„POLITEHNICA" UNIVERSITY of BUCHAREST

DOCTORAL SCHOOL within the
Faculty of Industrial Engineering and Robotics
Robots and Production Systems Department

DOCTORAL THESIS

MODERN METHODS OF MONITORING AND INTERVENTION IN THE MAINTENANCE ACTIVITY

ABSTRACT

Author: PhD candidate **HAGIESCU V. CORNELIU**
Doctoral advisor: Professor **VELICU ŞTEFAN**, PhD. Eng.

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POLITEHNICA University of Bucharest
Facultaty of INDUSTRIAL ENGINEERING and ROBOTICS
ROBOTS AND PRODUCTION SYSTEMS Department

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ABSTRACT

This doctoral thesis is intended to study and develop some innovative concepts to be applied in roads maintenance, necessary to be addressed in the professional activity.

The creation of new concepts and methods in the sphere of road infrastructure will allow maintaining traffic safety, anticipating the costs for maintaining the infrastructure within the optimum operating parameters and, last but not least, a friendly relationship with the environment.

The specific character of the activity helped to outline the following main objectives:

a) Studying and demonstrating the possibility to develop an autonomous equipment for intelligent monitoring of road traffic;
b) Research on a new procedure of corrective maintenance of the roadway wearing surface.

These objectives are interrelated with the specific objectives focusing on: analysis of the piezoelectric sensors; research on the roadway monitoring; analysis of the energy amount generated by the state sensors located in the roadway; analysis of new methods for the repair of the wearing surface; research on the use of an innovative technology for repairing the wearing surface by means of the injection procedure, the equivalent of the shotcreting method used in the civil and industrial engineering.

The research work carried out for the doctoral thesis led to the creation of a new concept, an innovative technology for repairing the wearing surface. Very good results were achieved regarding the possibility to use the energy produced by the sensors for car traffic information management in order to create energy autonomous and environment-friendly systems.

Key words: virtual system, autonomous equipment, shotcreting method, injection.

INTRODUCTION

Due to the complexity of the technological systems, keeping them in working condition is currently a complex and specialized activity that requires well-trained personnel expert in many fields. This activity aims at maintaining the equipment that makes up the production lines within the designed operating parameters. The maintenance manager must take into consideration the personnel resources, their continuous training, commitment, responsibility and involvement in the management and development of the complex information received from the technological system in order to have as few operation interruptions as possible.

The starting point of the experimental research presented in this paper is a variety of methods developed domestically and internationally at the present moment. These methods mainly monitor the roadway, its behavior in terms of technical characteristics of the materials used, processing technology, maintenance costs, reliability and environmental impact.

This Doctoral Thesis is structured in six chapters, Introduction, Appendices and Bibliography.

Chapter 1, called *″ Current stage of the research on the maintenance of the technological systems ″* highlights the specific methods and equipment used in the field of maintenance.

Through maintenance, technological systems can be efficiently kept in operation; at the same time, information can be obtained to contribute to the preparation of plans for the future interventions.

Thus, a great emphasis is currently placed on the implementation of sensors in the critical areas of the technological systems, on the intensive use of the Internet and hardware technologies for measuring and communicating the information received. The software necessary for processing the information is also important in making a maintenance decision.

The composition of a technical system for monitoring the equipment condition and establishing a certain maintenance is analyzed in Chapter 2 - *″ Preventive maintenance strategies ″***.** The monitoring system allows a complex analysis of the operation state; so the necessary technical operations for the intervention will be carried out according to a correct decision, which takes into account the real condition of the road and the required time for intervention (that entails the equipment stopping and the zonal impact on the transport).

Chapter 3 *" Theoretical contributions regarding the monitoring of the critical structures by means of autonomous transducers"* analyzes the evolution of a technical system that manages how the studied parameters change over time. The use of a physical process of power generation, that can be efficiently applied in various equipment for measuring force, traffic and so on, is taken into account. The equipment thus designed can be implemented in the roadway; the energy developed will be a source of green energy that does not affect the environment.

Chapter 4 entitled *" Experimental contributions regarding the monitoring of the critical structures by means of autonomous transducers"* presents the stages of a laborious experimental study that aims to determine and highlight a method to electrically autonomize an existing system meant to determine the speed and weight, in order to classify the motor vehicles and the traffic. The system uses one or more flexible piezoelectric sensors, maximizing the system functionality by using the energy produced by these ones, ensuring its own electric autonomy.

Chapter 5 called *"Contributions regarding the development of an equipment for the road wearing surface maintenance using the technological method of injection (shotcreting)"* shows the steps taken to create a concept and an innovative maintenance equipment for the roadway in the case of road transport. The achievement of the innovative concept personalizes a method often used in the civil and industrial engineering, to which an extension is given in the field of the roadways maintenance, from the road transport sphere.

Chapter 6 *"Final conclusions and personal contributions "* reviews the personal contributions made within the experimental studies, the advantages of using these innovative techniques and the future development paths.

The bibliography of this thesis includes a number of 185 technical and scientific works, 7 scientific articles already published or in publication progress, 25 links to web pages, which were accessed in the period 2016 - 2022 and also appendices with technical documents.

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I take this opportunity to express my gratitude to the persons who permanently supported and encouraged me throughout the whole preparation period of this scientific work.

I am really grateful to Mister Ștefan Velicu – Professor Dr. Eng who had a special contribution to the achievement/guidance of this work. This professor of great scientific value guided and encouraged me continuously; he gave me many technical guidelines, necessary for the realization of a new scientific concept, a Romanian one, which was experimented/accomplished in a particular institutional framework belonging to a prestigious institution such as the „Politehnica" University of Bucharest – education center of high importance for Romania. At the same time, I would like to thank Mr. Tănase Ion - Professor Dr. Eng., Mr. Bâșu Claudiu - Associate Professor Dr.Eng. and Mr. Dogariu Constantin - Professor Dr. Eng. for their kind scientific support: they made available to me the research laboratories and the technical matters studied during their teaching and laboratory activity, enabling me to benefit from an efficient technical documentation.

I also thank my colleagues and technical teams, Mister Ștefan Ioniță - Director, for fruitful exchanges of ideas and for the space put at my disposal in CESTRIN laboratory for the scientific experiments. I really appreciate all the persons who believed in me and who had the kindness to analyze this paper and let me know their remarks. I would also like to thank my good friend, the eternally young pensioner, Ionel Păunescu, for his constant encouragement, understanding and support in the completion of this work. I also thank the management of the faculty and the Doctoral School Department for their support and motivation throughout the creation of the paper.

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CHAPTER 1

CURRENT STAGE OF THE RESEARCH ON THE MAINTENANCE OF THE TECHNOLOGICAL SYSTEMS

The development of both software and hardware infrastructure, determined by the globally emerging national conceptual strategies, called „Industrie 4.0” in Germany, „Industrial Internet Consortium” (IIC) in USA, „Industrial Value-Chain Initiative” (IVI) in Japan, „Industrie du Futur” in France and, finally yet importantly, the Industrial Revolution in China, led to the appearance of what has been called „the fourth industrial revolution”. These strategies integrate the industrial processes primarily with everything that currently means the Internet of Things (IoT), the Internet, wired or wireless networks, hardware and software technologies.

The result has been an explosion of applications regarding the predictive maintenance of the technological systems in areas as the industrial equipment self-diagnosis, procedures of self-configuration of this equipment and of the lines of manufacture, supply and maintenance, virtual reality and augmented reality. All these are based on the development of sensors and algorithms software for interpreting the accumulated data, increasing the power (speed) of data calculation and transmission and also increasing their storage capacities. The Internet of Things (IoT) has a direct application in the manufacturing industry, for the equipment provided with sensors, offering the processing and transmission possibility, using hardware modules and software applications. It also gives the possibility of data processing and communication with other equipment belonging to the production line, using the Internet or any other type of communication network. Thus, Mr. V. Deac and others [1] cite four directions of evolution of the predictive maintenance: the restoration of an industrial equipment operating parameters; the anticipation of its operating state; the minimization of maintenance expenses and the prevention of the failure. This prevention involves the use of new technologies and procedures that determine the taking of measures as shown in fig.1.1. [2]

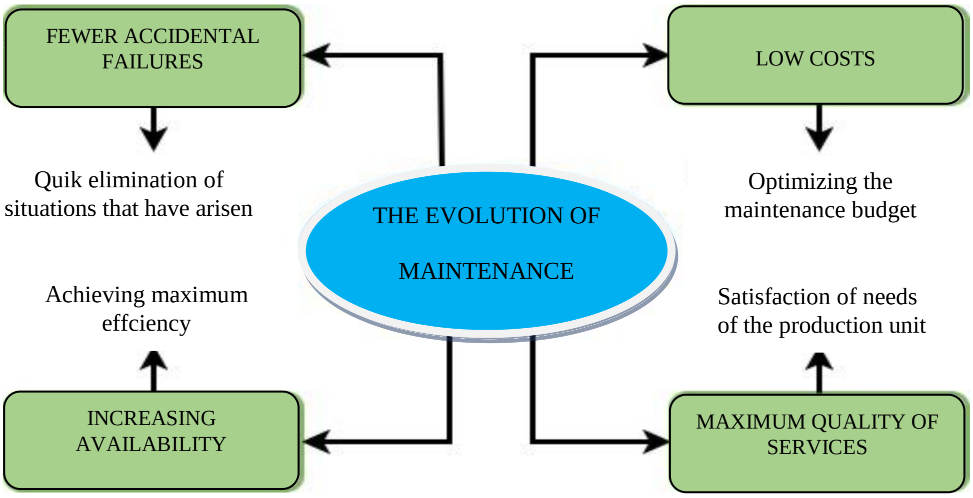


Fig.1.1. Evolution of maintenance

1.1. Evolution of maintenance

J.Bufferne defines five objectives that can ensure a high level of improvement in maintenance, namely: zero damage, zero mistakes, zero stocks, zero delays and zero papers [3]. If the objective of zero damage is related to the maintenance activity itself, the objective of zero mistakes primarily involves the quality management and the maintenance alongside it. The objective of zero stocks aims to reduce the intermediate stocks, but with high reliability of the equipment [4]. „Zero delays" refers to the diminution of intervention time in blockage situations and the objective of zero papers is associated to the computerization of this activity.

A very important technological leap was made when it was possible to build a mechanical element inside an integrated circuit. The engineering technologists in the field of semiconductor manufacturing, using the photolithographic and engraving technology of the silicon wafer, managed to introduce both the mechanical element (beam type, for example) and the junctions that make up the processing part of the signal resulted from the mechanical element, into a single C-mos type integrated circuit. This is how MEMS (Microelectromechanical systems fig.1.4) appeared, with dimensions of up to one millimeter and energy consumption of the maximum order of microamps. The exceptional characteristics of size and energy consumption have led to the evolution of these electronic components towards nanosensors that have found multiple applications in the fields of industry, health, environment etc. [6].

1.2. Formulating the objectives of the thesis

The doctoral thesis is closely related to the professional activity field. Therefore, it is possible to say that the **main objectives of the doctoral thesis** are related to the maintenance area /field, with application in road maintenance:

- Studying and demonstrating the possibility to autonomize an equipment for the intelligent monitoring of road traffic;
- Research on a new corrective maintenance procedure for the wearing surface of the roadway.

These ones will be achieved through the following **specific objectives**:

- Analysis of the piezoelectric sensors with a view to autonomization;
- Designing an autonomous module for monitoring the system evolution;
- Experimental configuration and on-site measurements;
- Calculation of the energy provided by the piezoelectric sensor by vectorizing the oscillograms;
- Demonstrating the hypothesis of autonomization of an equipment for system evolution monitoring.

The energy autonomization of such equipment allows its installation in the most convenient data measurement point. As it also operates on the basis of the energy produced by sensors, the application can be used in any field where it is necessary to monitor some physical quantities (temperature, vibrations, movements etc.), in order to make the maintenance activity more efficient.

The second main objective, regarding the research on a new method to repair the wearing surface of the roadway, focuses on the concrete shotcreting, a method often used in the civil engineering (for repairing the external surfaces of the buildings that need to be strengthened etc.)

1.3 Conclusions

Linear Technology (Analog Devices) also manufactures, in the same family of integrated circuits, in the range of ultralow energy consumption elements, the other components of the wireless sensor module, such as the Data Processing Element - for example: „Ultra Low Power ARM Cortex-M4F MCU with Integrated Power Management” and the Wireless Communication Element - for example ADF7901 „High Performance ISM

Band OOK/FSK Transmitter IC". It also produces a various range of Sensing Elements, such as the ADXL359 „Low Noise, Low Drift, Low Power 3-Axis MEMS Accelerometer"[179].

The information received from these sensors generally concerns the manufactured parts and the interconnection of the equipment with other surrounding equipment within the production line, in order to increase the efficiency of the activity. To this end, it is necessary to evaluate as fairly as possible the chosen solutions and to study over time the results obtained, taking into account the maximum optimization of the number of measurement points.

CHAPTER 2

PREVENTIVE MAINTENANCE STRATEGIES

The preventive maintenance strategy is the totality of important objectives for a long period of time, the most efficient modes to achieve them and the material and human resources allocated for this purpose. All these are the foundation of the preventive maintenance.

2.1. Methods of maintenance

The analysis of a technical system operation possibilities at technically well-established time intervals is highly important. It represents a decision-making factor for the operations needed to maintain the maximum availability.

Two models used in the preventive analysis of the technical system should be highlighted in the case of preventive maintenance, namely:

- The first one is based on the Eventual Replacement Policy (ERP), which takes into consideration that the technical system must be submitted to some checks at equal intervals of time (established by the strategy). If a certain level of wear and tear is found out, maintenance works must be performed;
- The second model is based on the analysis of the technical system state by monitoring some defined parameters.

Figure 2.1. shows the maintenance classification, based on technical interventions and criteria.

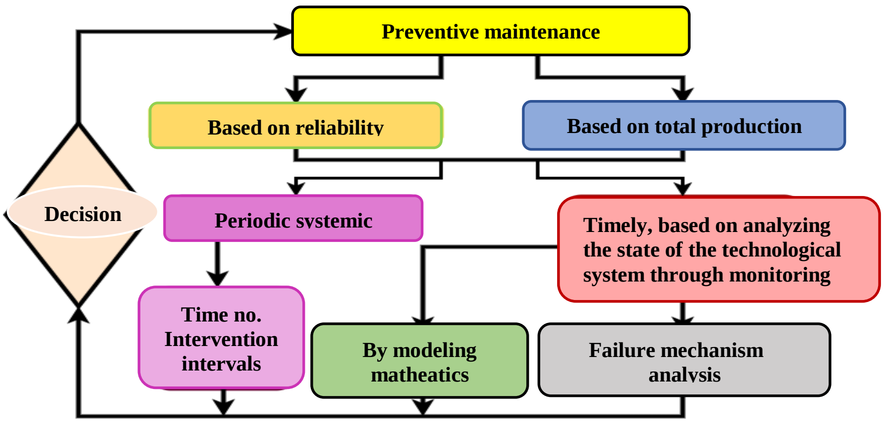


Fig.2.1. Preventive maintenance, analysis and criteria

2.2. Monitoring – a decision-making factor in the maintenance activity

The decisive role in the maintenance activity belongs to the monitoring of the technical system. Monitoring is carried out permanently or at periodic time intervals, depending on the complexity of the technical system. Information is taken over through monitoring and used to determine the maximum interval between the works of repairing and maintenance as part of keeping under control the costs associated to the interruptions in the technical system operations following possible failures.

2.4. Components of the monitoring system

The components of the monitoring system must meet at least the requirements below:

- measurement;
- optical/acoustic/thermal etc. surveillance;
- directing, blocking, switching;
- communication in fixed and mobile system.

The structure of the basic component includes all the functions and interfaces necessary to manage the technical system. It is assembled directly, without using intermediate control relays, with the possibility of independent operation and remote activation (computer/laptop/mobile phone etc.) with a specialized application[12]. The other component contains the display and operation unit, by means of which the maintenance specialist can quickly access the data functions of the equipment, the parametrization of the safety elements and the electrical control (fig.2.4).

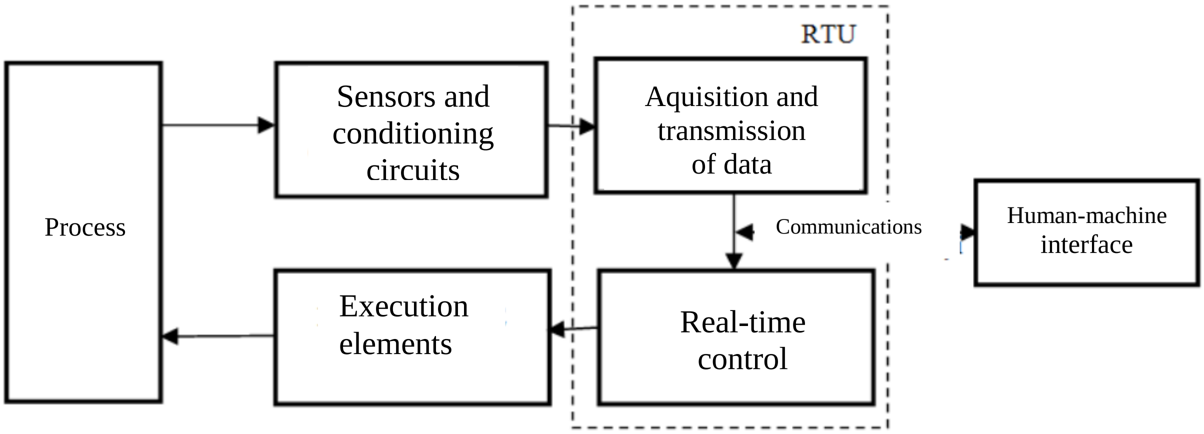


Fig. 2.4. Minimum composition of a monitoring system

2.6. Conclusions

The use of the maintenance monitoring systems requires significant changes in the computer systems, the acquisition and use of special programs, advanced techniques able to deal with the new technologies, leading to a better understanding of their performances and use, in order to diminish the production costs, with minimal impact on the environment and human being.

CHAPTER 3

THEORETICAL CONTRIBUTIONS REGARDING THE MONITORING OF THE CRITICAL STRUCTURES BY MEANS OF AUTONOMOUS TRANSDUCERS

At the present moment, due to the increasing price of the electricity, it is necessary to find solutions for the generation or cogeneration of electricity from alternative sources/ renewable energy. It can be noted that a number of systems are used that develop energy when actuated by an external force. In this sense, the effects produced in some crystals could be mentioned, namely the appearance of an electrical polarization. This phenomenon is intensively studied, because by applying some forces on the respective crystals or by inducing a temperature variation, a difference of potential appears, generating the electric current (piezoelectric effect, fig. 3.1).

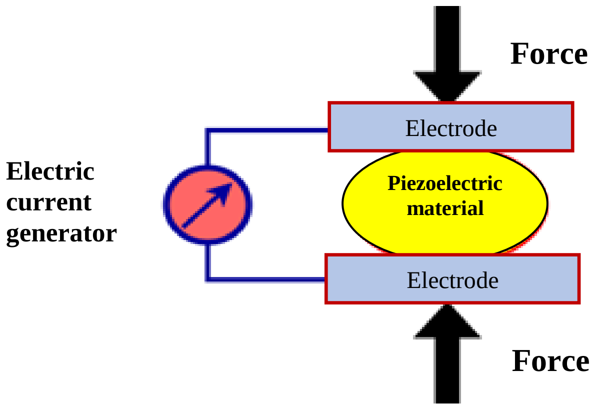


Fig. 3.1. Generation of electric current by applying the forces

3.1. Virtual modeling of the operation of an autonomous energy module

The studied technical documentation highlights the possibility of using independent systems formed of piezoelectric transducers with dual functionality of measurement and generation of energy.

Such a solution can be used in the case of a vehicle axle load measurement system by placing piezoelectric sensors on a certain area of the roadway; these sensors, in addition to measuring the load, will produce energy, so the system can generate part of its electricity needs (fig. 3.2).

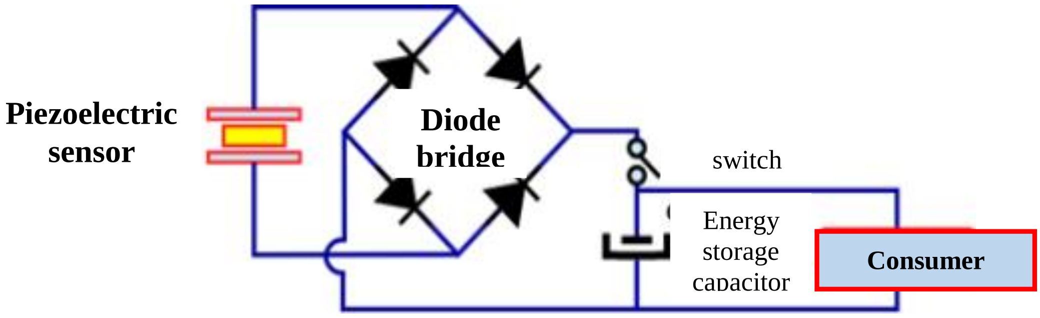
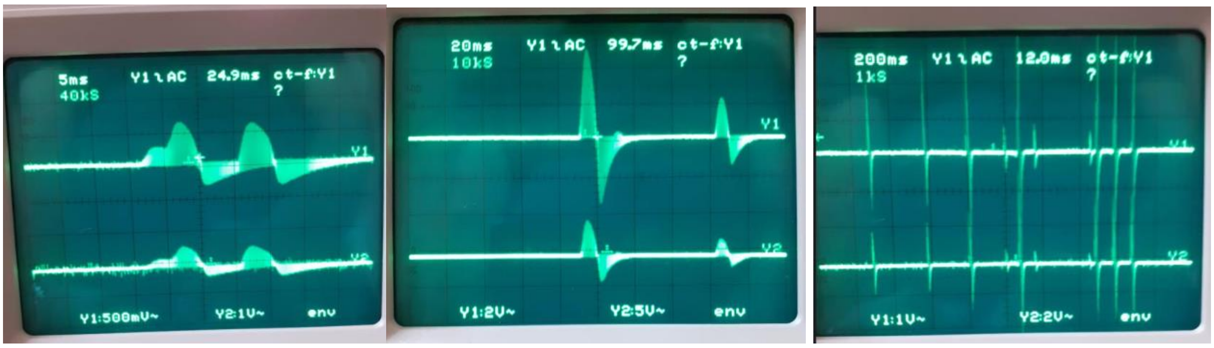


Fig. 3.2. Energy storage system

Analyzing if the cascade sensors assembled in the roadway have relevance when there are series connections or parallel ones, the current and the voltage were measured by means of an oscilloscope; the parallel connection had a higher generation of current, as shown in figure 3.4 and figure 3.5.



a) b) c)

Fig.3.3. Voltage recording at the passage of: a-car, b-truck, c-trailer

3.2. Conclusions

An experimental module was made using a system of axle load reading that has the potential to generate energy. Following the measurements, it was found out that a linear relation exists between the weight applied to the sensor and the energy generated. The obtained energy can be accumulated and can efficiently achieve the autonomy of the control system.

CHAPTER 4

EXPERIMENTAL CONTRIBUTIONS REGARDING THE MONITORING OF THE CRITICAL STRUCTURES BY MEANS OF AUTONOMOUS TRANSDUCERS

The information obtained and transmitted in real time regarding the traffic (both on highways and national roads) is of great significance, for two very important reasons.

The first one is the maintenance of roads. Knowing the number of vehicles, the weight on axle of each one and the number of axles, it is possible to estimate the degree of wear of the roadway over a period of time. Its subsequent verification can decide on the appropriateness of carrying out maintenance works on the roadway. The second reason is related to the implementation of the European ITS platform – Intelligent Transport System (EIP) [160]. The traffic data obtained from measurements (traffic classification, vehicle speed measurement, weigh-in-motion) and transmitted in real time are a component of the European ITS platform.

4.1. Flexible piezoelectric sensors, description, installation

The flexible piezoelectric sensors are elements of circuit that have been used for many years for measurements related to car traffic. For example, the "RoadTrax BL Traffic Sensor" type sensors, manufactured by Measurement Specialties, are widely used for traffic measurements; they have, in various configurations, an accuracy of up to 98% [4]. The manufacturer of Roadtrax BL sensor recommends a "piezoelectric sensor - inductive loop-piezoelectric sensor" configuration [158], as shown in figure 4.1., for maximum measurement accuracy.

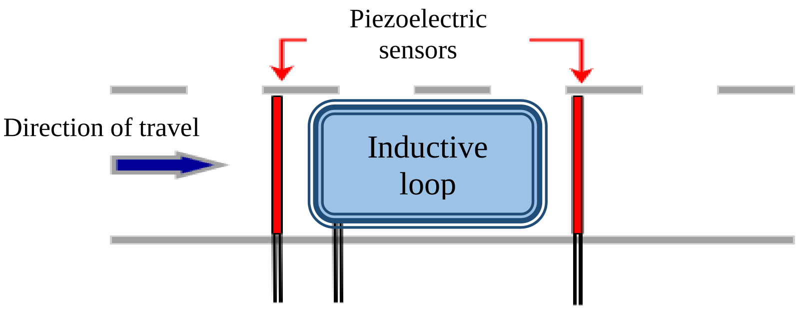


Fig.4.1. One of the methods to place the sensors (recommended by the manufacturer)

The paper published by Samer Rajab et al. [20] elaborates a study commissioned in the United States by Oklahoma Transportation Center [21] which checks the possibility to make measurements using only one flexible piezoelectric sensor placed diagonally to the roadway at an angle of 45 degrees(the tests were made at 45 and 38 degrees), as shown in figure 4.2.

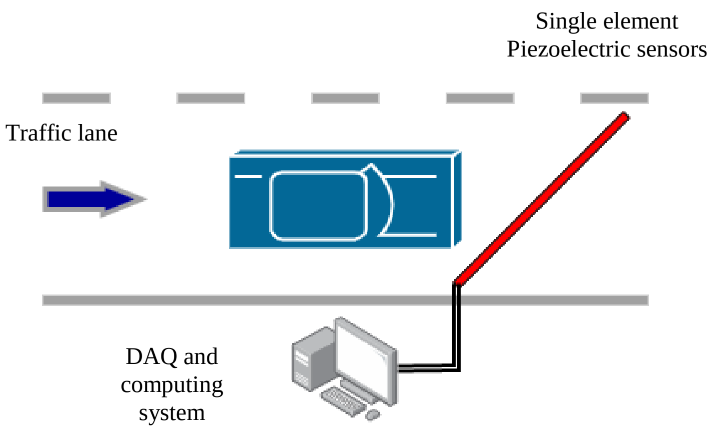


Fig. 4.2. Measuring system with a single flexible piezoelectric sensor (diagonally)

Another study, made by Taek M. Kwon [6], commissioned by “Minnesota Department of Transportation Research”, analyzes the possibility to build a portable weighing-in-motion system (WIM). The sensors chosen are of the same type “Roadtrax BL” as in our study.

4.2. Experimental configuration

As mentioned earlier, we choose a configuration of the equipment with two piezoelectric sensors. This configuration ensures two important advantages:

1. Measurements have a high accuracy, given in particular by the hardware module (processing unit) and software module (algorithms for calculating the traffic values) of the equipment;
2. The energy produced by the sensors is doubled.

4.3 Description of components

The two sensors used in this study are 6 ft. long (approximately 1.83 m.) The technical data, made available by the manufacturer [159], are listed in table 4.2

Table 4.2. Technical data of the traffic sensor

BL Traffic	Sensor
Sensor lenght	6ft.
Cable lenght	150ft.
Capacitance	8.31nF
Dissipation	0.0087
Average Sensitivity	55pC/N

The process is repeated, depending on further reception of pulses from the piezoelectric sensor. Thus, a sufficient amount of energy is accumulated in C6 to power some electronic circuits in the ultra-low consumption range.

Figure 4.11 shows the stages of programming:

a) Demonstration circuit 1459B-A,
b) Programming platform, configured according to the quick programming procedure [24]

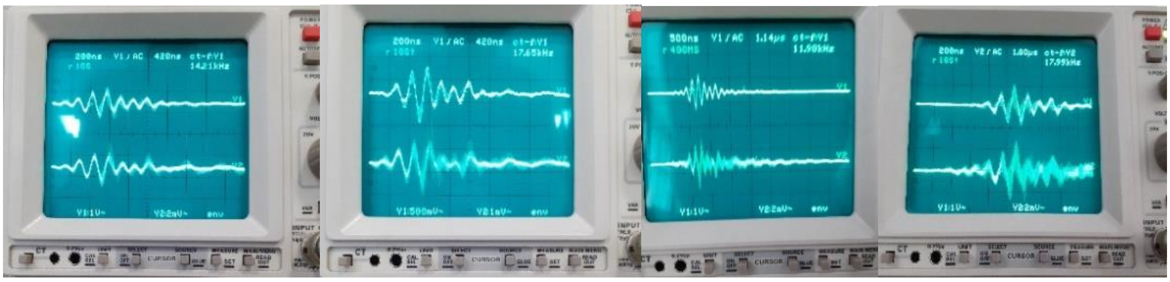
a) b)

Fig.4.11. Programming of power management module

4.4 Measurement of energy parameters in the laboratory

As we had the Cooper Wheel Tracker equipment [157] available, measurements were made in the laboratory with HAMEG HM507 oscilloscope [10], in terms of pulse amplitude at the sensor terminals to which different load resistances were connected.

Thus, it was possible to view the voltage pulse at the sensor terminals on the Y1 spot by connecting resistors of different values to its terminals. At the first measurement carried out, a load resistance with a value of 10 Ω was connected to the sensor output; then load resistances of 200 Ω, 625 KΩ and finally 900 KΩ were used. The resulting oscillograms are presented in figure 4.15, a, b, c, d.



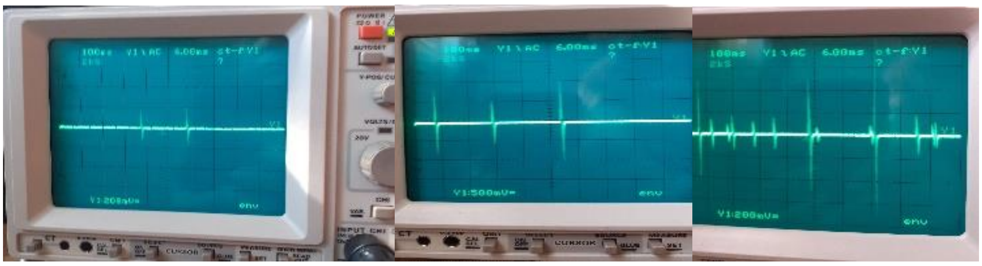
a) b) c) d)

Fig.4.15. Voltage pulses (Y1), with different load resistances connected to the terminals of the sensor (a.10 Ω, b. 200 Ω, c. 625 KΩ, d. 900 KΩ)

4.5 Measurement of energy parameters on site

4.5.1. Making measurements

The on-site measurements were made, in a first stage, at Călugăreni National Roads Section located in Călugăreni, Giurgiu County on DN 5 (Bucharest-Giurgiu), at km 28+140. The voltage pulse values measured at the terminals of the piezoelectric sensor placed in the roadway, during the passage of a passenger car, a truck and of a 5-axle trailer are shown in the oscillograms in figure 4.16, a), b) and c).



a) b) c)

Fig. 4.16. Oscillograms of the voltage pulse at the terminals of the piezoelectric sensor (a – passenger car, b –3-axle trailer, c – 5-axle trailer)

4.5.2. Calculation of the voltage pulse maximum amplitude (Um)

The analysis of these oscillograms highlights that, excepting the cars with 2 or 3 axles, the amplitude of the voltage pulses recorded when the steering rod passes over the sensor is smaller than the amplitude obtained at the passage of the other axles. For this reason, the maximum amplitude of the voltage pulses will be calculated taking into account the number of axles of the vehicle. It results a maximum average value of the voltage pulse on all axles of the vehicle that will be called “maximum amplitude“, the size of which will be measured next:

1) Passenger cars (Class 2), with a maximum amplitude of the resulting voltage pulse of 600mV (Y1 spot), in conformity with the measurement shown in the oscillogram of figure 4.20.

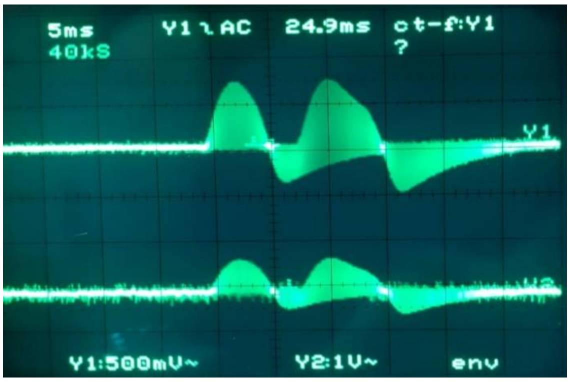


Fig. 4.20. Oscillogram of passenger car

4.5.3. Calculation of the number of pulses at sensor terminals for 24 hours

Next, the number of pulses generated by the piezoelectric sensor within 24 hours will be calculated taking into consideration the previously defined categories.

1) The total number of pulses with an amplitude of 0.6V, generated by passenger cars (Class 2) within 24 hours, will be calculated according to the formula:

$$No.tot.x = No.cls.2 * 2 \qquad (1)$$

where:

- No.cls.2 is the total number of cars (2 axles);
- No.tot.x is the total number of pulses with the amplitude of 0.6 V generated by the sensor within 24 hours;

The final result is: No.tot.x = 17.561 * 2 = 35.122;

In conclusion, a number of 35.122 pulses with the amplitude of 0.6V will be obtained at the sensor terminals during 24 hours.

4.5.4. Calculation of the pulse period

The analysis of the oscillograms taken on site and shown in the subchapter 4.5.2. “Calculation of the voltage pulse maximum amplitude” highlights the maximum amplitude of the voltage pulse measured at the sensor terminals. The subchapter 4.5.3. “Calculation of the number of pulses at sensor terminals for 24 hours” presents the number of pulses. To calculate the power, it is also necessary to know the pulse period.

4.5.4.1 Vectorization of the waveforms

The next stage was the measured pulses vectorization by means of ArcMap software [153], which is one of the applications of the ArcGis software platform [154] intended for geospatial image processing.

The ArcMap software makes possible the spatial analysis, implicitly the vectorization of some images saved in JPEG compression format [155], the same way as were saved the images with the oscillograms of the pulses measured „on site” at the traffic classification system installed in the roadway at the Sinești District, located on DN 2 at km 30+200.

In the case of the oscillogram corresponding to the signal measured at sensor terminals when a car passes, the result of the oscillogram vectorization is presented in figure 4.29.

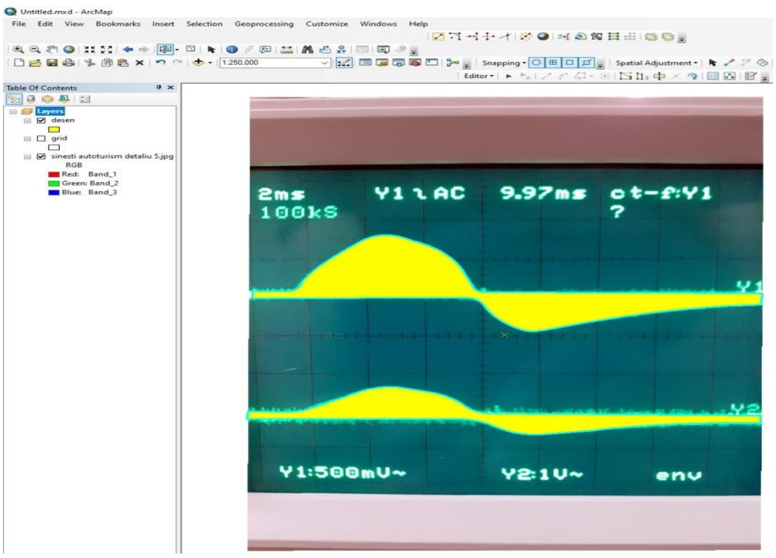


Fig. 4.29. Vectorized oscillogram of a passenger car

4.5.5. Calculation of pulse power

The instantaneous voltage (u) is calculated using the formula:

$$u = Um*\sin\omega t; \quad [V] \qquad (6)$$

Where Um is the maximum value of the voltage pulse, ω is the pulsation and t is the time. ω is calculated by means of the formula:

$$\omega = 2\pi/T; \ [rad/s] \qquad (7)$$

where T is the period of a pulse.

Using Ohm's law for alternating current [43], we get the formula for calculating the instantaneous current (i):

$$i = Um/R*\sin\omega t; [A] \quad (8)$$

where R is the value of the load resistance, in this case R = 100 Ω.

Knowing the instantaneous voltage and the instantaneous current, it is possible to calculate the instantaneous power (p), using the formula [151]:

$$p = u*i; [VA] \quad (9)$$

4.6. Conclusions

Evaluating all these data resulted from the research and taking into account the most unfavorable conditions defined for the measurements optimization in subchapter 4.5.1., it follows that the piezoelectric sensors for traffic measurement produce a sufficiently large amount of electrical energy. This energy, controlled by a "Power management" module like the one presented in the subchapter 4.3. figure 4.10. and stored in a supercapacitor or an accumulator, can ensure the electrical energy supply of a subsystem. The subsystem consists of a sampling module (in order to process the pulses generated by the sensors), a data processing module and a radio communication module. It is the same configuration as the one of the equipment proposed in chapter 4.2 of this research study.

CHAPTER 5

CONTRIBUTIONS REGARDING THE DEVELOPMENT OF AN EQUIPMENT FOR THE ROAD WEARING SURFACE MAINTENANCE USING THE TECHNOLOGICAL METHOD OF INJECTION (SHOTCRETING)

Currently, there is a big problem in the rational management of roads, the safe traffic and the preservation of the road components within the designed parameters, because of the increasing volume of transported goods and implicitly of the weight transported on the public roads. In order to reduce the blockages that lead to material losses and an excessive pollution, caused mainly by the motors running with fossil fuels, the national administrations that manage the roadways must constantly rely on an efficient audit, in order to update the maintenance requirements. That is why optimized road administration management systems are implemented, having two main components [177]:

1. PMS (Pavement Management System);
2. BMS (Bridge Management System);

5.1. Corrective maintenance of roads

In order to keep the roadways in normal working state, it is important to know their condition and to take the necessary corrective interventions that aim at the following elements:

- when damage appear in the wearing surface, maintenance works must be carried out in short periods of time;
- the corrective maintenance works must be of good quality, according to the provisions of AND 605-2016 [11] standard, taking into account the outdoor temperature values and the season;
- the technical standards in force must be respected;
- the technology applied in the case of corrective maintenance must be environmental-friendly as much as possible.

5.2.Description of the technology for repairing the wearing surface of the roadway by shotcreting

At the present moment, the roadway repairs are carried out according to the technical standard AND 605/2016 [10], using a series of technologies with low efficiency and high costs. The repair works are made by means of asphalt mixture, which must meet the quality requirements stipulated in the technical regulation SR EN 13108-1/2016 [16], based on the technical class and climatic conditions.

In civil engineering, the buildings reinforcement includes coating operations for the walls affected by meteorological factors, passage of time and works of strengthening or rehabilitation of the components of some reinforced concrete or masonry structures [173].

In this field, the coating with new material, the restoration of the affected structure is called “shotcreting operation”. This restoration involves the covering with new material of the surfaces submitted to repairs. It is a mechanized operation in which the cement is mixed with water and additive materials and is transported to the spraying nozzle by means of a mortar pump. Then the mixture is sprayed using compressed air, resulting in the application of a stream of concrete under pressure [172], figure 5.4.

Fig. 5.4. Shotcreting procedure used to reinforce a supporting structure

5.2.1. Designing an equipment for repairing the defects of the roadway by sealing, using the shotcreting method

In order to design a complex equipment that can be used to repair the asphalt coat on site, a similarity with the equipment used for shotcreting was established; changes were needed for applying the asphalt mixture by injection.

A block diagram of this equipment is shown in figure 5.5. It will be provided with systems for reading the temperature of the repaired surface, the height of the deposited layer, the roughness of the surface resulted from the intervention. The equipment can be self-propelled or pulled by a tractor head that drives the equipment.

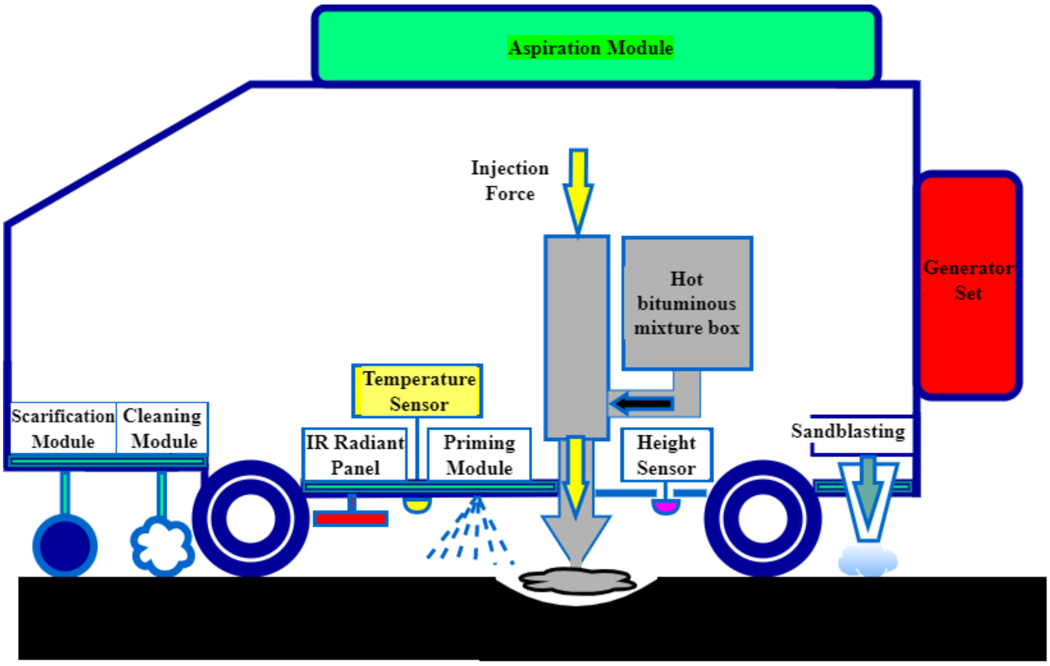


Fig.5.5. Design of the equipment for surface repairing by injection

5.2.2. Development of an experimental equipment

The working possibilities were studied in the CNAIR - CESTRIN S.A. laboratory, starting from the principle on which the shotcreting technology is based. Thus, the prototype of an experimental equipment and the kinematic diagram presented in figure 5.6 were achieved.

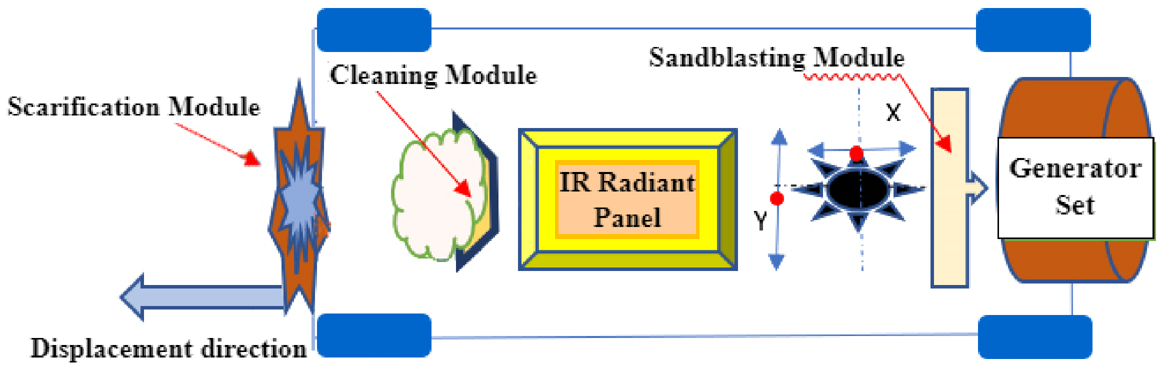


Fig.5.6. Kinematic diagram of the equipment prototype

The material used to cover the holes is a composition delivered in a polyethylene bag, representing a solution for asphalt coating (repairs) in cold season, with medium grain, fig. 5.8.

Fig. 5.8. Medium grain material for repairs

5.4. Experimental results and data interpretation

The basic diagram of the injection system is simplified in figure 5.10. In the experiment, the injection forces were increased to be able to materialize their influence on the bond with the base surface. An IR radiant panel was also assembled for a stronger bond between the deposited material and the base material.

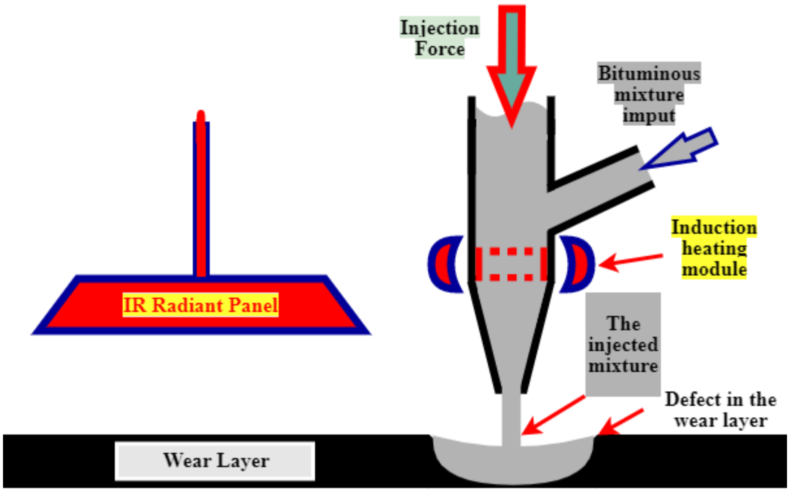


Fig.5.10. Asphalt mixture injection system

Three characteristics of the deposited layer of asphalt mixture were measured in the CNAIR – CESTRIN laboratory (accredited by RENAR) [170], compared to the asphalt mixture of the core on which the testing was done:

1. Determination of the softening point using the ring and ball test, according to the SR EN 1427:2015 standard [169];

   This test was done by means of the Automatic Ring and Ball Tester, shown in fig 5.11.

Fig. 5.11. “Ring and Ball Tester” automatic equipment

5.5. Conclusions

The experimental research conducted in the CESTRIN laboratory facilitates the implementation of a technology different from the existing ones, namely the injection of warm asphalt mixture, with very good results as for the sealing characteristics (both from the point of view of the adhesion of the deposited material with the base material) and the vertical uniformity of the final repair.

The implementation of this technology can determine the designing and finally the achievement of the equipment intended to be used for repairing the asphalt coating on site. The elimination of the wearing surface friction, which involves high costs and damaging of the roadway and of the vehicles too, until the final repairs of the wearing surface is an issue often reported by the public roads users.

CHAPTER 6

FINAL CONCLUSIONS AND PERSONAL CONTRIBUTIONS

6.1. General conclusions

By deepening the research fields that are the subject of this doctoral thesis, I realized the importance of the maintenance activity as a whole, but especially the importance of its efficiency. The new methods, resulted from the evolution of the technologies closely related to the Internet of Things (IoT), have brought new prospects to the management of this activity, new hardware technologies and software applications that offer possibilities unimaginable until recently.

These new possibilities are not only related to the increase of the calculation power, implicitly the speed of analysis of the variables resulting from the activity carried out in a manufacturing unit, but also to many other connected fields of activity, such as the maintenance of the equipment included in the production lines.

Considering that the doctoral thesis is closely related to my field of professional activity, I approached and accomplished, per chapters, the main objectives regarding the road maintenance, as follows:

- Studying and demonstrating the possibility to autonomize an equipment for intelligent monitoring of the road traffic;
- Research on a new procedure of corrective maintenance of the roadway wearing surface.

I also addressed and achieved the specific objectives, respectively:

- analysis of piezoelectric sensors with the purpose of autonomization;

- development of an autonomous module for the monitoring of the system evolution;
- experimental configuration and on-site measurements;
- calculation of the energy provided by the piezoelectric sensor through the vectorization of the oscillograms;
- demonstrating the hypothesis of autonomization of a system evolution monitoring equipment;
- analysis of road corrective maintenance;
- formulating the hypothesis of application of the roadway wearing surface repair technology by shotcreting;
- design of an equipment for repairing the roadway damage using the shotcreting procedure;
- development of the experimental equipment;
- laboratory research on the implementation of the new procedure and analysis of the results.

6.2. Personal contributions

During the preparation of the doctoral thesis, I had the possibility to make several original contributions, both theoretical and experimental ones, to the two research directions addressed, which I will detail below:

The first direction of research – the idea of energy autonomization of a traffic monitoring equipment, but especially the study I conducted afterwards, as detailed in chapter 4, enabled me to develop, in the form of a partially practical research for now, the possibility of using established technologies (the piezoelectric sensors) along with a new technology (integrated circuits of the latest generation) to reach the design and the subsequent production of ultramodern measuring equipment.

The second direction of research, detailed in chapter 5, had the final goal of designing a complex roadway repair equipment. It gave me the opportunity to study the possibility of performing technological operations of sealing the defects in the roadway wearing surface using the technology of warm bituminous mixture injection (shotcreting) and of measuring the resulting important parameters.

a) Theoretical contributions

The block diagram of a technological equipment for the injection of warm asphalt mixture was made. It was also estimated the behavior of the materials used in the operating conditions specific to the final destination of the equipment.

A complex equipment for the roadway maintenance was designed. It includes several modern machines for working on the wearing surface, grouped in a line of technological operations before and after the innovative equipment for injection (shotcreting) of warm asphalt mixture.

The kinematic chains were highlighted in the kinematic diagram of the developed equipment.

b) Experimental contributions

An equipment formed of a heated container for asphalt mixture, a hydraulically driven pump and a heated nozzle was built. Four indentations were made in a bitumen core to simulate the holes appeared in the wearing surface. Bituminous mixture used for hot repairs of the wearing surface was injected and afterwards, after cooling, a cross section of the core was cut in order to study the area where the repair was made.

The final results of this operation were analyzed in the CESTRIN laboratory, with very good findings. The sealing had a uniform aspect, without discontinuities in the zone of bond between layers, although no bituminous emulsion was used to improve the bonding of the wearing surface and the base layer. Three tests were carried out in the laboratory, namely: the softening point; determination of needle penetration at 25 degrees Celsius; determination of elastic recovery at 25 degrees Celsius. The results recorded after cooling were very good, with final values very close to the initial values.

6.3. Further research directions

1) I would like to continue the research in the direction of completing the design, realization and testing, both in laboratory and on site, of a sub-system for receiving, processing and transmitting the data resulting from the measurements, as described in chapter 4. The final goal is the production of a traffic measurement autonomous sensor equipment that can be installed on a national road, checked in traffic conditions, made compatible with the existing systems and improved. This will be the starting point for the development of a modern traffic monitoring system, managed as an autonomous wireless network node.
2) At the same time, I would like to develop the computer program that, once installed in the processing unit, will process the traffic data collected from the sensors that compose the

measurement system proposed in this thesis. I would also like to make this system compatible with the existing systems.

3) I intend to continue the research in the following directions: the completion of the design of the complex equipment for repairing the roadway wearing surface; the estimation of energy consumption for a correct sizing of the electric group; the estimation of the consumption of materials used for repairs, asphalt mixture, sand in order to determine the dimensions of the storage containers; evaluation of the amount of heat released by the component machines and studying the possibility to use this heat within the technological processes to be executed before its exhaust.

6.4. Valorization of the research results

The research carried out regarding the energy autonomization of the piezoelectric sensors, with application in the field of predictive maintenance, was turned into good account as follows: during the preparation period, a number of 5 scientific reports were produced and presented within the Doctoral School of Engineering and Management of the Technological Systems. The reports highlighted the current stage of the research in this field – analysis of piezoelectric sensors from theoretical and experimental points of view. The experimental research was conducted in the laboratories of CESTRIN and the "Politehnica" University of Bucharest.

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1. **S.Ioniță**, C.Hagiescu, S.Velicu, I.Paunescu - *Measurement of the micro-asperities of the asphalt carpet flat surface by means of virtual*. International Journal of Modeling and Optimization, vol.9, nr.5, October 2019.
2. **S.Ioniță**, C. Hagiescu, B. Iovu, S.Velicu, P.Paunescu - *Measuring the weight of a vehicle by monitoring the dynamic torque of a heat engine*. Reasearch and development in field of vecihles and transport, 05-07 septembrie 2019, IRMES 9th International Scintific Conference, Kragujevac, pp. 246;
3. **C. Hagiescu,** S.Velicu - *Autonomous equipment for monitoring the critical structures applied in the field of road traffic*, iulie 2022, Constanța - România, (The 5-th edition of SLS and the 17-th edition of OPTIROB 2022).
4. **C. Hagiescu,** M.Hagiescu, C.Păunescu, R.A.Sandu - *Innovative use of torcreting (guniting) for repairing wearing surface of roads*, Crimson Publishers - ACET (Advancement in civil engineering & technology), iulie 2022, New York, SUA
5. **C. Hagiescu,** M.Hagiescu, C.Păunescu - *Mentenance of the wear layer using the technological procedure of injections* (Shotcreting), iulie 2022, Constanța - România (The 5-th edition of SLS and the 17-th edition of OPTIROB 2022).

6. **C. Hagiescu,** Plan de afacere - *Servicii de reparații, dezvoltare de produse și execuție de lucrări în domeniul radiocomunicațiilor,* Program Operațional Capital Uman, Axa prioritară 6, Burse pentru educație antreprenorialăîn rândul doctoranzilor și cercetătorilor post doctorat, cod MySMIS 124539, *Bucuresti UPB 2021,*
7. **C. Hagiescu,** S.Velicu - *Mentenanță sau modernizare, o problemă azi?*, lucrare în curs de publicare în Buletinul UPB.

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