

# Contents

---

## SECTION I Support of Modelling

---

- 1 Classical and Fractional Mathematical Approaches to Modern control Theory *Jan Čermák, Josef Šlapa, .....* 3
- 2 Application of Fuzzy Logic to Automatic Control *Miloš Šeda .....* 15
- 3 Physical Engineering: Research Support of Mechatronic Models  
*Jaroslav Pokluda, Pavel Šandera, Miloslav Ohlidal, Miroslav Černý,  
Jan Pilch, Zdeněk Florian, Karel Slámečka, Petr Šesták, Miroslav  
Doložilek, Jana Horníková .....* 27

## SECTION II Modelling of Systems with Electromechanical Energy Conversion

---

- 4 Research of the Artificial Heart *František Pochylý, Simona Fialová.....* 43
- 5 Drive and control system for pumps application *Petr Huták, Josef  
Lapčík, Tomáš Lániček, František Pochylý .....* 59
- 6 Predictor for Control of Stator Winding Water Cooling of Synchronous  
Machine *Radek Vlach .....* 73
- 7 Development of Vibration Power Generator for Aeronautic Application  
*Zdeněk Hadaš, Vladislav Singule, Čestmír Ondrůšek .....* 81
- 8 Analysis and optimization of contact force vector *Petr Krejčí .....* 101

## SECTION III Modelling of Autonomous Systems Behaviour

---

- 9 Omnidirectional mobile robot with new conception using Mecanum  
wheels *Tomáš Kubela, Aleš Pochylý, Radek Knoflíček, Vladislav  
Singule, Miloš Synek .....* 111
- 10 Real-time robot motion planning based on the generalised Voronoi  
diagram *Petr Švec .....* 121
- 11 Four legged robot walking gait generation *Vít Ondroušek, Jiří Krejsa,  
Stanislav Věchet, Pavel Houška .....* 133
- 12 Simultaneous Localization and Mapping via Scan Matching  
*Stanislav Věchet, Jiří Krejsa, Vít Ondroušek.....* 141

## **SECTION IV Modelling of Systems with Special Elements**

---

- 13 Modelling, Virtual Prototyping and Design of Two Wheeled Unstable Mobile Robot *Robert Grepl, Pavel Švejda, David Vlachý, Pavel Zezula*..... 149
- 14 Modeling of Bifurcation and Chaos in Real Drive System *Ctirad Kratochvíl, Josef Koláčný, Lubomír Houfek, Martin Houfek, Jiří Krejsa* ..... 157
- 15 Noise emission of the mechatronic system *Ivan Mazůrek, Milan Klapka* ..... 165
- 16 GA In Shock Absorber Identification Task *Jiří Krejsa, Stanislav Věchet, Lubomír Houfek*..... 177
- 17 Analysis of Vehicle Dynamics using Kalman Filter *Petr Porteš, Marián Laurinec, Ondřej Blaťák* ..... 189
- 18 Multidimensional Simulation of Stirling Engine Regenerator *Václav Pištěk, Pavel Novotný*..... 207
- 19 The Numerical Model of  $\alpha$  Stirling Engine Modification *Michal Sikora, Radek Vlach* ..... 219

## **SECTION V Modelling of Biomechanical Systems Characteristics**

---

- 20 Device for Experimental Modelling of Biomechanical Systems Properties *Tomáš Březina, Pavel Houška, Lukáš Březina, Ondřej Andrš* ..... 231
- 21 Computational Modelling of the Biomechanical Systems Properties *Zdeněk Florian, Vladimír Fuis, Tomáš Návrat*..... 243

# Support of Modelling

---

- 1 **Classical and Fractional Mathematical Approaches to Modern Control Theory** *Jan Čermák, Josef Šlapal* ..... 3  
 Introduction • Description of the problems solved • Results obtained • Future work
  
- 2 **Application of Fuzzy Logic to Automatic Control** *Miloš Šeda* ..... 15  
 Introduction • Fuzzy logic • Fuzzy control and Mamdani model • Takagi-Sugeno fuzzy model • Further approaches • Conclusions and future work
  
- 3 **Physical Engineering: Research Support of Mechatronic Models** *Jaroslav Pokluda, Pavel Šandera, Miloslav Ohlidal, Miroslav Černý, Jan Pilch, Zdeněk Florian, Karel Slámečka, Petr Šesták, Miroslav Doložilek, Jana Horníková* ..... 27  
 Abstract • Introduction • First-principles modelling of mechanical properties of Nitinol • Actuation tests of Nitinol wires • Further activities

# Classical and Fractional Mathematical Approaches to Modern Control Theory

---

Jan Čermák, *FME BUT*

Josef Šlapal, *FME BUT*

1.1	Introduction.....	3
1.2	Description of the problems solved .....	4
1.3	Results obtained.....	7
1.4	Future work.....	13

## 1.1 Introduction

---

Differential equations are the key mathematical tool used when modelling problems of continuous control. The importance of various types of differential equations and their properties for problems of continuous control are well known. In particular, their contribution to the modelling of mechatronic systems has been reported also in (Čermák & Šlapal, 2005) and (Čermák & Šlapal, 2006). However, in addition to utilizing this branch of mathematical analysis, problems of continuous control essentially affect it, especially by formulating new problems requiring the development of original mathematical procedures and results. This mutual interaction is typical also in the areas which have been the subject of our research in the year 2007, namely the solving of some energy optimal control problems and mathematical modelling using differential equations with time lags or fractional differential equations. It is the problems connected with the control theory, which started huge development of these disciplines some years ago, that provided the original motivations for studying these topics.

The aim of our research as planned was to modify some advanced techniques of optimal control theory (such as Pontryagin maximum principle or the methods of parametric optimization) and apply them to some yet open problems of energy-optimal train control. In the mathematical modelling of control problems using differential equations, we have intended to analyze the qualitative as well as numerical solutions of some differential equations with time lags and develop new unified techniques for these investigations. The modelling via fractional differential equations has necessitated the study and development of classical as well original solving methods including the Laplace transform method. It is known that, by applying this integral transformation to fractional differential equations, we arrive at a generalized algebraic equation, i.e., an equation whose one side is formed by a generalized polynomial. This led us to the study of generalized polynomials.

As planned for 2007, we focussed on the study of basic properties of generalized formal power series and generalized polynomials over commutative fields. In (Karásek & Šlapal, 2007), we introduced a general approach to the study by considering the exponents to be arbitrary elements from a given commutative group. In particular, we studied the generalized polynomials with rational exponents, which can be defined as maps whose supports are finite sets. These polynomials occur most often in different applications. We extended some results

## Application of Fuzzy Logic to Automatic Control

---

2.1	Introduction .....	15
2.2	Fuzzy logic .....	15
2.3	Fuzzy control and Mamdani model .....	18
2.4	Takagi-Sugeno fuzzy model .....	22
2.5	Further approaches .....	23
2.6	Conclusions and future work .....	24

Miloš Šeda, *FME BUT*

### 2.1 Introduction

---

The classical literature, dealing with automatic control, describes many sophisticated methods of designing these controllers in accordance with their dynamic behaviour. Mostly, these methods require a precise mathematical model of the controlled system. However, for complex systems, such a model may be difficult or even impossible to find or it may be strongly nonlinear, which causes many difficulties in designing a controller. A promising way is to use the fuzzy logic approach to control (Jantzen, 2007), (Tanaka & Wang, 2001), (Zhang & Liu, 2006). Fuzzy logic uses the interval from 0 (False) to 1 (True) to describe human reasoning making it possible to formulate a rule base which is a major tool used to generate the values of the manipulated variable of the controller by its input values.

The basics of fuzzy sets can be found, e.g., in (Bosc, Kacprzyk, 1995), (Jantzen, 1998(a)), (Klir, Yuan, 1995), (Novák, 2000). We will mostly skip them and mention only notions that relate to fuzzy implication, because it plays a key role in inference engines.

### 2.2 Fuzzy logic

---

The most important contribution of fuzzy logic is the concept of a linguistic variable and the associated mechanism of fuzzy if-then rules (Zadeh, 2008). A *linguistic variable* is determined by: 1) name, 2) set of values that it can have (these values are called *terms* being represented by fuzzy sets), 3) universe defined for all terms and 4) function that maps words into values of a universe.

The simple fuzzy sets are mostly not sufficient and thus we use their composition. In fuzzy controllers, which can be studied in the next sections, combined conditions occur and an output variable is given by a combination of several rules. However, we must only determine one membership function from these combinations of rules. This operation is called *inference* being performed by an inference engine.

Let us define the basic operations over fuzzy sets – union, intersection and complement. We will assume that  $\mu_A: X \rightarrow [0,1]$  is the *membership function* of a fuzzy set  $A$  in a universe  $X$ ; the logical operators for disjunction and conjunction will be denoted by the symbols

## Physical Engineering: Research Support of Mechatronic Models

---

Jaroslav Pokluda, *FME BUT*

Pavel Šandera, *FME BUT*

Miloslav Ohlídal, *FME BUT*

Miroslav Černý, *FME BUT*

Jan Pilch, *FME BUT*

Zdeněk Florian, *FME BUT*

Karel Slámečka, *FME BUT*

Petr Šesták, *FME BUT*

Miroslav Doložilek, *FME BUT*

Jana Horníková, *FME BUT*

3.1	Abstract.....	27
3.2	Introduction .....	27
3.3	First-principles modelling of mechanical properties of Nitinol .....	29
3.4	Actuation tests of Nitinol wires .....	30
3.5	Future Activities .....	39

### 3.1 Abstract

---

Several results concerning the first-principles modelling of Nitinol properties, uniaxial and biaxial fatigue fracture and wear of metals that were achieved already at the end of 2006 were presented at international conferences held particularly in 2007 and submitted to scientific journals. Thus, a brief report concerning these results is included in the introduction of this chapter. In the year 2007, the physical support of mechatronic models was mainly focused on the research concerning the shape-memory alloys. In the frame of the basic research, the computation of elastic characteristics of Nitinol crystals in the martensitic phase was finished and compared with results achieved by analyzing the austenitic phase. Moreover, the ab initio analysis of elastic properties of martensitic phase containing crystallographic twins was started as a most important output of the basic research. Indeed, the presence of twins controls the efficiency of the shape-memory effect and is expected to change the elastic moduli. Therefore, the concentration of twins during deformation is expected to be indirectly measured in this way. The applied research was oriented on a continual testing of various kinds of Nitinol wires in order to find an optimum material and working conditions for an actuator in the Steward Platform model. First results of common investigations performed by groups of Physical Engineering, Mechanics of Solids and Biomechanics (both engaged in the research plan MSM 002163051) and Metal Physics (the Institute of Physics in Prague) were published in the AT&P Journal PLUS dedicated to mechatronics. These links established among groups involved in the research plan as well as those external provide a good example of a necessary interdisciplinary collaboration. A brief report about future activities particularly in the year 2008 is presented in the last section.

### 3.2 Introduction

---

In correspondence to the generally proposed research plan (Březina et al. 2004) and to the results achieved during the year 2006 (Březina et al. 2006), the investigations performed by the physical engineering group during the year 2007 were focused on modelling and testing

# II

## Modelling of Systems with Electromechanical Energy Conversion

---

- 4 **Research of the Artificial Heart** *František Pochylý, Simona Fialová* ..... 43  
Side channel pump • Cavitation utilization for the electric energy production • Conclusion
- 5 **Drive and control system for pumps application** *Petr Huták, Josef Lapčík, Tomáš Lániček, František Pochylý* ..... 59  
Introduction • Used approach • Realization of the magnetic bearing pump • Magnetic bearing control • Conclusion • Development and future trends • Future work • New proposal
- 6 **Predictor for Control of Stator Winding Water Cooling of Synchronous Machine** *Radek Vlach*..... 73  
Introduction • Used Approach • Implementation • Obtained results • Conclusion and discussion • Future work
- 7 **Development of Vibration Power Generator for Aeronautic Application** *Zdeněk Hadaš, Vladislav Singule, Čestmír Ondrůšek*..... 81  
Introduction • Used Approach • Implementation • Obtained Results • Conclusion and discussion
- 8 **Analysis and optimization of contact force vector** *Petr Krejčí* ..... 101  
Introduction • Used Approach • Implementation • Obtained Results • Conclusion and discussion • Future work

## Research of the Artificial Heart

---

4.1	Side channel pump.....	43
4.2	Cavitation utilization for the electric energy production .....	51
4.3	Conclusion .....	57

František Pochylý, *FME BUT*

Simona Fialová, *FME BUT*

### 4.1 Side channel pump

---

The basis of every theoretical pump solution is the specific energy equation derivation. The equations for the side channel pump specific energy solution (for example Lazarkiewicz & Trokolanski, 1965; Čerkaskij, 1984) are simplified and doesn't express the flow basics in these pump types. Therefore was derivate the new, generally true equation for the side channel pump specific energy which will better represent its function principle.

#### 4.1.1 The specific energy equation derivation out of the torsion moment

We start from the Navier-Stokesovy (N-S) equations for the absolute vector basis:

$$\rho \cdot \frac{dc_i}{dt} - \frac{\partial \Pi_{ij}}{\partial x_j} + \frac{\partial p}{\partial x_i} = 0 \quad (1)$$

The moment regarding the rotation axis is zero and its m-coordination can be expressed by the force F as:

$$M_m = (x \times F)_m = 0 = (F \times x)_m = \varepsilon_{mni} \cdot x_n \cdot F_i \quad (2)$$

The N-S equation for the steady state is institute into the moment equation and we get the relation:

$$\varepsilon_{mni} \cdot x_n \cdot \left( \rho \cdot \frac{dc_i}{dt} - \frac{\partial \Pi_{ij}}{\partial x_j} + \frac{\partial p}{\partial x_i} \right) = 0 \quad (3)$$

The torsion moment is determined by the x1 coordinate, so after the integration through the volume V (the inner pump volume – excerpt of the impeller – Fig. 1) it can be written:

$$\rho \cdot \int_V \varepsilon_{i1n} \cdot x_n \cdot \frac{\partial (c_i \cdot c_j)}{\partial x_j} \cdot dV - \int_V \varepsilon_{i1n} \cdot x_n \cdot \frac{\partial \Pi_{ij}}{\partial x_j} \cdot dV + \int_V \varepsilon_{i1n} \cdot x_n \cdot \frac{\partial p}{\partial x_i} \cdot dV = 0 \quad (4)$$

## Drive and control system for pumps application

---

	5.1 Introduction.....	59
	5.2 Used approach .....	59
	5.3 Realization of the magnetic bearing pump .....	60
Petr Huták, <i>FEEC BUT</i>	5.4 Magnetic bearing control.....	61
	5.5 Conclusion .....	66
Josef Lapčík, <i>FEEC BUT</i>	5.6 Development and future trends.....	66
	5.7 Future work.....	68
Tomáš Láníček, <i>FEEC BUT</i>	5.8 New proposal.....	70
František Pochylý, <i>FME BUT</i>		

### 5.1 Introduction

---

The paper presents a review of mechatronic systems which were used for TAH (Total Artificial Heart Pump system is double ventricle blood pump consisting of slotless PM axial flux synchronous machine and magnetic active bearings. Control part deals with the synchronous motor and magnetic bearing control. Two structures, voltage and current, were design and tested for the position regulation. Mathematical model was successfully simulated. On the base of this model the regulation structure for positional feedback control was design. Design of the regulators is based on the mathematical model description of controlled system. For the new design the measurements and hydraulic test were realized. Development and future trends are also presented.

### 5.2 Used approach

---

The drive control systems design of mechatronic system consisting the extra corporal pump for the artificial heart assist device including pump's electrical drive and modern control system for motor and magnetic bearing was the main aim of this work. The drive system consists of the slot-less permanent magnet synchronous motor, magnetic active bearing and modern control system for motor torque and bearing rotor position. Two ways conception, the extra corporal and intra corporal pump systems was concentrated to the extra corporal one, used as a heart assist device.

From the analysis realized on the different types pump's systems arises conclusion that blood flow the most dangerous are the places where the gradients of the speed components are too high. In the case of the impeller blades this place is the blade surface, area of the local whirl and for the all the other pumps the stator parts of the pump interior. From this point of view we can assess conception of the both pumps (extra-corporal and intra-corporal).

For the total artificial heart systems can be used only miniature pumps and drives. For the latest systems are mostly used high speed drive's motors. So the design for this pump's system must follow the design requirements for the small size, acceptable speed and power output.

## Predictor for Control of Stator Winding Water Cooling of Synchronous Machine

---

6.1	Introduction.....	73
6.2	Used approach .....	73
6.3	Implementation .....	76
6.4	Obtained results .....	77
6.5	Conclusion .....	79

Radek Vlach, *ÚMTMB FME BUT*

### 6.1 Introduction

---

The project is concerned with computational simulations of stator winding heating of synchronous machine. The synchronous machine operates as high-torque machine with maximal torque 675 Nm at 50 rpm. The machine is used for the direct drive of the rotary or swinging axis, for example rotary tables of the machine tools.

The aim was to find predictor of synchronous machine thermal phenomena, so that the thermal model would be used for pump control of water cooling systems.

Software MATLAB was used for computational simulation of synchronous machine thermal phenomena. Computational simulations describe direct stator winding cooling by water.

### 6.2 Used approach

---

The aim is to find optimal algorithm for control of water cooling. The control algorithms are tested on the experimental device, which is part of real synchronous machine with permanent magnets. The thermal model was built as a base for pump control algorithm model of a machine without thermal sensors. The Thermal model is possible used as predictor of machine heating in real time. This type of water cooling shows better effect on the machine heating than common water cooling system on the cover

#### 6.2.1 Thermal Model

The computational model geometry arises from real synchronous machine. It describes the heat of a part of synchronous machine mainly stator winding. The machine has 36 pair of winding slots and permanent magnets on the rotor. Rotor with magnets is not modelled, because the heat loss is only in the stator winding and rotor effect is negligible on the heating of stator. The brass tubes were comprised in the middle of each winding slots. Cooling water flows in the brass tube. Symmetry of machine was assumed so only one pair of winding slot is modelled.

## Development of Vibration Power Generator for Aeronautic Application

---

	7.1 Introduction.....	81
	7.2 Electromagnetic vibration power generator.....	82
	7.3 Power analysis of vibration power generator .....	83
	7.4 Function Product of Vibration Power Generator....	84
	7.5 Simulation of Electromagnetic Vibration Power Generator.....	85
	7.6 Function Product of Generator with Output Power around 30 mW.....	88
	7.7 Algorithm of Vibration Power Generator Development .....	90
	7.8 Vibration Power Generator for Aeronautic Application.....	91
	7.9 Final Function Product with Operating Frequency 17 Hz.....	95
	7.10 Conclusion.....	98
	7.11 Future work.....	98

Zdeněk Hadaš, *FME BUT*  
 Vladislav Singule, *FME BUT*  
 Čestmír Ondrušek, *FEEC BUT*

### 7.1 Introduction

---

This contribution deals with an alternative for supplying wireless sensors with energy in aeronautics applications. The ambient energy can be a suitable source of the electrical energy for several wireless sensors with an expected power consumption of several mW. The mechanical vibration is used as a source for energy harvesting devices, where electrical power is generated by use a vibration power generator. The generator feeds wireless sensor without or as a supplement to the use of primary battery in some aeronautics applications. The generator is a maintenance-free device and it extends the lifetime of the wireless sensor in case that the generator is excited by sufficient vibration during the operation.

The vibration power generator is complex mechatronic system which is capable of generating electrical energy from mechanical energy of an ambient vibration. It uses electromagnetic principle of this electromechanical conversion. The simulation modeling of this mechatronic system connects all mechanical and electrical parts which are affected mutually. The development of the generator goes in several cycles of design and simulation of individual generator parts. The simulation modeling of whole system is very useful instrument for development and design of this device.

The generator design has to be tailored exactly to required output power and the generator parameters must be tuned up to the frequency of used vibration because the vibration power generator operates only in narrow bandwidth. A suitable aeronautics application for using vibration power generator is helicopter, which has a constant angular velocity of the rotor

## Analysis and optimization of contact force vector

Petr Krejčí, *FME BUT*

8.1	Introduction.....	101
8.2	Results of sensor optimization.....	101
8.3	Structural analysis of sensor prototype.....	103
8.4	Verification of optimized sensor functionality .....	103
8.5	Summary of achieved results.....	106
8.6	Future work.....	107

### 8.1 Introduction

The information about interaction between robotic parts and surroundings is necessary for intelligent control of robot behavior. This research is connected to research of contact force vector sensor principle and verification of its functionality which was performed in last year (Březina, 2006). The research of this year was focused on further optimization of sensor body with ambition to improve its sensitivity for loads in all directions. The paper describes optimization procedure of sensor body as well as results of experimental verification of optimized sensor functionality.

### 8.2 Results of sensor optimization

During the previous research the worst sensor sensitivity was observed in axial direction. Therefore sensor optimization was focused on increasing of sensitivity for load applied in this direction (Krejčí, Vlach & Grepl, 2007). New optimization procedure was done for increasing the sensitivity in other directions. This optimization was extended to 2 steps for load forces oriented in different directions. The first step of optimization procedure is done for axial load of sensor head while second step is done for radial load. The result of optimization is shown for volume reduction of 80 % in **Fig. 2**. The figure shows distribution of pseudodensity in sensor body. The boundary conditions used during optimization procedure are shown in **Fig. 1**.

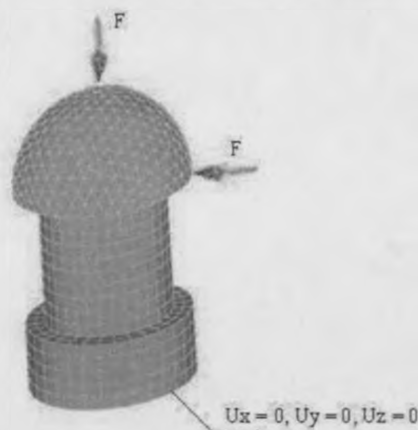


Fig. 1: Loads of sensor used in topological optimization procedure

# III

## Modelling of Autonomous Systems Behaviour

---

- 9 **Omnidirectional mobile robot with new conception using Mecanum wheels** *Tomáš Kubela, Aleš Pochylý, Radek Knoflíček, Vladislav Singule, Miloš Synek* ..... 111  
Introduction • Vehicle kinematics and dynamics • Robot model • Results • Future work
- 10 **Real-time robot motion planning based on the generalised Voronoi diagram** *Petr Švec* ..... 121  
Introduction • Voronoi Diagram • Robot model • Robot Motion Planing • Conclusions and Future work
- 11 **Four legged robot walking gait generation** *Vít Ondroušek, Jiří Krejsa, Stanislav Věchet, Pavel Houška* ..... 133  
Introduction • Used Approach • Implementation • Obtained Results • Conclusion
- 12 **Simultaneous Localization and Mapping via Scan Matching** *Stanislav Věchet, Jiří Krejsa, Vít Ondroušek* ..... 141  
Introduction • Simultaneous localization and Mapping • Potential-based scan matching • Practical experiments • Conclusion and future work

## Omnidirectional mobile robot with new conception using Mecanum wheels

Tomáš Kubela, *FME BUT*

Aleš Pochylý, *FME BUT*

Radek Knoflíček, *FME BUT*

Vladislav Singule, *FME BUT*

Miloš Synek, *FME BUT*

9.1 Introduction .....	111
9.2 Vehicle kinematics and dynamics .....	113
9.3 Robot model .....	117
9.4 Results .....	118
9.5 Future work .....	119

### 9.1 Introduction

This contribution deals with an omnidirectional mobile robot where the omnidirectional (also holonomic) movement is reached by means of omnidirectional wheels. The robot platform is capable of translating in both directions and rotating about its center of gravity. A practical benefit of this type of robots can be seen in providing very good mobility, especially in areas covered with static or dynamic obstacles, such as offices, workshops, warehouses and hospitals or for industrial applications such as surveillance, inspection and transportation tasks. One of the aims of the project will also be to verify how the omnidirectional capability may greatly reduce the amount of area and time required for maneuvers.

The content of the contribution is based on (Knoflíček, et al. 2006), though there has been completely redesigned the whole robot platform. Based on some simulation experiments, practical results and a feedback from the RAAD 2007 conference (Kubela & Pochylý, 2007), we decided to change the conception of the robot and instead of using standard and commercially available Interroll wheels (Fig. 1a), we newly rely on a new conception of Mecanum wheels of our own design structure (Fig. 1b).

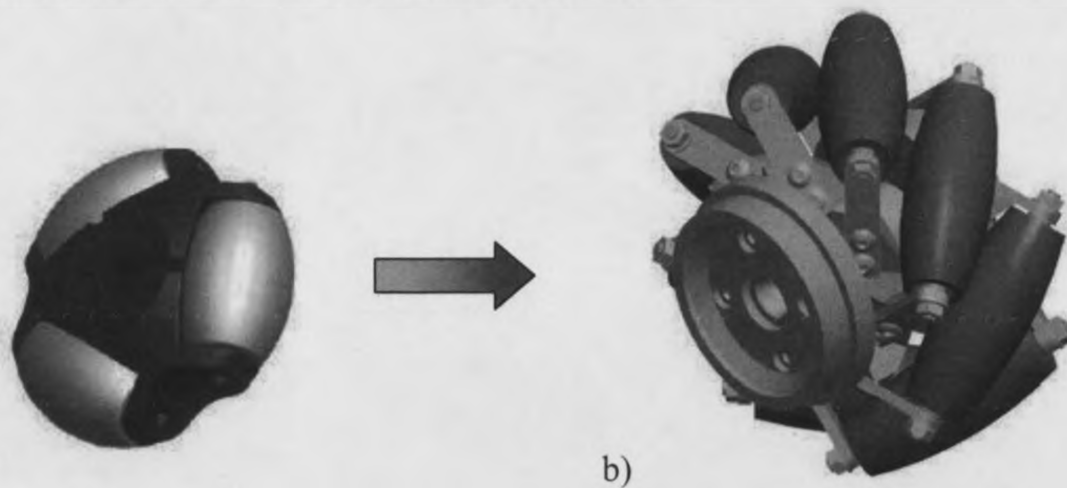


Fig. 1: Interroll wheel – former conception (a), Mecanum wheel – new conception (b)

## Real-time robot motion planning based on the generalised Voronoi diagram

---

10.1 Introduction.....	121
10.2 Voronoi Diagram.....	122
10.3 Robot model.....	123
10.4 Robot Motion Planing.....	128
10.5 Conclusions and Future Work.....	130

Petr Švec, *FME BUT*

### 10.1 Introduction

---

Real-time motion planning of an *autonomous robot* (Xie, 2003) in an unknown or partially known indoor or outdoor environment is a challenging task, particularly when the robot must preserve the largest possible (the safest) distance from surrounding obstacles, and uncertainty, localisation, kinodynamic properties of the robot, and path relaxation techniques are also considered (see Fig. 1). See (Švec, 2007) for an overview of the basic motion planning methods.

The technique presented solves this real-time motion planning task efficiently by means of the *computational geometry* (Berg et al., 2000). The computational geometry emerged from the field of algorithms design and analysis in the late 1970s. Its success of the problems studied, practical and efficient solutions from the asymptotic time complexity point of view, and its huge range of application domains laid grounds for its future expansion into robotics.

One of the most useful structure in the computational geometry for the robot motion planning is the *Voronoi diagram* (Berg et al., 2000; Okabe et al., 2000). It has a lot of applications in various fields since it preserves the largest distance from surrounding point generators. This property can be employed as a base for several motion planning tasks, where these generators are formed by obstacles. In addition to this, its *retraction property* assures that the robot is always capable of transferring itself onto this diagram along a collisionless sight line, from which follows, that the Voronoi diagram entirely captures the continuity of the whole space as a topological graph (Okabe et al., 2000). The extension of this diagram for point, segment, or polygonal generators is called the *generalised Voronoi diagram* (Okabe et al., 2000).

The usability of this generalised diagram for the robot motion planning is conditioned by an existence of efficient, robust, and practical algorithms for its computation. A novel approximation algorithm is presented together with its asymptotic time complexity. The added value of this algorithm lies in robustness and simplicity of its implementation and high computational efficiency in comparison to algorithms of the same class. This algorithm is further utilised in a new real-time robot motion technique, which exploits main properties of the Voronoi diagram leading to improving localisation hence reducing uncertainty.

## Four legged robot walking gait generation

---

Vít Ondroušek, <i>FME BUT</i>	11.1 Introduction.....	133
Jiří Krejsa, <i>FME BUT</i>	11.2 Used Approach.....	133
Stanislav Věchet, <i>FME BUT</i>	11.3 Implementation .....	134
Pavel Houška, <i>FME BUT</i>	11.4 Obtained results.....	136
	11.5 Conclusion.....	138

### 11.1 Introduction

---

The development of an autonomous mobile robot is still a challenging problem in present day. There are several possible approaches towards the design, currently the most common one uses hierarchical architecture of the robot, regardless the design type (wheeled, walking). In the hierarchical architecture the lowest layer is represented by hardware, i.e. construction of a robot with driving gears. For example (Kubela, 2007) solves problems of this layer for the purpose of the omnidirectional robot OMR III. Higher (second) layer includes control units of the driving gears and motors (Houška, 2007). The third layer ensures basic movements of the robot, in the case of legged robot the actual walking. Solving this problem is the main aim of this contribution. The highest layer usually involves suitable algorithm of global localization, e.g. pre-computed scan matching (Věchet, 2007) and path planning (Krček, 2006).

This contribution is focused on the walking gait generation for a four legged robot using state space search algorithms and extends previous work, mainly (Ondroušek, 2006, 2007). A-star algorithm and beam search algorithm were implemented and verified by means of software simulation in 2006. Following goals were set for 2007: improvement of walking gait generation by using branch-and-bound algorithm and performing real tests on the four-legged walking robot with two degrees of freedom for each leg.

### 11.2 Used Approach

---

Continuous deterministic graph can be used for representation of walking gait of a mobile robot. Each state of the graph represents current configuration of the robot, i.e. orientation and position of the robot's body and legs. Each edge of the graph represents an operator. Activation of the operator determines the rule for changing robot's configuration. Any walking gait can be described by a sequence of states and operators. Therefore the task of finding an appropriate walking gait means to find an optimal path in the graph. Heuristic methods of state space search can be successfully used for this purpose, e.g. A-star or beam search (Ondroušek, 2006).

Further improvement can be obtained by combination of such algorithms with branch & bound methods; methods which refuse solution evidently worse than solutions already found

## Simultaneous Localization and Mapping via Scan Matching

---

Stanislav Věchet, *FME BUT*

Jiří Krejsa, *FME BUT*

Vít Ondroušek, *FME BUT*

12.1 Introduction .....	141
12.2 Simultaneous Localization and Mapping.....	141
12.3 Potential-based scan matching .....	142
12.4 Practical experiments .....	142
12.5 Conclusions and future work .....	146

### 12.1 Introduction

---

There are several problems in mobile robotics e.g. localization, mapping, path planning, which are usually handled separately, in spite of the fact that the problems solving methods use the same sensor data and often also the surrounding world representation. Moreover the methods for localization and path planning should be sufficiently fast so the robot would not have to “stop and think” whenever exhibiting a move. The first fact is not an issue in the perfect case, when environment map is known and static. E.g. Markov localization method is suitable for determining the robot position and orientation, as previously examined (Krejsa, 2005). However the computational requirements for the method seems to be impractical. This fact, together with the necessary condition of known map significantly reduces the usability of the method. To speed up the localization, one can use e.g. Precomputed Scan Matching method, developed lately (Věchet, 2007a). This method (however fast) also requires the map to be known. The path planning methods examined by our team (as all the methods for path planning) require the map as well, sometimes with even more restrictions (Věchet, 2007b; Dvořák, 2007). The key issue seems to be fast and reliable method capable of localizing the robot in partially or totally unknown environment together with creating the map of such environment. These methods belong to SLAM (Simultaneous Localization and Mapping) category. In following paragraphs we introduce such a method, which might be a start for solving the issue.

### 12.2 Simultaneous Localization and Mapping

---

Main usage of SLAM approach in mobile robotics is in building online maps of a local neighborhood of the robot in unknown environment. Local maps can be further combined to the global map. In such a case we need a precise method for accurate local maps building. In standard SLAM approach a scan matching technique is used to combine two consecutive scans of local robots neighborhood to build the consistent local map. This local map serves as basement for building the consistent global map of the environment. Such global map is used for localization of the robot’s true position, which is critical for path planning methods. In this contribution we describe the creation of the consistent local map via potential-based scan matching method. This method was developed for small robots moving in unknown indoor

# IV

## Modelling of Systems with Special Elements

---

- 13 **Modelling, Virtual Prototyping and Design of Two Wheeled Unstable Mobile Robot** *Robert Grepl, Pavel Švejda, David Vlachý, Pavel Zezula* ..... 149  
Introduction • Modelling and control • Design and production of mechanical part of system • Identification of parameters of used actuator • Sensorial system, power electronics, control hardware • Future work
- 14 **Modeling of Bifurcation and Chaos in Real Drive System** *Ctirad Kratochvíl, Josef Koláčný, Lubomír Houfek, Martin Houfek, Jiří Krejsa* ..... 157  
Introduction • Deterministic chaos • Bifurcation behavior of real drive system • Results • Conclusion • Future work
- 15 **Noise emission of the mechatronic system** *Ivan Mazurek, Milan Klapka* ..... 165  
Introduction • Used Approach • Obtained Results • Conclusion
- 16 **GA In Shock Absorber Identification Task** *Jiří Krejsa, Stanislav Věchet, Lubomír Houfek* ..... 177  
Introduction • Model • Identification details • Tasks in question • Conclusion and future work
- 17 **Analysis of Vehicle Dynamics using Kalman Filter** *Petr Porteš, Marián Laurinec, Ondřej Blaťák* ..... 189  
Introduction • Goal Measurement • Vehicle dynamics model • Kalman Filter • Application of Kalman Filter • Software solution • Comparison of results • Conclusion • Future work, List of symbols and signs

<b>18 Multidimensional Simulation of Stirling Engine Regenerator</b>	
<i>Václav Pištěk, Pavel Novotný</i> .....	207
Introduction • String Engine Regenerators • CFD Approach to Stirling Engine Regenerator Modelling • Project of up to 3 kW Micro Plant • Conclusion	
<b>19 The Numerical Model of <math>\alpha</math> Stirling Engine Modification</b>	
<i>Michal Sikora, Radek Vlach</i> .....	219
Introduction • Used Approach • Implementation • Obtained Results • Conclusion	

## Modelling, Virtual Prototyping and Design of Two Wheeled Unstable Mobile Robot

---

	13.1 Introduction .....	149
	13.2 Modelling and control .....	149
Robert Grepl, <i>FME BUT</i>	13.3 Design and production of mechanical part of system .....	151
Pavel Švejda, <i>FME BUT</i>	13.4 Identification of parameters of used actuator .....	153
David Vlachý, <i>FME BUT</i>	13.5 Sensorial system, power electronics, control hardware .....	155
Pavel Zezula, <i>FME BUT</i>	13.6 Future work .....	156

### 13.1 Introduction

---

The methodology of the dynamic system modelling towards the virtual prototyping is presented in previous volume "Simulation Modelling of Mechatronic Systems II" and also in (Grepl, 2007).

In this chapter, we describe the particular case study of mentioned approach. The modelling, design and control of unstable two-wheeled mobile robotic platform is based on following key principles:

- model based design
- linear state space control applied on nonlinear system
- testing of sensory processing and control using virtual prototype
- selective laser sintering (SLS) rapid prototyping technology for fast production of mechanical parts
- effective development and testing of control algorithm using input/output multifunctional card MF624

The project was inspired by widely known commercially successful product Segway but also earlier research projects nBot and Joe le pendule (Švejda, 2007).

### 13.2 Modelling and control

---

The mechanical system considered as MBS is modelled in Matlab/Simulink/SimMechanics environment. Electrical DC motor is used as an actuator and modelled as system with lumped parameters. Based on differences of eigenvalues of mechanical and electrical system, we can efficiently model the motor as a static system. More information about mechanical system modelling is presented in (Grepl, 2007).

The nonlinear model built in SimMechanics has been linearized and resulting LTI model has been used for LQR design via standard Matlab tools. The first iteration of complex model

## Modeling of Bifurcation and Chaos in Real Drive System

---

Ctirad Kratochvíl, <i>FME BUT</i>	14.1 Introduction.....	157
Josef Koláčný, <i>FEEC BUT</i>	14.2 Deterministic chaos.....	157
Lubomír Houfek, <i>FME BUT</i>	14.3 Bifurcation behavior of real drive system.....	158
Martin Houfek, <i>FME BUT</i>	14.4 Results.....	162
Jiří Krejsa, <i>FME BUT</i>	14.5 Conclusion.....	162
	14.6 Future works.....	162

### 14.1 Introduction

---

Chaos can be defined on bounded-state behavior that isn't equilibrium solution or a periodic solution or a quasiperiodic solution. The attractor associated with chaotic motion in state space isn't a simple geometrical object like a finite number of points, a closed curve or a torus. Chaotic attractor are complicated geometrical objects that posses fractal dimensions.

In contrast with the spectra of periodic and quasiperiodic attractors, which consist of a finite number of sharp spikes, the spectrum of a chaotic signal has a continuous broadband character. In addition, the spectrum of chaotic signal often contains spikes that indicate the predominant frequencies of the signal. We can also say, that chaotic motion has a very large number of unstable periodic motions. Thus, a chaotic system may dwell for a brief time on motion that is very nearly periodic and then may change to another periodic motion with a period that is  $k$  times that of the preceding motion. These constant evolutions from one periodic motion to another a long-time impression of randomness while showing short-term glimpses or order (Nayfeh, 1995).

Chaotic systems are also characterized by sensitivity to initial conditions or some structural parameters of model of drive systems. That is, tiny differences in the input can be quickly amplified to create overwhelming differences in the output (this is so-called butterfly effect)

### 14.2 Deterministic chaos

---

Deterministic chaos is a term used to denote the irregular behavior of dynamical systems arising from a strictly deterministic time evolution without any source of noise or external stochasticity. This irregularity manifests itself in an extremely sensitivity dependence on initial conditions (or some structural parameters), which precludes any long-term prediction of the dynamics. Most surprisingly, it turned out that such chaotic behavior can already be found for dynamical systems with a small degree of freedom and it is, moreover, typical for a great number of mechatronic systems.

A dynamical system can be described simply as a system of  $N$  first order differential equations

## Noise emission of the mechatronic system

---

Ivan Mazůrek, *FME BUT*Milan Klapka, *FME BUT*

15.1 Introduction.....	165
15.2 Used Approach.....	165
15.3 Obtained results.....	174
15.4 Conclusion.....	175

### 15.1 Introduction

---

The driveline of a modern car can be regarded as a complex mechatronic system. There are high demands put on the vehicle handling control. The driveline and the braking system therefore have to be able to solve independently various tasks, such as detection of the vehicle sideway skid, control of the slip of driving wheels, active driving assistance etc. These functions of the system can be reached only by truly synergetic contribution of many mechatronic branches. Designing such a complex unit can be comparatively difficult under the conditions of highly competitive car manufacturing environment. This could easily cause overall overrating of the importance of the regulating functions of the system, as well as malfunction of even a relatively simple machine component.

In practice, the same uncompromising environmental requirements have to be met with mechatronic systems as with any other machinery unit. Apart from exhaust emission limits, the noise emission is another closely watched quality of the driveline systems in passenger cars. There has been a significant progress in this discipline recently, and the noise behavior of groups, which were marked as “trouble free” a few years ago, are now in forefront of auditors’ interest. For example, in case of a driveline, where the streaming gases (exhaustion, intake) and gear teeth frequencies can definitively be regarded as the major sources of the noise, the phenomena, such as various chattering caused by the mechanical looseness, has become more and more important. It is interesting, in point of view of the psychoacoustics, that these irregular sounds, which occur in particular operation modes only, are found more disturbing than more intensive regular noise caused by the driving system.

### 15.2 Used Approach

---

We have recently cooperated with the development department of car manufacturer Škoda, and the mechatronic approach to the solution of the problem proved to be very important. It was the key aspect applied in the research into the irregular chattering noises which spread from the front axle. The major source of the noise in the nearest joint of half axle between differential and wheel was localized by the help of the noise source localization method. The noise was then lead through the noise transmission path to a large brake disk which served as an acoustical radiator. The real mechanical source of the problem is the sleeve bearing which supports the half axle through the differential (Fig. 1). The complex mechanism can be operated in case of appropriately adjusted clearances in the whole kinematic scheme.

## GA In Shock Absorber Identification Task

---

16.1 Introduction .....	177
16.2 Model .....	178
16.3 Identification details .....	179
16.4 Tasks in question .....	179
16.5 Conclusions and future work .....	186

Jiří Krejsa, *FME BUT*

Stanislav Věchet, *FME BUT*

Lubomír Houfek, *FME BUT*

### 16.1 Introduction

---

Mathematical modeling of vehicles dynamic characteristics consists of several blocks (rear and front axle mechanisms, dampers, tyre, etc.). In order to obtain the realistic models the modeling should be integrated with measurement in order to correctly identify various properties (Mazurek, 2007). This contribution is focused on one of such cases – identification of shock absorber damping characteristics.

Shock absorber characteristics can be identified off-line from the time course of kinematic variables using stochastic optimization. The model of the shock absorber is required, together with the model of the car, in order to compare the responses of measured output with the output of the model for which the values of characteristics to be identified are fed as the identification method parameter. Genetic Algorithm can serve as such method, with flexible structure of parameters to be identified. In our case the piecewise linear dumping force function parameters were to be found (both the “breaking” values and the slope). Model response was obtained from the kinematic excitation, which can be easily introduced for the real car by running over defined bump.

There are several factors which might be put under investigation, we focused on following three:

- definition of the cost function – as not all the kinematic variables are practical to measure, cost function which uses only some variables is required, potentially reducing the precision and reliability of the results.
- initial population parameters boundaries – using the outside information about expected range of values of the parameters should speed up the search and increase precision.
- response to noise – measured values always contain certain level of noise, it’s influence on the task is therefore essential.

The following paragraphs describe briefly the model used, the ranges and definitions used in the identification, and finally the responses regarding the cost function definition, initial population parameters boundaries and noise levels.

## Analysis of Vehicle Dynamics using Kalman Filter

---

Petr Porteš, *FME BUT*

Marián Laurinec, *FME BUT*

Ondřej Blaťák, *FME BUT*

17.1 Introduction .....	189
17.2 Measurement .....	189
17.3 Vehicle dynamics model .....	191
17.4 Kalman Filter .....	193
17.5 Application of Kalman Filter .....	194
17.6 Software solution .....	198
17.7 Comparison of results .....	199
17.8 Conclusion.....	203
17.9 Future work .....	203
List of symbols and signs.....	204

### 17.1 Introduction

---

The main goal of this project is to improve tools for modelling of vehicle dynamics. Our primary focus is to enhance the process of verification of models with the measured data and the development of tools that would make it possible to utilize mathematical models when analyzing dynamic states of an existing car during road tests. To date, road tests have been evaluated only based on the analysis of the measured signals. These problems are closely related also with estimating vehicle parameters for the purpose of vehicle dynamics control systems such as ESP, ABS etc.

The project goals are detailed in (Mazůrek, Porteš, Pražák, Blaťák, 2006). In 2007, the project efforts focused on using Kalman filter to integrate mathematical models with the measured signals. For these purposes we used the data measured during avoiding manoeuvre of a vehicle. As the data file included also the trajectory of vehicle movement, it was possible to verify usability of Kalman filter for correction of vehicle path.

### 17.2 Measurement

---

BUT's Institute of Forensic Engineering in cooperation with BUT's Institute of Automotive Engineering created a sample of measurements of vehicle handling manoeuvres that were published in (Kledus, Porteš, Vémola, Zelinka, 2001).

For the application of Kalman filter, we selected testing manoeuvre of a passenger car whose technical specifications necessary for the calculation are stated in Tab. 1. Tests were realized on a test track arranged according to ISO/WD 3888-2 international standard (Fig. 1). The vehicle was driven in such a manner as to suddenly change lanes when avoiding an obstacle. During the manoeuvre, the car is driven from the original lane to the neighbouring lane and then back again. For further information about the manoeuvre see ISO/WD 3888-2,

## Multidimensional Simulation of Stirling Engine Regenerator

---

18.1	Introduction.....	207
18.2	Stirling Engine Regenerators.....	207
18.3	CFD Approach to Stirling Engine Regenerator Modelling.....	210
18.4	Project of up to 3 kW Micro Plant.....	215
18.5	Conclusion.....	216

Václav Píštěk, *FME BUT*

Pavel Novotný, *FME BUT*

### 18.1 Introduction

---

Research topics for the year 2007 covered sensitivity analyses of Stirling engine CFD computational models and the activation of micro combined heat and power plants for combined production of electricity and heat with Stirling motor.

For computation of thermodynamic cycles of Stirling engine, computational models of different levels were worked out in the past decades (Siegel, 2000). However, up to now, the output parameters of the realized Stirling engines generally did not reach the calculated values because computational modeling of their real working cycles is extremely difficult. Periodic courses of pressure and gas mass flow in the Stirling engine show that for the description of the ongoing processes a system of simultaneous nonlinear differential equations has to be constructed for the balance of mass, energy, and momentum. For simulation programs, it is also necessary to supply the equations for pressure losses and heat transfer in all characteristic volumes of Stirling engine. These are usually obtained empirically and their validity is highly restricted by the conditions under which they have been obtained. For regenerators of the Stirling engine, empiric relations for computations of pressure losses and heat transfer are not available so far. Therefore, this paper deals with the ways of using the computational models based on CFD to offer solutions to these problems.

### 18.2 Stirling Engine Regenerators

---

#### 18.2.1 Ideal Regenerator of Stirling Engine

It is known that thermodynamic cycles of real Stirling engines differ significantly from an ideal cycle (Siegel, 2000). However, to understand the importance of the regenerator function, it is useful to briefly describe the process of heat accumulation and also the properties needed for an “ideal” regenerator.

For an “ideal” regenerator, a zero temperature difference between the working gas and the regenerator material is assumed so that the “ideal” regenerator has a lower temperature of expansion space on the expansion side, and a higher temperature of the compression space on the compression side. A temperature curve of regenerator material is linear between these two boundary temperatures (see Fig. 1). Heat capacity of the regenerator is assumed to be infinite

## The Numerical Model of $\alpha$ Stirling Engine Modification

---

Michal Sikora, *FME BUT*

Radek Vlach, *FME BUT*

19.1	Introduction.....	219
19.2	Used Approach .....	220
19.3	Implementation.....	223
19.4	Obtained results .....	225
19.5	Conclusion .....	226

### 19.1 Introduction

---

When we don't take the steam engine into account, the engines with external heat inlet were never widespread in the past. Nowadays, it is necessary to solve some global problems and looks for new alternative sources of power. One of advantages of the engines with external heat inlet is modesty of fuel quality that can be combustion continually. It is possible to use low-quality, renewable sources of power, e. g. biomass.

The design of small heat and power unit which is propelled by Stirling engine is our aim. The decentralized generation of electrical energy and heat is not efficient. On the contrary the waste heat from heat and power unit can be use for e. g. heating of house, see Fig. 1.

Achieving of good thermodynamical Stirling engine efficiency represents relatively difficult optimizing task. But attaining of maximal thermodynamical efficiency is not necessary, when we plan use the waste heat. The composition of enough accurate thermal model is important. We cannot neglect many energy losses. Only the theory of ideal cycles is not usable. Even the models dividing the volume of working gas into two or three sub-areas are not too accurate (Walker, 1973). The dividing of engine into many volume elements (the control volumes method) makes better results. But the accuracy of CFD calculations is not achieved by the model. However, this model is faster and more suitable for future optimization of engine parameters.

So, our goals for year 2007 were as following:

- Try to make numerical model of Stirling engine ( $\alpha$  modification), which use the control volume methods.
- Improve the model algorithm in order to simulate the pressure losses of working gas.
- Implement the influence of gas leakages from the working space - we consider non ideal piston seals.
- Study the model behaviour and estimate the influences of previous phenomena.

# Modelling of Biomechanical Systems Characteristics

---

- 20 **Device for Experimental Modelling of Biomechanical Systems**  
**Properties** *Tomáš Březina, Pavel Houška, Lukáš Březina, Ondřej  
Andrš* ..... 231  
Introduction • Engineering design • Model of Steward platform  
dynamics • Control design • Conclusion and discussion • Future  
work
- 21 **Computational Modelling of the Biomechanical Systems**  
**Properties** *Zdeněk Florian, Vladimír Fuis, Tomáš Návrat* ..... 243  
Introduction • Used Approach • Implementation • Obtained  
Results • Conclusion and discussion • Future work

## Device for Experimental Modelling of Biomechanical Systems Properties

Tomáš Březina, *FME BUT*

Pavel Houška, *FME BUT*

Lukáš Březina, *FME BUT*

Ondřej Andrš, *FME BUT*

20.1 Introduction.....	231
20.2 Engineering design .....	232
20.3 Model of Stewart platform dynamics .....	234
20.4 Control design.....	236
20.5 Conclusion and discussion.....	240
20.6 Future work.....	241

### 20.1 Introduction

Design, modeling and construction of universal device for experimental determination of biomechanical components mechanical properties is solved within project MSM 0021630518 Simulation modelling of mechatronic systems. Output of the project should be device capable of motion as close as possible to the motion of chosen parts of human body.

General motion and effector action forces are simulated by parallel mechanism called Stewart platform (hexapod). Typically the hexapod structure has six linearly actuated links, these are connected to the base plate and the top (mobile) plate by universal joints located at both ends of each link (Fig. 1). The six DOF top plate position and orientation depend on the length of each link. Great advantage of the device is very high stiffness, on the other hand the control of hexapod is not a simple task at all.

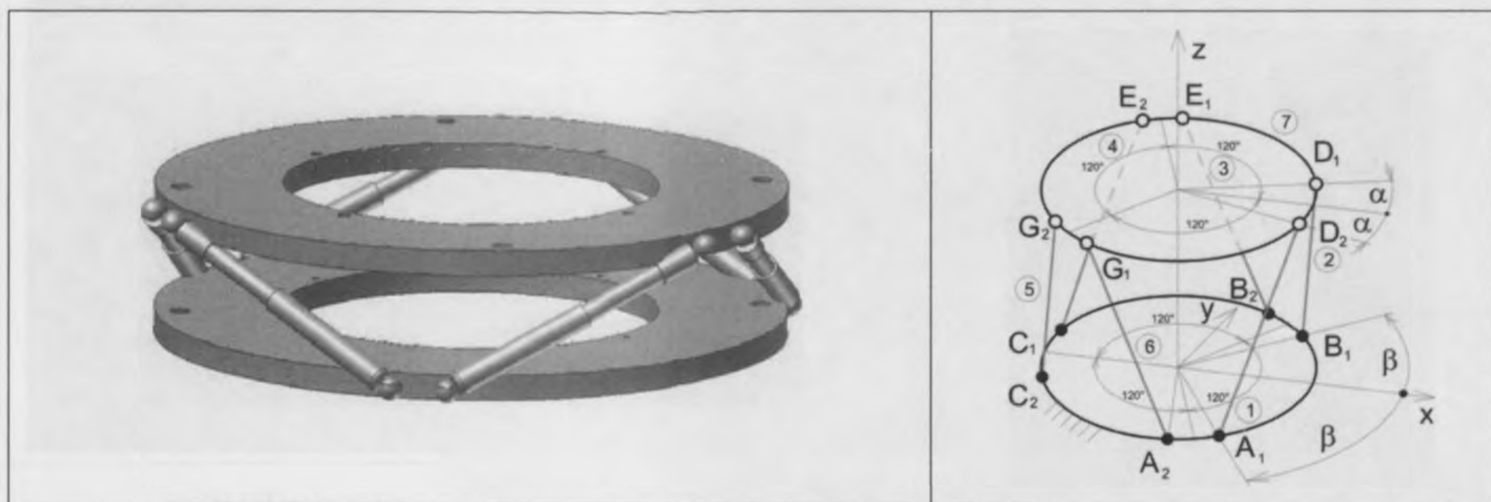


Fig. 1: Stewart platform

## Computational Modelling of the Biomechanical Systems Properties

---

	21.1 Introduction.....	243
Zdeněk Florian, <i>FME BUT</i>	21.2 Experimental determination of material characteristics of polyethylene.....	243
Vladimír Fuis, <i>FME BUT</i>	21.3 Computational modelling of the contact pressure in the hip endoprosthesis cup .....	246
Tomáš Návrat, <i>FME BUT</i>	21.4 Future work.....	254

### 21.1 Introduction

---

The part of the project presented in the SECTION V is aimed at determining the dependencies of the abrasion on the mechanical properties of the total endoprosthesis (TEP), or of the mechanical properties and their behaviour in contact with TEP. The size of abrasion for the given type of the endoprosthesis can be determined by means of experiments only. The project therefore deals with the development of the device specified in (Březina, 2005) and the design alternations and the operation of the experimental device are presented in the Chapter 20.

Mechanical quantities describing the features of the contact between two bodies (process of contact pressure, size of contact area) can be determined effectively only by calculation that enables generalization of the obtained results and thanks to that it raises their importance for the clinical practice. Therefore the computational modelling of the contact pressure distribution at a physiological hip joint and its comparison with the case, when the surface or total artificial joint was used, was implemented in 2006. Possible shape deviations in the connection between head and acetabulum (Březina, 2006) were considered with the total endoprosthesis. Material characteristics used for modelling of the acetabulum with the use of ultra high molecular weight polyethylene (UHMWPE) were employed according to (Návrat, 2005) and they were assumed as linearly elastic ones, defined by the modulus of elasticity and the Poisson ratio. The question remains whether a computational model with a linearly elastic model of polyethylene can be applied in all cases when solving the tension and deformation in the hip joint. Thus, experiments have been planned with a set of samples (Březina, 2006) to determine the material characteristics that will then be used in the computational model of the hip joint endoprosthesis.

### 21.2 Experimental determination of material characteristics of polyethylene

---

Samples for a pulley test were taken from the used polyethylene components of tibial plates utilized for the knee joint replacement – Fig. 1, provided by doc. MUDr. Zbyněk Rozkydal, PhD., St. Anne's University Hospital Brno. In order to ensure maximum possible utilization of the material, samples with rectangular cross section were cut from the tibial