Technical solution

Program system OGIFLEX

(one mode)

(elastic ropes F-type Cable Suspended Parallel Robot, **eFCPR,** with one mode)

Mirjana Filipovic,

Mihailo Pupin Institute, University of Belgrade, Volgina 15, 11060 Belgrade, Serbia.

This research was supported by the Ministry of Education, Science and Technological Development, Government of The Republic of Serbia for financing the national research project “Ambientally intelligent service robots of anthropomorphic characteristics” TR-35003 and partially supported by the project: SNSF Care-robotics project no. IZ74Z0_137361/1.

email:

mira@robot.imp.bg.ac.rs mirjana.filipovic@pupin.rs

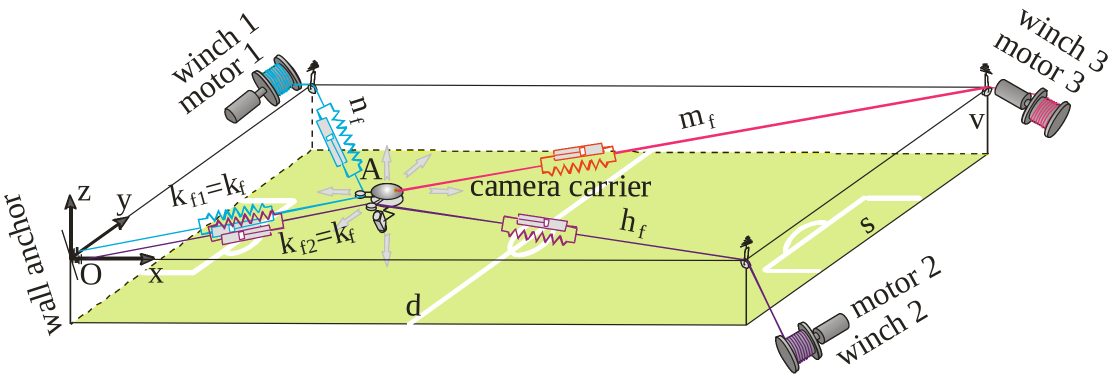

Figure1. **eFCPR with one mode, in the 3D space.**

This program system is generated in MATLAB. This paper is about modeling and analysis of the complex elastic Cable-suspended Parallel Robot named **eFCPR** (elastic F-type Cable-suspended Parallel Robot with one mode).

Prior to the modeling and analysis of the flexible system, the kinematic and dynamic model of the rigid system **RFCPR** has been developed and analyzed in depth. See paper [1]. This result represents the fundamental base for understanding the rigid system behavior and the importance of comprising the elastic characteristics of the **FCPR** system.

The **RFCPR** system represents the reference model, which plays a key role in comparative analysis, defining the reference trajectory and the control structures.

The presented **eFCPR** system is an important and attractive outcome for the engineering and scientific community due to its future intensive development. The most important element of the observed system is its natural elastic property, which is included in the calculation. This property represents the elastic characteristics of the camera ropes which will allow the system to follow and record a moving object with high precision wherever the object moves in the 3D workspace. The **eFCPR** with one mode will be used in future for the full automated system which will be able to precisely lead the camera in the workspace with the minimum involvement of the human interference. The elastic characteristics of the **eFCPR** with one mode are implemented by formulating the highly authentic mathematical model. The synthesis and analysis of the **eFCPR** model with one mode will enable further development and implementation of different control laws. The synthesis and analysis of the **eFCPR** model with one mode will enable further development and implementation of different control laws. The **eFCPR** system with one mode has eight DOF.

The area to which the technical solution refers

Robotics, Theory of Mechanics, Applied theory of oscillations and Nonlinear dynamics in robotics, Applied theory of elasticity in robotics.

Problem solved by technical solution

This technical solution solves the problem of efficient synthesis and analysis of aerial robot model with elastic ropes in its construction, as well as testing its behavior under simulated real conditions of **eFCPR** system task realization.

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

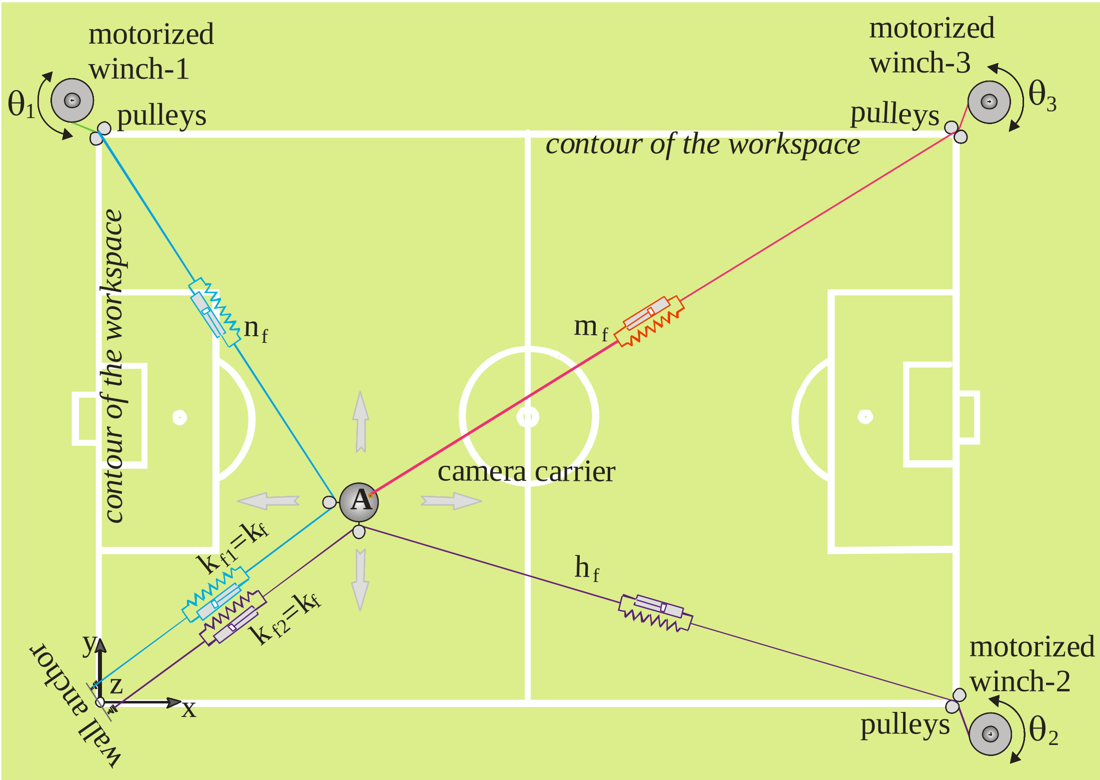

Figure2. **EFCPR**, top view.

State of the problem solution in the world

47 years ago i.e. in 1967, Meirovitch prescribed "modal technique" ("assumed modes technique"). At that moment it was a huge contribution that was supposed to stimulate scientists to new speculations, new researches and new ideas. Then it was solution of one visionary who interpreted the Euler-Bernoulli equation in a new manner. That was supposed to be a flywheel in the evolution of the Theory of elasticity and the Theory of oscillation and, of course, Robotics which in that period was in expansion.

The author elaborated a particular application of the Euler-Bernoulli equation, supposing that elastic deformation was a value defined in advance according to the amplitude and frequency and, formed in this way, it was entered into the dynamic model.

Not finding any other solutions, many researchers in robotics, applied the Meiroitch's solution in describing real dynamics of the robot system elastic deformations,

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

overlooking the fact that the “assumed modes technique” solution was derived under the conditions:

1. the elastic deformation defined in advance by both amplitude and frequency, and thus introduced into the model,
2. misinterpretations of Euler-Bernoulli equation solution.

The double substitution of thesis was done because the term "elastic deformation" was identified with the term "elastic line form", and these were two completely different values.

Until now the authors implemented the elastic deformation as a value based on the “assumed modes technique” principles and they did not get any real values as a result of the robot system movements. Not finding any other solutions it was obvious that the researches in this area were reduced in the last 15 years. However, present development of, first of all, knowledge from the robot system dynamics modelling enables to establish and analyze new models which will treat the elastic deformation as a dynamic value. This research is directed in that way in order to describe this theory in the real environment, without assumptions i.e. limitations of the elastic deformation on which the “assumed modes technique” is based.

The essence of the technical solution

The area which we deal with i.e. robotics is very important, because the modelling of the **eFCPR** system (with one mode) movement dynamics with both rigid and elastic elements comes from it directly. The robotics is the area which can offer the solution and it represents the foundation of the further researches in many other areas. The reason for that is quite simple: the robotics progressed significantly in the last 50 years. It is important to emphasize the importance of the further researches which are now based on the new principles set in this program system **OGIFLEX**.

The elastic deformation of ropes is a dynamic value which depends on the total dynamics of the **eFCPR** system movements (with one mode). That means that the elastic deformation of rope in its amplitude and frequency changes depending on the forces (inertial forces, centrifugal forces, gravity forces as well as coupling forces

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

between the present modes, and the play of the dynamic external forces). It, of course, depends also on the configuration fo the mechanism, camera carrier weight, the size of the workspace, the reference trajectory choice, dynamic characteristics of the motor movements etc.

The elastic deformation of the ropes exists even in the state of inaction and then it depends on the gravity forces i.e. **CPR** configuration. That means that the elastic deformation depends on the **CPR** system characteristics and it can be calculated in any chosen moment.

Euler-Bernoulli equation was written in 1750. It was written by Bernoulli, physicist and Euler, mathematician, his long-time friend and colleague. They did not even dream about the robotics, CPR systems and the knowledge we have now. But, although it was made more than 250 years ago, the Euler-Bernoulli equation is still actual and it can be connected logically with the contemporary knowledge from the robotics as presented in [2]-[5]. Papers [2]-[5] address industrial configurations and one humanoid configuration, where the presence of elastic gears and segments is modeled, while the paper [1] addresses the F-type Cable Suspended Parallel Robot where the elasticity in ropes is modeled. The principles used for modeling the elasticities defined in papers [2]-[5] are used in program package **OGIFLEX**.

Detailed features description

The CPR camera carrier has working space of the parallelepiped shape. This system is designed such that the camera carrier hangs over the ropes which are connected to the four highest points i.e. the four upper angles of the workspace. The suspension system is defined in these four points.

A camera workspace is an area where a camera can move silently and continuously following the observed object.

A camera carrier moves freely in the 3D space and record the moving objects without collision. This gives a unique feeling to the event observer to watch objects from the unusual proximity without disturbances. The observer will be very close to

Volgina 15, 11060 Belgrade, Serbia
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Fax: (+381 11) 2776-583
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the action regardless the size of the observed space.

This paper analyzed only the mechanism for positioning the camera carrier. For a large workspace, this is an optimal solution. In the future research will be added a small mechanism for the camera orientation.

The camera carrier is moving in 3D space by the motion of the controlled connected ropes. The ropes can uncoil or coil, which allow the camera to reaches any position in the space. The control system provides three-dimensional motion of the camera. The commands for synchronized motion of each winch are provided by controlling the motion of each motor which ultimately provides the three-dimensional continuous camera carrier motion. The gyroscopic sensor that is installed in the camera carrier is stabilized to the horizon.

The axial elastic deformations of the ropes cause oscillatory behavior of the camera courier motion in 3D space. This causes the spatial motion of the ropes perpendicular to the all four directions k_f, h_f, m_f, and n_f. It can be concluded that the presence of axial elastic deformations along the ropes causes the transversal elastic deformations of ropes.

The camera carrier ropes of the **eFCPR** system with one mode are exposed to the transversal oscillations in the 3D space.

Involving the elastic characteristics of the ropes caused the modeling of the **CPR** system highly complex.

The mechanism was designed with three ropes.

The ropes of the pulley system are run on the winches (reel) 1, 2, 3, powered by the motors. The ropes coil or uncoil on the winches of radius R_1, R_2, and R_3. The motors rotate winches directly and its angular positions are θ_1, θ_2, and θ_3. This motion moves the camera in the x, y, z Cartesian coordinates.

The first rope related to the first motor is marked in a blue color. The rope motion is connected to the first winch through the motor motion in both directions. The blue rope has stiffness C_1, damping B_1 and the variable length k_f plus n_f.

The second rope related to the second motor is marked in a violet color. This rope motion is connected to the second winch through the motor motion in both directions.

Volgina 15, 11060 Belgrade, Serbia
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The violet rope has stiffness C_2, damping B_2 and the variable length k_f plus h_f.

The third rope related to the third motor is marked in a pink color. This rope motion is connected to the third winch through the motor motion in both directions. The pink rope has stiffness C_3, damping B_3 and the variable length m_f .

The blue and the violet ropes are connected to the wall anchor, while the pink rope is connected only to the camera and the third motor. See Fig. 1 and Fig. 2.

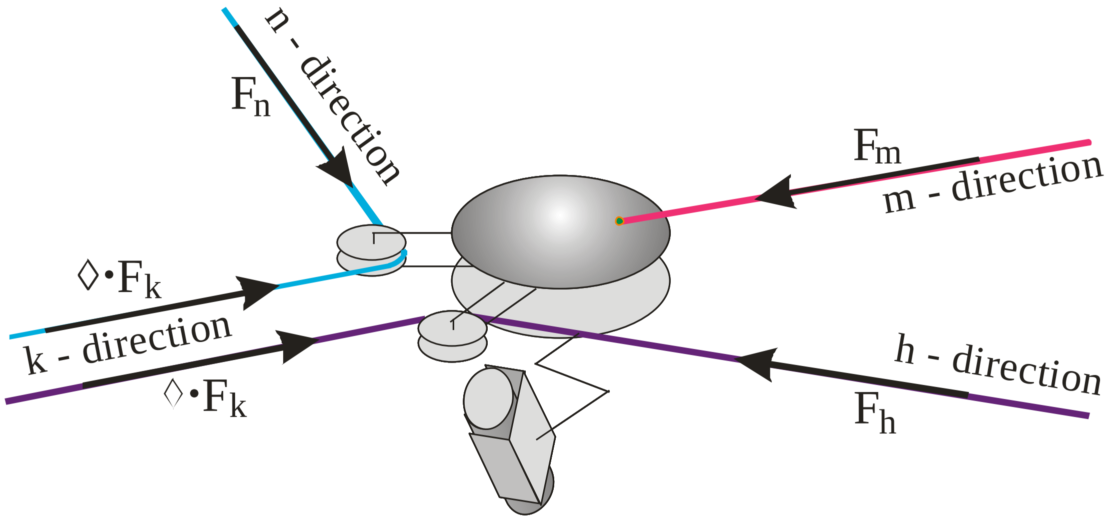

Figure 3. The forces in the camera carrier ropes.

The **eFCPR** system with one mode is modeled and analyzed by the software package **OGIFLEX**. The software package **OGIFLEX** is used for validation of the applied theoretical contributions.

The software package **OGIFLEX** includes three essential modules, which are the kinematic, dynamic and motion control law solvers for the **eFCPR** system with one mode.

The most important element of the **eFCPR** system with one mode is the motor mathematical model which is an integral part of software package **OGIFLEX**. Through the simulation results it is shown that the dynamic characteristics of the motor significantly affect the response of the system and its stability.

The camera carrier motion dynamics directly depends of the mechanism's dynamic parameters and elasticity characteristics of the ropes. The motors are selected by Heinzman SL100F and the gear boxes are HFUC14-50-2A-GR+belt.

Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
Fax: (+381 11) 2776-583
WWW.INSTITUTEPUPIN.COM
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The complexity of the **FCPR** system has been significantly increased by involving the elastic characteristics of the ropes which kinematic model is defined via the Jacobian matrix. The key element in the **eFCPR** system modeling (with one mode) is the relation between the elastic deformations of the ropes and the motors' angular positions. This novel procedure (generated using the fictitious coordinates) is named **ED+M method**, which means Elastic Deformations plus Motor motion.

The kinematic model is defined via the Jacobian matrix. This methodology is named **KineFCPR-solver** and it represents a general guideline for solving any kinematic structure of the **eFCPR** system types (with one mode).

The relation between the forces in the ropes and the forces at the camera carrier is described by the Lagrange principle of virtual work. Because of the **eFCPR** system complexity (with one mode), the Lagrange principle of virtual work has been adapted to support the presence of two ropes in the k_f direction.

Highly authentic solution of the **eFCPR** system model **(with one mode)** has been defined.

The trajectory of the rigid system **RFCPR** has been used as the reference trajectory of the elastic system **eFCPR** with one mode**.** In the control design of the **eFCPR** trajectory tracking (with one mode) the only disturbance is the elastic characteristic of the ropes, which are unknown at the reference trajectory.

The "PD" controller has been used for a control low.

The software package **OGIFLEX** has been developed and used for the individual and comparative analysis of the **eFCPR** system with one mode.

The software package **OGIFLEX** is used to verify the validity of the generated mathematical model.

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Volgina 15, 11060 Belgrade, Serbia
Phone: (+381 11) 2771-398, 2772-876
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WWW.INSTITUTEPUPIN.COM
email: info@institutepupin.com

Subject: Opinion on meeting the criteria for recognition of the technical solution

According to the submitted material and in accordance with the provisions of *The Rules of procedures and methods of evaluation and quantitative presentation of scientific research results of researchers,* brought by the National Council for Scientific and Technological Development of Serbia *("Official Gazette of the Republic of Serbia", No. 38/2008)* **reviewer: Prof. dr Ana Djuric, Wayne State University , 4855 Fourth St. Detroit, MI 48202, U.S.A.,** has evaluated that conditions for the recognition of the properties of the technical solution are fulfilled for the following result of the scientific research paper:

Title: **program system OGIFLEX** (elastic ropes F-type Cable suspended Parallel Robot with one mode, **eFCPR** with one mode) (*Project:* Ambientally intelligent service robots of anthropomorphic characteristics, TR-35003 and the project: SNSF Care-robotics project no. IZ74Z0_137361/1*)*

Author: **Mirjana Filipovic**

Category of technical solution: **M85** *„Acknowledged program system" **– Software.***

Objective and significance: *The area which we deal with, the robotics is very important, because the modelling of the robot system movement dynamics with both rigid and elastic elements comes from it directly. The robotics is the area which can offer the solution and it represents the foundation of the further researches in many other areas. The reason for that is quite simple: the robotics has progressed significantly in the last 50 years. It is important to emphasize the importance of the further researches but now based on the new principles which set in this program system **OGIFLEX**.*

Proposed solution is done in: *2014.*

Proposed solution is used in the following way: *It is used for further researches and discoveries of new phenomena in analysis and synthesis of kinematics and dynamics of elastic ropes F-type Cable-suspended Parallel Robots, **eFCPR** system with rigid and elastic elements.*

Area to which the technical solution refers is: *Robotics, Theory of Mechanics, Theory of elasticity and Theory of oscillations.*

Problem that is being solved with this technical solution: T*his technical solution is used for solving the problem of the effective implementation of the model of **eFCPR** system with elastic ropes (one mode), as well as testing their behavior in designed implementation conditions of the **CPR** task. It is also point to the need for implementation of various control laws.*

State of the problem solution in the world: *Not finding any other solution, some researches in **CPR** systems, applied the Meirovitch solution in the description of the real dynamics of the **CPR** system deformation defined in advance and by the amplitude and the frequency, or they used ways to modify the same solutions. By now the authors implemented the elastic deformations as the values on the principles "assumed modes technique" and they did not get any real values as a result of the robot system movements. Not finding any other solutions it is obvious that the researches in this area have been reduced in the last years.*

Essence of technical solution. *The elastic deformation of rope cannot be defined in advance (with both amplitude and frequency) and put in the system but completely inversely. The elastic deformation is a dynamic value which depends on the total dynamics of the **CPR** system movements. That means that the elastic deformation amplitude and its frequency change depending on the forces (inertial forces, Coriolis, centrifugal forces, gravity forces as well as coupling forces between the present modes, and the play of the environment forces). It, of course, depends also on the **CPR** configuration, camera carrier weight, dimension workspace, the reference trajectory choice, dynamic characteristics of the motor movements etc.*

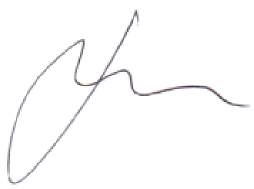
Characteristics of the proposed technical solution are following:
This technical solution enables:

- *The key element in the **eFCPR** system with one mode modeling is the relation between the elastic deformations of the ropes and the motors angular positions. This novel procedure is named **ED+M method**, which means Elastic Deformations plus Motor motion.*
- *The kinematic calculation is named **KineFCPR-Solver** (Kinematic elastic F-type Cable suspended Parallel Robot (with one mode) Solver), and it gives a precise, direct and inverse kinematic solutions.*
- *The KinRSCPR-Solver represents the basis for generating the dynamic model of the **eFCPR** system.*
- *The Lagrange principle of virtual work has been adapted to support the presence of two ropes in the k_f direction.*
- *The software package **OGIFLEX** has been developed for the **eFCPR** model (with one mode) evaluation.*
- *The influence of changing any parameters of the system can be analyzed through the **OGIFLEX** software package.*

Possibility of implementation of proposed technical solution: *Solution can be applied to the future researches in this and associated areas. It enables implementation of different control laws. And just because it is in the pioneering research phase it can be expanded from different viewpoints, depending on the user's imagination.*

On the basis of the above mentioned, the reviewers have concluded that the result of the scientific research paper titled: program system OGIFLEX presents the recognized program system that beside expert component also provides the original scientific research contribution.

February 2014. **Reviewer:**



Ana Djuric, PhD, Peng Assistant Professor
1153 ETB, 4855 Fourth St. Detroit, MI 48202
Ph: (313)577-5387 **ana.djuric2@wayne.edu**

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December 2014. **Reviewer:**

Dr Milovan Živanović, dipl.ing.
Digital Control Systems Oziris, Kosmajska 32,
11450 Sopot, Belgrade, Serbia
e-mail: dsu.oziris@open.telekom.rs

WAYNE STATE UNIVERSITY

Division of Engineering Technology
College of Engineering
Wayne State University
4855 Fourth Street
Detroit, MI 48202

DECLARATION
OF USING THE PROGRAMME SYSTEM **OGIFLEX**

The program system: **OGIFLEX** (for **eFCPR** system with one mode, elastic ropes F-type Cable suspended Parallel Robot with one mode), *Projects:* "Ambientally intelligent service robots of anthropomorphic characteristics" TR-35003 and SNSF Care-robotics project no. IZ74Z0_137361/1, whose author is **Mirjana Filipovic**, Ph.D,El.Eng. presents a scientific and technical achievement in robotics which we, the below-signed, use in education and research purposes as well as during the realization of our theoretical and practical solutions. We, the below-signed, confirm that we have used the program system **OGIFLEX** since September 2014.

December 2014.

Ana Djuric, PhD, PEng,
Assistant Professor,
1153 ETB, 4855 Fourth St.
Detroit, MI 48202,
Ph: (313)577-5387
ana.djuric2@wayne.edu

Dr. ChihPing Yeh
Department Chair,
1159 ETB, 4855 Fourt St.
Detroit. MI 48202
Ph: (313)577-0800
yeh@eng.wayne.edu

DIVISION OF ENGINEERING TECHNOLOGY
12.12.2014
DATE

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ИНСТИТУТ „МИХАЈЛО ПУПИН“ ДОО
Број: 62/32 -15
32. јануар 2015. године
Б е о г р а д

На основу чл. 24. Статута Института „Михајло Пупин“ДОО Београд – *Пречишћен текст* („Билтен“ бр.15/2014.), а у складу са одредбама Правилника о поступку и начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача („Службени гласник РС“ бр. 38/2008), Научно веће Института „Михајло Пупин“ доноси следећу:

О Д Л У К У

Прихвата се техничко решење под називом:

Program system **OGIFLEX** (for **eFCPR** system with one mode, elastic ropes **F**-type **C**able-suspended **P**arallel **R**obot with one mode)

Техничко решење је резултат рада на пројекту:

Ambientally intelligent service robots of anthropomorphic characteristics, 2011-2015, TR-35003;

Техничко решење спада у категорију: Program system, software, **M85.**

Аутор: Мирјана Филиповић.

Кратак опис решења:

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Рецензенти:

- **Prof. dr Ana Djurić,** Engineering Technology Division, Wayne State University, 4855 Fourth St. Detroit, MI 48202, U.S.A.;

- **Dr Milovan Živanović, dipl. ing.** Digital Control Systems Oziris, Kosmajska 32, 11450 Sopot, Belgrade, Serbia.

На основу позитивног мишљења два рецензента – експерта из области техничког решења, Научно веће је донело предметну одлуку.

ПРЕДСЕДНИК НАУЧНОГ ВЕЋА
ИНСТИТУТА „МИХАЈЛО ПУПИН“ д.о.о.

ИНСТИТУТ МИХАЈЛО ПУПИН БЕОГРАД

Др Драган Радојевић*, дипл. инж.,*
Научни саветник

Достављено:

- ауторима
- Секретаријату Института