

Technical solution

Program system ORFLEX

(one mode)

(elastic ropes S-type Cable Suspended Parallel Robot, **eSCPR**, with one mode)

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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.

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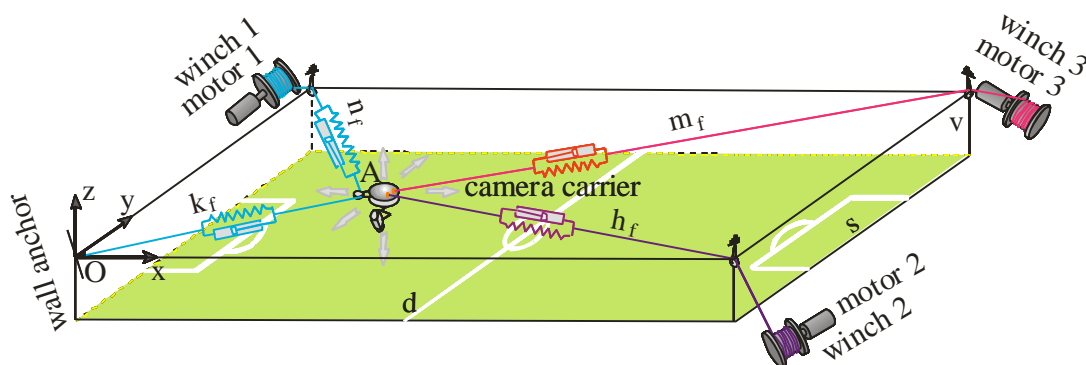


Figure1. **eSCPR** with one mode, in the 3D space.

This program system is generated in MATLAB. In this program the mathematical model of the elastic S-type Cable-Suspended Parallel Robot with one mode - **eSCPR** system with one mode is presented. The mathematical model of the rigid system of the same configuration named Rigid S-type Cable-Suspended Parallel Robot - **RSCPR** is calculated first. The mathematical model of the same rigid system **RSCPR**

is calculated and analyzed first in paper [1] for better understanding the elastic **eSCPR** system.

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

The presence of the elastic property in the ropes significantly increases the complexity of the **eSCPR** system with one mode.

The significance of the **eSCPR** system modeling with one mode is the relation between the motor angular position and the elastic deformation of the corresponding rope which is defined by the fictitious coordinates. This relationship is determined for each motor motion and its corresponding rope deformation. This novel procedure is named **ED+M method**, which means Elastic Deformations plus Motor motion.

The Jacobian matrix of the **eSCPR** system with one mode relates the velocities of the external coordinates with the velocities of the fictitious coordinates. This novel procedure is named **KineSCPR-Solver** which means Kinematic elastic S-type Cable Parallel Robot Solver.

The relation between the fictitious elastic load moment and the external force, which is calculated using the Lagrange principle of virtual work, is expressed with the Jacobian matrix. The complexity of the **eSCPR** system has been significantly increased by involving the elastic characteristics of the ropes with one mode. The number of DOF is increased too. The **eSCPR** system has 7 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 **eSCPR** system task realization.

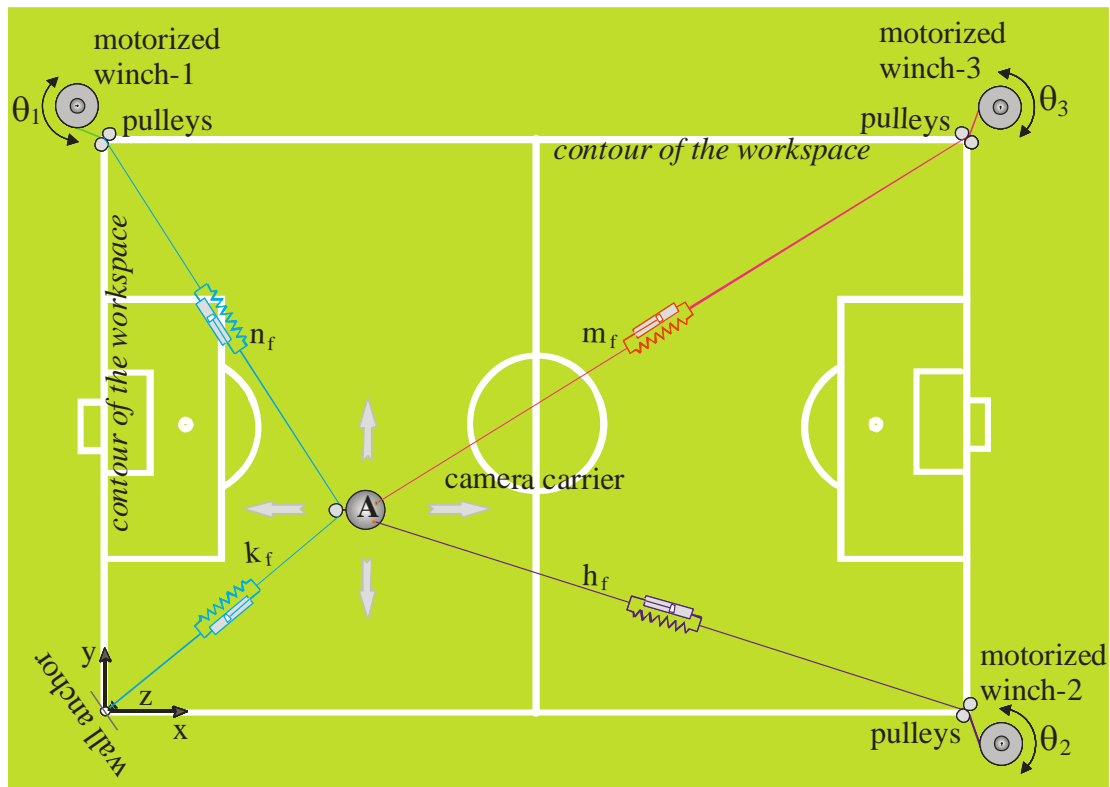


Figure2. eSCPR, top view.

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, 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 **eSCPR** 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 **ORFLEX** and in publications [2] and [3].

The elastic deformation of ropes is a dynamic value which depends on the total dynamics of the **eSCPR** system (with one mode) movements. That means that the

elastic deformation of rope in its amplitude and its frequency change depending on the forces (inertial forces, centrifugal forces, gravity forces as well as coupling forces between the present modes, and the play of the dynamic external forces). It, of course, depends also on the mechanism configuration, 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 [4]-[7]. Papers [4]-[7] address industrial configurations and one humanoid configuration, where the presence of elastic gears and segments is modeled, while the papers [2] and [3] address the S-type Cable Suspended Parallel Robot where the elasticity in ropes is modeled. The principles used for modeling the elasticities defined in papers [4]-[7] are used in program package **ORFLEX** and papers [2], [3].

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 (x , y , z directions) 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 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 presented **eSCPR** model with one mode includes elasticity properties. The elastic ropes are modeled with the elastic characteristic in the axial direction. The elastic characteristic of the ropes cause the oscillations of the motors angular positions and oscillations of the camera position. The effect of the ropes axial elastic deformations are their transverse elastic deformations. 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.

The violet rope has stiffness C_2 , damping B_2 and the variable length 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 . All these parameters are involved in the camera motion described in the Cartesian x, y, z space.

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

The elastic deformation l_1 belongs to the n_f direction, deformation l_k belongs to the k_f direction and both of them belong to the blue rope. The elastic deformation l_2 belongs to the violet rope and l_3 is related to the pink rope.

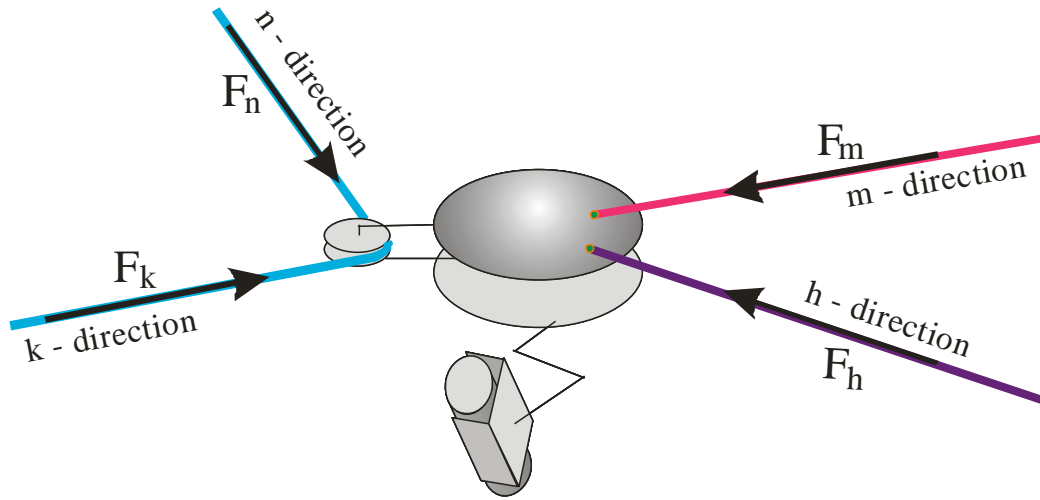


Figure 3. The forces in the camera carrier ropes.

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

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

The most important element of the **eSCPR** system with one mode is the motor

mathematical model which is an integral part of software package **ORFLEX**. 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 **eSCPR** system with one mode presented in Fig. 1, and Fig. 2, is analyzed. The camera carrier motion dynamics directly depends of the mechanism dynamic parameters and elasticity characteristics of the ropes. The **eSCPR** model with one mode has been analyzed using the trajectory and the selected system parameters.

The motors are selected by Heinzman SL100F and the gear boxes are HFUC14-50-2A-GR+belt.

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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 ORFLEX** (elastic ropes S-type Cable suspended Parallel Robot with one mode, **eSCPR** 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 **ORFLEX**.*

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 S-type Cable-suspended Parallel Robots, **eSCPR** 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: *This technical solution is used for solving the problem of the effective implementation of the model of **eSCPR** 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 **eSCPR** 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 **KineSCPR-Solver** (Kinematic elastic S-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 **eSCPR** system.*
- *The software package **ORFLEX** has been developed for the **eSCPR** model (with one mode) evaluation.*
- *The influence of changing any parameters of the system can be analyzed through the **ORFLEX** 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 ORFLEX presents the recognized program system that beside expert component also provides the original scientific research contribution.

February 2014.

Reviewer:



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December 2014.

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DECLARATION OF USING THE PROGRAMME SYSTEM ORFLEX

The program system: **ORFLEX** (for **eSCPR** system with one mode, elastic ropes S-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 **ORFLEX** since September 2014.

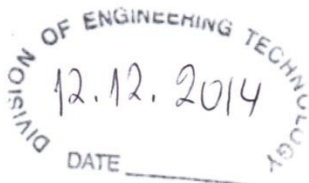
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ИНСТИТУТ „МИХАЈЛО ПУПИН“ ДОО

Број: 62/ 31-15

13. јануар 2015. године

Београд

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:

ОДЛУКУ

Прихвата се техничко решење под називом:

Program system **ORFLEX** (for **eSCPR** system with one mode, elastic ropes **S-type Cable-suspended Parallel Robot** 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, Kosmajaska 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.**

Др Драган Радојевић, дипл. инж.,
Научни саветник

Достављено:

- ауторима
- Секретаријату Института