ROMANIAN ACADEMY

INSTITUTE OF SOLID MECHANICS

PhD Thesis

Short version

Contributions to the Development of Hybrid Force-Position Control Strategies Applied on Mobile Robots

Contribuții la elaborarea strategiilor de control hibrid forță-poziție pentru conducerea roboților mobili

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SUMMARY

Introduction

The main purpose of this paper is to develop a new and innovative hybrid force/position control method able to adapt in real time to any kind of situation and event that the robot may encounter in the workspace. For this, in hybrid control development phase, multiple control laws are chosen, and to them is associated their way of use, followed by the definition of a real time control laws' set that the robot will use according to the situation met in the workspace, by states and uncertainty areas for which will be defined control laws and methods with wide spectrum applicability.

Conducted research, analyzing the concept developed by the Professor Luige Vlădăreanu[41, 62, 69, 72, 161] method in force-position hybrid dynamic control [7] to which was applied the neutrosophic logic, founded by Professor Florentin Smarandache [8, 76, 77]from NewMexico University, USA, and Dezert-Smarandache (DSm) theory, led to the development of an original switch function. Due to the fact that the input data in a control system may be ambiguous and contradictory, this new control technique has been used, and uses the truth, falsity and uncertainty probabilities, computed through the modeling process of raw data received from certain sensors acting as system observers.

In order to improve and increase hybrid force-position control performances has been developed a new real time force-position control architecture, improved with neutrosophic logic, which can manages to determine, for each task or robots and environment data change, the control law required to control each degree of freedom and motion axis of the robot. In this way, neutrosophic logic acts as a switching law determining the n-dimensional matrix S parameters, specific to hybrid force-position control. There results a new and improved real time force-position control method with high performances regarding stability on uneven and unstructured terrains, which is based on DHFPC dynamic hybrid force-position control, with the addition of inferences with control laws specific to robot movement in a constrained environment, such as neutrosophic logic for optimal switching decision, sliding control method, cvasi-static contact in 3D protection, etc. The possibility to change internal control laws of each joint / degree of freedom in dynamic way is assured, such that the robot may move in the work environment, despite the perturbations, uncertainties and external actuations over it. The new real time hybrid control method is superior through high performances of robot stability on uneven terrains, being characterized through fast response and robustness to constrains that occur in robot environment, adaptability in obstacle avoidance and to cooperation actions with other robots, being in the same time more efficient treating incompatibility problems between robot objectives and control laws used. These performances superior to other actual research published in known journals, BDI indexed ore ISI, are relevant in present paper through original concepts, results obtained from simulations and experiments, known in country and abroad by publishing research results in international conferences at Harvard, Houston, Paris, Bucharest, in BDI and ISI indexed journals, and through national and international awards, gold medals granted at International Expositions from Geneva 2010, Moscow 2010, Bucharest 2010, Warsaw 2009.

Improvements brought to hybrid force position control, are within areas of concern of many scientific research groups from universities and research institutes worldwide [160-172], proved by analysis studies on many valuable scientific papers, published in last years in international journals, BDI or ISI indexed by worldwide known research teams [135, 137, 138-142, 144, 145, 147, 151, 155, 156, 160, 161, 164, 166, 168, 169, 171, 172].

In order to obtain the improvements brought to hybrid force-position control many research has been conducted in collaboration with universities from abroad such as University of Gallup New Mexico, USA, National Autonomous University of Mexico City, Mexic and University of Houston USA.

The PhD thesis contains results obtained by the author during PhD stage. These results are totally original and their aim is one of the most studied research fields, mobile robots control, within great universities and research institutes. The importance of the conducted research, and also their correctness, has been validated by public discussion within various national and international scientific manifestations, by publishing them in prestigious scientific journals or through national and European patents.

To be mentioned that in 2011 a collaboration contract with Professor Florentin Smarandache, founder of neutrosophic theory and author of Dezert-Smarandache (DSm) theory, from Gallup University from New Mexico USA. The results of this collaboration had contributed to the research that I have developed for this PhD thesis by applying the DSm theory in robotics and developing the neutrosophic logic concept in dynamic systems control. Neutrosophic logic has a special significance in scientific research due to the fact that it starts from fuzzy logic concepts and extends it introducing and using uncertainty and contradiction elements, extremely needed by all systems modeling. Neutrosophic logic has various applications in different research fields such as mathematics, chemistry, biology, etc. In this paper original methods and concepts are developed

and they allow the gathering of high performances in walking robots motion control and stability applying neutrosophic logic and DSm theory.

The present paper is divided into 10 chapters, from which the first 7 comprise the actual paper with a chapter of original contributions and one of conclusions. The last 3 chapters contain the author's published paper list, used references, annexes with graphics, figures and algorithms that could not be introduced in the paper content, in order to easily understand the developed concepts.

Computer assisted experimental research; simulation and validation of developed mathematical models

In this chapter, it is presented the mobile walking robot structure, used in simulations and to prove the developed and improved control methods and algorithms, through original contributions.

I have choosen the hexapod robot structure, presented in figure 5.1.1 which has 18 rotational DOF, with 3 DOF on each leg.
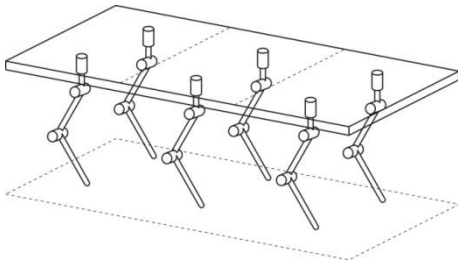
Figure 5.1.1 - The mobile walking hexapod robot
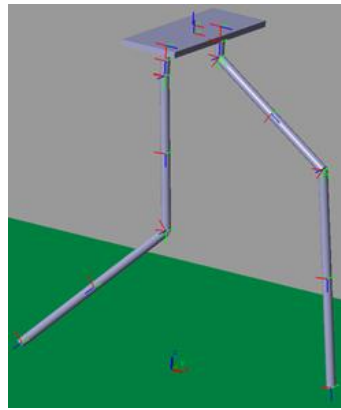
Figure 5.1.2 – The mobile walking biped robot(A. Gal)
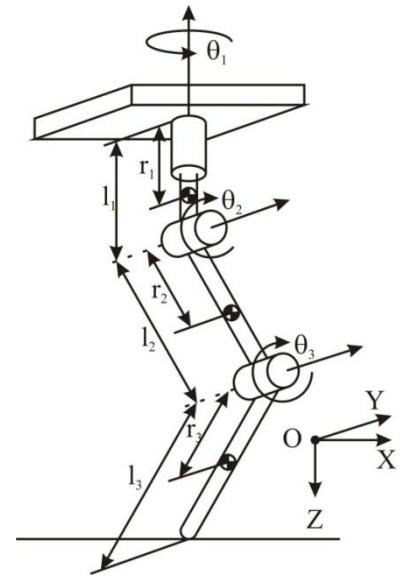
Figure 5.1.3 - The kinematic structure for a leg of the mobile walking robot

Using the robots presented in figure 5.1.1 and 5.1.2, we choose one leg of the robot, to detail its kinematic structure, and to choose the rotational axis for the joints (Figure 5.1.3).

Neutrosophic logic in determining the contact with the supporting surface

This section presents the original contributions which use the neutrosophic logic [8, 76, 77] and DSm theory to achieve an original environment detection method using the sensors as observers.

The neutrosophic logic is considered as a general frame to unify the majority of existent logic theories, and the basic concept is represented by the characteristic of each statement in a 3D space, composed by the procentage of throuth (T), falsity (F) and indetermination (I) [75].

The Dezert Smarandache theory, DSmT, is a plausible reasoning and paradox theory which was developed to be able to use vague, uncertain or conflicting sources of informations. This theory is used mostly where other theories fail due to the conflictual states between the data sources, like tracking a trajectory, satelite surveillance, state analisys, image processing, object recognition, robotics, mediceine, biometrics, etc.

After applying the classic DSm method, we obtain 4 sets of data. These are the certainty values for **Thruth** and **Falsity** for a certain event, the values of **Uncertainty** for the events and the values of **Contradiction**.

The developed method using DSmT, aims to control the motion of rescue robots on uneven and unstructured terrains with express reference to the RABOT rescue robots from the FP7, IRSES project „Real-time adaptive networked control of rescue robots". It is assumed that the mobile walking robot structure is a simple one, and for each leg we have 3DOF to position the robot foot in a 3D space. For this type of mobile

robot, going down steps on which the robot has no data about its structure, shape or position of each step, is a real chalenge to generate the leg position reference. This is why we used sensors to detect each step on which the robot will walk on. The sensors used as observers from the DSmT are a proximity and force sensors, and are placed on the bottom of each leg foot. Through the data given by the two observers it is determined if the robot foot is or not in contact with the support surface.

By applying the presented theory, I have achieved a logical diagram, which states the way in which the neutrosophic decision is made. By using the logical diagram the algorithm choses which of the control methods (kinematic or dynamic based methods) will control the movement of the mobile walking robot at one time.

The original contributions presented in this sections represents the use of the neutrosophic logic in designing the switching method and also the logic diagram used in the de-neutrosophication phase of the computed data using and decision making.
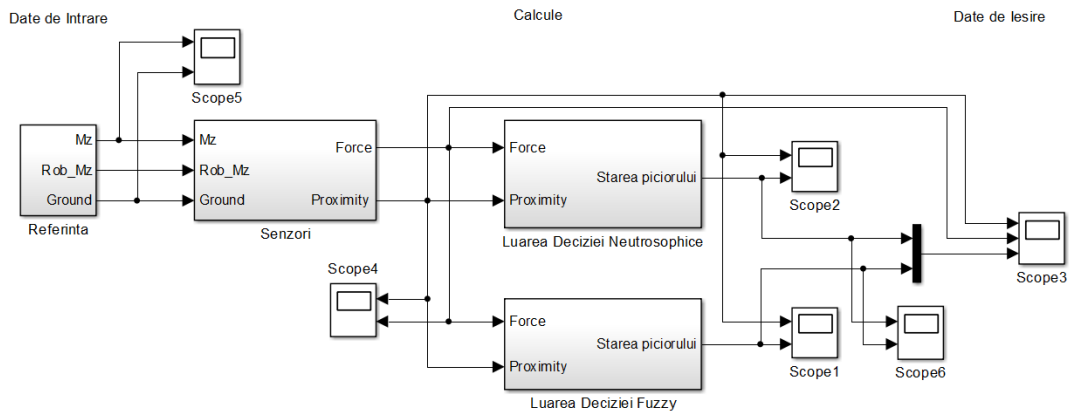
Figure 4.3.4 –The comparisson system of the switching methods

A simulation has been developed, which is simple but also complex enough to highlight the difference between the two switching methods.
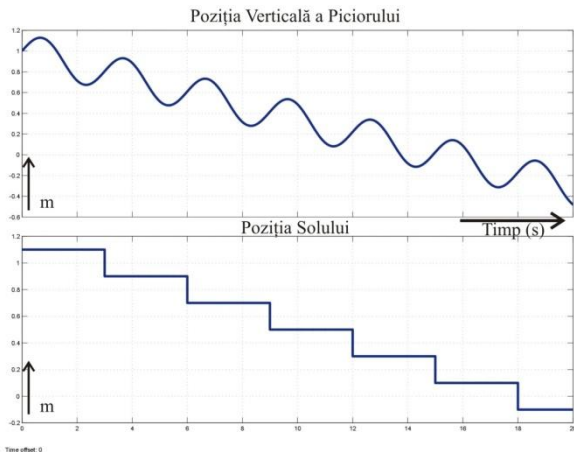
Figure 4.3.7 –The input data for the switching system
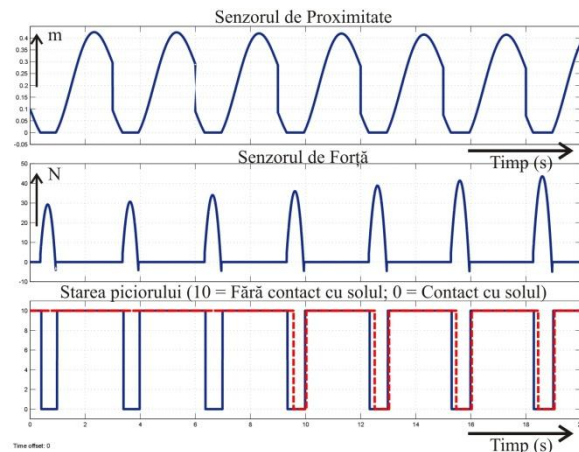
Figure 4.3.9 - The output of the switching system and the sensors data

Figure 4.3.7 presents the graphs of the input data represented by the vertical position of the robot foot in relation to a fixed point in space. Also the second graph presents the vertical position of the support surface in relation to the same fixed point in space.

By using the original switching system, which is based on the DSm theory, we observe in comparation with the one based on the fuzzy logic (Figure 4.3.9), that the original one establish more accurately the contact state with the support surface according to the observers data, as against the outcome of the fuzzy logic based switching algorithm.

The most important contribution of this section is the design, developing and experimentation of the new switching method used in mobile walking robots control by using the neutrosophic logic, and improving the environment sensing in which the robot is moving, by detecting in a safe way the states of the robot. The

comparative analisys with the fuzzy based switching methods, proved the increase of performance for the robot motion in uneven and unstructured environments.

In conclusion, the switching method based on the neutrosophic logic, succeeds in achieving in real time, the switching and decision making for a robot system, with almost null errors. Instead, it is required an additional condition to maintain the switching state for a time Δt, so that the systems will not become one that has a chattering effect.

The contributions in the robotics area presented in this section are based on the state of the art studies in this research area, like the research conducted in colaboration with Professor Vladareanu Luige, Romania, Professor Florentin Smarandache,USA, Professor Hongnian Yu, UK, Professor Ovidiu I. Sandru and Professor Radu I Munteanu, Romania. Following these collaborations, I have designed original hybrid force-position control strategies, for controlling mobile walking robots. These control strategies were designed at first in terms of mathematical relations which are the basis of any mechatronic and system control design. Further, these relations were simulated using advanced software environment for mobile walking robots and their control methods, proving by comparison with results of other international research teams, the usefulness of the proposed contributions in the area of mobile walking robots control.

The Fuzzy- PID – Sliding Motion Control

The dynamic method of sliding motion control (SMC) applied to a leg of the mobile walking robot, is nonlinear, variable and robust, and is also capable to control different type of systems with different type of uncertainties, including the nonlinear systems, MIMO systems and time discrete systems [80, 81].

By using the above mentioned control, I have developed a Matlab Simulink simulation to test the sliding motion control method which used the proposed contributions. Among these is the use of fuzzy logic for computing the gain parameters. Also it has been observed that the system has overreach and a propagation of errors within the system when a high amplitude perturbation occurs. This is due to the integral parameter of the PID sliding surface equation. Therefor it has been decided to alter the sliding equation by adding a parameter to multiply the integral parameter as shown in equation (5.2.35).

$$s = \dot{e} + \lambda_1 e + k * \lambda_2 \int_0^t e \, dt \qquad (5.2.35)$$

This relation that computes the sliding surface, coresponds to the stability conditions and represents one of the original contributions which improves the sliding motion control.

After conducting the virtual experiments by simulation, we obtained the following data, which figures 5.2.7 and 5.2.10 are presenting. Because I wanted to highlight the systems' robust behaviour I have added some perturbations to the reference system. These perturbations add high amplitude step signals at different times (second 4, 6 and 8) to the reference signal, and also a resisting torque applied to the joint motors which varies in time, according to a sine shape signal of amplitude 0,5Nm.
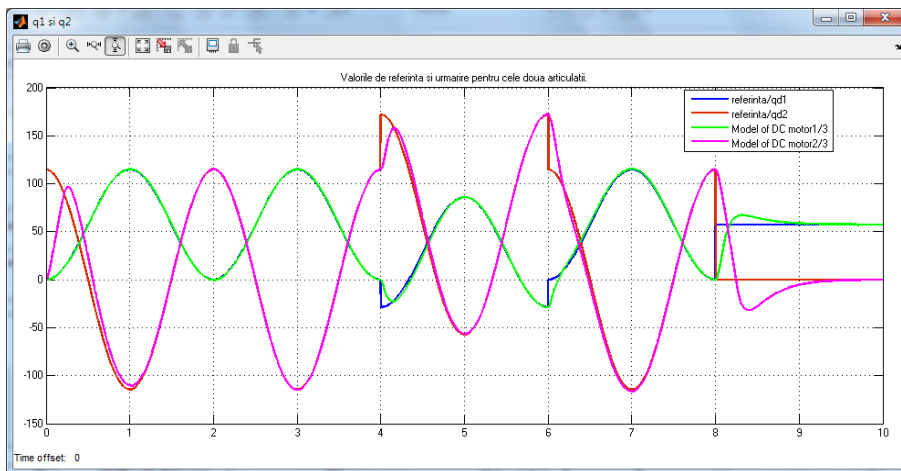

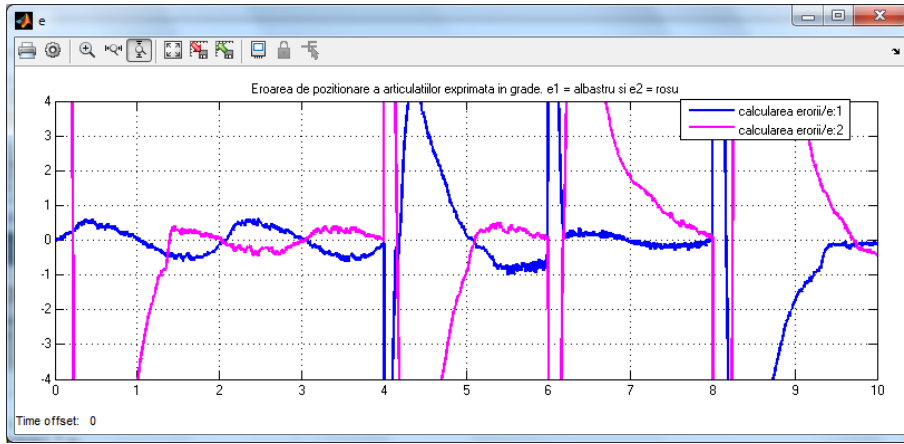Figure 5.2.7 –Joint position in comparison with the reference signal

Figure 5.2.10 –The positioning error magnified for the two presented joins

One can observe that the new Fuzzy-PID-SMC improved control with the fuzzy logic and by adding the „k" parameter, has a lower positioning error as well as a higher speed for tracking the reference, after the perturbations occur, highly increasing the control method robustness.

The first contribution to the SMC control method is the use of fuzzy logic to compute the control gains. This method involves developing a linear fuzzy function which is based on the classic defuzzification table. Thereby the fuzzyfication and defuzzyfication is made within a special built function to control a mobile walking robot. The resulting equation has optimized the real time computing of the required gain.

A seccond contribution is the modification of the sliding surface equation by adding the parameter „k", without affecting the stability condition. With this parameter I succeeded in lowering the angular error and by optimizing its rquired computing power it lead to a precise and stable control law. Moreover, because the integral component is lowered, the systems' over reach are reduced, improving the robustness of the SMC.

Hybrid force-position control of a mobile walking robot

This section of the thesis presents the hybrid force-position control strategies for the mobile walking robots, developed based on mathematical relations. The presented equations are part of the original contribution list in the area of mobile robot control.

One of the main contributions presented in this thesis is the development of a hybrid force-position control diagram, based on the clasic hybrid control [9] and Profesors' Vladareanu Luige DHFPC method [41, 62, 69, 72, 161]. The control law selection for the hybrid controlled is made through the selection matrix, computed in real time, by an original switching controller, based on the neutrosophic logic [8, 76, 77] and DSmT [75, 79, 159]. The mathematical relation which is the basis of the switching matrix S is presented in relation (4.1).

$$\sum_{i=1}^{n} Sp_i + \sum_{j=1}^{m} Sf_i = I_{nr_{DOF}} \qquad (4.1)$$

where, Sp_i and Sf_i are the matix which designates the position and force control laws for the mobile robot control, and the unit matrix I_{nrDOF} has the dimension according to the number of the degrees of freedom which governs the robot kinematic position.

The proposed control diagram that improves the hybrid force-position control is presented in figure 4.2. This hybrid force-position control diagram, can control a variety of different robots, for which, their environment is in a constant state of transformation, and allowing the robots to work in a efficient and stable way, with uncertainties and dynamic parameters of the work environment, without beeing necessary to adjust the control laws for every change in the environment parameters.

Starting for research conducted by Profesor Vladareanu [7, 37, 38, 56, 58, 59, 62, 63, 69, 72, 161, 163, 195], I have developed the new hybrid force-position control diagram based on the DHFPC control method, and use the original switching method based on the neutrosophic logic and Profesors' Smarandache DSmT [8, 75, 76, 77, 79, 159].

To demonstrate the validity of the designed hybrid force-position control method, were conducted simulations, using a virtual model of the mobile walking robot. Two robot control methods were used, for which original contributions were made, to optimize the walking robot control. The first methos is the the control using linear techniques based on robot kinematic and PID regulators. The second method controls the robot joints by

using the Fuzzy-PID-SMC control method, starting from a reference in the operational space and transforming it in the joint space through inverse kinematics methods.
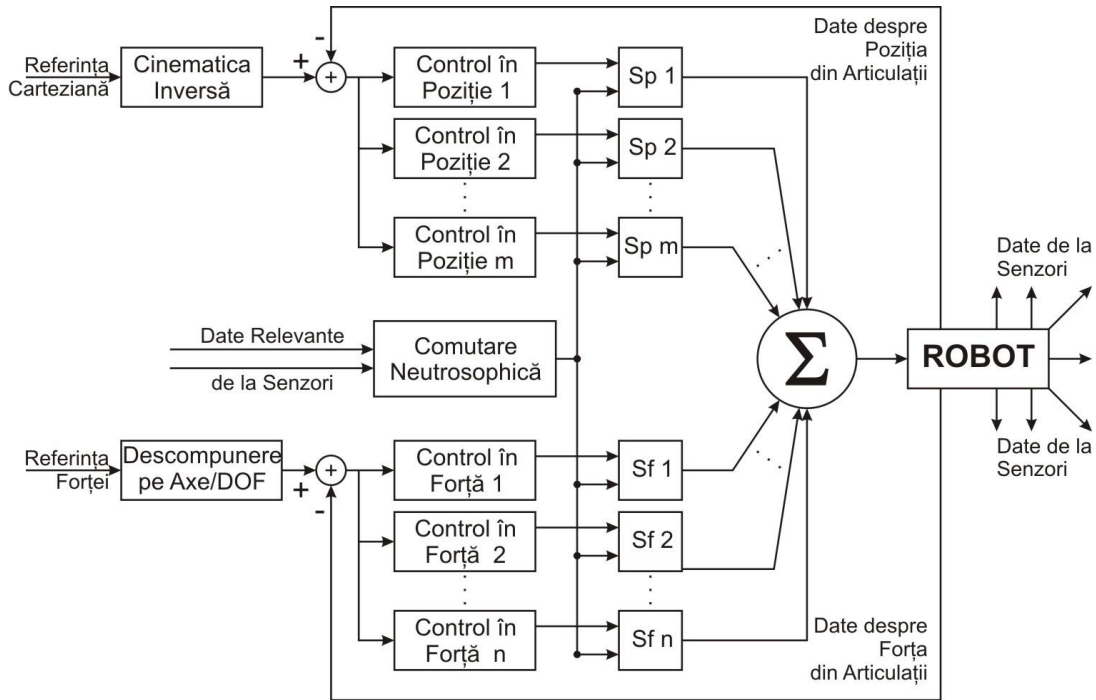
Figure 4.2 –The improved hybrid force-position control diagram

The new control diagram for the hybrid force-position control in figure 4.2, is bettern that the clasic one because it gains the benefits of a larger group of control laws which controls the robot movements at different moments in time.

For a better understanding of the improved hybrid force-position control, a control diagram was developed. This diagram is the customized version of the general diagram in figure 4.2. Here we have two control laws: a kinematic based controller and a dynamic based one. The control methods will lead the walking robot movements, starting from a Cartesian reference and transformed by the inverse kinematic algorithms into a joint space reference.

The next relation express the general control law for the improved hybrid force-positon controller and customized for the two described control methods.

$$\tau_{ctrl} = S\left[\tau_{prev} + K_p \; q_{ref} - q_{real} \; - \omega_{real} - K_d\alpha_{real}\right] + \; I - S \; \left[SMC \; \Delta q, s, K_{fuzzy}, Rob_{Dinamica} \; \right]$$

The main contributions added by this section are the use of the improved hybrid force-position control on the mobile walking robots that move on unstructured terrains; simulations of interaction conditions between the robot and environment using equations for the quasi-static contact, the friction force; and the use of Matlab libraries to simulate as close to reality as possible a model of the mobile walking robot.

Mobile walking robot simulation in Matlab Simulink

To achieve the virtual simulation of the mobile walking robot kinematic structure, the Matlab Simulink software was used, along with the SimMechanics-V2 3D modelling library, whose aim is to simulate the interaction between the mechanical system and its environment. Figure 5.4.7 presents a module for the simulated mobile hexapod walking robot.

To compute the friction force, the published research in [36, 175] were used. The relation upon which the friction force was calculated is:

$$\sqrt{R_1^2 + R_2^2} = \mu R_3 \qquad\qquad (5.4.5)$$

where, R_1, R_2 and R_3 represents the decomposition on the three Cartesian axes of the robot weight force which presses on the support surface through the robot foot. The (5.4.5) condition represents the slip-stick limit for one foot.
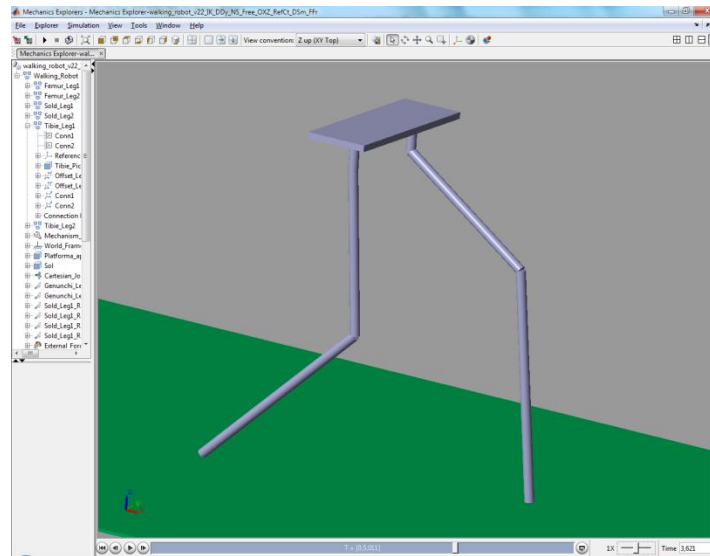
Figure 5.4.7 – The simulated mobile walking robot,
using Matlab Simulink and SimMechanics library

Figure 5.4.8 shows how the robot model looks like when designed in Matlab Simulink – SimMechanics. This one presents the hip join of the mobile walking robot.
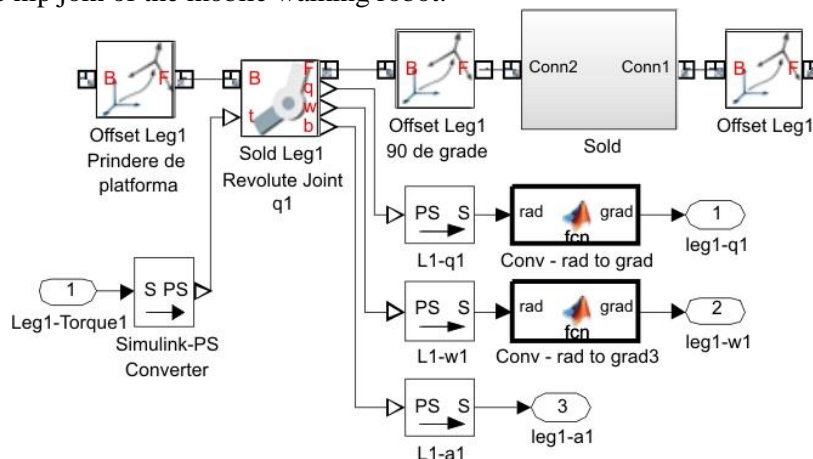
Figure 5.4.8 – Building the robot hip joint

The main contributions of this section are: building with the help of Matlab Simulink – SimMechanics V2 library, the mobile walking robot, in a virtual environment; adding the detection conditions for the cvasi-static contact between the robot foot and the support surface to predict if the robot is about to slip on the ground; and compute the friction force required for the robot to move forward.

The mobile walking robot simulation, controled by the improved hybrid force-position controller

Using the control diagram from figure 5.4.2, a simulation for the mobile robot control was conducted. The control laws used are the PID kinematic based controller and the Fuzzy-PID-SMC controller. The resulted control law for the entire control system is:

$$\tau_{ctrl} = S\left[\tau_{prev} + K_p\left(q_{ref} - q_{real}\right) - \omega_{real} - K_d\alpha_{real}\right] +$$

$$+ \left(I - S\right)\left[H\left(\ddot{q}_d + \lambda_1\dot{e} + \lambda_2 e\right) + C\left(\dot{q}_d + \lambda_1 e + \lambda_2\int_0^t edt\right) + G + K_v s + K\,sat\left(s\right)\right]$$

These control laws, were combined using the neutrosophic logic according to the sensors data. The switching method logic diagram, which selects the right control law for the robot is the one from figure 5.4.12, presented earlier, and figure 5.4.40 presents the output of the switching method dorring the 10s simulation time. For the first 0,5 seconds one can see the predifined selection for the switching method, during the robot homming phase.
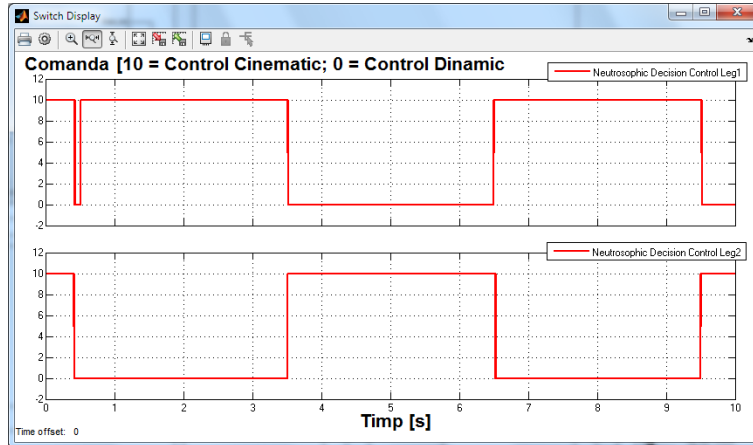
Figure 5.4.40 –The neutrosophic decision for the two robot legs

By using this decision, I obtained the following positioning data for the mobile walking robot legs, which was controlled in position by the two control methods, and swithich between them as the neutrosophic logic dictates.

Figures 5.4.41, 5.4.42 and 5.4.43 present the positionig on the three axis for the mobile walking robot foot of leg 1. The ones for the leg 2 are similar, and only the time stamp is different. Comparing with the kinematic positioning law, we observe that in the phase of robot weight support, the positioning error on OX axis is higher that when the robot is controlled by the Fuzzy-PID-SMC method, but the moving speed is constant which provides a good moving speed for the leg on the forward reaching phase, when the robot is preparing to carry out another step.
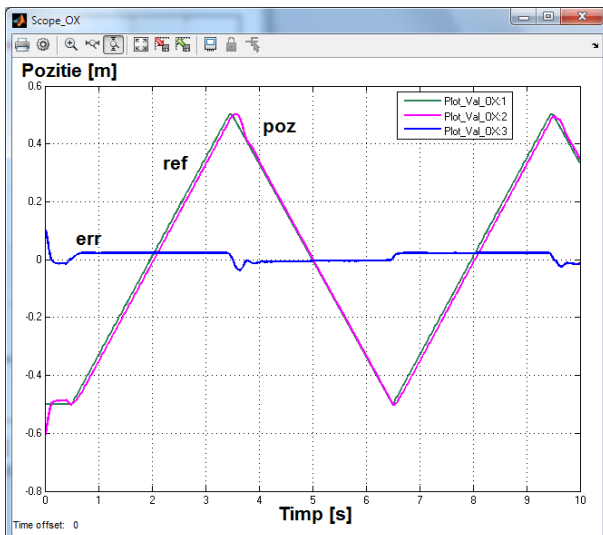
Figure 5.4.41 –Leg1 positioning on the OX axis by using the hybrid controller
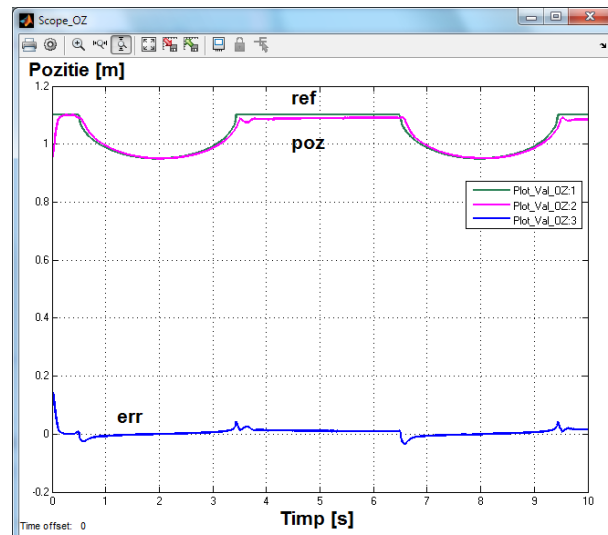
Figure 5.4.43 –Leg1 positioning on the OZ axis by using the hybrid controller

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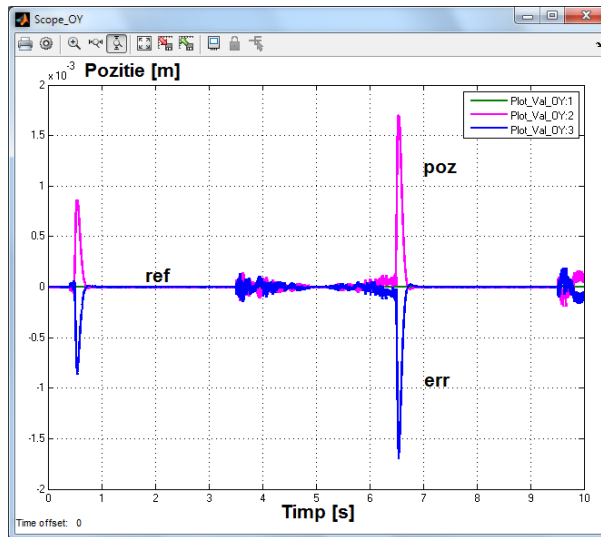
Figure 5.4.42 –Leg1 positioning on the OY axis by using the hybrid controller

The positioning errors can be better seen in figures 5.4.44 and 5.4.45.

One can see that the positioning error is periodical, because it has the same shape for the same robot motion phases, which provides the repetition characteristics which is desired in a robot. Also, we can observe that errors for the kinematic controller are asimptotical and in the phase when the robot is controlled by the dynamic controller, the error is almost constant, for both joints of the robot leg. This highlights the differences between the two control methods and the fact that using the Fuzzy-PID-SMC method is required for the phases where the robot weight is supported by the controlled leg, so the entire hexapod robot structure doesn't become unstable.
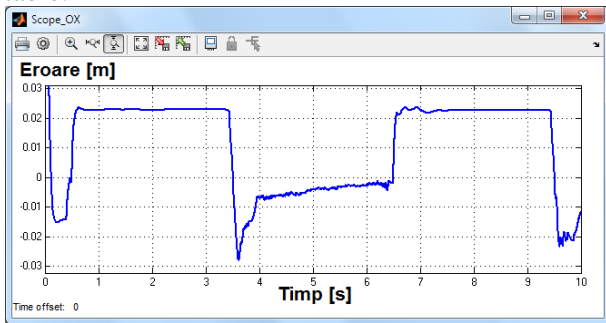
Figure 5.4.44 –The positioning error of leg 1 on OX axis using the hybrid controller
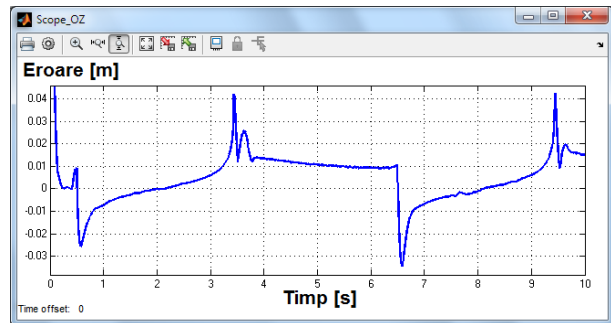
Figure 5.4.45 –The positioning error of leg 1 on OZ axis using the hybrid controller

By using the positioning performances for both control laws and their improvements one can observe that this type of hybrid controller is an improved one, which combines all the performances of the used control laws. The used neutrosophic logic, manages to provide the required data in real time, so the control type change is made at the right moments in time.

The main contribution of this section is that through virtual experimentation of the hybrid controller, we managed to point out that the new hybrid and improved control law is more efficient and better than the clasic one, because it can achieve many combinations of the control laws during the robot movement. Thus, one application can have a combination of control methods as high as the relation (5.4.8) can get, because for each control method added to the hybrid controller, as in figure 5.4.1, it can be combined at any moment in time with any other control laws within the hybrid controller.

$$Nr_{comb} = C^{x}_{x\ n+m} \qquad (5.4.8)$$

where Nr_{comb} represents the total number of combinations which can be achieved between the control laws, **x** is the robot number of DOF, **n** and **m** is the number of control methods used for position and force control, respectively.

The data analisys is another contribution of this section, which proves that the developed improved hybrid controller, in combination with the original switching method based on neutrosophic logic and DSmT, has better performances in controlling the mobile walking robots besides the classic hybrid controller and research conducted by other international teams. Moreover, operationl and joint space analisys were conducted, to

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highlight the errors of high amplitude and their cause of occurence, so that further research can reduce and even remove those errors.

Simulation workbench for testing the control laws of a mobile walking robot leg

In this section the simulation workbench for testing the control laws of the mobile walking robot leg is presented. This was mainly used to test the Fuzzy-PID-SMC controller, because it implies many of the original contributions of this thesis. This simulation workbench was obtained through the research project on which this thesis author participated in collaboration with Professor Luige Vladareanu and PhD. eng. Lucian Marius Velea: „Foundamental and aplicative research for the hybrid force-position control of modular mobile walking robots in open ahitecture systems", ID 005/2007-2010. The project was part of the IDEAS programm; its coordinator was Prof. Luige Vladareanu and was financed by National Authority of Scientific Research.

Figure 6.1 –The simulation bench for the control laws

The basic control relation used is:

$$\tau_{ctrl} = SMC\left(\Delta q, S, K_{fuzzy}, Rob_{Din}\right) = \left[H\left(\ddot{q}_d + \lambda_1\dot{e} + \lambda_2 e\right) + C\left(\dot{q}_d + \lambda_1 e + \lambda_2\int_0^t e\,dt\right) + G + K_v s + K\,sat\,s\right]$$

This relation uses the Fuzzy-PID-SMC method with the fuzzy dynamic parameters, as well as the sliding surface equation.

In building the simulation workbench, we used industrial standard equipments, with PLC and ACSM1 frequency converters for motor driving.

By using this workbench, a testing software was built, to test the conducted research. But, because we didn't want to simulate all the hardware components of the robot, we simulated only the Fuzzy-PID-SMC method for a robot leg with 2DOF. All the parameters for the simulation and its reference signals were taken from the previously presented Matlab simulations so we can compare the obtained results.
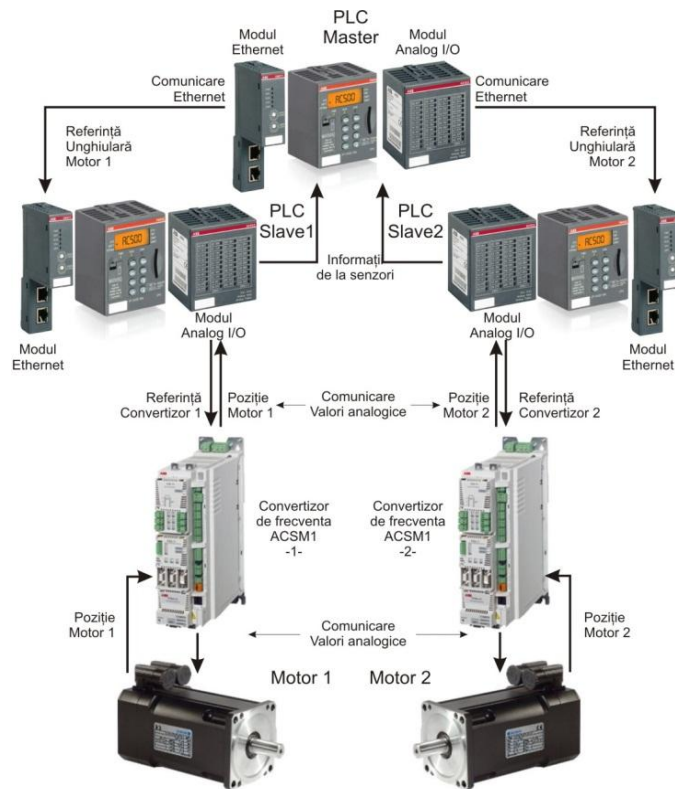
Figure 6.14 –The command and control diagram for the simulation workbench

Figure 6.14 presents the command and control diagram for the experimental workbench used in the experiments, and figure 6.15 presents the simulation results after implementing the control method.
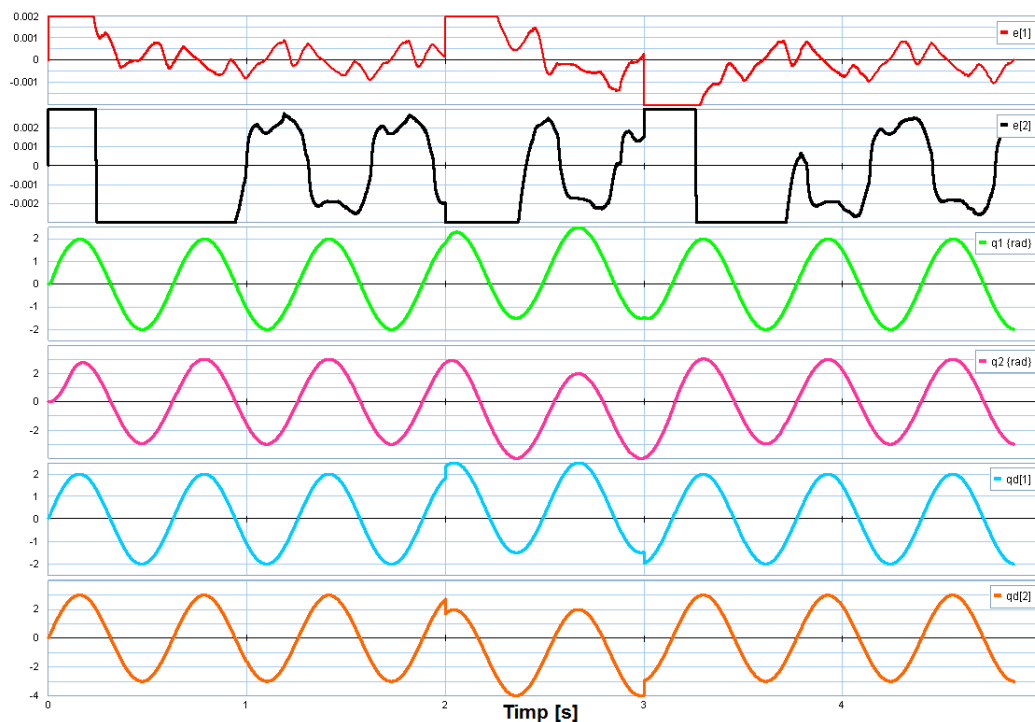
Figure 6.15 –The input and output values of the conducted experiment on the Fuzzy-PID-SMC method

As in the previos simulations, for second 2 and 3 we added a fixed value as error in the reference signal, to test the behaviour of the control system in the case of external perturbations and in the case when the reference signal is bad conditioned. Thus, one can see that the error for joint 1 is within the [-0,001; +0,001] degrees interval and for joint 2 the interval is [-0,0025;+0,0025] degrees. These errors are much lower that the ones obtained thorugh virtual experiments.

By analysing the obtained data, we observed an improvement of the measured performances besides the Matlab simulations. This means that the simulation software still have some issues that needs to address, and that the high errors obtained following the simulations, are due to the used algorithms in optimizing the mathematical equations by the mechatronic simulation software.

In conclusion, the experimental data were proved to be mode precise in controlling the robot joints besides the ones obtained throught virtual experimentations, proving the utility and performances of high level for the proposed contributions on the control methods.

The first contribution which this section highlights is the adaptation of the simulation workbench to fulfill the simulation condition for the mobile robot leg control. Moreover, the PLCs and frequency converters were configured to match the required parameters.

Another contribution is the development of the PLC software for the Fuzzy-PID-SMC method, the mathematical equations that needed to be implemented and the communication functions that transmited the data over the Ethernet comunication medium using the UDP protocol.

The comparative analisys and the proof that the Fuzzy-PID-SMC method has greater results as seen from the experimental data, besides the simulated ones, increases the contribution lists presented in this thesis.

Original Contributions and Conclusions

Original Contributions by the Author

Following the research described in this Doctoral Thesis, a number of original solutions in the field of robot control have been presented. From the most important contributions by the author throughout the doctoral work the following is noted:

1. An in-depth comparative study has been undertaken, from which results the state of the art in research and a validation of the broached research field being of major interest and being found in the focus of the most reputable universities and research centers in the world.
2. A new scheme for hybrid force/position control has been conceived based on the real time DHFPC control method by applying neutrosophic logic to the optimal selection of control laws for the robot motion, through an original commutation technique developed by the author, which leads to increased motion performance and improvements in the stability of mobile robots on unstructured and rough terrains.
3. An original commutation method has been conceived which uses neutrosophic logic and DSm Theory, to be further used in:
   - Walking mobile robot control, improving the perception of the movement environment
   - Implementing an algorithm based on this method which allows the detection of mobile robot states during its movement.
4. Modelling and simulations of mobile robots have been developed using:
   - The Matlab Simulink environment and the function library SimMechanics V2, resulting in a very realistic testing environment which manages to outline the contributions brought to the control laws
   - Bond Graphs, which allow the verification of developed and improved control laws, using advanced simulation tools
5. Positioning precision and robustness in sliding motion control of mobile robots through:
   - Using fuzzy logic to calculate the sliding motion control gains, resulting in the Fuzzy – PID – SMC control;
   - Implementing a linear fuzzification/defuzzification function for efficient control of walking mobile robots;
   - Developing the calculation of the sliding surface for the best possible disturbance rejection, reducing its intergral component after a saturation function.
6. Starting from the stability conditions of walking mobile robots controlled with DHFPC laws there were studied and obtained certain robot stability conditions, which were then tested through virtual simulation:
   - By studying the elastic 3D contact between walking mobile robots and the support surfaces, the critical torques were determined for which the legs of the mobile robots are in a quasi-stable state in which they can leave the stability conditions by sliding;

- By analyzing methods of obstacle avoidance, the stability conditions a walking mobile robot must satisfy were determined when it is necessary for the robot to move on avoidance trajectories, in cases of cooperation with other robots, when it is part of a hexapod robot structure or for different cases of constraint during motion.
7. Numerous virtual experiments were undertaken for:
    - Testing the contributions to the control laws;
    - Optimal adjustment of the parameters of the control laws, using the developed relations;
    - Testing the performance of hybrid force-position control;
    - Testing the performance of sliding motion control;
    - Improving the fuzzy laws for calculating gains;
    - Improving and rigourously testing the calculation algorithms for inverted kinematic and dynamic.
8. Experiment were undertaken using a testing stand, through which was shown the improvement in preceision performance, stability and robustness of the mobile robot motion control laws in comparison with the results obtained through virtual experimentation.
9. On the testing stand were developed and implemented:
    - The communication programs through Ethernet and the UDP protocol;
    - The calculation functions and mathematical relations of real time control for the motors used in the developed simulation stand;
    - Appropriate conFiguretion of programmable automates and frequency converters to control the motors simulating the joints of the walking mobile robot.

Obtained Results and Dissemination

Based on the accomplished research, the author has written, presented and published a number of 24 scientific papers in the field of the thesis. From this total, 6 were published as first author within prestigeous national and international scientific events, as well as expert journals. Two papers were published in the journal Revue Roumaine Des Sciences Techniques - Série de Mécanique Appliquée of the Romanian Academy, 3 ISI Proceedings – indexed papers presented at the University of Houston-Downtown, the 15th International Conference on Systems in Corfu, Greece and the 9th International Conference on Applications of Electrical Engineering in Penang, Malaesia, a paper as first author is in publication in the journal Revue Roumaine des Sciences Techniques Série Électrotechnique et Énergétique, ISI indexed with an impact factor and 10 papers were presented in conferences organized under the supervision of the Romanian Academy. The visibility of the author's research is proven by the publication of joint papers with authors at home and abroad, such as Prof. Hongnian Yu [37, 181] from Bournemouth Universitaty in the UK, Prof. Mingcong Deng [175, 181] from Tokyo University of Agriculture and Technology in Japan, Prof. Radu Ioan Munteanu, from the Technical University of Cluj-Napoca [36, 49], Prof. Ovidiu I. Sandru and Prof. Nicolae Pop [38, 75] from the University of Baia Mare.

Many of the results were further realized through research grants in which the author has participated, as well as invention patents awarded to research team the author is or was part of. In the following are presented all publications, patents, international award, gold medals and national and international scientific research program to which the author has contributed during his doctoral program.

The high level of scientific research was further accentuated through the collaboration agreement with the University of New Mexico - Gallup SUA, coordinated by Professor Florentin Smarandache, founder of neutrosophic theory and author of the Dezert Smarandache (DSm) Theory and through the international collaborations for applicative research within the FP7, IRSES program, the RABOT „Real-time adaptive networked control of rescue robots" project, with Bournemouth University in the UK as project coordinator and project partners in Staffordshire University in the UK, Shanghai Jiao Tong University in China, Institute of Automation of the Chinese Academy of Sciences in China and Yanshan University in China.

The obtained results, superior to current research published in reknowned journals, indexed BDI or ISI, are forthcoming in the present paper through original concepts, validated through simulations and experiments, acknowledged on a national and international scale through the publication of the research results in internation conference in Harvard, Houston, Paris and Bucharest in BDI and ISI indexed journals and also through the national and international awards and gold medals obtained in the International Expositions in Geneva 2010, Moscow 2010, Bucharest 2010 and Warsaw 2009.

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