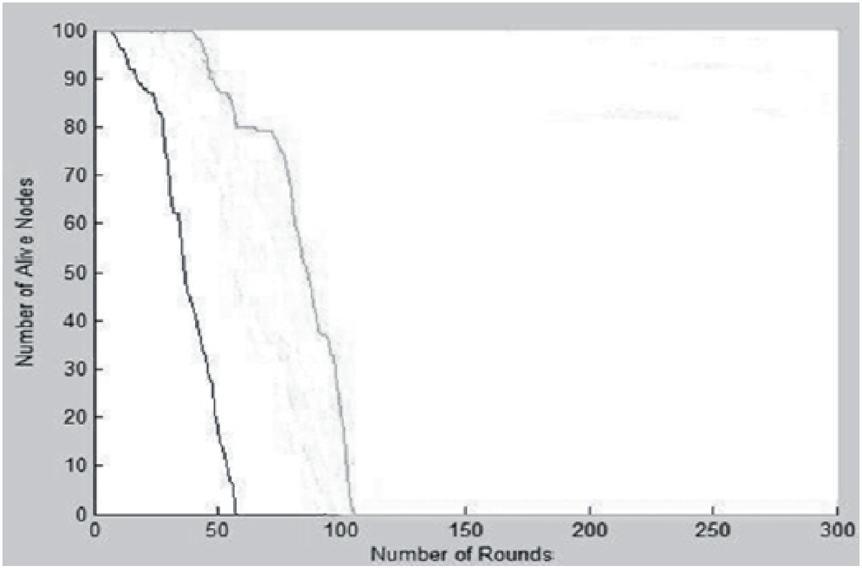

Figure 16: Comparison of node lifetime for second level hierarchical formations and a different clustering method, the black line indicates geographical clustering and the grey one indicates clustering using K-mean method.

4.4 Results Discussion

The designed, prototyped and tested system consisting of an Arduino board, equipped with modules such as AltIMU- 10 V4, GPS/GPRS/GSM V3.0, Polar T34 Heart Rate monitor and WiDo Wi-Fi IoT Node, is a suitable solution allowing monitoring patients in nursing home care.

Simulations results prove that modification of the LEACH routing protocol causes that death of first node occurs ten times later than in basic method and the system lifetime becomes 50% longer.

Moreover, residual energy after 300 rounds for second- order hierarchical structure surpasses the one with non- hierarchical structure, confirming longer operation time and superiority of hierarchical structure.

Furthermore, K-mean cluster formation method results in death of first node six times later and prolongs almost twice the system lifetime compare to geographical method.

5 Conclusions

The authors analyse the system design procedure from perspective of healthcare WSN in IoT domain. The analysed design procedure shows complexity and interdependency of the comprehensive design process. The procedure requires combined effort of many actors approaching the problem from different perspective. Precise pre-defined functionalities and constraints are essential to optimise choice of applied technologies.

The presented case study concerns a solution for nursing home care dedicated to patient supervision by means of their localization using Arduino technology equipped with accelerometer, magnetometer, health rate monitor, Wi-Fi and GPS modules.

The case study illustrates how to modify the applied methods and technologies to meet to system constraints. For instance the lifetime of analysed system can be extended by choice of the suitable energy efficient algorithm of root node selection and cluster formation method.

Future works consider implementation of the design procedure in real world. The design implementation is going to be realised as an EU project involving several contributes including institutions of public conveniences, industry and academia. Furthermore the analysis of security issues in the proposed system is planned. Moreover, the system could be extended with additional sensors useful for healthcare applications.

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Paper IV

IoT-Based Information System for Healthcare Application - Design Methodology Approach

Paper IV

IoT-Based Information System for Healthcare Application - Design Methodology Approach

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Abstract

Over the last few decades, life expectancy has increased significantly. However, elderly people who live on their own often need assistance due to mobility difficulties, symptoms of dementia or other health problems. In such cases, an autonomous supporting system may be helpful. This paper proposes the Internet of Things (IoT)-based information system for indoor and outdoor use. Since the conducted survey of related works indicated a lack of methodological approaches to the design process, therefore a Design Methodology (DM), which approaches the design target from the perspective of the stakeholders, contracting authorities and potential users, is introduced. The implemented solution applies the three-axial accelerometer and magnetometer, Pedestrian Dead Reckoning (PDR), thresholding and the decision trees algorithm. Such an architecture enables the localization of a monitored person within four room-zones with accuracy; furthermore, it identifies falls and the activities of lying, standing, sitting and walking. Based on the identified activities, the system classifies current activities as normal, suspicious or dangerous, which is used to notify the healthcare staff about possible problems. The real-life scenarios validated the high robustness of the proposed solution. Moreover, the test results satisfied both stakeholders and future users and ensured further cooperation with the project.

Keywords: accelerometers; activity recognition; classification algorithms; design methodology; fall detection; healthcare; dead reckoning; thresholding

1 Introduction

Nowadays, life expectancy significantly differs from that of 25 years ago. Research of the World Health Organization [1] indicates that over the last 25 years, life expectancy in Poland lengthened six years. Moreover, the research of Kontis et al. shows that with high probability, by the year 2030, life expectancy could lengthen for another three years [2]. However, men's and women's life expectancy differs in most cases in favor of women, e.g., in Poland by eight years. Such a situation causes a significant part of the elderly population to live alone. In some cases, such people have mobility difficulties, symptoms of dementia or other health problems, but still would prefer to live in their homes and surroundings. Therefore, there is a need for information systems that could facilitate such a life without compromising people's safety. This can be done by means of an autonomous system, which monitors people's position and their vital signs and is able to distinguish different activities and situations, reacts accordingly to the degree of danger and alarms, e.g., appropriate services or caregivers.

The aim of this paper is to propose an Internet of Things (IoT)-based healthcare information system intended for indoor and outdoor use where a methodological approach to the design process is in focus. A distinguishing feature of this approach is that the contracting authority's and future users' perspectives and needs are included in most stages of the design process. Moreover, in the proposed approach, the designer from the beginning has to think comprehensively to merge human and technical constraints and requirements. The proposed user-driven Design Methodology (DM) is used to solve the problems of the real-life scenario of supporting seniors living alone, especially those with limited abilities to manage their daily lives. The conducted design process results in a system proposal that meets the required assumptions.

The conducted case studies verified that the designed system, consisting of the Inertial Measurement Unit (IMU) with a built-in three-axis accelerometer, gyroscope, magnetometer and altimeter, together with Wi-Fi and heart rate modules and applying thresholding, Pedestrian Dead Reckoning (PDR) and decision trees algorithms, works properly in the tested real environment. The achieved person's localization accuracy within one meter fits the required four room-zone level localization accuracy in an apartment environment. The developed fall detection algorithm proved effectiveness of 98%, and other required activities were recognized with 95% compliance. Moreover, the proposed behavior classification algorithm is able to distinguish normal behaviors from suspicious and dangerous ones, working properly in almost 100% of cases.

2 Survey Of Related Work

The Design Methodology (DM) of a product or system has been of interest to many researchers. Already in 1991, A. McKnight proposed a definition of DM as "... a sequence of activities required to get from one stage of the design process to another" [3].

R. Prasad and H. Kobayashi, in order to improve hardware description language design productivity, propose the nine-step multi-methodology design process model consisting of system specification, system partitioning, modeling or adaptation, component simulation, system binding, system simulation, pre-synthesis modification, logic synthesis and logic simulation [4]. Their solution enables the diminution of the time required for modeling and simulation-related activities by 31% and 16%, respectively, compared to the classical hardware description language-based design.

The design methodology proposed by S. A. Mengel et al. contains the three stages: requirements, specification and implementation [5]. At the requirements stage, the designers should focus on the key concept of the problem and propose a graph with the structure of the system. At the specification stage, they refine the proposed graph into the content flowchart, which should be easily implementable into the considered system in the last design stage. Moreover, after each DM stage, the validation and verification should be carried out to ensure that the key concepts would have been met.

To improve the productivity of the complex electronics system design, H. Eskelinen proposes to apply two questionnaires to the traditional four-stage electronics system design, which are: system design, electronics design, mechanical design and design for manufacturing [6]. Those questionnaires are used to form requirements lists of electronic system components.

F. Wang and M. J. Hannafin state that the design-based research should be "pragmatic, grounded, interactive, iterative, flexible, integrative, and contextual" [7]. Based on this assumption they form nine principles of the design-based research: support design with research from the outset; set practical goals for theory development and develop an initial plan; conduct the research in representative real-world settings; collaborate closely with participants; implement research methods systematically and purposefully; analyze data immediately, continuously and retrospectively; refine designs continually; document contextual influences with design principles; and validate the generalizability of the design.

A. Saini and P. Yammiyavar chose the user as the focal point of the design of m-health system [8]. They use the object-oriented system design methodology, typical for software development, and then study interactions and relationships between the system requirements and the components of user's needs and goals. User-driven design becomes especially useful in health applications, where the stakeholders and different kinds of users may express different requirements and constraints.

The suggested DM approach of M. Ahmad considers five design aspects: the target field failure rate, expected use environment, expected environment use conditions, expected enclosure use conditions and expected product internal conditions [9]. The method is applicable to estimate the target's lifetime in the Internet of Things (IoT). It uses the probabilistic approach for estimating hardware reliability with given uncertain use conditions while considering overall system reliability.

Emerging technologies create new opportunities, and the robust monitoring of persons or things, alike, in indoor and outdoor environments, becomes of interest to many scientific and industrial applications, where one of the most important is the healthcare domain. However, the conducted survey reveals that design methodologies, despite their efficacy, have not yet been of great interest to designers in the field of healthcare information systems in IoT. The emerging healthcare applications are possible due to the development in Micro-Electro-Mechanical Systems (MEMS), which enable the integration of various devices like actuators, sensor nodes or mobiles [10],[11].

It is preferable that the devices used for monitoring purposes operate wirelessly [12], forming Wireless Sensor Networks (WSNs), which constitute the substantial part of IoT [13]. WSNs are widely used in healthcare applications due to their advantages and diversity. In [14], C. Rotariu and V. Manta propose WSN for monitoring patients' heart rate and oxygen saturation. W. Y. Chung, S. C. Lee and S. H. Toh embed Electrocardiography (ECG) and blood pressure sensors into a cellular phone [15]. The wireless body area network is an example of a suitable approach to the IoT healthcare paradigm. S. -L. Tan, J. Garcia-Guzman and F. Villa-Lopez use Wi-Fi technology to transmit data about the blood pressure, heart rate, body temperature and oxygen saturation to the base station [16]. J. Wannenburg and R. Malekianc apply Bluetooth technology and a smartphone for monitoring the patient's health parameters [17].

In IoT healthcare applications, one of the most frequently-monitored issues is the localization of patient or equipment. For this purpose, depending on the application, various methods and technologies are used. Numerous approaches are based on Received Signal Strength (RSS) [18]. M. Shchekotov uses RSS measurements from several known Wi-Fi access points assuring the localization accuracy at a four room-zone level on a single floor of a building. In order to localize an asset in the healthcare environment, the authors of [19] use the existing infrastructure of the Wireless Local Area Network (WLAN), extended just with six access point beacons. Based on Wi-Fi RSS measurements and small Wi-Fi tags, they are able to localize the assets like wheelchairs, beds, etc., with an accuracy of about 2 m in the hospital clinic environment of 63 m $\times$ 46 m size. W. H. Chen et al. use RFID RSS measurements of the reference and monitored tags to estimate the cost function consisting of the disparity and similarity of RSS between monitored and reference tags [20]. In this way, the three optimal reference tags are found, and the position of the monitored tag is determined as the center of mass of the triangle, which they form. The average localization error of a patient or asset in a 5 m $\times$ 10 m healthcare environment is about 0.74 m. F. Palumbo et al. propose the stigmergy approach combined with RSS measurements of Bluetooth Low Energy (BLE) [21]. Their approach results in a localization error of less than 1.8 m in 75% cases in a 6 m $\times$ 6 m furnished office. J. Wyffels et al. propose a healthcare dedicated indoor localization algorithm based on BLE RSS measurements and least squares-support vector machine, resulting at the four room-zone level localization accuracy [22]. The authors of [23] focus on patients' localization, tracking and monitoring in the nursing institute environment. They use RSS measurements of the ZigBee standard and a particle filter. As a result, they achieved an average localization error of less than 2 m in 80% of cases.

Different algorithms and methods can be used to improve the localization accuracy. In [24], the authors use the Radio Frequency Identification (RFID) fingerprints method and the artificial neural network, which enables a 3D localization accuracy of about 70 cm within a room-sized environment. A different approach to the indoor localization problem is shown in [25] where the authors used fingerprints of Wi-Fi and barometric pressure to localize a target with the floor accuracy of a six-floor building. Their Barometer-aided Wi-Fi (BarFi) floor localization approach detects the target's floor correctly in 96.3% of cases.

An interesting solution of the Pedestrian Dead Reckoning (PDR) algorithm is presented by Kang and Han in [26]. They use data from off-the-shelf three-axis gyroscope, magnetometer and accelerometer smartphone sensors in an in-building environment. The proposed method ensures the mean localization accuracy of 1.35 m with the maximum localization error of 1.62 m. The authors of [27] use data from the accelerometer, magnetometer and gyroscope to recognize a person's posture and to detect the tumbling of the person [28].

Information about the position of a monitored person or equipment is valuable not only for localization, but also it could be used for patient's behavior recognition. This is especially useful while monitoring the elderly living alone or a person at the first stages of dementia. For this purpose, L. Wang et al. apply coin-sized RFID readers on both hands of a patient and one accelerometer on the patient's waist [29]. Using this set, along with a passive RFID tag, they are able to recognize 25 different activities of the supervised person. H. Martin et al. are able to recognize a person's activities and body position by means of Google Nexus S embedded sensors like the magnetometer, gyroscope, accelerometer, light and proximity sensors and a fuzzy classifier [30].

Most of the mentioned monitoring solutions have the common drawback of being dedicated just to indoor environment applications. In the case of an outdoor healthcare monitoring purpose, most of the enable solutions apply the Global Positioning System (GPS) [31], which in the in-city environment provides localization accuracy of about 6 m. Ch. Wu et al. combine GPS data with gyroscope and accelerometer data using the dead reckoning algorithm, which results in an improvement of the in-city localization accuracy up to 4 m [32]. For outdoor behavior recognition, L. Sun et al. apply the mobile embedded accelerometer and Support Vector Machine (SVM)-based classifier, to recognize activities like bicycling, running and walking [33].

The mentioned monitoring solutions are dedicated exclusively to just one, an indoor or outdoor, environment. A multi-environment localization solution was proposed by Millner et al. in [34]. The authors, using the Symeo local positioning radar, are able to localize animals with an accuracy of 0.5 m in 75% of cases in both indoor and outdoor environments; however, the major constraint of the system is its applicability in an environment with low multipath distortions. J. Gonzalez et al. combine Ultra-Wide Band (UWB) and GPS technologies and a particle filter to localize a robot in the indoor and outdoor environments with a localization accuracy of about 2 m [35].

However, these multi-environmental solutions, in turn, are difficult to implement in healthcare applications inter alia due to the size of the devices used. A localization system relatively easily implemented in healthcare, both indoor and outdoor environments, is presented in [36]. It is based on RSS measurements in a ZigBee network [37]. The major drawback of this solution is a significant number of needed reference nodes with known positions and the maximum distance from the reference node of 15 m, which considerably reduces the applicability of the system from the large outdoor environment.

A promising approach to the multi-environmental patient monitoring system is proposed by R. Tabish et al. [38]. They propose a monitoring system of the patient's temperature and ECG based on 3G/Wi-Fi IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN). While the monitored person occurs in an indoor environment, the system uses local Wi-Fi for sensors' data transfer, and in the case of the outdoor environment, the 3G/4G technology is applied. The drawback of this solution is a limited number of monitored vital parameters.

3 Problem Statement and Main Contributions

The number of related publications is enormous, and this review provides only examples of solutions, which in the authors' opinion give a map of the development fields. However, the review of related works indicates that although a variety of solutions is used in the IoT healthcare-monitoring domain for indoor and outdoor environments, a methodological approach to the design process is still missing; where design is understood as "scientific principles, technical information and imagination in the definition of a structure, machine or system to perform pre-specified functions with the maximum economy and efficiency" [39] classification requires improvement and development.

To fill the gap in the methodological approach to the design of a comprehensive information system for healthcare applications, the objective of this paper is to propose a systematic design procedure, which can enhance the development of healthcare appliances. Apart from technical requirements, the procedure considers multifarious constraints, including the lifetime, energy efficiency, usage comfort and even the price. The case study of the design process is an IoT-based system for monitoring people and things multi-environmentally capable inter alia of behavior recognition and diagnosis. The system is dedicated to support and localize elderly people in their multi-room apartments along with a multi-story building, but even outdoors in the building's surroundings. The system's functionalities consist of monitoring vital signs, posture recognition, suspicious behavior detection and classification.

The development procedure approaches the design target from the perspective of the stakeholders, the authority in charge and the potential users, as the view of the system developers. The proposed design methodology is modelled and then implemented and validated on the case study of the system for multi-environmental monitoring of elderly people living alone. The system has been implemented and validated in real scenarios.

4 Methodology of System Design

The problem of exclusive indoor or outdoor monitoring of patients or elderly people is complex; including both indoor and outdoor cases is even more compounded, especially in the case of IoT. Therefore, to carry out the design of such a system, we propose to systematize the design process. The proposed design methodology illustrated in Figure 17 is composed of two main stages: problem formulation and product development, each consisting of three different steps. Moreover, to avoid the omission of any important aspects of the designed system, the stakeholder's, future user's and designer's perspectives are taken into consideration at each stage of the design process.

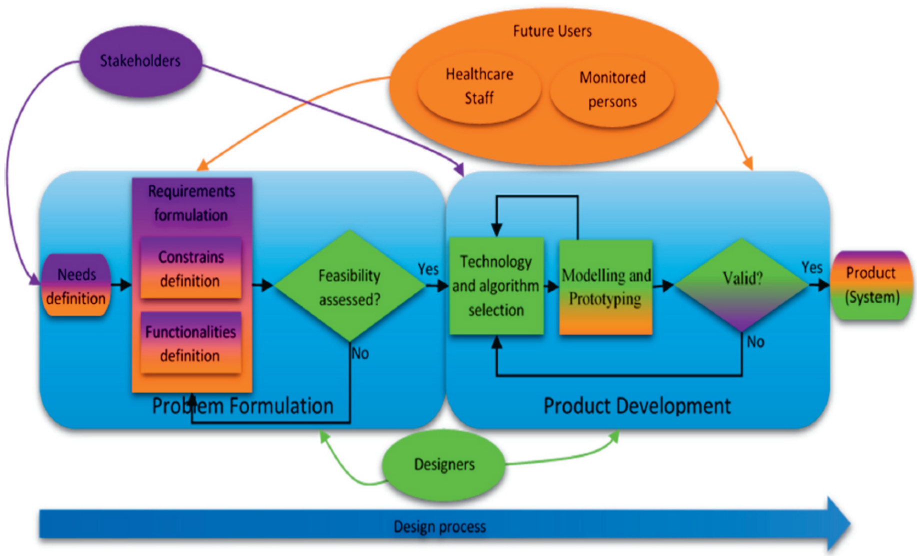

Figure 17: Flowchart of the proposed design methodology

4.1 Problem Formulation

The problem formulation stage consists of three steps: need definition, requirement formulation and feasibility assessment. Since an essential aspect of the proposed DM is the involvement of all project contributors, i.e., stakeholders, future users and designers, each of them may have a contribution to the problem formulation. However, their goals and expectations of the future system can differ. For example, the user can focus on convenience, safety and confidentiality; the healthcare staff may aim at the system's reliability, ease of operation and maintenance, along with the utility of the obtained information. The stakeholders additionally consider financial and marketing aspects of the product, and then, the designers focus on the design tools and their knowledge and experience.

4.1.1 Needs Definition

This step begins the design process when the stakeholders introduce to the designers the concept and define the general problem. In the proposed DM, this stage should be performed together with the future users in order to include their desires. With such an approach, both stakeholders and future users can express their needs and expectations of the outcome of the working system. In this step, participants should not focus on detailed requirements, but rather general goals of the system, so that the designers would be able to preliminarily assess whether the problem is solvable with their resources.

4.1.2 Requirements Formulation

The requirements formulation is the essential step of the proposed DM. At this stage, the stakeholders and future users firstly formulate the desired system's functionalities such as fall detection or localization of monitored person. Furthermore, the constraints associated with the developed system like costs, size and required lifetime are introduced. In a case of multi-environmental usage, the functionalities and constraints in each of the considered environments have to be defined. These functionalities and constraints constitute the requirements for the designers; moreover, this is how the stakeholders and future users can indirectly affect the structure of the developed healthcare system.

4.1.3 Feasibility Assessment

The designers have to assess the feasibility of the general needs and specified requirements formulated by the stakeholders and future users. Moreover, they have to consider whether the existing possible solutions are able to solve the stated problems and assess whether the needs and requirements are realizable at all. The designers have to take into account also the constraints resulting from the desired working environments. If the designers encounter a problem in accomplishing the requirements, the stakeholders and future users would be asked to modify the requirements in a way that can satisfy them. After assessing that, all requirements can be met, and then, the product development stage can begin.

4.2 Product Development

Usually, due to the challenging trade-offs and diversity of the desired functionalities and constraints, the selection of suitable technologies and algorithms has to be carried out carefully in the following three steps: technologies and algorithms' selection; modeling and prototyping; and then solution validation. Furthermore, at this design phase, the stakeholders and future users are involved; however, it is the designers' responsibility to lead the dialog with all contributors. The main duty of the future users and stakeholders during the product development is to supervise whether all of their needs and requirements are implemented. After verification of the functionalities and constraints, the eventual necessary improvements can be postulated.

4.2.1 Technologies and Algorithms Selection

At this stage, the designers propose technologies and algorithms, which are in line with the desired functionalities and constraints stated by the stakeholders and future users at the problem formulation step. Then, in choosing technologies and algorithms, the constraints arising from the environment, like indoor/outdoor or high humidity, in which the designed system will operate, have to be considered. Furthermore, the suitable technologies and algorithms have to be pondered with respect to the price constraint, and then, after the primary elimination, only a few possible solutions would remain; therefore, the price may indicate the final decision. However, if there are no suitable solutions accomplishing the requirements, or the solutions lack some of the functionalities or constraints, then the designers have to propose and develop new solutions or adapt the existing ones.

4.2.2 Modeling and Prototyping

Modeling and prototyping the system are the main tasks of the designers. These tasks require the most time and may involve experts of different fields. However, in user-oriented design, the models and prototypes have to be endorsed by both designers and future users. This is an iterative process. The designers evaluate the solution's performance, and the future users check if the functionalities and constraints defined by them are accomplished. If something is missing or needs an improvement, the designers have to get rid of bugs and complement any shortcomings. The process continues until all contributors are satisfied. Then, the final outcome has to be validated.

4.2.3 Validation

The stakeholders along with the designers have to validate whether all system's needs and requirements have been accomplished. Now, it is also possible to verify the costs of the product and accept the price. In the case of any discrepancy between the desired needs and requirements and the prototyped multi-environmental healthcare information system, the designers have to examine the proposed technologies and algorithms and come back to the initial stage of product development. Nevertheless, if both stakeholders and designers approve the results, the system is ready to be implemented and launched into a service.

5 Case Study: Problem Formulation

The proposed design methodology is implemented and validated on the case study of a healthcare system for multi-environmental monitoring of elderly people living alone in the Silesia region in Poland. The designed system can be used not only to support and localize the elderly people in their multi-room apartments located in multi-story buildings, but even outdoors in the buildings' neighborhood.

5.1 Needs Definition

The growing number of elderly people is a global problem, and many local authorities, also of the Polish region Silesia, acknowledge its importance and are working on it. The general needs and targets introduced by the stakeholders and future users represented by elderly people and their families have considered possibilities to support elderly people, especially those of limited mobility, living alone or patients with the first symptoms of dementia. The support can be yielded by means of an autonomous system monitoring the target's position, their vital signs and able to recognize different activities and even classify human behavior.

5.2 Requirements Formulation

The functionalities, desired by the stakeholders and future users, consist of the localization of the monitored person in his or her apartment with up to four room-zone level accuracy, but also within a multi-story building, where the apartment is located, with a floor level accuracy. Furthermore, the person's positioning in the building's outdoor neighborhood with an accuracy of at least 10 m is desired. Moreover, the system, in all of these surroundings, should be able to monitor the target's vital signs and even detect the person's fall.

To recognize the required behavioral changes of the monitored person, in addition to the localization and fall detection, there is a need to distinguish the person's postures, like sitting, standing, walking or lying. It is even requested that the system should classify if a current behavior is normal, suspicious or dangerous for the monitored person and, in the case of unusual occurrences, notify the people responsible for care. In the instance of conduct that is classified as suspicious or dangerous, a subsidiary part should provide supplementary information about some vital signs.

According to a division of constraints into the two categories of general and particular, the reliability, size and comfort of device-wearing and even a maximum price of 200 EUR for the complete system are classified as the general constraints of the system. Moreover, the demands that the system should be easy to install, operate and maintain and even assure the subject's privacy are also the general constraints of the system. The operational time of at least one week, necessary for many reasons, can be categorized as particular. The localization accuracy in the considered environments along with the reliabilities of activities and fall recognition are particular constraints. Furthermore, real-time secure non-invasive measurements are crucial particular constraints of the vital signs' monitoring. The high validity of the behavior classification is also considered as a particular constraint. Both general and itemized functionalities, along with the particular requirements, are summarized in Table 3. The table consists of possible technologies and algorithms, and these, which fulfill the stated requirements, are bolded.

5.3 Feasibility Assessment

The needs, functionalities and constraints presented by both stakeholders and future users need to be scrutinized by the designer. After the comprehensive analysis, the general needs of a system supporting elderly people living alone with limited mobility or with the first signs of dementia are assessed as technically accomplishable and feasible. Furthermore, the performed research proved that the related functionalities and constraints concerning the working environments, activity recognition, vital signs' monitoring and behavior classification are also technically feasible at a moderate level of technical and algorithmic complexity. Nevertheless, the trade-off between the desired low price and the system's reliability and the further constraints has been acknowledged as challenging.

Table 3: Technologies and algorithms related to itemized functionalities and particular constraints.

Functionalities		Particular Constraints [1]	Possible Technologies and Algorithms [2]
General	Itemized		
Localization	In apartment	four room-zones level accuracy	Bluetooth, **PDR**, RFID, Wi-Fi fingerprints, UWB
	In building	floor level accuracy	**Atmospheric pressure**, RFID/**Wi-Fi fingerprints**, Bluetooth, UWB
	Outdoor	10 m accuracy	Bluetooth, **GPS**, GSM, **PDR**, Wi-Fi
Activity recognition	Fall	validity >95%	**Accelerometer**, RFID, Wi-Fi, decision trees, genetic algorithms, neural networks, **thresholding**
	Lying Standing Sitting Walking	validity >85%	
Vital signs monitoring	Heart rate	non-invasive method	acoustic, electrocardiogram, **infrared**
Behavior classification	Normal Suspicious Danger	high validity	**Decision trees**, genetics algorithms, neural networks, **support vector machines**, **k-nearest neighborhood**
Control	Easy to handle	fast	**Inter-Integrated Circuit**, Serial Peripheral Interface
Communication	Possible long range up to 40 m	secure	Bluetooth, **Wi-Fi**, RFID

[1] General constraints: wearing comfort, convenience of use, high reliability, assuring privacy, reliable, one-week operation time
[2] Selected technologies/algorithms are indicated in bold

6 Case Study: Product Development

6.1 Technologies and Algorithms' Selection

The selection of appropriate technologies and algorithms from a set of possible solutions was carried out for the preliminary defined functionalities and constraints. Table 1 presents the specified functionalities along with the related constraints and facilitating the possible technologies and algorithms, where the technologies and algorithms recommended by the designer as most suitable are bolded.

For an indoor localization in an apartment at four room-zone level resolution, the PDR algorithm, based on three-axial accelerometer and magnetometer data, is chosen. The reason for this recommendation is the small size of the accelerometers and rotation sensors, which should ensure comfort during use. Another motive of this solution is the use simplicity of the PDR algorithm, which fulfills the convenience of use constraint. Moreover, this solution does not require any extensive infrastructure or any additional sensors, making it easily implementable in any environment. Another advantage of this solution is that the same acceleration and orientation readings can be also used for the recognition of other monitored people's activities.

The BarFi algorithm [25], which applies the Wi-Fi signal and fingerprints of atmospheric pressure measurements, is selected for an indoor localization in a multi-story building with a floor level accuracy. This combination, in addition to meeting the floor level accuracy constraint, maintains the easy operation of the system. Moreover, due to its versatility and simplicity, the Wi-Fi technology can also be useful for communication between the designed device and the PC.

The (GPS) and the PDR-based hybrid method introduced by Ch. Wu et al. [32] are chosen for the outdoor localization with an accuracy of at least 10 meters. This alternative is justified by the GPS's availability and easy feasibility. Moreover, the PDR algorithm is likewise proposed for the indoor localization, which allows increasing the outdoor localization accuracy without any additional equipment.

To detect a subject's fall, we propose to apply the three-axial accelerometer along with the thresholding method. The same set of technologies would either be sufficient for the required identification of the subject's four different postures and activities.

Due to the lack of an accessible suitable behavior classification method, we developed the classification algorithm based on the decision trees algorithm, which should assure the required reliability.

The heart rate can be noninvasively measured by the water-resistant wireless Polar T34 heart rate monitor, which is mounted on the person's chest with an adjustable elastic strap, ensuring comfort while in use. The applied simple noninvasive acoustic-based method does not require any additional electrodes nor gels. Moreover, the adjustable elastic strap can be useful to mount other elements of the designed system.

The general design constraints of the system, including the small size, low energy consumption, easy installation and use along with low price, are supported by applying the Arduino technology and its compatible devices [40]. The system's long-life demand can be assured by using energy-saving adaptive algorithms, which for instance adjust the localization sampling with respect to the actual subject's position.

The selected technologies and algorithms operate in an unobtrusive manner without contravening the integrity of the monitored person. The system collects and processes only insensitive data like the monitored person's position, activity or heart rate. It monitors people without the violation of their privacy. This way of handling personal integrity is appreciated by the future users. Furthermore, the procedures of data treatment assure the restricted access of exclusively trusted people including the healthcare and medical staff, doctors and, if necessary, the liable family members of the monitored person.

6.2 Modeling

6.2.1 Localization Method

The proposed PDR method for the indoor localization applies the measurements from the three-axial accelerometer gathered with a sampling frequency of 90 Hz. In the case study, the accelerometer's normal working position is vertical; Figure 18 shows the orientation of the accelerometer axes. The person's localization is based on the information about the previous position, number of steps, their length and their direction.

The previously estimated position is stored in the device memory or in

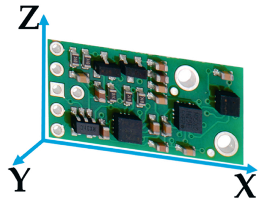

Figure 18: Accelerometer $x-$, $y-$ and $z-$ axis orientation.

the case of the first use of a device, it is set manually at the calibration point. The number of counted steps S_c is estimated using three-axial accelerometer data consisting of acceleration readings in the x, y and z directions, which define the Signal Magnitude Vector (SMV) calculated as:

$$SMV = \sqrt{x_i^2 + y_i^2 + z_i^2} \tag{5}$$

where x_i, y_i, z_i are the i-th sample of acceleration in the $x-$, $y-$ and $z-$axis, respectively. The step is detected when SMV exceeds the empirically chosen threshold. The threshold has to be adjusted to the walking manner of the monitored person.

The step length S_l, approximately unalterable, due to the walking manner of an individual, should be set as fixed and also has to be determined individually. Using such data, the M factor is determined as:

$$M = S_l \times S_c \tag{6}$$

In the last stage of PDR, the magnetometer along with gyroscope readings are used to estimate the direction θ of the step [26]. Finally, the person's position can be calculated as:

$$\begin{bmatrix} \widehat{x}_k \\ \widehat{y}_k \end{bmatrix} = \begin{bmatrix} \widehat{x}_{k-1} \\ \widehat{y}_{k-1} \end{bmatrix} + M \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \tag{7}$$

where $\hat{x_k}$ and $\hat{y_k}$ are the coordinates of the estimated position, $\hat{x_{k1}}$ and $\hat{y_{k1}}$ are the coordinates of the previously estimated position, θ is the heading direction and M is the factor from (6).

Foremost, occasionally, the system has to be calibrated by activating the device in a known location of the apartment; for instance, while the person is sitting in an armchair or while standing on the clearly marked place in the middle of the antechamber.

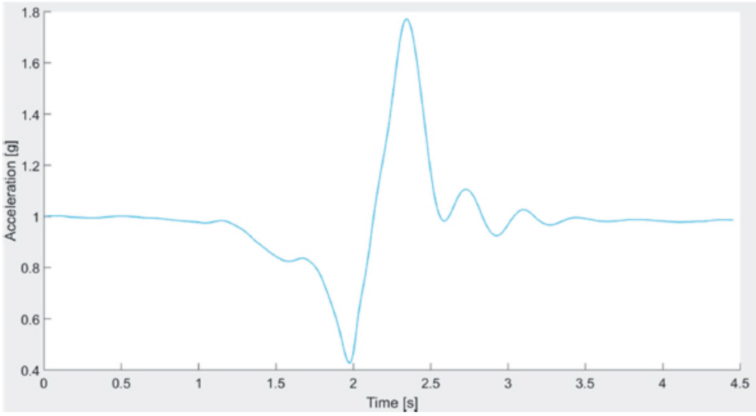

Figure 19: Exemplary SMV characteristics for the fall test.

6.2.2 Activity Detection

The activity detection means recognition of the subject's posture and/or action. There are five different states that should be distinguished, such as sitting, lying, standing, walking and falling.

As the most dangerous case, reliable fall detection is the most vital. The SMV defined by (5) is a suitable measure to detect a fall. The tumble causes changes in the SMV with distinctive positive and negative acceleration peaks corresponding to its beginning and the final contact with the floor, as shown in Figure 19. However, in some cases, e.g., a rapid onset of the walk could create similar SMV changes. Nevertheless, it is possible to avoid false alarms by monitoring also the accelerometer measures in the $x-$, $y-$ and $z-$axes or by an additional localization and posture checking.

The information about a dynamic posture, such as walking, is determined on the basis of the three-axial accelerometer and magnetometer along with the PDR algorithm, used also for the localization method described in the previous subsection. Whenever the designed system detects a step, the system interprets such activity as walking.

The subject's static postures, such as lying, sitting and standing, can be recognized and distinguished by means of the three-axial accelerometer and magnetometer. The lying position can be easily distinguished from the other postures because in this position, gravity affects mostly the acceleration z-component, whereas when standing and sitting, the y direction is the dominant acceleration component caused by gravity. Therefore, a suitable discriminator can determine when the z-component exceeds the other two components. The most difficult is to distinguish between sitting and standing. These postures cause similar acceleration with just small acceleration deviations resulting from slight movements of the body. Therefore, the system cannot differentiate between characteristic features of sitting and standing; however, it can detect the change of posture. Analyzing the accelerations in the x, y and z directions along with the SMV vector makes it possible to find out the threshold levels to distinguish between sitting down from standing up. Moreover, using appropriate threshold levels makes it possible to distinguish the actions of lying down on a bed from a sitting position and also the action of getting up from the lying down position.

6.2.3 Person's Behavior Recognition

Beside the auxiliary activity recognition, the core function of the designed system is the classification of normal, suspicious and dangerous behaviors of the subject. To make it possible, we propose to create a fingerprint of ordinary behaviors in a given temporal and spatial environment of a subject's life. Following the stakeholder's constraint, Figure 20 illustrates a layout of the possible living environment, which consists of five rooms, including the bathroom, bedroom, corridor, kitchen and living room. Furthermore, each room could be divided into two or three zones dedicated to specific activities. For example, the bedroom could be divided into two zones; one zone around the bed, where sitting and lying activities are considered as normal behaviors, but longer walking or standing should be considered as suspicious and even dangerous when prolonged. The second zone is located near the entrance to the bedroom and around the closet, where standing and walking activities are normal, but sitting and lying should be indicated as suspicious or dangerous.

The flowchart of the behavior classification as normal, suspicious or dangerous is presented in Figure 21. Data obtained from the sensors are combined with information about the occurrence, such as the time of day, section of apartment and its zone, then how the current activity is defined and placed in the current activity map. Next, the map is compared with the pattern map of normal behaviors and by means of the machine learning method, and the occurrence is classified.

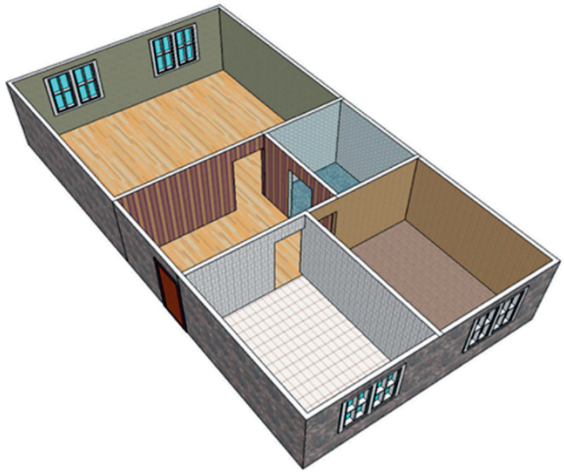

Figure 20: Sketch of an exemplary five-room apartment.

The behavior classification method can make use of the advantages of different machine learning algorithms like decision trees, Support Vector Machines (SVM), k-Nearest Neighbor (KNN) and the Behavior Vector, (BV). The authors propose to base the behavior classification on the six-component BV consisting of five components based on collected data, such as Time of Day (ToD), Section of Apartment (SoA), Zone of Activity (ZoA), Form of Activity (FoA), Duration of Activity (DoA), and the sixth component is Class of Behavior (CoB), based on the previous observations of the monitored person.

The ToD component is measured using the microcontroller's timer and configurable timeframes, which can be adjusted to personal habits and even changes due to seasons. The SoA and ZoA components are determined from the predefined layout of the apartment and estimates of the PDR indoor localization method. The FoA component results from the proposed activity recognition method, and the DoA component is calculated from timings of recognized activity. The timeframe patterns of normal behaviors of CoB components will be adjusted based on observations of three different elderly persons, two females and one male, during their daily activities.

The behavior is considered as suspicious if its duration exceeds the timeframe of normal behavior up to the 150%. The dangerous behaviors are those that cannot be recognized either as normal or as suspicious behaviors.

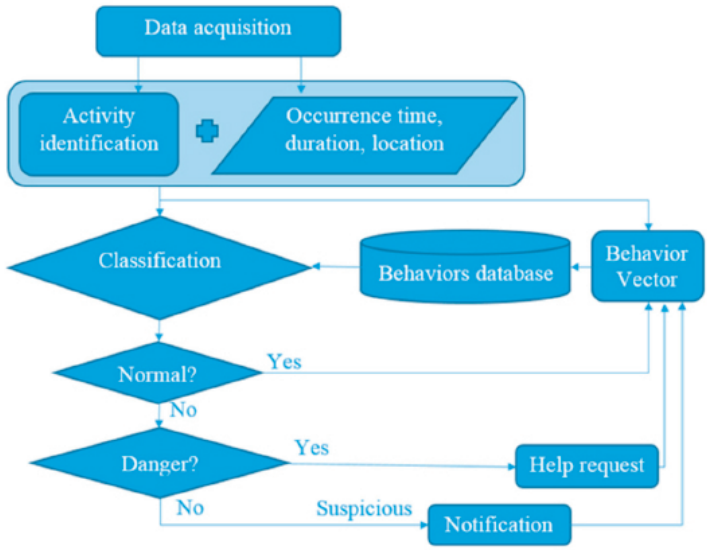

Figure 21: Behavior classification scheme.

Table 4 presents the possible states of each component of BV.

Table 4: Components of the behavior vector.

ToD	SoA	ZoA	FoA	DoA (min)	CoB *
Morning	Bathroom	of lying	Lying	10/15/30/ 120	Normal
Afternoon	Bedroom	of sitting	Standing	15/23/45/ 180	Suspicious
Evening	Antechamber	of standing	Sitting	>15/>23/ >45/>180	Danger
Night	Kitchen	of walking	Walking	-	-
-	Living room	-	Tumble	-	-

* ToD, Time of Day; SoA, Section of Apartment; ZoA, Zone of Activity; FoA, Form of Activity; DoA, Duration of Activity; CoB, Class of Behavior.

According to the requirements, in the case of suspicious and dangerous behaviors, additional information about the monitored person's heart rate, H_r is required.

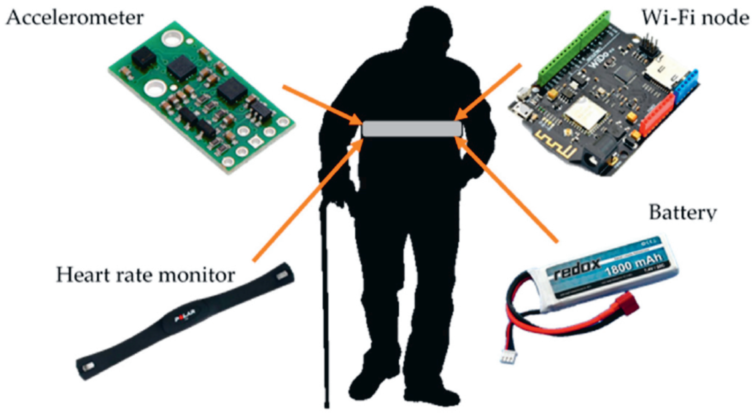

Figure 22: Component setup of the designed system prototype [41].

6.3 Prototyping

The realized prototype of the system consisting of the designed components is illustrated in Figure 22, where the core of the system is the Arduino-compatible WiDo WiFi WG1300 module equipped with a microcontroller ATmega32u4 and supporting communication with the 2.4-GHz IEEE 802.11 b/g standard. Moreover, the system consists of the Inertial Measurement Unit (IMU), AltIMU-10 v4 with built-in three-axis gyroscope, accelerometer and magnetometer and altimeter. Both devices are mounted on the Polar's T34 Heart Rate Transmitter chest strap and powered with the Li-Pol Redox 1800 mAh 20C 2S 7.4-V battery.

The behavior identification and its classification are implemented on a Lenovo ThinkPad T440s with i5-4200u 1.6-GHz CPU and 8 GB of RAM with the Windows 7 64-bit operating system and modeling environment MATLAB Version 2015a.

6.4 System Validation

To prove that the proposed solution works properly and fulfills the stated needs and requirements, the validation process is necessary. It begins with an analysis of the accuracy of step detection and direction estimation. Then, the performance analysis of the used localization method is done. Further steps concern the detailed investigation of activity recognition and the developed behavior classification method. The last step of this process is to check if the costs meet the stakeholders' assumptions.

6.4.1 Path Tracking Algorithm

After applying a simple Butterworth low-pass filter of a 2-Hz cutoff frequency to the raw SMV readings of the accelerometer, it was possible to discern single steps with 98% validity for 1500 steps in the test environment. The test of direction estimation, θ, resulted in the mean uncertainty of 1.33°, the standard deviation of 1.15° and the maximal error of 3°. Such high sensitivity causes even the small motions of the body arising from the walking characteristics to be considered as direction changes, imposing an error in the position estimation. The authors' empirical studies indicate that this effect, for a four-meter walk back and forth repeated three times, causes location error in the y-axis of 1 m and 0.5 m in the x-axis. To eliminate the error of walking characteristics, the direction changes smaller than 6° are neglected. This approach allows reducing the localization error from one meter up to 40 cm.

The proposed PDR algorithm with the 6° threshold was investigated in the tested environment. The test path of a walk back and forth each consisted of five sections: I, seven steps ahead, then turn 45° to the left; II, three steps ahead and turn 90° to the left; III, five steps ahead and turn 90° to the left; IV, five steps ahead and 45° turn; and V, five steps ahead; see Figure 23. Then, the volunteer returned to the starting point in the reverse order. The walking pattern was repeated three times.

To comprehend the localization characteristics, Figure 24 shows the localization uncertainty for each step of the test's first round with a division of the path sections for a walk back and forth. The orange dots indicate the localization uncertainty for the first seven steps ahead. The green dots show uncertainty for the three steps after the 45° turn to the left.

The blue dots correspond to the five steps after the 90° turn to the left; the red dots indicate the five steps ahead after another 90° turn to the left; and finally, the purple dots show the last five steps ahead after the 45° turn. For the test path of going one direction, the mean localization uncertainty is 4 cm with a standard deviation of 2 cm. However, the same quantities for the direction of returning to the origin are worse and are 40 cm and 12 cm, respectively. Nevertheless, this difference can be caused by the physiological effect of repeating exactly the same path, especially the V section. This

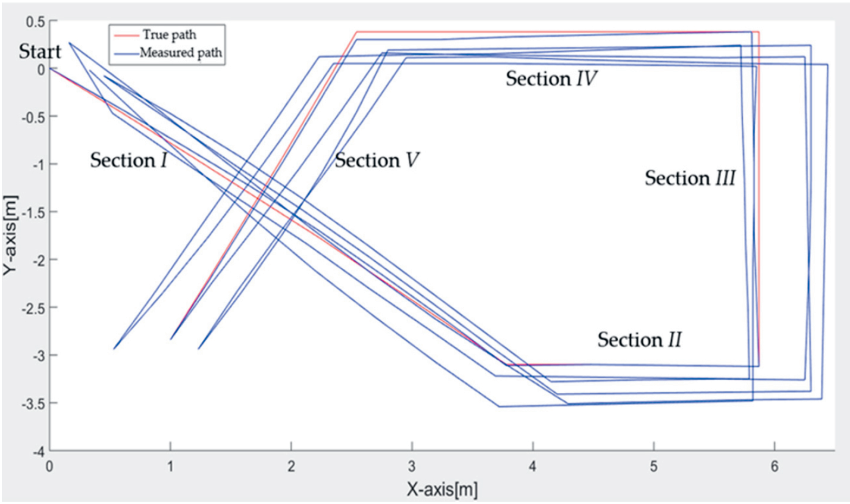

Figure 23: Test path for validation of PDR indoor localization.

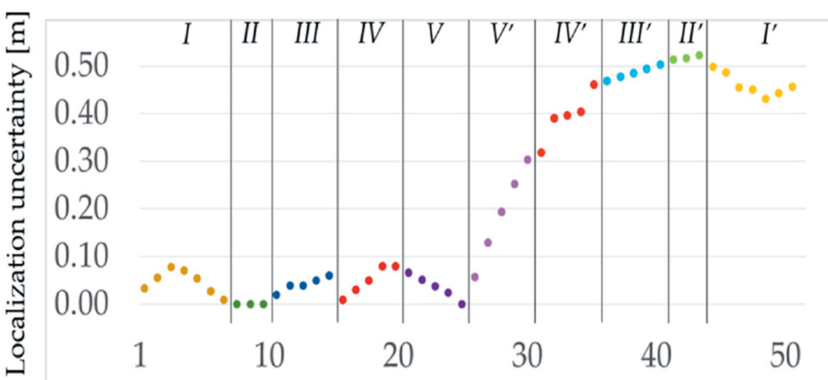

Figure 24: PDR indoor localization uncertainty for each step of the first round of the test path from the start to the end points and in the reverse direction.

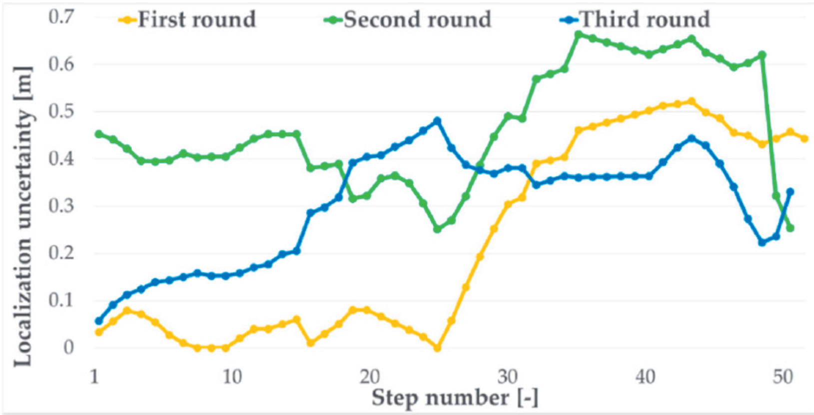

Figure 25: PDR indoor localization uncertainty for each step of three rounds of the test path from the start to end points and in the reverse direction.

effect is further analyzed in the following part of this section.

Figure 25 shows the localization uncertainty for each step of the three rounds of the test five-stage path from the start point to end and in the reverse direction. The mean localization uncertainties for each round are 22 cm, 46 cm and 30 cm, with standard deviations of 20 cm, 12 cm and 11 cm for the first, second and third round, respectively. From these data, one can see that there are clear differences in the two phases of walking back and forth. Probably, this is an effect of a test psychological bias, which cannot necessarily affect the measurements in a real environment. For the whole test path, the mean localization uncertainty is 33 cm, with a standard deviation of 18 cm and maximal localization error of 66 cm.

Figure 26 shows the averaging of the three rounds of localization uncertainty for each step with distinction for each path section for the two directions. The average of the mean uncertainty for the forward direction is almost the same and equal, about 21 cm. However, the same uncertainty for the back direction is about double and equal, almost 40 cm. The exception is the section V when both directions have almost the same average values. It is noticeable that the standard deviations of the measurements are much smaller than the mean uncertainty. It seems that the turns are the cause of the increasing localization uncertainty.

The performed tests prove that the localization accuracy of the proposed

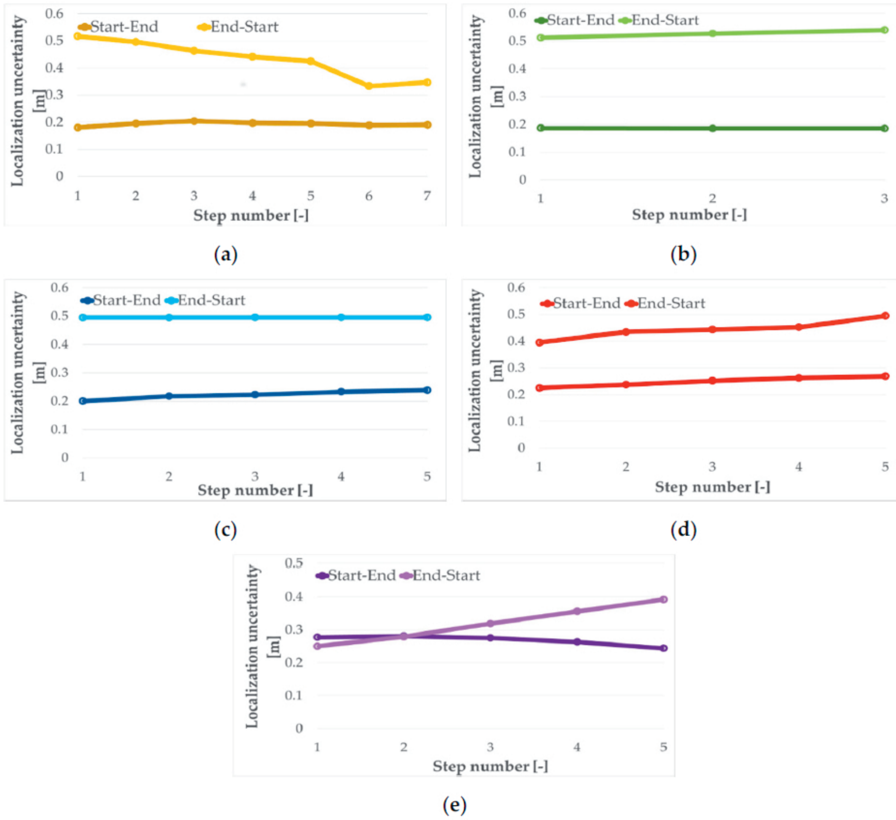

Figure 26: Localization uncertainty for each step for the two directions of the test path sections: (a) for I; (b) for II; (c) for III; (d) for IV; (e) for V

algorithm is sufficient for the requirement of the four room-zone level accuracy. However, it also indicates that the longer use of the algorithm causes localization drift, which could lead to losing calibration. Therefore, the load sensors, similar as in car seats, are used as re-calibration points. Those distinguishable sensors, with fixed x and y coordinates, should be mounted at the most frequently-used places, such as the bed, armchair, sofa or kitchen chair. Moreover, those sensors can even be used for the primary calibration of the system. The presented results are consistent with the results reported in [26].

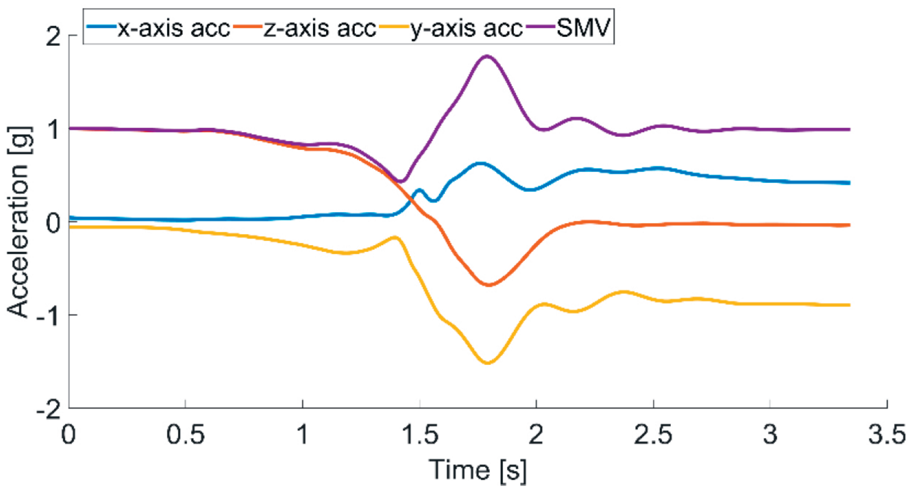

Figure 27: Forward fall test: accelerations in $x-$, $y-$ and $z-$axis and SMV characteristic

6.4.2 Form of Activity Recognition

One of the requirements, stated by the future users and stakeholders, was to detect a fall of the monitored person in a distinguishable way from the other activities such as standing, sitting, lying down and walking. In order to perform the activity recognition, the SMV and accelerations in the $x-$, $y-$ and $z-$axis are measured, and based on the test data, the appropriate identification thresholds for each activity have been justified and set.

To adjust the identification thresholds of a fall, the SMV and accelerations in the $x-$, $y-$ and $z-$axis of fall tests of two volunteers were analyzed. Figure 27 presents an example of accelerations in the $x-$, $y-$ and $z-$axis along with the SMV measurement of the forward fall test. As one can see, due to the characteristic peaks concerning the beginning of the fall and the contact with the floor, it is possible to justify such thresholds to recognize the fall. Moreover, the decreased levels in the $y-$ and $z-$axis indicate that the person is lying, which also confirms a fall if at the initial instant, standing positions were recognized.

The final fall test consisted of 350 different falls including forward, backward, lateral falls to left or right, fainting with rotation to the left or right side and tumbling preceded by flexing the knees, 50 times each case.

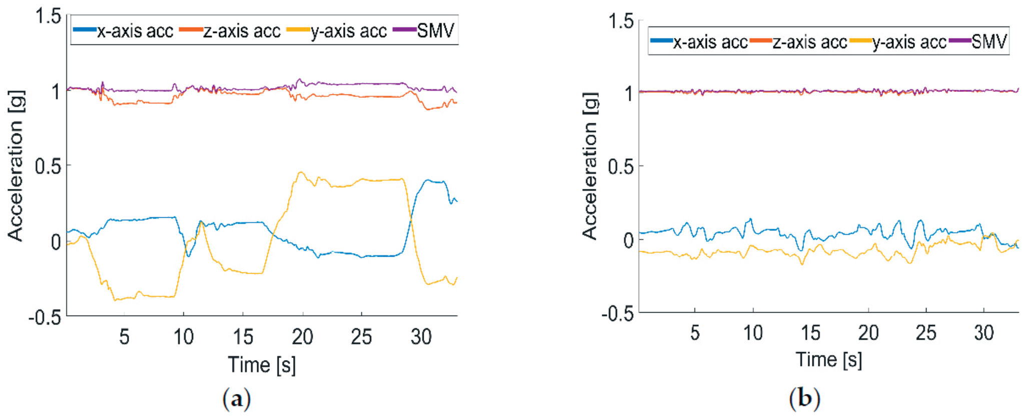

Figure 28: Accelerations in the $x-$, $y-$ and $z-$axis and SMV readings during activities: (a) standing; (b) sitting

Up to 342 falls were identified correctly, which gives a satisfying fall detection validity of 98%.

As was predicted, the proposed system cannot directly distinguish between standing and sitting postures, which can be seen in Figure 28a,b, presenting the SMV along with accelerometer readings from the $x-$, $y-$ and $z-$axes for standing and sitting activities, respectively. The signals of all four measured variables are not specific for different activities, and the noticeable changes around 0g of the $x-$ and $y-$axis in Figure 28a occur due to the natural movement of the body. Therefore, it proves that the observed differences are not sufficient to distinguish between these two activities.

The solution of the problem could be to identify the dynamic activities of sitting down and standing up along with lying down and getting up, instead of static activities of sitting or standing. The volunteers were asked to perform the activities of getting up and sitting down, shown in Figure 29a,b, respectively. As is visible, when the activity of getting up starts, the acceleration in the y-axis and hence SMV changes quickly, and when the volunteer straightens, both acceleration in the y-axis and SMV gently stabilize. During the sitting down activity, the curves are opposite, while bending, the change is mild, and at the end of sitting down, both acceleration in the y-axis and SMV changes quickly. These differences allow for finding the identification thresholds to distinguish between the activities of standing up and sitting down.

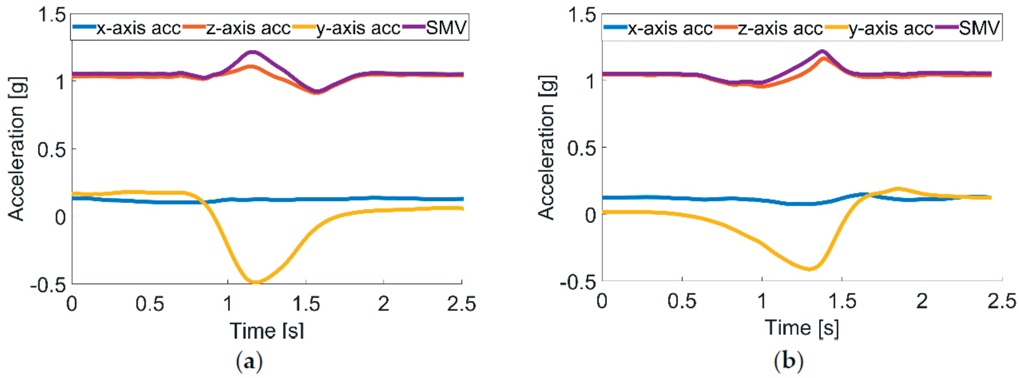

Figure 29: Accelerations in the $x-$, $y-$ and $z-$axis and SMV readings during activities: (a)) getting up and (b) sitting down

Figure 30 shows the SMV and accelerometer readings for the activities of lying down on a bed or sofa and getting up from them. During the activity of lying down shown in Figure 30a, the acceleration in the z-axis rapidly decreases, and the acceleration of the y-axis sharply increases, which is caused by an orientation change of the accelerometer and shifting of an axis, which is most influenced by the gravity force. During the activity of getting up presented in Figure 30b, the acceleration curves of the $z-$ and $y-$axes behave conversely; the $z-$axis rapidly increases; and the acceleration of the $y-$axis sharply decreases. These phenomena allow one to distinguish between those two activities.

To validate the proposed solution, volunteers performed different activities: they fell 350 times, laid down almost 200 times, stood over 200 times, sat 400 times down and performed 200 walks. Table 5 summaries the recognition accuracy reached for each activity.

Table 5: Activity recognition accuracy.

Activity	**Recognition Accuracy (%)**
Falling	98
Standing	94
Lying	96
Sitting	92
Walking	98

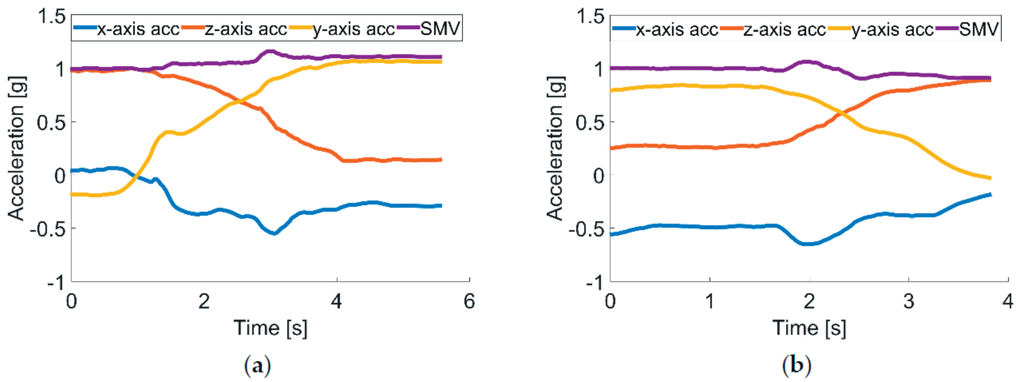

Figure 30: Accelerations in the $x-$, $y-$ and $z-$axis and SMV readings during activities: (a) lying down; (b) sitting getting up.

The overall system activity detection and identification accuracy was 95.5%, while 2.5% of activities were recognized incorrectly, and 2.0% were not detected at all. The achieved accuracies do not differ from those reported in [27], [30].

6.4.3 Behavior Classification

In general, we distinguish three classes of behaviors: normal, suspicious and dangerous. The behaviors identified as dangerous or suspicious require further dedicated actions. The behavior classification procedure starts with the establishing of pattern database of normal, suspicious and dangerous behaviors. Timeframes of the normal behavior are chosen based on the monitoring of three elderly people, two females and one male, during their daily activities for three days. Based on the observation data, the suspicious behavior timeframes are set between 101% and 150% of the timeframes of the normal ones, whereas the timeframes of dangerous behavior exceed the timeframes of normal and suspicious behaviors. However, some activities in an unusual time or place, e.g., standing on a bed, are considered as suspicious or dangerous situations, independently of their timeframes. The behavior classification training-database consists of more than 1200 situations coded as combinations of five variables: ToD, SoA, ZoA, FoA and DoA, similarly as in Table 6, which consists of examples of normal, suspicious and dangerous behaviors from the data gathered during monitoring tests of volunteers. These examples include the morning teeth brushing, sitting on the floor in the middle of the living room and too long standing in one place during the night.

Table 6: Classification of exemplary behaviors.

ToD	**SoA**	**ZoA**	**FoA**	**DoA** (min)	**CoB**[*]
Morning	Bathroom	of standing	Standing	3	Normal
Afternoon	Living room	of standing	Standing	5	Suspicious
Night	Bedroom	of lying	Standing	17	Danger

[*] ToD, Time of Day; SoA, Section of Apartment; ZoA, Zone of Activity; FoA, Form of Activity; DoA, Duration of Activity; CoB, Class of Behavior.

The created training database was applied to six different machine learning techniques to establish patterns of normal, suspicious and dangerous behaviors. Using the behavior classification, training-database, the five-fold cross-validation method [42] was applied to evaluate and grade the machine learning techniques. The tested machine learning techniques are: the I and II decision trees, the I and II support vector machines and the I and II k-nearest neighbor classifiers. The I and II decision tree classifiers differ from each other with the maximum possible numbers of splits, which are 20 and 100, respectively. The I and II SVMs differ from each other with the kernel functions, which are linear and cubic, respectively. The difference between I and II KNNs is a distance metric, which is Euclidean and cosine, respectively.

Table 12 shows the percentage of overall classification validity and classification validity including normal, suspicious and dangerous behaviors for the tested machine learning techniques.

The II decision tree along with I and II KNNs show the highest classification validity; therefore, they were applied for the optimization by tuning their parameters. However, the tuning of I and II KNN classifiers did not lead to improvement of their overall classification validity. Nevertheless, increasing the number of splits up to 140, in the II decision tree classifier, enhances the overall classification validity up to 99.1%. The further increasing of the number of splits did not increase the classification validity.

Table 8 shows the confusion matrix for the optimized decision tree with the maximum possible number of splits, up to 140. The behavior classification validity of normal is at a level of 99.1%, suspicious at a level of

Table 7: Classification validity of validated machine learning techniques.

Classifier	**Classification Validity (%) of**			
	Overall	*Normal*	*Suspicious*	*Danger*
Decision Tree I	82.4	92.8	92.9	74.1
Decision Tree II	94.8	93.7	93.8	96.5
SVM I	54.1	60.0	0.0	50.5
SVM II	85.1	87.2	75.2	86.8
KNN I	96.0	97.9	90.9	96.8
KNN II	95.8	97.6	89.9	97.1
Tuned Decision Tree	99.1	98.8	98.4	99.6

98.4% and dangerous at a level of 99.5%. It is noteworthy that only 0.2% of tested dangerous behaviors were classified as normal, which can be treated as a critical mistake, and 0.3% of them were classified as suspicious, which is less critical since the suspicious behavior should be checked anyway. The classification validity of the proposed method can be justified as up to the mark.

Table 8: Confusion matrix for the optimized decision tree.

Predicted Class / **True Class**	**Normal**	**Suspicious**	**Danger**
Normal	99.1%	0.7%	0.2%
Suspicious	1.1%	98.4%	0.5%
Danger	0.2%	0.3%	99.5%

For the final verification of the designed behavior classification method, the tuned decision tree was fed with 50 different behaviors with randomly-chosen timeframes. The test resulted with overall classification accuracy at a level of 100%, and all of the 25 normal, 7 suspicious and 18 dangerous behaviors were classified correctly.

7 Results Discussion

The system design process was conducted using the proposed DM, and based on validation results, the stakeholders and future users approved the solution and continued the project towards implementation and commercialization.

The applied DM resulted in the system consisting of hardware and software components, shown in Table 3, suitable to realize required functionalities and fulfilling general constraints.

The presented system validation concerned the crucial requirements of stakeholders and future users such as a four room-zones level localization accuracy, fall detection, activity recognition and classification of normal, suspicious and dangerous situations.

The 1500-step test proved that the proposed step detection method, based on data gathered with the three-axial accelerometer and magnetometer, together with the signal magnitude vector and the pedestrian dead reckoning algorithm, shows a high robustness of 98%. The direction estimation test gave 1.33° of the mean uncertainty of the angular walking direction with a standard deviation of 1.15° and maximal error of 3°. Such high accuracy and sensitivity confirm the usefulness of the method for indoor location monitoring.

However, the further investigation indicated that small natural motions of the body during walking caused up to a 1-m error in the position estimation. Therefore, the 6° threshold filter was applied, which resulted in the reduction of uncertainty in position estimation by up to 40 cm.

For the walk test path consisting of five sections performed back and forth and repeated three times, the mean localization uncertainty was 33 cm with a standard deviation of 18 cm where the maximal localization error was 66 cm. The same test's results indicated that for one round of the walk from the start to end points, the mean localization uncertainty was just 4 cm with a standard deviation of 2 cm. However, for a walk in reverse order, the mean value and standard deviation increased up to 40 cm and 12 cm, respectively. The detailed analysis of the test data resulted in the mean localization uncertainties for each round of 22 cm, 46 cm and 30 cm, with standard deviations of 20 cm, 12 cm and 11 cm for the first, second and third round, respectively. Moreover, average localization uncertainties for the forward direction are almost the same and equal about 21 cm, and the same uncertainty for the back direction is about double and equal to almost 40 cm. This means that the proposed localization algorithm has a small localization uncertainty, and the most distortive movements are turns. It seems that the turns are the cause of the increasing localization uncertainty. The test results verified that the designed method is sufficient for the four room-zone level accuracy requirement.

Analysis of test results of forward fall accelerations in the $x-$, $y-$ and $z-$axes and SMV, showing the characteristic peaks concerning the beginning of the fall and the contact with the floor, was applied to define the signal thresholds used to recognize the fall. Moreover, the acceleration change in the $z-$axis, which the gravity force influences the most, indicating the lying position of the monitored person, is used for the fall confirmation. The performed tests proved that the designed method of fall detection is valid in 98% of cases.

The data gathered during standing and sitting activities indicated that the observed differences in accelerations in the $x-$, $y-$ and $z-$axes and SMV are not sufficient to distinguish between these two activities. However, possible identification of getting up and sitting down activities can be used to recognize standing and sitting activities. The beginning of the getting up activity causes the acceleration in the z-axis; hence, SMV changes quickly, and at the end of the activity both acceleration in the $z-$axis and SMV gently stabilize. In turn, the start of the sitting down activity causes the mild change in acceleration in the $z-$axis, and at the end of the activity, both acceleration in the $z-$axis and SMV change quickly. Based on appropriate thresholds, the identification for both of these changes allows one to distinguish between those two activities. Similar analysis can be used to distinguish between lying down and rising activities. When lying down, due to an orientation change of the accelerometer causing a shift of the axis that the gravity force influences the most, the acceleration in the $y-$axis rapidly decreases, and acceleration of the $z-$axis sharply increases; while when rising, the acceleration curves of the $y-$ and $z-$axes behave conversely; the $y-$axis rapidly increases; and acceleration of the $z-$axis sharply decreases. These phenomena are used to distinguish these two activities. The proposed activity recognition method was validated based on tests consisting of 350 falls, 200 lying down, 200 standing up, 400 sitting down and 200 walks, and the results are summarized in Table 5. The overall validity of the system activity recognition was 95.5%, where 2.5% of activities were recognized incorrectly and 2.0% not detected at all.

The activity categorization in class of behavior as normal, suspicious or dangerous is based on the analysis of five components: time of day, section of apartment, zone of activity, form of activity and duration of activity. The classification procedure is grounded on the comparison of current measures with the existing behavior database. The behavior database was created from regular three-day observation of three volunteers' activities. From six evaluated machine learning techniques, the decision trees II, KNN I and KNN II showed the highest classification validity of 94.8%, 96.0% and 95.8%, respectively. The conducted optimization of the three best methods indicated that only the tuned decision trees II increased classification accuracy up to 99.1%. The confusion matrix for the tuned decision tree indicates that only 0.2% of the tested dangerous behaviors were classified as normal, which can be treated as a critical mistake, and 0.3% of them were classified as suspicious, which is less critical since the suspicious behavior should be verified anyway. The chosen behavior classification technique of highest validity was verified with a set of 25 normal, 7 suspicious and 18 dangerous behaviors of random timeframes, and as a result, 100% of them were classified correctly.

8 Conclusions and Future Work

Due to the lengthening of life expectancy, society is aging, and more and more people live to an older age. Therefore, it is highly important to assure life quality and safety. Existing and emerging technologies can provide tools that can support elderly people in their everyday life, making it easy and safe. This paper concerns the design methodology of such tools especially for indoor and outdoor localization, health monitoring, fall detection and behavior recognition and classification.

The authors propose the design methodology for the IoT-based home care information system intended for indoor and outdoor environment use. The presented DM approaches the home care problem not only from the designer's perspective, but also considering the contracting authority's and potential users' requirements, which means that apart from the technical requirements, the design procedure considers the multifarious constraints, including the lifetime, energy issue, usage comfort and even the price.

The proposed DM was verified with a case study of real-life scenarios where there is a need for supporting elderly people, especially those of limited mobility living alone. The desire stated by the stakeholders and future users required the system for identifying people's position and their vital signs, but also to be able to recognize basic activities, especially falls, and to classify them as normal, suspicious or dangerous.

The outcome of the conducted design procedure is the system based on IMU, with a built-in three-axis accelerometer, gyroscope, magnetometer and altimeter. It is also equipped with Wi-Fi, GPS and heart rate modules. For an in-apartment localization with four room-zone level resolution, the IMU with PDR algorithm is used. For in-building localization with floor level accuracy, the BarFi algorithm based on pressure and Wi-Fi fingerprints is proposed. For an outdoor localization with an accuracy of at least ten meters, the GPS module and PDR algorithm are applied. In order to detect activities of falling, lying, standing, sitting and walking, the IMU and thresholding algorithms are used. As a method for classifying activities as normal, suspicious or dangerous, the authors developed the six-element behavior vector and used it together with a decision tree algorithm.

The validation procedure performed for the most crucial requirements of the four room-zone level in apartment localization, fall detection, activity recognition and its classification as normal, suspicious and dangerous situations proves that the system works according to the required functionalities and constraints.

The future works concern the verification step, conducted together with the stakeholders and future users, of designed modules and algorithms for a multi-story building environment and nearby outdoor environments. Another future improvement of this system could be further recognition of specific activities like teeth brushing, cooking, watching TV or taking medication. Such information would be informative for caregivers whether the monitored person skipped a meal or forgot to take a medication. Moreover, it could be also included in the behavior vector and inform caregivers about behavior changes within a given period. The other improvement of the system may concern the usefulness of additional sensors for monitoring vital signs. The lifetime extension of the device by means of energy-saving algorithms and methods is another direction for future work.

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Abbreviations

The following abbreviations are used in this manuscript:

BLE	Bluetooth Low Energy
BV	Behavior Vector
CoB	Class of Behavior
DM	Design Methodology
DoA	Duration of Activity
ECG	Electrocardiography
FoA	Form of Activity
GPS	Global Positioning System
IMU	Inertial Measurement Unit
IoT	Internet of Things
KNN	k-Nearest Neighbor
MEMS	Micro-Electro-Mechanical Systems
PDR	Pedestrian Dead Reckoning
RFID	Radio Frequency Identification
RSS	Received Signal Strength
SMV	Signal Magnitude Vector
SoA	Section of Apartment
SVM	Support Vector Machine
ToD	Time of Day
UWB	Ultra-Wide Band
WSN	Wireless Sensor Networks
ZoA	Zone of Activity

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Paper V

Wireless Monitoring System for Fireman's Competence Objective Assessment

Paper V

Wireless Monitoring System for Fireman's Competence Objective Assessment

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Abstract

Developing technologies associated with tracking human movement and behaviour enable new applications for competence assessments from training results of professionals, such as medical staff, sportsmen or emergency servicemen. This article considers a methodological approach to design a system for firefighter's skills and competence assessment. Assessed training features such as in-building behaviour and tasks execution are analysed based on data gathered with wireless Ultra-Wideband Real-Time Location System, UWB RTLS, and Inertial Measurement Unit, IMU. The assessment is based on the predefined required training tasks, the expert's expertise and results of the trainee's test. The Unity game engine is used for data processing and visualization. As the comprehensive final map of the trainee's skills, the spider diagram is applied and the single score method provides the conclusive statement. The proposed solution was verified experimentally in real environment.

Index Terms——Inertial measurement unit; real-time location system; spider diagram; tracking; training quality assessment; wireless multi-sensor system.

1 Introduction

The problem of an objective assessment of professional skills and competences, or precision and progress in rehabilitation is a research topic that gains interest due to the capacity of new technologies, especially wireless sensor networks, Internet of Things and advanced algorithms. However, because of the variety of professionals' performance that might be assessed, it is still an open-ended problem. The comprehensive evaluation of professional competences is even more problematic because of a need to map the different skills into the final score.

Currently, such evaluation is commonly done by means of observation and eventually simple measurements, which are limited and subjective. Moreover, most trainings, like emergency serviceman training often performed under conditions of limited visibility, consist of many elements whereas one observer is able to focus only on a few training features. Therefore, an automated assessment system can reduce the number of evaluators, shorten the time of the evaluation process, and what is probably the most crucial, the assessment is objective.

This article, using the methodical design, resolves the problem of objective assessment of training skills and competences of a fireman as a case study. Based on an analysis of both stakeholders' and future users' needs and requirements, the wireless monitoring and assessing system using a Real Time Location System, RTLS, and Inertial Measurement Unit, IMU is proposed.

The designed system applies location and orientation sensors to acquire data about the completed training path, trainee's Field of View, FoV, execution time, range of explored area, and a number of accomplished tasks. The data, compared with the expert's pattern, provides an objective assessment of the trainee's professional skills and his/her competence. Moreover, using the modern game engine and visualization method along with a spider diagram, the evaluation is presented in a comprehensive way and the training competences are objectively scored.

The simulated results and real field training data validated the design idea and its implementation.

2 Survey Of Related Works

Surgery, rehabilitation, sportsmen, military, fire brigade and other secure services are the professions where objective assessment of people's competence is crucial. However, each profession may have very specific skills that are important and which need to be assessed.

The key features of assessment systems applied in medicine are high precision, repeatability and speed. Such systems are used to assess surgeons e.g. in performing laparoscopy. Taffinder *et al.*, to objectively evaluate surgical dexterity use Imperial College Surgical Assessment Device, ICSAD, consisting of an electromagnetic field generator and two sensors attached to the surgeon's dorsum [1]. They assess the surgeon's skills based on measurements of hand movement speed, the distance travelled by his/her hands during the task, along with execution time of the operation. The authors of [2] developed an objective assessment device for speed and accuracy evaluation of the laparoscopic surgery. Their solution consists of laparoscopic simulator and computer-based skills assessment software. Another approach is considered in [3] where a virtual reality is used. The assessment of surgical skills is done using laparoscopic simulator Minimally Invasive Surgical Trainer-Virtual Reality, MIST-VR, where laparoscopic novices perform six tasks and their results are compared with results of experienced surgeons.

In [4], an UWB RFID system by Zebra Technologies has been installed at football stadiums. It identifies players and localizes them with 15 cm accuracy at the frequency of 25 Hz. This solution is used for game statistics for broadcasters and post-game analysis by the coaching staff. The authors of [5] propose the system, which uses multiple cameras to track each of players on the court or field in single player sports for the statistical analysis of covered distance, as well as average and instant speed. The usage of multiple cameras in order to analyse behaviour of players is also described in [6]. The authors use them for localization of players in soccer games and display virtual offside lines, players' positions and motion patterns. Similar applications for soccer and basketball games are presented in [7] and [8] respectively.

To objectively assess motion of a person's body or its parts' location is needed in many cases. Most of such solutions require an accurate location, tracking and orientation, which lead to high price systems. However, IMU devices are the reasonable alternative to expensive solutions. In [9] a wearable device for motion detection based on tri-axial accelerometer and two gyroscopes using expert's knowledge is presented. This system compares pattern movements of an expert with the motion of rehabilitated patient during an exercise to correct his/her body position. The average motion estimation error varies from 0.69° up to 1.75°, depending on the speed and exercise difficulty.

To assess soldiers' competences, the authors of [10] use UWB RFID technology. They track the localizations of soldiers engaged in a training in multi-floor buildings, then analyse their movements, actions and interactions to each other, for post-action review lessons.

Some researchers go a step further and work with recognition of specific behaviours based on location and orientation data. In [11], Rossi et al. track human movements with humanoid robot and apply the Haar-like features method, to detect human faces. Their solution, in the best scenario, obtains performance of 55px. Ruan in [12] recognizes humans' activity by means of a wireless RFID sensor network. In the proposed method, the received signal strength indicators, from the passive RFID tags array, are used to estimate the subject's activity pattern. The disadvantage of this method is an extensive infrastructure needed to cover all considered area.

The authors of [13], based on information about spatial location of three parts of human body derived from Ultra- Wideband Radio Frequency IDentification, UWB-RFID, tags and Ubisense RTLS, recognize six human behaviors. Applying the data to Artificial Neural Network, the authors obtained activity recognition accuracy of 82% in the worst case scenario.

3 Problem Statement

The reported studies indicate that the existing solutions of the training assessment of emergency serviceman e.g. firefighters are not rewarding due to the subjectivity factor of the most of applied methods. Therefore, there is a need for a development of the smart multi-sensor system, which would objectively and holistically assess the trainees' skills.

Hence, the objective of this research is to methodically design, implement and validate a system, which would objectively assess trainees' skills and provide a comprehensive map of their skill profile. The skills of interest include, among others their speed, in-building behaviour and tasks execution. The system consisting of handy convenient devices should operate wirelessly even under conditions of limited visibility.

The proposed solution consists of the wireless multi- sensor system, which, based on RTLS and IMU devices, yields information about trainees' movement in the test-field in real-time. Moreover, using the modern game engine, the particular elements of the training are visualized. The judgment of trainees' skills is based on a template created by experts. The trainees' individual skill characteristic, as a complex variable, is visualized in graphical way using the spider diagram. The trainee's competence is assessed using a singular score, which is related to the expert's pattern.

The main contribution of this paper is applying methodical tools to design, model and prototype the system supporting assessment of trainees when firefighters are the application case study. Moreover, the holistic mapping of the results is proposed and visualized using a suitable chart. Furthermore, the developed system's performance is validated and verified by means of simulation and real measurements from training scenarios.

4 Primary Steps Of System Design

The design approach used is based on User Centered Design methodology, UCD, where both stakeholders' and future users' needs and requirements are considered, albeit the designer's perspective is taken into account [14]. The authors propose to divide the design process into two main stages: the problem formulation and product development. Whereas each step is further divided into sub-steps summarized in Table 9.

Table 9: Stages Of Design Process

Problem formulation	**Product development**
Needs and functionalities definition	Technology and algorithms selection
Requirements formulation	Modelling and implementation
Feasibility assessment	Prototype verification

The problem formulation step started with the definition of the general need of the system as supporting the evaluation of the firefighter's training.

According to the stakeholders and future users, the final comprehensive score of the trainee's performance should be based on the evaluation of five features of the training performance, which constitute the system functionalities:

1. a number of examined checkpoints, a,

2. the examined area coverage, c,

3. a number of examined objects, o,

4. the execution time, t,

5. an average speed, s.

4.1 Number of examined checkpoints

The first feature concerns how many of the predefined checkpoints are examined by the trainee. In most cases, a single room is considered as a singular checkpoint. However in a case of large space corridor, the space could be arbitrarily divided into several smaller areas as checkpoints, which is illustrated in Fig. 31. To assent an area as checked, the trainee has to enter it, which can be verified from localization data and the Unity's feature, which indicates when one object interacts with another one - in this case one object is the trainee and the second is the defined checkpoint. The score, a, from this feature is the ratio of the number of checked areas to the number of all required areas for the training.

4.2 Area coverage

The second key feature concerns the area coverage, which indicates to what extent the room is combed out. It complements information whether the trainee just entered the room or he/she also examined it carefully by looking around. Each area is divided into a number of subzones as illustrated in Fig. 31. However, some subzones could be overshadowed by obstacles such as furniture etc., which requires from the trainee an entry into the area and examine the space behind the obstacle.

The area coverage assessment is done by combining location and field of view data along with the colliders built in the Unity game engine. The score, c, is based on the ratio of how many subzones are passed to a number of all subzones in the training field.

4.3 Number of examined objects

The third key feature of training assessment deals with a number of examined objects. It corresponds to the cases when somebody hides or lies e.g. unconscious. The example objects, which need to be examined, are depicted by white cubes in Fig. 31. It is assumed that the object is examined if

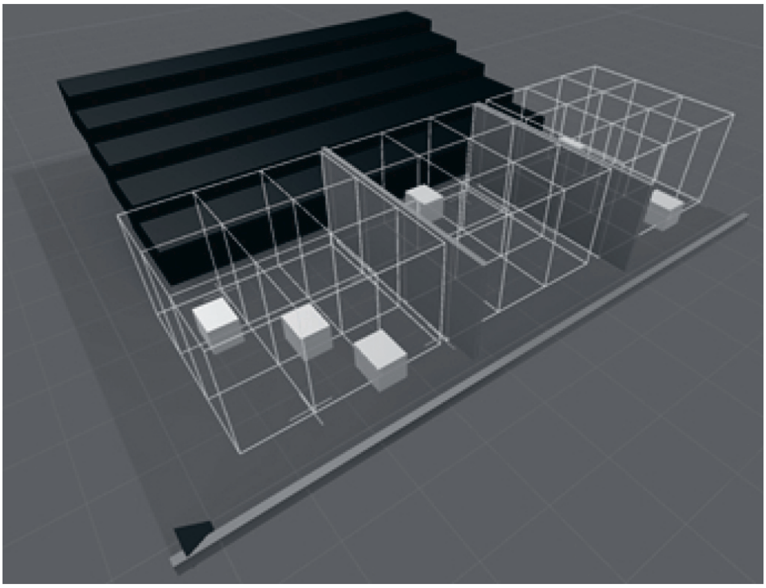

Figure 31: Example of training environment model with three areas and six objects.

at least 80% of its area appears in the trainees' field of view, however not farther than one meter from the observer, for at least 0.5 second.

In Fig. 32, the light grey colour indicates the estimated FoV, the darker rectangles are the objects, which are considered as properly examined and the lighter grey rectangles indicate objects, which are not checked. Similarly as in the previous cases, the assessment score, o, depends on the ratio of the number of examined objects to the number of all objects, which should be examined.

4.4 Execution time

The fourth feature contributing to the final assessment is a total time of the training, t. The system starts measuring the time when the trainee begins moving and ends when a button on the IMU board is pressed. Then the system compares the performance time with an expert's guidelines and assesses the performance.

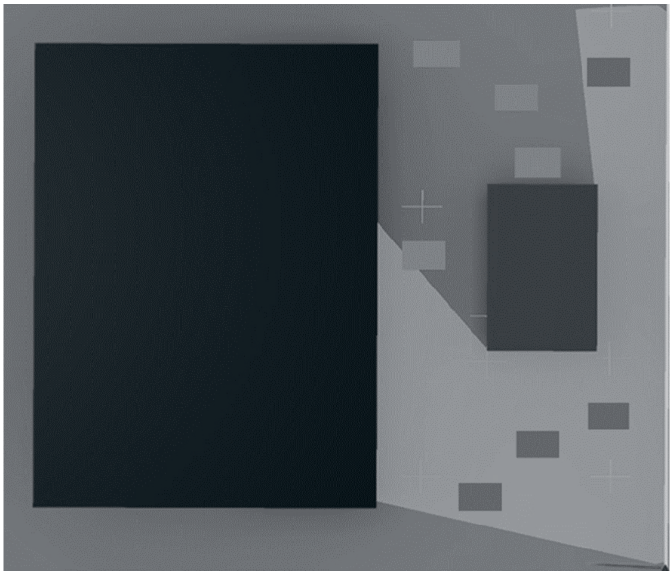

Figure 32: Field of view estimation.

4.5 Execution average speed

The fifth feature of the assessment is average speed, which is estimated from the length of the trainee's path and execution time. The length of the path is calculated from location system data. This feature gives the combined information about the ability to execute all tasks in required time.

The complementary requirements consist of the wireless nature. The system should be wearable and operate even under conditions of limited visibility. Moreover, it is crucial to present the comprehensive results in a user-friendly manner.

The stated needs, functionalities and requirements have been evaluated as feasible and the product development step could be continued.

5 Product Development

5.1 Technology and Algorithms Selection

The Ubisense Real Time Location System using UWB technology was evaluated as the sufficient *trainee localization platform*, fulfilling the stakeholders' and future users' needs and requirements. This system consists of sensors located outside the training facility and throughout the building rooms and corridors along with small wearable tags. The localization process is based on the analysis of the Received Signal Strength, RSS, and Time Difference of Arrival, TDoA, from the UWB active tag to the system's sensors. With these technologies, the system is able to estimate a tag's position in 3D with accuracy of about 30 cm at 8 Hz sampling frequency.

To check which areas and objects in the training field have been examined by the trainee, a direction measurement system based on Adafruit's *BNO055 Absolute Orientation Sensor* and *Pro trinket* board, are applied. These devices, placed on the trainee's head, give information where the trainee's face is directed, to estimate his/her field of view FoV. The dynamic accuracy of a system's roll, pitch and yaw estimations equal 5° and its weight is less than 150 g with dimensions of 5 cm × 4.5 cm × 2 cm. The operation frequency is at least 50 Hz, and the built-in battery enables at least 2-hour training data logging. The system is equipped with USB interface.

The data processing of the trainee's performance is carried out in the application built in the Unity3D game engine [15], [16]. The engine is useful because of its capabilities, offering Integrated Development Environment, IDE, with a built-in editor, scene builder, scripting, physics engine, networking and more. Its deployment ability of the application for different platforms and operating systems was also an important reason for choosing this software.

To visualize the results of skills evaluation in a userfriendly and objective manner, the spider diagram is chosen. This comprehensive method shows all considered training aspects on a single diagram to help the evaluator easily judge the trainee's skills levels. Moreover, this solution can be used to graphically compare the trainee's results with the expert's or with the average results of all trainees.

The modelling, prototyping and verification steps are introduced in the following chapters.

5.2 Modelling

The main goal of the system is to support an assessment of firefighters' training. As mentioned, the two monitoring systems are responsible for data collection. At the hardware layer, these two systems work independently. At the software layer, information from the systems are synchronized. From

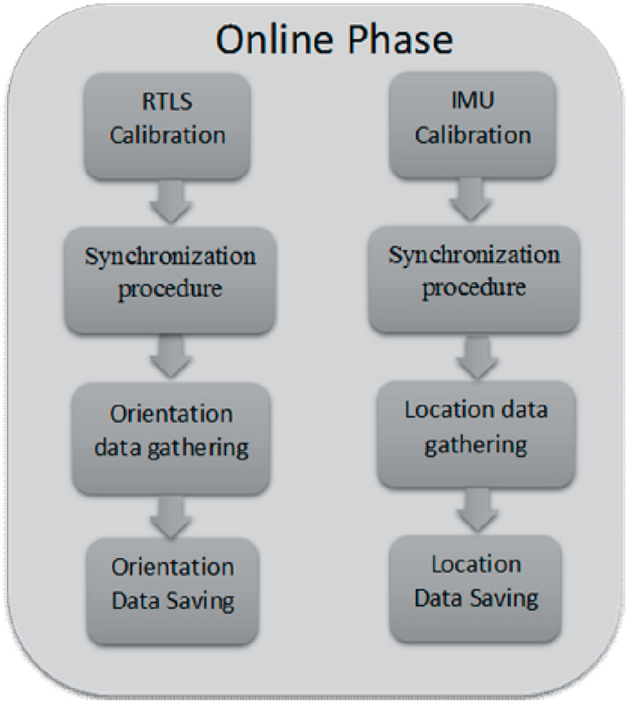

Figure 33: Steps of online system operation.

a perspective of operating principles the evaluation process consists of two phases: *online* and *offline*, Fig. 33 and Fig. 34 respectively.

When the *online* phase begins, both systems are independently calibrated, and then their data are gathered and saved. The calibration of the localization system is done by means of the calibration tag placed at the known position, and RSS and TDoA signals are measured using all sensors. The system parameters are adjusted to the actual system state and environment. The calibration of the direction system requires calibrations of gyroscope, magnetometer and accelerometer. For calibration, the gyroscope has to be placed vertically for at least one second. To calibrate the magnetometer, the device needs to be rotated in a figure eight-like pattern. The accelerometer calibration is accomplished after the device is rotated around its axis while stopping for one second for every $\sim 45°$. In such manner the direction angle and FoV are adjusted and upgraded. After the calibration the system is ready to be used to monitor the training performance.

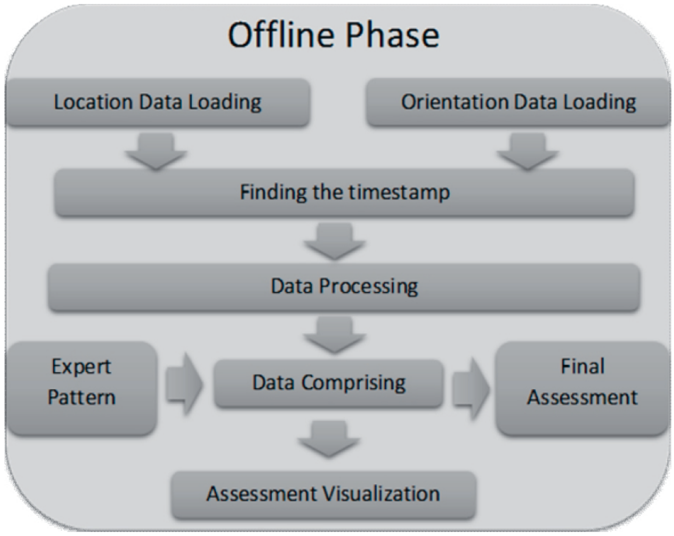

Figure 34: Flowchart of the system offline operation.

To be able to synchronize data of the two independently operating systems, there is a need to establish a timestamp of the training start. To do so, the trainee is asked to perform the starting procedure, which is as follows: go to the starting point; stand upright for one second, lean forward for one second and straighten up again for one second.

Location of the trainee is found by using the wearable tag, RTLS and Location Platform. Orientation of the trainee's head is monitored by means of the IMU device installed on the top of his/her helmet. During the training the data are saved in an internal system memory.

After finishing the training, the data are transferred to the Unity application, where the *offline phase* takes place.

The *offline phase* starts with synchronization of the data from the two systems. The two synchronization timestamps in each data set are recognized, and then the procedure adjusts a suitable offset of the both systems' time control.

A disadvantage of the used localization system, which is the low sampling frequency, can be overdriven by an algorithm duplicating a number of localization samples. Besides duplication, the algorithm smoothes out the sharp turns on trainee's path and reduces measurement noise. To double the number of localization samples the Chaikin algorithm [17] is used. The advantage of the algorithm is its adjustment by means of two curving factors. The algorithm set of equations is:

$$\begin{cases} P_n(n) = P_c(n) + (P_c(n+1) - P_c(n)) \times f_1, \\ P_n(n+1) = P_c(n+1) + (P_c(n+2) - P_c(n+1)) \times f_2, \end{cases} \tag{8}$$

where $P_n(\cdot)$ corresponds to new position points, $P_c(\cdot)$ corresponds to the current position points;f_1 and f_2 are the curving factors.

To further reduce noises in the estimate of the trainee's path, a follower filter is proposed.

The key features extraction, comparison with expert's pattern, data visualization and final assessment are described in following chapters.

5.3 Visualization and Final Assessment

The final assessment can be established and visualized using a spider diagram, where all assessed features are represented, as shown in Fig. 35. The darker part of the figure depicts the specific scores of the trainee and the lighter part represents the expert's results or the average results from all assessed trainees. The visualization provides easily readable information, which trainee's skills have to be improved, and which skills are satisfactory.

In a case of five features, the data representation forms a pentagon, whose surface areas depicts the trainee's comprehensive score T_s and can be calculated from the formula [17]:

$$T_s = \frac{1}{2} \times \sin(72^\circ) \times (st + to + oa + ac + sc), \tag{9}$$

where s, t, o, a and c represent scores of each of the five key features of the training. In this manner, it is also possible to assess trainee skills in comparison with an expert's ones

$$F_s = \frac{T_s}{E_s} \times 100\%, \tag{10}$$

where F_s is the final relative score of training and T_s and E_s are trainee's and expert's scores respectively.

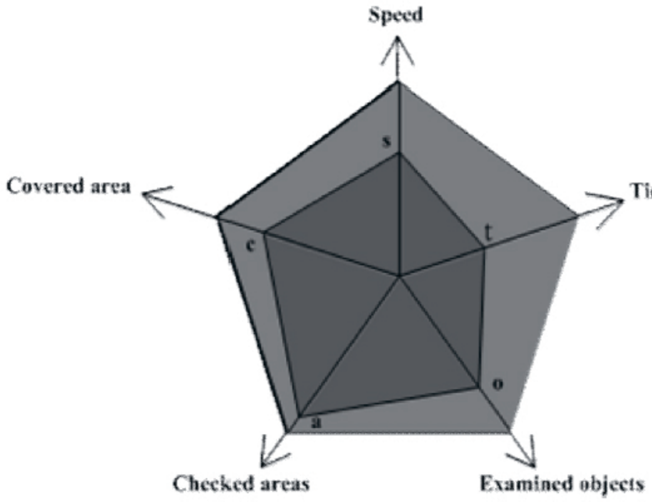

Figure 35: Pentagram for trainee's performance evaluation.

6 Product Development – Implementation And Verification

6.1 Implementation

Localization data are gathered using Localization Platform provided by Ubisense. It consists of a few interrogators located throughout the building and wearable tags, see Fig. 36(a). The system was verified and it was proven that the position measurement is very precise and it has about 15 cm–20 cm accuracy.

The trainee's FoV is measured using the designed and prototyped IMU device and authors' own application written in C++ programing language based on the Adafruit's BNO055 Absolute Orientation Sensor and Pro Trinket board, see Fig. 36(b). IMU sensor's data are processed by the dedicated Arduino program using the open source library provided by the board's manufacturer. Several different tests for both axes that are crucial in our application, which are yaw and pitch, confirmed that the system meets all defined requirements.

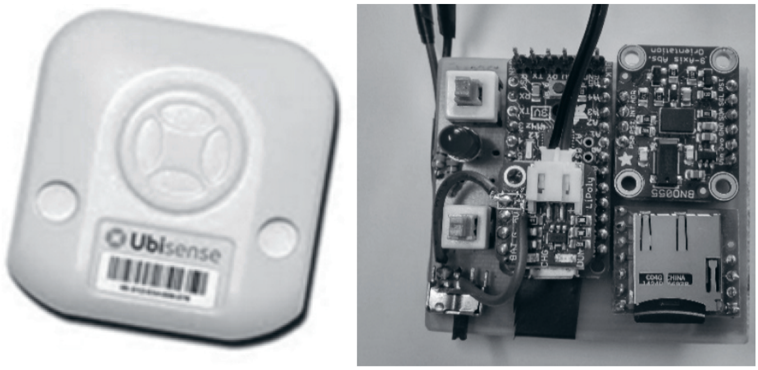

Figure 36: Trainee's wearable equipment: a) Ubisense tag, b) prototype board of IMU device.

6.2 System Verification

System verification was preceded by validation of location data preprocessing consisting of the Chaikin algorithm combined with the follower filter. Fig. 37(a) presents an example of the recorded training path. One can observe that the path consists of many sharp turns and some inconsistencies, which could be an effect of RTLS accuracy and precision. These effects could cause a problem when the location data are merged with data of FoV. To avoid the issue, the path is smoothed using the Chaikin algorithm and then the follower filtering is applied. The combination of these two algorithms leads to results shown in Fig. 737(b). The path smoothness after preprocessing is sufficient to synchronize location and direction data.

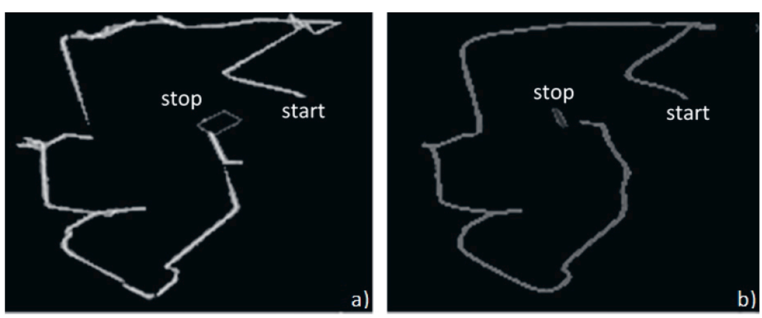

Figure 37: Example path measurement: a) without filtering, b) after using Chaikin algorithm along with follower filter.

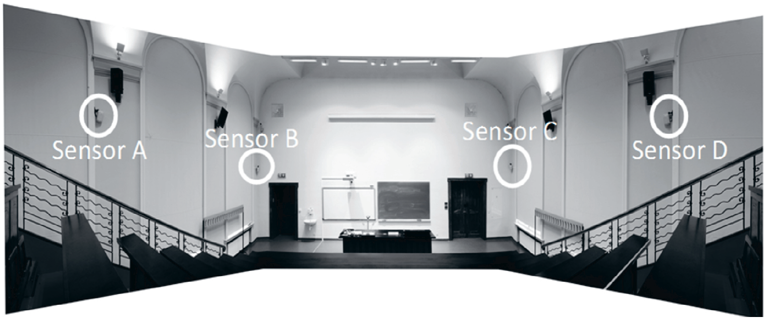

Figure 38: View on the simulating training field.

The verification scenario includes three phases. First, the training path has to be defined including a number of areas and objects, which need to be examined. Then a performance pattern of the test run by an expert is established. After that, the system is ready to use. The second step comprises trainee's training attempt when the real data are recorded. The last step includes visualization and assessment of the trainee's performance.

To verify the designed system, the training field was implemented in a lecture hall at Gdansk University of Technology in Poland, where the Ubisense RTLS system is installed. Figure 38 presents the used lecture hall with localization sensors.

To place trainee's location and FoV data into the training field, mapping of the training environment in the Unity application is required. The map of verification training field is shown in Fig. 39.

The desired training path including defined areas, objects and the expert's test run need to be entered into the application. As the test field, the front part of the lecture hall and first two rows of seats were used, see Fig. 40. The chosen space is divided into six areas, in the figure separated with dotted lines, where there are five objects, depicted by the grey rectangles, which have to be examined. In addition, to make the test more realistic, two artificial walls are added. To avoid vagueness of the figure, the subzones of the area coverage estimation are not displayed. However, in reality, each area is divided into a nine equal subzones as it is presented in Fig. 31.

Figure 40 and Fig. 41 present expert's and trainee's test run respectively. From Fig. 41 one can see, that the assessed trainee missed one area. Moreover, the trainee did not sufficiently examine all areas and thereby missed

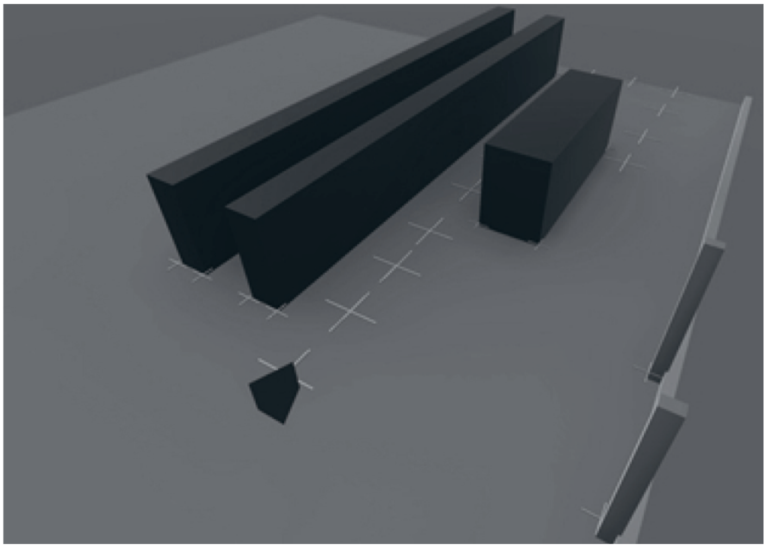

Figure 39: Training field recreated in the Unity application.

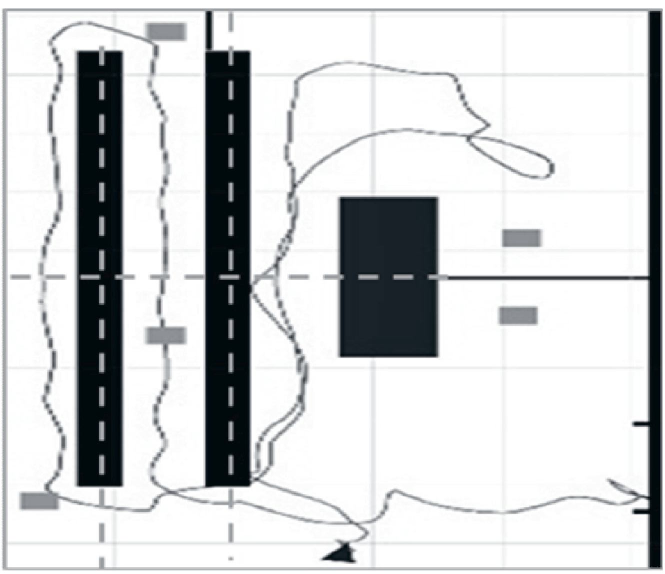

Figure 40: Expert's training path.

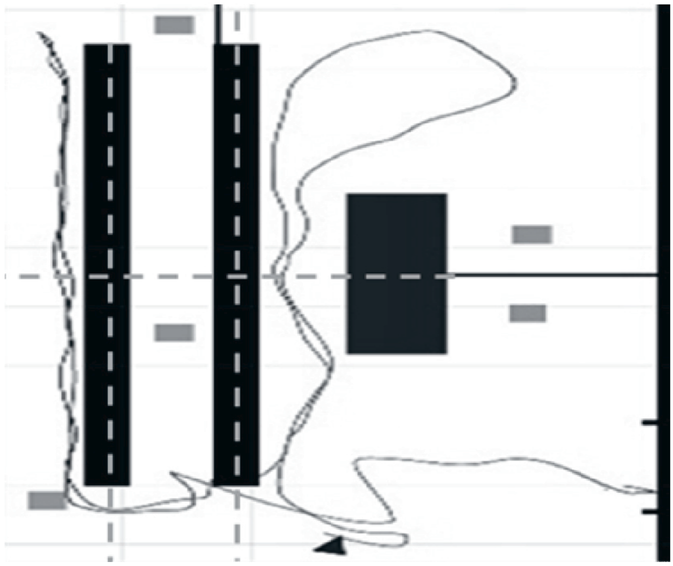

Figure 41: Trainee's training path.

two objects required in the desired training path.

Table 10: Performance Assessment Results.

Evaluated factor	**Expert**	**Trainee**
A number of check-points	6/6	5/6
Area coverage [%]	100	80
Number of examined objects	4/4	3/4
Time [s]	27	31
Average speed [m/s]	1.8	1.3
Final relative score [%]	100	60

Table 10 summarizes the trainee's performance in comparison with the expert. It shows that the trainee's execution time was longer than the expert's and therefore the average speed was also not up to mark.

Figure 42 shows the final trainee's skills evaluation using the spider diagram. The lighter pentagon indicates the expert's result and darker pentagon depicts the trainee's performance. The graph visually depicts that trainee needs to improve precision of field examination. The final score of

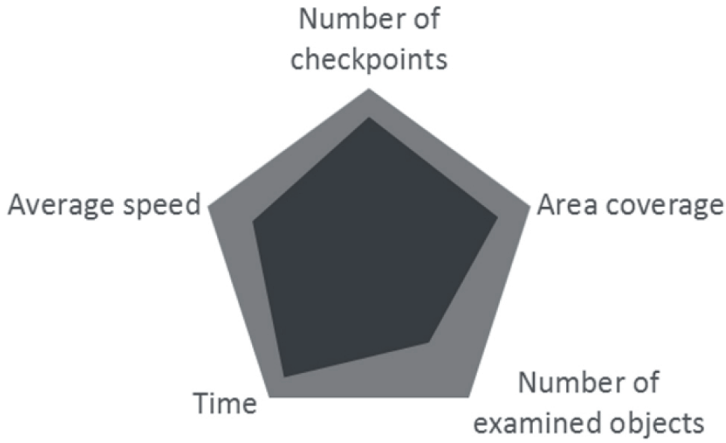

Figure 42: Result visualization of expert's and trainee's performance using the spider diagram.

trainee's competence F_s equals 60 % of the expert's one.

7 Conclusions

The presented study proves that the wireless multi-sensor system, based on RTLS and IMU devices and yielding information about trainees' movement in the test-field in real-time, is capable to objectively assess the trainees' skills and provide a comprehensive map of their skill profile.

The applied UCD methodology, which takes into account the stakeholders' and future users' requests, demonstrates the capacity to facilitate a precise definition of the problem and corresponding requirements. This design approach results in an appropriate selection of the algorithms and technologies.

The proposed solution is dedicated to operate even under condition of low visibility. The used devices are convenient to handle even during very dynamic and intensive firefighters' training and their performance is visualized in a user-friendly manner.

The system implementation based on Ubisense RTLS and dedicated IMU device, performs all required functionalities under given constraints.

The trainee's performance is assessed based on five key features, which are: an average speed, a number of examined checkpoints and objects, area coverage, and a tasks execution time. The selection of the features is done by experts, and in their opinions this selection is most relevant for vocational trainings.

Synchronization of the two independent measurement data channels is done by mean of the timestamp established at the training start. The defined calibration procedures of sensor used ensure the require accuracy and precision.

A combination of the Chaikin algorithm along with follower filter is used to smooth the training path, which enables clear estimation of the trainee's FoV.

The Unity game engine software along with the spider diagram are used to visualize trainee's skills and judge his/her advantages and weaknesses in user-friendly manner. Moreover, it provides the final comprehensive score, which facilitates comparison of trainees' results with experts' and other trainees' results.

Future research may concern an extension of the number of analysed training key features. Moreover, it is planned to improve the Unity application to visualize the scores of the assessed people on the background of all trainees participating in training. Another development could focus on a comparative analysis of history of trainee's results.

The proposed method after adequate modifications could be easily adapted to other applications, such as military or miners rescue training.

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Paper VI

IoT On-Board System for Driving Style Assessment

Paper VI

IoT On-Board System for Driving Style Assessment

B. JACHIMCZYK, D. DZIAK, J. CZAPLA, P. DAMPS, W. J. KULESZA

Abstract

The assessment of skills is essential and desirable in areas such as medicine, security, and other professions where mental, physical, and manual skills are crucial. However, often such assessments are performed by people called "experts" who may be subjective and are able to consider a limited number of factors and indicators. This article addresses the problem of the objective assessment of driving style independent of circumstances. The proposed objective assessment of driving style is based on eight indicators, which are associated with the vehicle's speed, acceleration, jerk, engine rotational speed and driving time. These indicators are used to estimate three driving style criteria: safety, economy, and comfort. The presented solution is based on the embedded system designed according to the Internet of Things concept. The useful data are acquired from the car diagnostic port—OBD-II—and from an additional accelerometer sensor and GPS module. The proposed driving skills assessment method has been implemented and experimentally validated on a group of drivers. The obtained results prove the system's ability to quantitatively distinguish different driving styles. The system was verified on long-route tests for analysis and could then improve the driver's behavior behind the wheel. Moreover, the spider diagram approach that was used established a convenient visualization platform for multidimensional comparison of the result and comprehensive assessment in an intelligible manner.

Keywords: driver's behavior; driving style; skills assessment; eco driving; embedded system; internet of things; real-time vehicle tracking

1 Introduction

Modern technologies pave the way to the objective assessment of professional skills. The simulation and real-time systems supporting such assessment can be found in evaluation of medical and security staff as well as many other professions where mental, physical, and manual skills are crucial. Each such solution focuses on specific measures for the assessed trade. For example, transportation companies search for a solution allowing objective driver skill assessment based on measures of the transportation cost including fuel consumption and fleet maintenance, driving safety, and delivery time. However, these factors are ambiguous and may be affected by external circumstances such as road conditions, traffic accidents and even a vehicle's technical condition, which are independent of the driver.

The problem can be solved by assessing the drivers based on their driving style, independent of external conditions. However, emerging technologies and methods, especially in remote sensing and Internet of Things (IoT), obtain information about driving parameters as well as external conditions to evaluate the person's driving style. Such assessment can be used to grant professional drivers, who preserve passenger's convenience or a cargo's safety and consider economy along with eco-driving tips. Moreover, the insurance and car rental companies, with monitoring possibilities of the person's driving style, could grant special discounts for those driving economically and safely. With the proper assessment program, driving schools could get information on trainees, i.e., ready for examination or more practice needed. Also, people who would like to improve their skills may gain from such a system showing their weaknesses to guide progress [1].

To address the problem of the objective assessment of driving style, we propose the vehicle monitoring system based on the IoT approach, using the car's diagnostic port—OBD-II—and the designed and developed additional acquisition module using an accelerometer sensor and GPS module. Moreover, we propose sets of indicators and criteria, which can be used to comprehensively assess driving style. The indicators, which are associated with the vehicle's speed, acceleration, jerk, engine rotational speed, and driving time, are used to assess three criteria of driving style: safety, economy, and comfort. The gathered multidimensional data are normalized based on expert results and then visualized and assessed using the spider diagrams approach. The modelled driving skills assessment method has been designed and implemented on a real car. For this purpose, an embedded On-board Measurement and Communication Unit (OMCU) has been developed. The system was then evaluated and verified experimentally. The obtained results prove the system's ability to distinguish different driving styles, which are based on three assumed criteria consisting of eight indicators and categorized as ordinary, calm, aggressive or unnatural. Moreover, the spider diagram approach established the convenient visualization platform for multidimensional data, and the comprising comprehensive assessment is presented in an understandable manner.

2 Survey of Related Work

The progress in technology enables users to assess the competence of professionals, such as medical staff or emergency serviceman. A methodological approach for tracking human movement and behavior resulted in a proposed system for firefighter's skills and competence assessment [2]. The spider chart is chosen to visualize and graphically compare the results of the trainees with the expert. The result is quantified by the surface area of the polygon in the chart.

The major interests in analysis of driving style using different systems and algorithms are comprehensively reviewed in [1], and they are not iterated here. The following review focuses on areas, which are directly related to the proposed solution: human and quality aspects of driving; driving style indicators and instrumentation, along with classification methods, however to avoid redundancy, in some references these areas cannot be separated.

2.1 Human, Social and Quality Aspects of Driving Styles

A driving style can be described as a combination of driving abilities and behind-the-wheel behavior. Driving abilities depend on the driver's knowledge, skills, and experience. The driver's behavior reflects driving abilities, developmental factors, personality, demographic factors, biological features, perceived environment and driving environment [3],[4],[5]. All those factors influence driving tendencies: speeding, unsafe passing, impaired driving, and tailgating [3]. Studies show that young drivers have a higher rate of crashes and offences in comparison to experienced ones [4]. In a case of teen drivers, the presence of passengers inside the vehicle has an influence on crash risk, because of the distracting effect of social interaction during driving [5].

Psychologists identify seven different driving personalities depending on an interaction with other motorists and the driver's own behavior [6]. There is even a claim the way that a driver holds a steering wheel reflects his personality [7].

As stated in the introduction, driving styles might have a great influence on transportation quality aspects such as safety, comfort, and economy. According to [8],[9], safety on the road is of highest national importance and many road accidents might be prevented. Apart from using mobile devices and drunk-driving, a driver must also not exceed the speed limits. A driver should take into consideration the weather and road conditions and adjust the driving speed cautiously. Harsh accelerating and braking along with sharp cornering are recognized as dangerous behaviors. Driver's fatigue is often ranked as a major factor of serious road crashes. The safety aspect of driving style is mentioned in almost all related publications.

Economy is widely researched topic related to drivers' assessment. Authors of [10] directly address their application to improving driving economy. In [11],[12], authors proposed an eco-driving assistant to assesses the driver's driving style considering both environmental and vehicle's variables. Authors of [13] proposed to evaluate the long-term impact of an eco-driving training course.

Apart from the economic aspects, a driving style has a big impact on comfort of the passengers traveling by cars, buses, or trams [1]. According to [14], the driver's behaviors that may affect the passenger comfort experience are: uneven driving, heavy braking, sharp accelerating and harsh cornering. The author of [15] has proposed to model the driving style using the acceleration of the bus in three axes. The passengers were asked to grade their experience during the journey and meanwhile the data from the accelerometer were collected. The correlation between the acceleration in three axes and the passengers' comfort experience was found.

2.2 Driving Style Indicators and Instrumentation

Several of Information and Communication Technology (ICT) solutions for increasing the safety and the economy of driving have been developed worldwide. An eco-driving assistant for Android is proposed in [11],[12]. The solution is based on the use of a mobile phone, Bluetooth and OBD-II diagnostic port module. The system assesses the driver's driving style considering both environmental and vehicle's variables. To evaluate the relationship between fuel consumption and driving style, an expert system with Random Forest classification is run on the mobile device. In [16], simulations are conducted to analyze an impact of eco-driving behavior. It concludes that in normal and free traffic conditions, the eco-driving reduces CO_2 emissions by 10–15%.

In [13], an on-board logging device is proposed to evaluate the long-term impact of an eco-driving training course. The collected data include the mileage, engine rotational speed, position of the acceleration pedal, gear selection and instantaneous fuel consumption. Ten participants have undertaken the four-hour course during the examination period. The project showed that based on the eco-driving tips, the mean value of fuel consumption for all drivers decreased by 5.8% and changes in the driving behavior were observed.

Driving styles define a dynamic behavior of a driver on the road [17]. In this paper, the authors classify the driver's style using the measure of how fast he accelerates and decelerates. The experiments were conducted using a vehicle simulation program. Applying the same normalized parameters, the driver is classified into one of three classes: calm, ordinary or aggressive.

There are available built-in-systems that assist drivers in eco driving, e.g., Scania Driver Support [18], which was developed for Scania trucks. The system analyses the data from the truck's sensors and provides safety and eco driving tips to the driver. There is a high potential in using the inertial sensors to differentiate between different drivers using features associated with acceleration, cornering, and braking behaviors. The authors of [19] propose Support Vector Machine and k-mean clustering as their training algorithms. In [20], authors applied k-nearest neighbors classification algorithm classifying driving style as aggressive or ordinary.

In [21] several measures of driving style and their correlation with the predictability of the driver in different conditions are proposed. Drivers are distinguished as aggressive and non-aggressive based on the lateral and longitudinal accelerations and their derivatives with respect to time, called respective jerks. Different driving styles such as aggressive, calm and careful, and the division between them are discussed in [22],[23]. The authors defined specific features, their indicators, and the possibility of measuring them.

2.3 Driving Style Classification Methods

In [24], a self-developed GPS-based device is used to collect driving parameters and send them to a server where Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA) are used to identify drivers' behavior. This method may be valuable especially for those involved in fleet management, and it can be used to increase traffic safety.

Using frequently occurring patterns of vehicle driving, such as a left or right turn or curve, stop or making a U-turn, the author presents a method for a driving event recognition using Hidden Markov Models (HMMs) [25]. The used data acquisition system collects information about the speed along with lateral and longitudinal accelerations from a vehicle. The research shows that HMMs are accurate and reliable for driving events recognition. Deng et al. proposed driving style classification using braking characteristics based on HMM [26].

Dynamic Time Warping (DTW) algorithm and a smartphone sensor fusion can be used in [27]. Neural Networks can be utilized to characterize the road type and the driving style [28].

Applications of some common classification methods for driving style assessment, such as Fuzzy Logic, Clustering, Bayesian approach, Decision Tree and others are presented in [1].

3 Problem Statement

From the review of related works, one can observe a rising interest on monitoring and assessing of motorists' driving style, which defines driving skills and behind-wheel behavior. The advance in car embedded systems and an availability of standardized on-board diagnostic systems, provide data from the vehicle's internal sensors, which indicate a driving style. The related works show different ways of assessing safety [8],[9], economy [10],[11],[12],[13], or comfort [14],[15] using speed, speed limit, engine rotational speed, driving without rest and jerks. Often, the OBD-II diagnostic port, GPS module or mobile phone are used [11],[12],[13],[15],[18],[24],[27]. Nevertheless, none of the works combines all criteria into one system. Moreover, most of the assessments were done on a predefined route or by simulations. Furthermore, none of the solutions applies information about an actual speed limit of road. Additionally, usage of graphical visualization combined with driver's assessment has not been reported. Although recognition and classification of the driver's style is done in various manners however, there is no solution of quantitative evaluation of criteria and overall assessment as a single score.

The objective of this research is an objective driving style assessment method based on indicators, which are acquired from a measurement system monitoring the car's dynamic driving parameters.

We assume that driving style assessment can be grounded on the three driving quality criteria: safety, economy and comfort [1]. These quality criteria can be estimated based on vehicle's speed, accelerations and jerks in three axes, engine RPM and driving time. The applied indicators are normalized to the expert-based pattern as defined in Table 11.

The proposed embedded system is designed in accordance with the IoT concept where data acquisition is done using the available diagnostic port—OBD-II, along with an additional accelerometer sensor and GPS module. The Raspberry PI and GPRS modules provide data via the GSM network. Moreover, the spider diagram is assumed to be a suitable way to visualize and score the multidimensional assessment of driving style.

The main contribution of this work is a proposed method for driving skills assessment, considering more information than time of delivery and fuel consumption. Moreover, this work offers multi-quantitative visualization of the results using spider charts on a single diagram. Furthermore, the proposed solution is validated and verified based on real measurements and with real-world scenarios. The resulting system, due to its small size, low cost, simple architecture, and applicability to wide range of vehicles, can be easy customized to different commercial applications.

4 Driving Style Assessment Indicators and Criteria

The basic design stage of a driver style assessment system is to choose driving style criteria and corresponding measures that reflect interactions between the driver and a car along with the surrounding environment. In this approach, the driving style defines the driver's skills and behavior behind the wheel. However, surrounding environmental aspects such as daylight condition, weather conditions in terms of precipitation and ambient temperature, road type and condition are not considered in this driver style assessment. However, they can be added to the assessment criteria easily

Table 11: The *safety*, *economy* and *comfort* criteria and corresponding indicators, their symbols, units, and definitions.

Criterion	Indicator	Symbol	Definition
Comfort, Economy, Safety	De- and accelerating ratio	jr_x	$$\frac{N \cdot \overline{Ex}}{\sum_{i=1}^{N} \lvert \frac{\Delta a_{xi}}{\Delta t} \rvert} \quad (1)$$
	Bumping ratio	jr_z	$$\frac{N \cdot \overline{Ez}}{\sum_{i=1}^{N} \lvert \frac{\Delta a_{zi}}{\Delta t} \rvert} \quad (2)$$
Comfort, Safety	Cornering ratio	jr_y	$$\frac{N \cdot \overline{Ey}}{\sum_{i=1}^{N} \lvert \frac{\Delta a_{yi}}{\Delta t} \rvert} \quad (3)$$
	Driving time without rest ratio	dtr	$$\frac{2 \cdot N_{os}}{t_{str}} \quad (4)$$
Safety	Car speeding ratio	spr	$$\frac{1}{M} \sum_{i}^{M} \frac{SL_i}{CS_i} \pm \sigma_{spr} \quad (5)$$
	Car speeding duration ratio	$spdr$	$$1 - \frac{M}{N} \quad (6)$$
Economy	Excessive engine rotational speed ratio	rsr	$$\frac{1}{L} \sum_{p}^{L} \frac{ERSR}{EERS} \pm \sigma_{rsr} \quad (7)$$
	Excessive engine rotational speed duration ratio	$rsdr$	$$1 - \frac{L}{N} \quad (8)$$

where: N—a number of samples acquired within a single test ride; $\overline{Ex}$, $\overline{Ey}$, and $\overline{Ez}$—mean expert's values of ratios of de- and accelerating, cornering and bumping ratios respectively; δa_{xi}, δa_{yi} and δa_{zi}—successive accelerations in $x-$, $y-$ and $z-$axes respectively; δt—sampling ratio; N_{os}—a number of rest stops during the test ride, $tstr$—time of single test ride; M—a number of samples of exceeding speed limits; SL and CS—speed limit and current speed respectively; L—a number of samples of exceeding recommended engine rotational speed; $ERSR$ and $EERS$—recommended engine rotational speed and difference between engine rotational speed and recommended one respectively and without special investment.

Since the driving style assessment is to be used for different purposes and to make it more flexible, we propose the aforementioned assessment criteria: safety, economy, and comfort. Selection of these criteria is in line with references presented in Section 2 and with the results of the authors' user-driven-design. The interviewed stakeholders have chosen these three criteria as most relevant for their applications.

These three criteria can be used exclusively to guide the drivers in improving their style and may be useful for risk analysis and professional skills assessment. Each assessment criterion is quantified using various indicators, which are normalized. Some of them refer to established regulation standards, and others refer to expert's ride and behavior measures. Selection of indicators is limited to the quantities accessible via the OBD-II socket of an ordinary personal vehicle along with the commonly used 3D acceleration and data from a GPS module. The applied eight indicators were defined based on reports presented in the Review of Related works [3],[8],[9],[10],[12],[13],[14],[15],[16],[17],[22], but also on our pre-study and -test. All indicators are estimated from measures acquired within a single test ride time tstr, when N samples of the defined sampling rates are collected.

The criteria, corresponding indicators, symbols, and the proposed definitional equations are summarized in Table 11.

4.1 Indicators

Each of the eight proposed indicators is used for single, two and even three criteria. This means that some aspects of the criteria overlap or even include each other.

The most common for all criteria is the *de- and accelerating ratio*, jr_x (1), which indicates a driver's tendency for aggressive driving. The indicator is obtained by analyzing the car's dynamics represented by mean jerks in x axis, where jerk is understood as the first derivative of the car's acceleration ax in respect to time. To assess if a driver does not accelerate or decelerate too rapidly, his mean value is related to respective *mean expert's jerk* Ex. The acceleration can be measured using conventional accelerometers.

Bumping ratio, jr_z (2), is a measure of driver's tendency to pass over speedbumps or road holes with too much speed. The indicator estimated from the mean jerk in z axis relates to the *mean expert's jerk Ez*.

Cornering ratio, jr_y (3), identifies if corners are taken smoothly and calm or sharply and fast, which indicates both driver's skills and behavior. The indicator is measured as the mean jerk in y axis. To assess if the sharpness of the bend matches the speed, the mean value is related to *mean expert's jerk Ey*.

Driving time without rest ratio, dtr (4), assesses if the driver follows the rule of resting after a recommended driving time. It can be mapped from engine uptime information, which shows time of driving without stopping and is available using OBD-II interface. This indicator is reasonable for a ride, which takes more than two hours.

Car speeding ratio, spr (5), is the average driving speed over the limit during the test ride. This value is calculated based on M samples of *current speed, CS, of the speed above the limit, SL*. However, to comprehensively assess the driver's style, the speeding distribution is more informative. Therefore, apart from the mean value, the normalized standard deviation σ_{spr} is also used.

Car speeding duration ratio, $spdr$ (6), shows length of time the driver exceeds the speed limits. It is estimated by relating the number of samples M of the exceeding speed limit to all N samples of the test ride.

Excessive engine rotational speed ratio, rsr (7), assesses mostly an economical aspect of driving style. This mean value of revving is calculated based on L samples of $enginerotationalspeed$, $RERS$, exceeding the recommended value related to the recommended value $EERS$. However, to comprehensively assess this indicator, the excessive engine rotational speed distribution is needed. Therefore, apart from the mean value, the normalized standard deviation σ_{rsr} is also used. These measures are acquired via diagnostic ports.

Excessive engine rotational speed duration ratio, $rsdr$ (8), measures length of time the engine rotational speed was exceeded in comparison to the test drive time. Since short-term engine rotational speed overrun may sometimes be necessary, the time ratio of exceeded engine rotational speed is proposed.

4.2 Criteria

The driving safety criterion, SAFC, is based on six indicators (1)–(6) [3],[8],[9],[22]. Most of the ratios: bumping, jr_z, de- and accelerating, jr_x, along with cornering ratio, jr_y, together with car speeding, spr, and car speeding duration, spdr, are measures of driving dynamics and may show a hazardous loss of tire friction. The first three indicators show how the driver's behavior differs from the expert's one, which is a pattern of safe driving. Two other indicators, i.e., the car speeding and car speeding duration are used to estimate how much and how frequently, the driver exceeds the speed limits, which are laid down by regulations.

Apart from behavioral factors, a habit of resting-less driving time is important for safety. Therefore, driving time without rest ratio, dtr, is included in the *safety* criterion.

The economy criterion, $ECOC$, is relevant not only from an economy point of view but also due to the sustainability issue. The criterion is very substantial for the professional drivers and their employers. The $ECOC$ can be based on the car's engine rotational speed and how much it exceeds the eco-driving standards, which are directly related to fuel consumption [10],[11],[12].

Bumping ratio, jr_z, indicates a habit of fast passing over the road speedbump or holes, which lead to damages and shortens life time of the car's parts. Furthermore, an excessive usage of brakes and throttle, indicated by de- and accelerating ratio, jr_x, affects both fuel combustion and wear of parts, i.e., tires and brake pads [12],[13],[17].

Long driving with high engine rotational speed, measured *by excessive engine rotational speed ratio*, rsr, affects fuel consumption [29],[30]. Moreover, when the driver exceeds the recommended engine rotational speed for longer periods, it indicates uneconomical driving on too low of a gear ratio [13].

The comfort criterion, $COMC$, measures passenger's convenience and the cargo's safety in terms of its displacement and damage. The criterion is assessed using four indicators of driving smoothness, which mostly depends on ways of deceleration and acceleration, i.e., turning too fast or hesitantly [14],[15]. Moreover, the manner of driving through speedbumps or potholes is important for the passenger's experience. All these events can be indicated by acceleration measures in the car's three axes and jerk calculations given

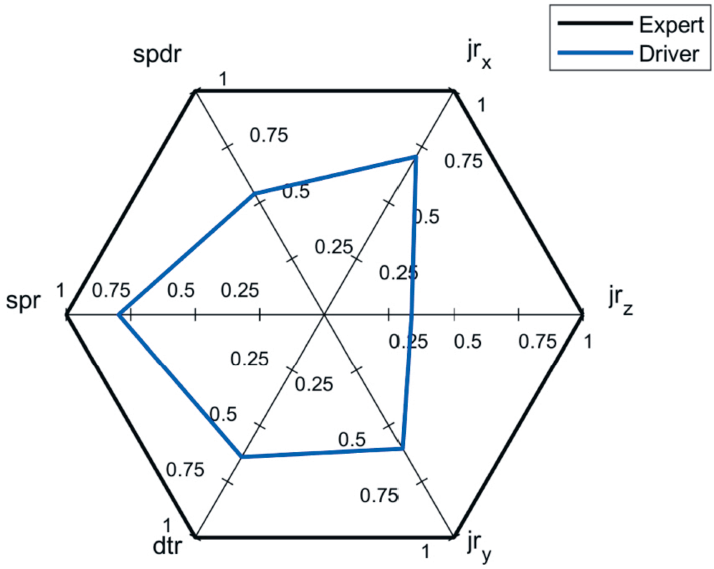

Figure 43: Example of spider diagram of SAFC.

by (1)–(3).

Apart from the safety issue, the long drive without a rest can be inconvenient, both for the driver and passengers. Therefore, the *driving time without rest ratio indicator*, *dtr* (4), contributes to the comfort criterion.

4.3 Assessment

To objectively assess and visualize a multidimensional problem of driving style assessment, the spider diagram approach [2] is proposed. This driving style assessment is based on analysis of $SAFC$, $ECOC$ and $COMC$ criteria, with an overall assessment including each indicator. Figure 43 shows an exemplary assessment based on $SAFC$, with six indicators jr_x, jr_z, jr_y, dtr, spr and $spdr$, where all of them have the same weights. The black contour line represents the expert's scores of each indicator and the blue contour line depicts assessed driver's results.

Analyzing the surface area of the resulting blue hexagon, it is possible to depict the driver's *safety* criterion score DSC_s that can be calculated as a sum of six triangles from the formula:

$$DSC_s = \frac{1}{2} * sin(60°) * (jr_x * jr_z + jr_z * jr_y + jr_y * dtr \\ + dtr * spr + spr * spdr + spdr * jr_x) \tag{9}$$

The driver's DSC_s related to an expert safety criterion score, ESC_s forms the *normalized safety criterion* score, NSC_s:

$$NSC_s = \frac{DSC_s}{ESC_s} = (jr_x * jr_z + jr_z * jr_y + jr_y * dtr \\ + dtr * spr + spr * spdr + spdr * jr_x)/6 \tag{10}$$

A similar assessment method may be used for driver's *normalized economy criterion* and *normalized comfort criterion* scores, NEC_s, NCC_s, respectively:

$$NEC_s = \frac{DEC_S}{EEC_s} = (jr_x * jr_z + jr_z * rsr \\ + rsr * rsdr + rsdr * jr_x)/4 \tag{11}$$

$$NCC_s = \frac{DCC_s}{ECC_s} = (jr_x * jr_z + jr_z * jr_y \\ + jr_y * dtr + dtr * jr_x)/4 \tag{12}$$

where EEC_s and ECC_s are the expert's scores for safety and comfort criteria respectively. The proposed overall assessment score composed of all eight indicators, and the driver overall normalized final score NO_s can be calculated as:

$$NO_s = \frac{DO_s}{EO_s} = (jr_x * jr_z + jr_z * jr_y + jr_y * dtr + dtr * spr \\ + spr * spdr + spdr * rsr + rsr * rsdr + srdr * jr_x)/8 \tag{13}$$

where DO_s and EOs are driver's and expert's overall score, respectively.

The proposed graphical visualization facilitates a comparison of the latest results of assessment of driving style with the previous ones, showing which indicators of driving style have been enhanced and which still need to be improved.

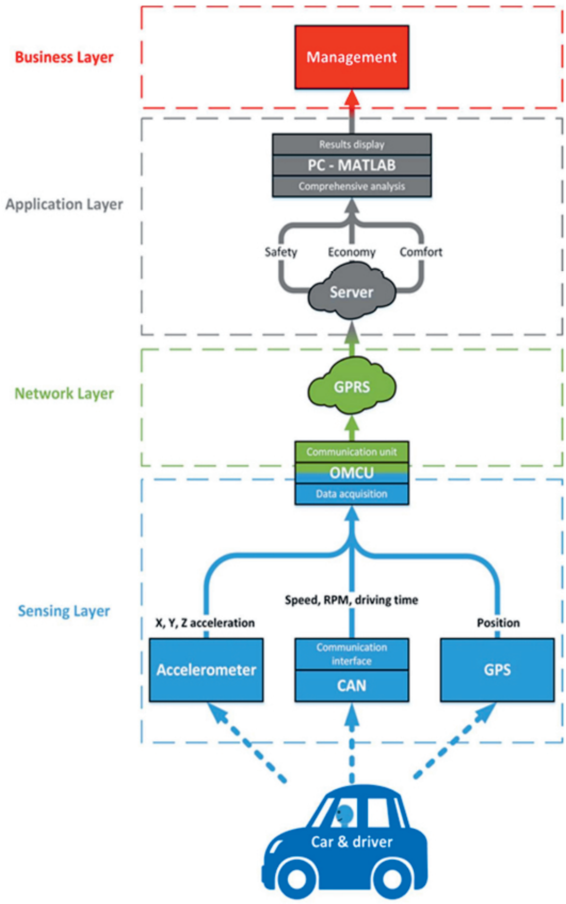

Figure 44: Architecture of the IoT-based driving style assessment system.

5 System Architecture

The driving style assessment system is designed according to the IoT reference model [31] and consists of the four functional layers: *Sensing-*, *Network–*, *Application-*, and *Business-layer*. The functionalities of each layer are supported by the relevant hardware and software. The system structure is presented on the block diagram in Figure 44.

The *Sensing-layer* is responsible for data collection during the driving, data pre-processing including filtering and edge computing. The functionalities are executed at OMCU hardware.

A part of OMCU hardware performs communication functionalities, therefore, it also belongs to the *Network-layer*. The included communication module provides data for further analysis via a mobile network through GPRS. All standardized communication protocols of data transmission belong to the Network-layer of the model.

In the *Application-layer*, high-level data processing such as filtering, data synchronization and calculations of the driving indicators are performed. In this layer, the cloud-level comprehensive analysis and results visualization are realized. These processes are supported by dedicated algorithms from MATLAB.

The final *Business-layer* includes the management and decision-making functions, where relevant algorithms are implemented. At this layer, the previously acquired and pre-processed data are used to deliver information required by specific applications. The applications can also aim for a specific business purpose, such as risk analysis or assessment of driving style required by a car rental or insurance company.

6 System Implementation

Hardware and software implementations have been executed within the project frame and are described in detail in the following sections.

6.1 Hardware Implementation

The On-board Measurement and Communication Unit, OMCU, is the main hardware system, which acquires data and communicates with the server, as shown in Figure 44. It consists of a single-board computer Raspberry Pi and expansion modules: the accelerometer, GPS module, GPRS module and real-time clock. Additionally, the OMCU is integrated with the OBD-II adapter via a Bluetooth module of the Raspberry Pi.

The single-board computer Raspberry Pi 3 constitutes the main component of the OMCU embedded device. It runs on a Debian-based Linux operating system called Raspbian. On the Raspberry Pi, data are acquired, stored, and processed. It can be powered either from the car's 12 V socket via USB adapter or a power bank.

For the acceleration measurement, the 3-axis ADXL345 accelerometer with selectable measurement ranges is applied. For this application, ±4g range is chosen, and the data rate can be between 0.1 Hz and 3200 Hz. Based on a conducted empirical test, the data rate of 12.5 Hz is found as sufficient for driving style analysis. It measures both dynamic accelerations resulting from motion or shock and static accelerations, including gravity. The module is connected to Raspberry Pi using I2C bus.

The actual car's position is determined via the NEO-7M-C GPS receiver module, which communicates with Raspberry Pi by a Universal Asynchronous Receiver and Transmitter (UART) interface applying the NMEA 0183 standard.

To acquire in real-time the vehicle's variables such as speed, engine load and engine rotational speed, the iCar III OBD Scan-tool adapter is applied. This module also enables reading, erasing, and displaying of the diagnostic codes, which are used in troubleshooting. The adapter is plugged into the vehicle's OBD-II socket and communicates with Raspberry Pi via the Bluetooth module.

None of the available Raspberry Pi models consists of a built-in real-time clock, so they are unable to keep track of daytime without an Internet connection. Therefore, a real-time hardware clock DS3231 with a battery backup is added to the system using the I2C bus to provide the current time offline.

The GSM/GPRS dual SIM-c-uGSM μ-shield v.1.13 module is used to enable a communication between the computer and Internet. The GPRS module provides a low speed high range mobile Internet connection. However, it requires a SIM card and an additional 250 mAh LiPo battery due to possible current spikes higher than 1.5 A. The module is connected to the Raspberry Pi using the serial communication protocol via USB interface.

6.2 Software Implementation

According to the IoT architecture presented in Figure 44, the software part of the system is implemented at three IoT layers, i.e., Sensing-, Network- and Application-layer. For Sensing- and Network-layers, the OMCU's application program has been developed in Python programming language and runs on Raspberry Pi in the auto start mode. The program is divided into threads working independently and simultaneously in an infinite loop. Each thread is responsible for different functions of the system: collecting and sending

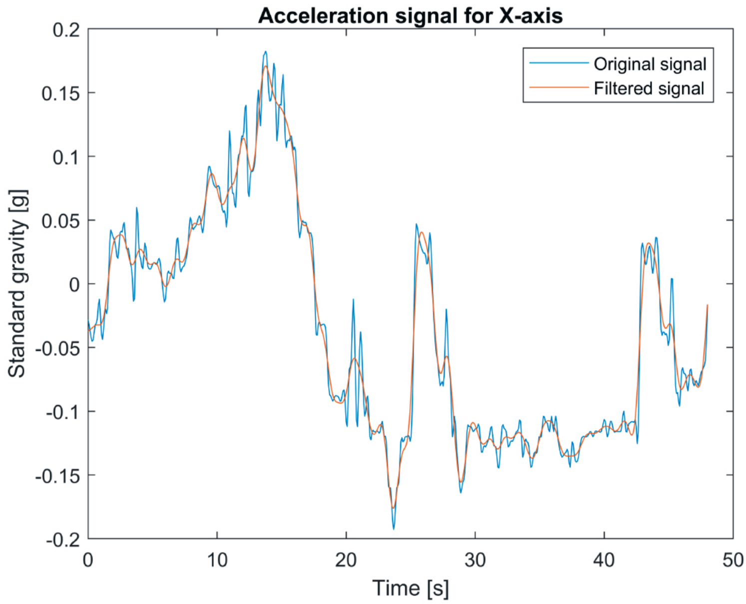

Figure 45: Original and filtered acceleration signal for x-axis.

data to the server and control of the whole system. In the IoT Application-layer, the collected data are sent to the server via OMCU and processed in MATLAB R2017a environment.

The data from the accelerometer are filtered using two types of filters: low-pass filters for measurements in x and y axes and band-pass filter for measurements in z axis. The 4th order lowpass Butterworth filter with cut-off frequency at 0.8 Hz is applied. For the case of the z axis, useful information needs to be extracted from the signal corrupted by the vehicle vibration response component varying between 1 Hz and 2 Hz [32]. Another disturbance component of low frequency is caused by landform. Therefore, to clear out these components, a 4th order bandpass Butterworth filter with cut-off frequencies 0.1 Hz and 0.8 Hz is applied. The filters' parameters were chosen empirically. Figures 45 - 47 show examples of accelerometer measurements for x, y, and z-axes respectively, before and after filtering.

Based on the vehicle's GPS position, the road speed limits (needed to estimate an exceeded speed limit), are received from a dedicated API with OpenStreetMap.

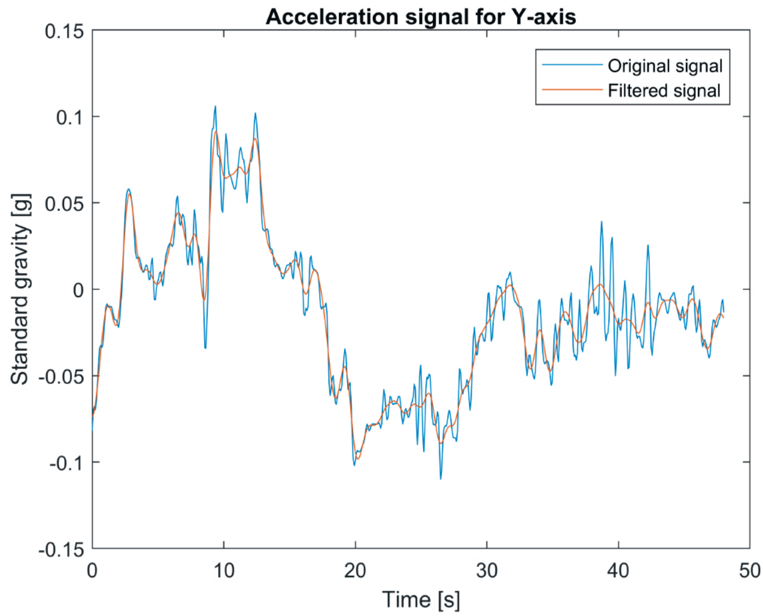

Figure 46: Original and filtered acceleration signal for y-axis.

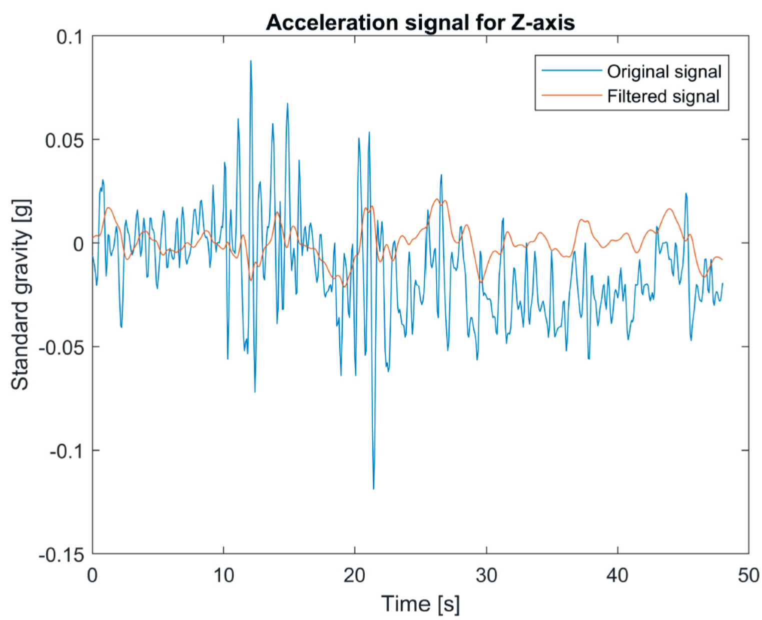

Figure 47: Original and filtered acceleration signal for z-axis.

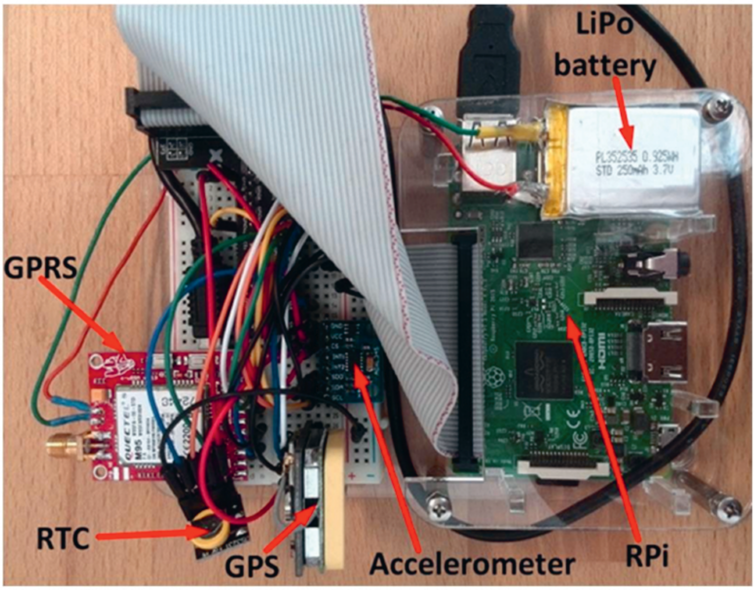

Figure 48: The OMCU prototype.

6.3 Embeded System Prototype

To interconnect all system parts, the solderless breadboard with 400 connection points is used. The GPIO breakout expansion board is connected to the Raspberry Pi by a ribbon cable. All expansion modules are jointed to the appropriate pins using jump wires. The breadboard is mounted on the Raspberry Pi plastic case. The photo of the assembled device is presented in Figure 48.

The developed OMCU device was mounted on the test car's dashboard as shown in Figure 49. The accelerometer measurements are sensitive to the device location, i.e., matching between the device's axis and the car's axis significantly affects the measurements. Therefore, mounting of the device for each test was very accurately done. The final system version consists of an automated start-up axes calibration regardless of the device's placement.

7 Evaluation and Verification

The developed embedded system was evaluated by tests of multiple drivers on the same short route of 16 km. All defined indicators were measured

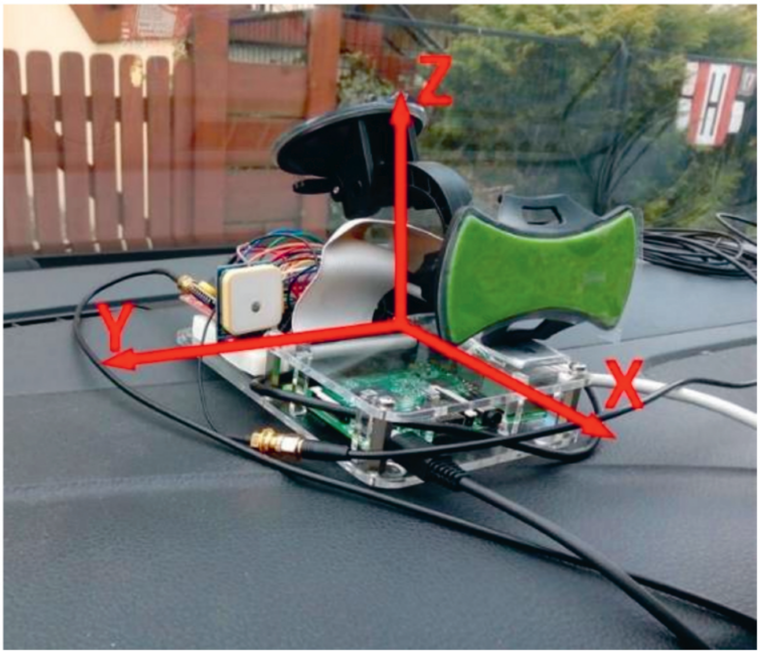

Figure 49: Device prototype mounted in the car, with depicted accelerometer axes.

to assess the criteria of *safety*, *economy*, and *comfort*, as well as an overall assessment. Then, the system was verified on the long-route test of 325 km, when the same parameters were assessed.

The evaluation and verification tests were conducted using the same car, Opel Astra H 2005, 1.6, 16 V, 105 HP equipped with a manual gearbox. During the test drives, the basic indicators of speed, engine rotational speed and engine uptime were obtained through an OBD-II interface, while the indicators of accelerations in $x-$, $y-$ and $z-$ axes and car's location were collected by the acceleration and GPS expansion modules, respectively.

The evaluation was done by assessing the driving style of five drivers who imitated different driving styles described in Table 2. The test data set is limited because our validation is based on a case study approach, since the proposed assessment method is based on expert approach and does not apply any statistical model. Moreover, the results prove usefulness of the proposed solution in a sense that the diversities in scores among different driving styles are very distinguishable. Due to safety reasons we could only

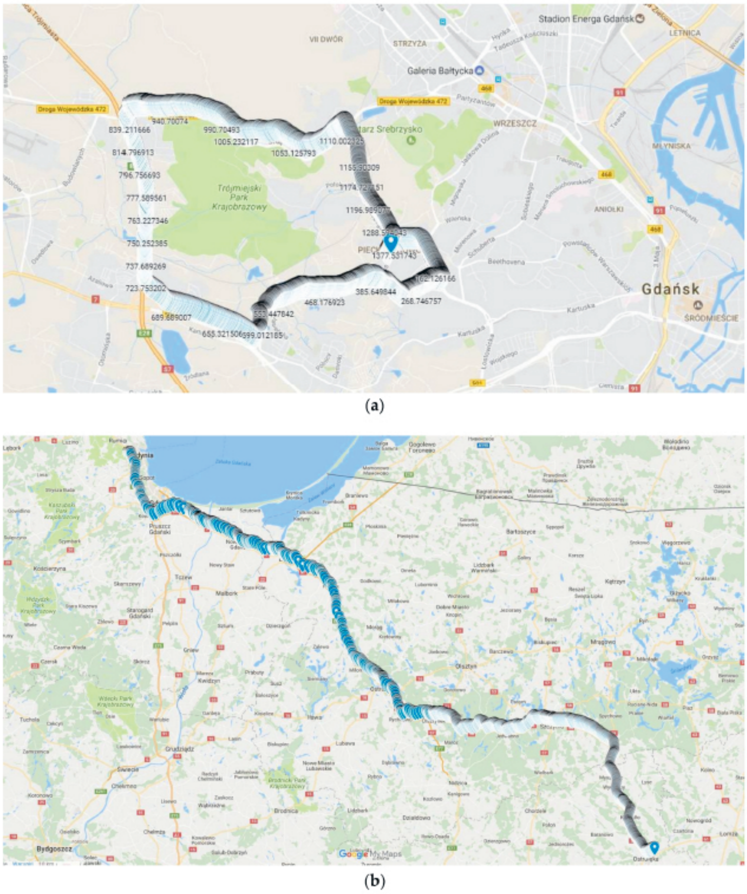

Figure 50: The GPS tracker of test route of (a) evaluation; (b) verification.

imitate/simulate driving styles, since a drunk, drugged, or sick person is not allowed to take such test. This kind of limitations is common in behavioral sciences. To map the expert's behavior, a professional driver took the same route. The short route test included different road types, i.e., highways, ramps, and urban streets. Figure 50a depicts an example route from the GPS tracker; the positions are labelled with the driving time in seconds. Depending on the driver, each test lasted from 21 min to 26 min.

The test data were used to calculate all indicators apart from the *dtr*, which is set to the maximum score one since the tests were shorter than two hours and rest was not required. The test results, summarized in Table 13

Table 12: Test rides and their descriptions [1,22].

Driver	Simulated Driver Style	Driving Style Description
A B	Ordinary	- driving in a common, ordinary way; - medium dynamic of braking; - accelerating and deaccelerating regularly; - not too many speeding events; - turning smoothly.
C	Aggressive	- driving fast and sharp braking; - accelerating and deaccelerating rapidly; - many speeding incidents; - maintaining high speed while turning.
D	Unusual	- simulating sickness or unnatural behavior; - braking unexpectedly; -accelerating and deaccelerating suddenly; - alternately low and high speed; - turning inconsistently and aggressively.
E	Calm	- driving calmly; - avoiding excessive braking; - accelerating and deaccelerating suddenly; - accelerating and deaccelerating smoothly; - turning inconsistently and aggressively.

and on the bar-diagram in Figure 51, show that the used indicators clearly differentiate the driving styles. Drivers D and C, who simulated *unusual* and aggressive styles obtained the lowest values of all indicators, while the Driver E, who simulated *calm* driving style almost reached the $expert's$ level.

The jr_x is the most diversified of all indicators and has values of 0.95 and 0.32 for simulated calm and unusual driving styles, respectively. The least varied indicator is *spr* with values between 0.80 and 0.88 for Drivers D, C and E, respectively. It is noticeable that *std* of *rsr* for Driver A is much greater than others, which may indicate that he was less consistent with using the gas pedal. Also, *std* of *spr* for Driver C and Long-route test may indicate some inconsistency in driving speed.

The comprehensive assessments of each criterion and overall assessment

Table 13: Indicator values for the test rides

Indicator	Driver A	Driver B	Driver C	Driver D	Driver E	Expert	Long-Route Test
jr_x	0.67	0.82	0.47	0.32	0.95	1.00	0.99
jr_z	0.77	0.97	0.80	0.74	0.93	1.00	0.69
jr_y	0.81	0.86	0.69	0.61	0.95	1.00	0.90
dtr	1.00	1.00	1.00	1.00	1.00	1.00	0.70
spr	0.82	0.84	0.80	0.80	0.88	1.00	0.85
(std)	(0.11)	(0.11)	(0.13)	(0.11)	(0.11)	(0.00)	(0.13)
$spdr$	0.51	0.66	0.61	0.54	0.77	1.00	0.67
rsr	0.85	0.93	0.91	0.92	1.00	1.00	0.84
(std)	(0.10)	(0.05)	(0.06)	(0.05)	(0.00)	(0.00)	(0.08)
$rsdr$	0.95	0.91	0.88	0.82	1.00	1.00	0.78

by the spider diagrams, where the relevant normalized indicators are mapped, are shown on Figure 52 - 55. Moreover, Figure 56 summaries the normalized scores of each test driver for all criteria and the overall score.

The results of the normalized criterion scores show that Driver E, called *calm*, has the closest match to the *expert's* driving style map. This is especially the case for *economy* NEC_S and *comfort* NCC_S criteria along with the overall score NO_S of values 0.94, 0.92 and 0.88, respectively. The worst scores of all three criteria were of Driver D, who imitated the behavior of a sick or affected person and obtained only 0.45, 0.48 and 0.40 for *safety*, *economy*, and *comfort* criteria respectively, along with an overall score of 0.51. Driver C, following the *aggressive* style, significantly deviates from the *calm* and *expert* drivers. However, the *ordinary* driving of A does not have much better results than aggressive driving, especially for *safety* criterion and overall score, which can depict that his style was at limits of *ordinary* style. It is worth noticing that in most cases the NO_s averages the other criteria, however in a case when just one indicator especially differs from the others, the effect of this indicator can be reduced in the overall score. It is a case of Drivers C and D whose jr_x are relatively low compere to other drivers, nevertheless their effect on the final score is reduced.

The designed system was verified on the long-route test of 325 km, including typical types of roads. In Figure 50b, the road is mapped from

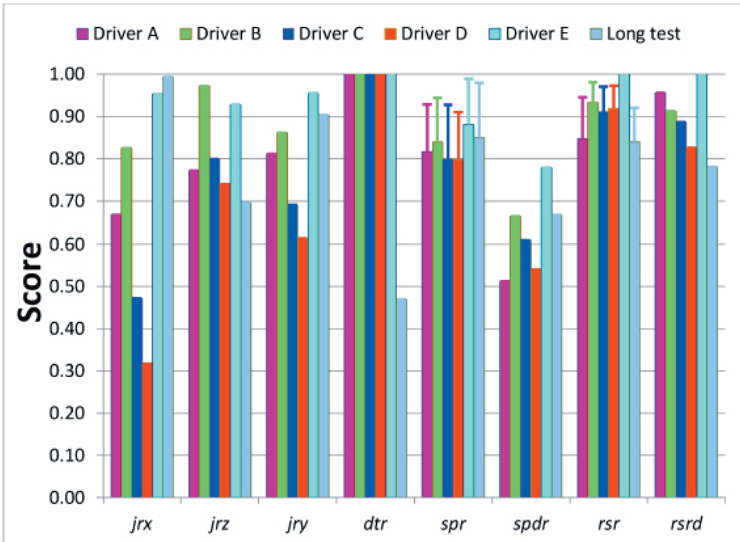

Figure 51: Bar graph of normalized indicators values from the test rides, where '1' is the expert level.

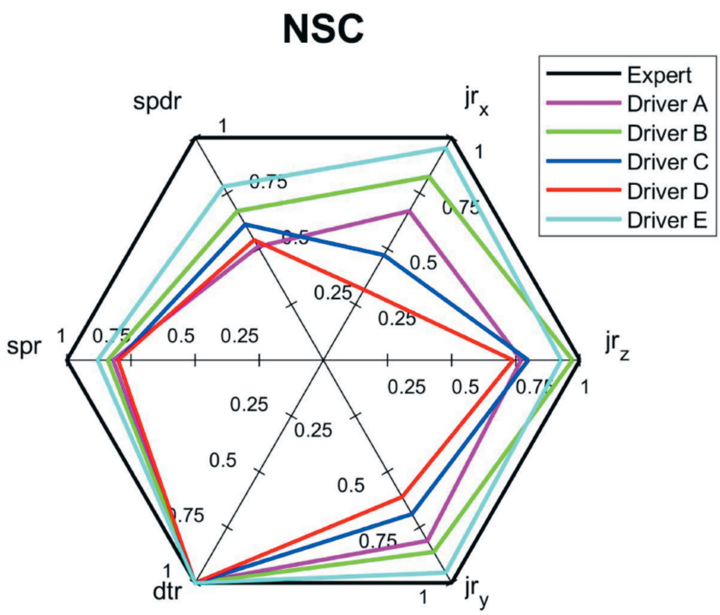

Figure 52: Spider diagram for *safety* criterion of short routes (*dtr* indicator is not distinct due to short time of the test).

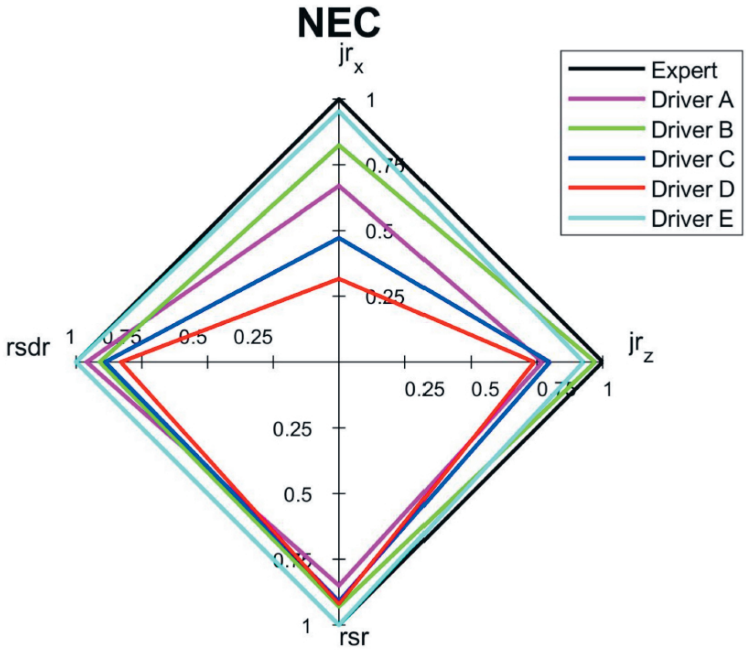

Figure 53: Spider diagram for *economy* criterion of short routes (*dtr* indicator is not distinct due to short time of the test).

a GPS tracker of four-hour trips. The results included in Table 13 and Figure 51 show that on the long-route test, with majority of highways and freeways, the changes of speed (driving dynamic) measured by the jr_x, are less than in an urban environment. One of the lowest scores of 0.70 for the *dtr* indicator depicts the lack of rest since the assessed driver stops the car just once over a four-hour driving period. Another low score of jr_z identifies that the driver tends to pass over speedbumps or road holes with high speed. The indicators *spr* and *spdr* of 0.85 and 0.67, respectively, show the driver slightly exceeded recommended speed limits but he has tendency to speed for a longer time. Also, the $rsdr$ value of 0.78 is lower than corresponding values of the evaluation tests because driving on highways and freeways is characterized by high speed causing the excessive rotational speed.

The low values of *dtr* and jr_z measured during the long-route test greatly influenced the NSC and NCC of 0.63 and 0.66, respectively. Even *economy* criterion NEC of the long-route test show low value. The overall score of this test is also worse than one would expect. Figure 57 shows the spider

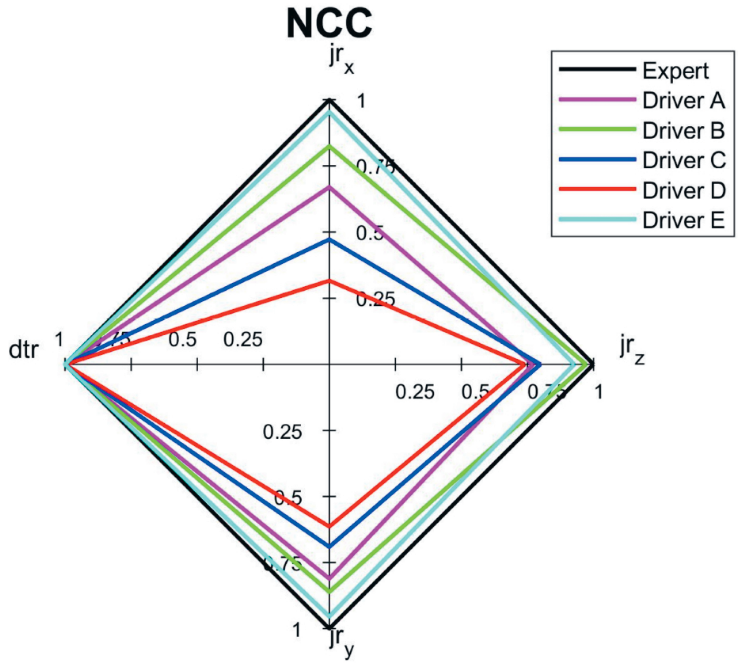

Figure 54: Spider diagram for *comfort* criterion of short routes (*dtr* indicator is not distinct due to short time of the test).

diagram for the long-route test, which can be used by the driver to analyze his skills and learn how to improve his driving style.

8 Discussion

To evaluate the proposed assessment method, test rides were conducted by five different drivers and an additional verification test drive have been performed. The experiments provide real measurement data and were carried out in real-world scenarios.

The validation results show that the best normalized overall score of driving style, 0.88, was obtained by the Driver E, which imitated *calm* driving style. The worst normalized overall score, 0.51, was obtained by the Driver D who drove unnaturally imitating the driving style of a sick person. Driver C who was driving aggressively scored 0.59. Drivers A and B were asked to drive naturally, however, their results are different since Driver A

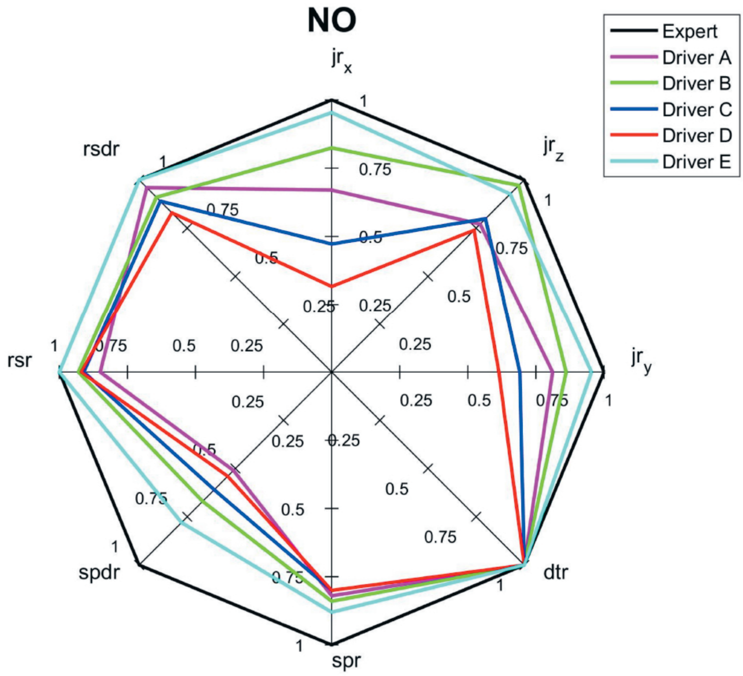

Figure 55: Spider diagram for overall scores (*dtr* indicator is not distinct due to short time of the test).

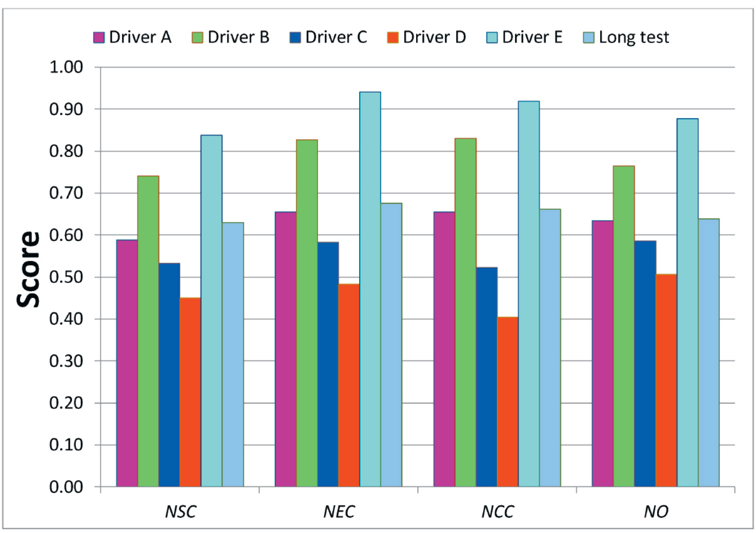

Figure 56: Bar graph of normalized criterion scores from the test rides, where '1' is the expert level.

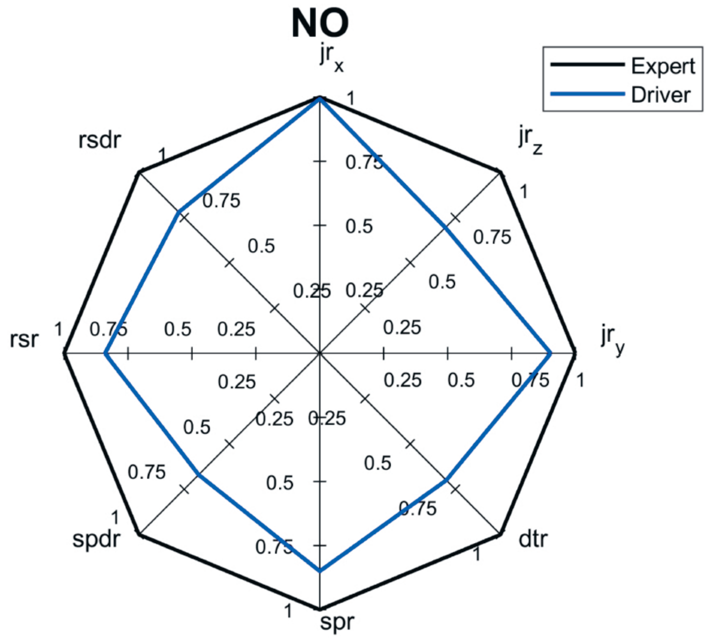

Figure 57: Spider diagram for overall scores.

obtained results of 0.63, while Driver B scored 0.77.

The biggest difference of the normalized overall score of 37% is between Driver E and Driver D, which shows how significantly the applied indicators vary among different driving styles. The differences between these two most distinctive drivers are even greater in terms of normalized safety, economy, and comfort scores of 39%, 46% and 52% respectively. Such gap in scores between the drivers proves that the analysis of driving style could be based on very distinguishable measures.

Comparing disparity of different normalized scores of driving quality criteria, one can see that the biggest diversity among tested driving styles appears for *comfort* criterion, 52%, while the *safety* criterion varies least of all (39%, from 45% to 84%). Furthermore, all considered driving quality criteria show a bigger diversity than the normalized overall scores.

Analysis of diversities among the applied indicators show that they vary from 63% to 8%. The jr_x is the most diversified of all indicators with extreme values of 0.95 and 0.32 for simulated *calm* and *unusual* driving styles, respectively. The least varied indicator is spr with values between 0.80 achieved by Drivers C and D and 0.88 scored by Driver E. Therefore, the indicators can be ordered from the most to least sensitive as: jr_x, jr_y, $spdr$, jr_z, $rsdr$, rsr, spr.

The proposed embedded system and assessment method were experimentally verified on the long-route test. The normalized overall score of this driving style was assessed for 0.64, which corresponds to *ordinary* driving style. Furthermore, all normalized criteria, i.e., *safety*, *economy* and *comfort* can be also considered in ordinary range. Moreover, the long-route test results show high similarity to the results of Driver A in all considering criteria. If the dtr, which indicates time of stops for a four-hour driving period, were better, the normalized overall score of driving style could reach 0.70.

Figure 52 - 56 visualize the multi-variable quantities of driving style in a clear and legible way. Moreover, this approach facilitates a comparison of the driver's score with an *expert* one, with other drivers and even with previous scores of the same driver. Therefore, among other applications, the designed system could be used by insurance or rental companies for awarding discounts to drivers of correct driving style. The proposed assessment approach can be customized to different needs and applications.

9 Conclusions

A system consisting of the embedded OMCU device for assessing driving style has been designed and developed according to the IoT concept and user-driven-design approach. The measurement data are acquired from the diagnostic port—OBD-II—additional accelerometer sensor and GPS module.

The prototyped system used for driving style assessment was validated experimentally in real-world scenarios.

The evaluation experiments conducted by five drivers on short routes proved that it is possible to differentiate and assess the person's driving style in terms of *safety, economy*, and *comfort* criteria. The normalized scores of criteria are estimated based on the eight measurable indicators such as: normalized *de-* and *ac-celerating, bumping, cornering, driving without rest, car speeding, car speeding duration, excessive engine rotational speed* and *excessive engine rotational speed duration ratios.*

The analytical assessment of driving style based on criterion and overall score visualization using a spider diagram approach can be easily customized by users according to their application need.

The presented solution can be extended by implementing big-data statistical methods with a representative database of drivers and corresponding driving styles. Along with statistical analysis, an automatic data visualization engine can be applied. Such a module allows visualization of the driver's assessment in the broader context. This feature could be especially desired by analysts and managers and may be used for business decisions. The proposed approach could be complemented by recognition of drivers' dangerous behavior.

The designed OMCU system could be supplemented with additional vision and noise sensors used to monitor the external driving conditions such as weather, road conditions, along with using more parameters from the car's on-board computer e.g., acceleration pedal position or belt fastening. A customization and adjustment of the system prototype to other vehicles such as trains, trams, and busses would extend its application field.

Author Contributions: TAll authors made great contribution to the work. Jacek Czapla and Pawel Damps designed the system and performed the experimental part. Bartosz Jachimczyk and Damian Dziak modeled and analyzed results and wrote the paper. Wlodek J. Kulesza guided the whole research and supported the structure of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

COMC	Comfort Criterion
DCC	Driver's Comfort Criterion
DEC	Driver's Economy Criterion
DO	Driver's Overall
DSC	Driver Safety Criterion
DTW	Dynamic Time Warping
ECC	Expert Comfort Criterion
ECOC	Economy Criterion
EEC	Expert Economy Criterion
EO	Expert's Overall
ESC	Expert Safety Criterion
HCA	Hierarchical Cluster Analysis
HMMs	Hidden Markov Models
ICT	Information and Communication Technologies
IoT	Internet of Things
NO	Normalized Overall
NCC	Normalized Comfort Criterion
NEC	Normalized Economy Criterion
NSC	Normalized Safety Criterion
OMCU	On-board Measurement and Communication Unit
PCA	Principal Component Analysis
RPM	Revolutions Per Minute
SAFC	Safety Criterion
UART	Universal Asynchronous Receiver and Transmitter

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ABSTRACT

The detection and classification of features or properties, which characterize people, things or even events can be done in reliable way due to the development of new technologies such as Internet of Things (IoT), and also due to advances in Artificial Intelligence (AI) and machine learning algorithms. Interconnection of users with sensors and actuators have become everyday reality and IoT, an advanced notation of a Multi-sensor System, has become an integral part of systems for assessment of people's habits and skills as well as the evaluation of quality of things or events' performances. The assessment approach presented in this thesis could be understood as an evaluation of *multidimensional fuzzy quantities*, which lack standards or references.

The main objective of this thesis is systematical design of multi-sensor systems for *industrial* and *behavioral* applications. The systematization is based on User Oriented Design (UOD), the methodology where stakeholders and future users are actively involved in all steps of the development process. An impact of the application environment on design principles is quantitatively and qualitatively analyzed. It shows different design approaches, which can be used for developing systems monitoring human activities or industrial processes.

The features identification approach applied in this thesis involves the extraction of the necessary data, which could be used for behavior classification or skills assessment. The data used for these purposes are vision or radio-based localization and orientation combined with measurement data of speed, acceleration, execution time or the remaining energy level.

Background removal, colour segmentation, Canny filtering and Hough Transform are the algorithms used in vision applications presented in the thesis. In cases of radio-based solutions the methods of angle of arrival, time difference of arrival and pedestrian dead reckoning were utilized. The applied classification and assessment methods were based on AI with algorithms such as decision trees, support vector machines and k-nearest neighborhood.

The thesis proposes a graphical methodology for visualization and assessment of multidimensional fuzzy quantities, which facilitate assessor's conceptualization of strengths and weaknesses in a person's skills or abilities. Moreover, the proposed method can be concluded as a single number or score useful for the evaluation of skills improvement during of training.

The thesis is divided into two parts. The first part, *Prolegomena*, shows the technical background, an overview of applied theories along with research and design methods related to systems for identification and classification of people's habits and skills as well as assessing the quality of things or performances. Moreover, this part shows relationships among the papers constituting the second part titled Papers, which includes six reformatted papers published in peer reviewed journals. All the papers concern the design of IoT systems for *industrial* and *behavioral* applications.

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