Contents

SECTION IV Modelling of Systems with Special Elements

SECTION V Modelling of Biomechanical Systems Characteristics

7

Sensor of Contact Force Vector – Verification of Functionality and Optimization

Petr Krejčí, *FME BUT*

7.1 Introduction

The aim of this research is to create an algorithm for robotic hand gripping force control. Such algorithm will modify the magnitude of the gripping force enabling a secure holding of the object with prevention of contact loss as well as of object damage. The algorithm will modify robotic hand behavior based on measuring of contact force vector. The sensor and its principle suitable for this kind of task was designed and described in previous research. During simulation and also by experimental verification of sensor functionality, a small sensitivity of sensor in axial direction was observed. It is necessary to optimize the geometry and material of sensor in order to increase the sensitivity in critical direction.

For experimental verification, the commercial measuring unit *SPIDER 8* is used for measuring real sensor body strain. This unit is produced by HBM Company and is designed, among others, for strain gauges measurement. In order to use this sensor for real application, the concept of electronic measuring and control unit is described below.

7.2 The aims of research in 2006

The aims of this project are as follows:

- Experimental verification of sensor functionality
- Improvement of sensor sensitivity in axial direction
- Creation of optimized sensor based on new design
- Design of measuring and control electronic unit

7.3 Achieved results in 2006

Sensor prototype

Based on previous research (Krejci, Vlach, Grepl, 2006), a working prototype of sensor was developed. This sensor is made from aluminium alloy (AlMgSi0.5) and contains three strain gauges produced by Hottinger Baldwin Messtechnik (HBM). Strain gauges that are connected

III

Modelling of Autonomous Systems Behaviour

8

Simulation Modelling of Mobile Robot with Omnidirectional Undercarriage

Radek Knoflíček, FME BUT
Tomáš Kubela, FME BUT
Aleš Pochylý, FME BUT
Vladislav Singule, FME BUT
Miloš Synek, FME BUT

8.1 Introduction

The main advantage of mobile robot undercarriages with omnidirectional wheels is mainly its very good maneuverability. Using omnidirectional wheels was the basic and initial assumption of the project. Particularly for the reason of very good maneuverability, it can be considered an ideal tool for verification of various types of algorithms intended for local navigation, path planning, mapping and further development with respect to university-indoor environment and robotics classes.

The Institute of Production Machines, Systems and Robotics (IPMSaR) has been commissioned to design and to develop a mobile robot with this type of undercarriage. However, each design process should be preceded by optimally chosen parameters that can influence the resulting behaviour of the whole platform; mechatronic and systemic approach. The simplest form of how these parameters can be achieved is connected with a description of a complex simulation model which results in an assessment of the final platform behaviour with these parameters. The purpose of this contribution is to describe extended kinematical and dynamical model of the mobile robot with a possibility to implement skew wheel angles overcoming the problem of miss-alignments of the wheels that have an impact on the real robot's trajectory.

Furthermore, the design of the robot, selected wheels, driving units, gear boxes and incremental encoders and a simulation of power demands with respect to specified conditions and limitations are shortly described.

8.2 Kinematical model of the robot

Provided that the robot is moving only within 2D environment, its absolute position in a global coordinate system is defined by the vector $[x, y, \theta]$. The kinematical model is shown in the Fig. 1.

9

Using Virtual Prototype for the testing of algorithms generating robot's walking gait

Vít Ondroušek, *FME BUT*
Tomáš Březina, *FME BUT*
Jiří Krejsa, *FME BUT*
Pavel Houška, *FME BUT*

9.1. Introduction

The ability to perform prescribed tasks autonomously is nowadays the common requirement for the mobile robotic systems. In the case of a walking robot such a system should be able to develop its own walking gait that could be considered optimal (e.g. regarding the energy consumption). Choosing the appropriate walking gait belongs to the set of planning tasks. The aim of such a task is to find the optimal path, in our case defined as a sequence of states and operators that perform transitions between states. Each state represents a particular configuration of the robot. The rule for robot's configuration change represents the operator realization and such operator performance thus creates a new state.

To find a solution for such task, informed methods of the state space search can be successfully used.

This contribution describes and compares the ordered search algorithm A* with its modification called the beam search algorithm (Pearl, 1984). The article evaluates namely the capability of finding the optimal solution, the algorithm response time and complexity of the tree that is generated. To obtain an acceptable complexity of the task, the choice of algorithm is important, as well as the set of rules for the new states generation together with the cost function that essentially influences the size of generated state space and thus also the complexity (and memory / computational requirements) of the whole task.

This contribution proposes a set of production rules and an appropriate cost function that lead to the generating the state spaces of different sizes containing different styles of a four-legged robot walking.

The suitability of the discussed algorithms and proposed rules is verified using virtual prototype of the four-legged robot. It means through a software simulation, where both the simplified kinematic model of the four-legged robot performing planary movement (constant distance of the robot body above the surface is considered) and walking gait generating algorithms are implemented.

10

Nonholonomic Mobile Robot Path Planning by Means of Case Based Reasoning

Jiří Dvořák, *FME BUT*
Petr Krček, *FME BUT*

10.1 Introduction

The purpose of the robot path planning is to find a path with minimum weight from a robot start configuration to a goal configuration without collisions with known obstacles. The weight of a path is determined mainly by its length. Other aspects such as difficulty and risk may also be considered.

Robot path planning is usually based on searching in a discretized space because such methods are faster than those for a continuous space. Methods for a discretized space are classified according to the way the search space is discretized. Methods of the first class decompose the continuous space into a set of small cells (convex polygons or a grid of regular cells). Methods of the second class are known as *roadmap methods*. These methods decompose the continuous space into a set of partial possible paths, called a roadmap, which joins a number of key-points scattered within the environment. The roadmap methods are based on Voronoi diagrams, for example, or on rapidly-exploring random trees.

If there are some additional constraints on the robot motion (except for the constraints following from the environment modelling method), then the robot is characterized as a nonholonomic. Path planning of nonholonomic robots is studied e.g. in (LaValle, 2006) and (Podsedkowski et al., 2001).

10.2 Problem field, goals definition

We assume a dynamic partially known two-dimensional space in which known polygonal obstacles and hazardous areas are defined. When an environment is dynamic and partially unknown, then robots with the ability to learn and explore the environment are needed. This ability is often achieved by using neural networks, reinforcement learning or evolution algorithms. We investigate the use of another machine learning method, which is known as *case-based reasoning* (CBR). Case-based reasoning solves a new problem by suitably adapting known solutions of similar previously solved problems. It seems that the CBR is a suitable method for robot navigation because robotic applications usually include repeated tasks.

Our goal consists in the investigation of possibilities to improve existing path planning methods by combining them with CBR. This year, we have focused on path planning methods

11

On Shortest Paths in Partially Known Environment

Miloš Šeda, *FME BUT*

11.1 Introduction

The shortest path problems are among the most important tasks of graph theory with many practical applications, e.g. in transportation, routing and communication. They include such problems as finding the shortest path between two given vertices of a graph, finding the shortest paths from a given vertex to all other vertices, and finding the shortest paths between all pairs of vertices. While geographical distances can be stated deterministically, costs or times can fluctuate with traffic conditions, payload, and so on. In the last two cases, deterministic values for representing the edge weights cannot be used. A typical way of expressing these uncertainties in the edge weights is to utilize fuzzy numbers based on the fuzzy set theory.

In the literature, several different approaches can be found for solving fuzzy graph problems. (Zadeh, 1999) shows that fuzzy graphs may be viewed as a generalisation of the calculi of crisp graphs. (Blue et al., 2002) give a taxonomy of graph fuzziness that distinguishes five basic types combining fuzzy or crisp vertex sets with fuzzy or crisp edge sets and fuzzy weights and fuzzy connectivity. The paper also introduces an approach to finding the shortest path based on level graphs. (Boulmakoul, 2004) proposed a new algebraic structure to solve the problem of the K-best fuzzy shortest paths and showed that the generalized Gauss-Seidel algorithm solving this problem always converges. However, all these approaches are rather theoretical and do not address the implementation point of view that will be in the center of our considerations.

11.2 Problem and Its Time Complexity

The All-Pairs Shortest Paths Problem for graphs with crisp edge weights is usually solved by the Floyd-Warshall algorithm (Cormen et al., 2001; Gross & Yellen, 1999), which is based on the idea of gradual improvement so that the set of intermediate vertices of considered paths grows with every iteration until it encompasses all the vertices.

11.2.1 Floyd-Warshall Algorithm

Let $G=(V,E)$ be a connected weighted graph with nonnegative edge lengths and $d_{ij}^{(k)}$ be the length of the shortest path from i to j such that any intermediate vertices on the path are chosen from the set 1,2, … , k. A path consisting of a single edge has no intermediate vertices.

12

Mobile Robots Localization and Path Planning

Stanislav Věchet, *FME BUT*
Jiří Krejsa, *FME BUT*

12.1 Localization

12.1.1 Introduction

Mobile robots navigation belongs to the actual problem in robotics. We developed simple but fast method for real-time localization in static environment (only static obstacles are considered) based on a popular Markov localization which can not be used in real world application due to computational demands. PCSM (Pre-computed Scan Matching) localization method was developed for small robots with low memory and low speed processors. PCSM belongs to the group of global localization algorithms which solve the problem of unknown initial position. Modification of this method to be useable in dynamic environment and incorporation to the SLAM (Simultaneous Localization and Mapping) technique seems to be a perspective approach to successful navigation in complex environment. We prepare a probabilistic model of robot movemets and this model is used in SLAM for prediction of robots position.

12.1.2 Issues in localization

There are various issues in robot localization: The simplest one is local localization or position tracking, when the initial position and orientation is known. The only problem is odometry error elimination. More challenging is the global localization problem. Here a robot doesn't know its initial pose but has to determine it from scratch instead. Even more difficult is the kidnapped robot problem, in which a well-localized robot is teleported to some other place without being told. The kidnapped robot problem is often used to test a robot's ability to recover from catastrophic localization failures. Finally, all these problems are particularly hard in dynamic environment, if robot operates in the proximity of moving objects which corrupt the robot's sensor measurements.

12.1.3 Localization method

PCSM (Pre-computed Scan Matching) algorithm was first described in Věchet & Krejsa, 2005. The algorithm is based on pre-computed world scans and matching of the scans with actual neighborhood scan. The key idea is to define a value function used to describe the difference between two scans over the state space. This is typically called the "Match" and is denoted as

IV

Modelling of Systems with Special Elements

13

Towards Virtual Prototype of Controlled System with High Dynamics and Complexity

Robert Grepl, *FME BUT*

13.1 Introduction

In mechatronics, the modelling plays an essential role. A former one domain analysis (e.g. kinematic, dynamic, stress analysis) has been often replaced with a complex model (CM) and presently is being developed to a virtual prototype (VP). Surely, the border between CM and VP can hardly be defined clearly. Simply said, the VP can be understood as the CM with additional interaction with dynamic environment, visualization and possibly with human – computer/machine control interface. The nature of the used CM strongly depends on the particular task; usually it is a description of dynamics of system.

The aim-oriented definition of VP can be formed as follows: VP is an entity built virtually on the computer with a goal to perform the same or similar experiments that are practicable on a real physical prototype of technical object.

This year we have continued our work on components for VPs of several technical objects with high dynamics of behaviour and degree of complexity. Modelling of a gantry crane and a differentially driven soccer robot has been added to ALRs modelled before. Furthermore, we have improved the classification of used models and also made some progress in the visualization techniques using VRML.

13.2 Aims of work

The aims for this year have been based on the previous results in 2005 as well as on the later update based on consecutive progress. The aims have been defined in this way:

- more specific classification of models used in design process
- improvement of generally usable techniques related to visualization components of VP
- further development of models of several technical objects towards the full VP (particularly a design of simulating models of sensors and implementation of algorithms on microcontrollers)

I

Support of Modelling

14
Bifurcation and Chaos in Drive Systems

Ctirad Kratochvíl, *FME BUT*
Lubomír Houfek, *FME BUT*
Martin Houfek, *FME BUT*
Jiří Krejsa, *FME BUT*
Josef Koláčný, *FEEC BUT*
Roman Kříž, *FEEC BUT*

14.1 Introduction

The stability analysis cannot be omitted when examining the dynamic properties of controlled drive systems. In case of nonlinear systems and their models, one can also expect occurrence of chaotic movements. The approach towards the analysis of their occurrence possibilities will be different when analyzing models with one or a few degrees of freedom, or models of real technical systems. Those problems are addressed in the contribution.

14.2 Occurrence of chaos in dissipative systems and its modelling

A dissipative dynamic system can be characterized as a system whose behaviour with increasing time asymptotically approaches steady states if there is no energy added from the outside. Such a system description is possible with relatively simple nonlinear equations of motion. For certain values of parameters of those equations, the solution does not converge towards expected values, but chaotically oscillates. Strong dependency on small changes of initial conditions occurs as well. When analyzing such phenomena, their mathematical essence can be connected with the existence of "strange attractor" in the phase plane. Possible creation of chaos can be seen in repeated bifurcation of the solution, with the so-called cumulation point behind which the strange attractor is generated. Then the phase diagram of the system solution is transferred from a stable set of trajectories towards a new, unstable, and chaotic set. Creating the global trajectory diagrams is of essential importance. When it is successful, the asymptotic behaviour of the system model is described.

14.3 Global behaviour of the simple model of the drive system

Let us assume that the mathematical model of the simple system can be described by the nonlinear equation:

$$I\ddot{\phi} + b_T\dot{\phi} + k_T\phi + f\left(\phi\right) = 0 \tag{1}$$

15

Adjustments and Regulation of Interactions between Working Mechanisms and Transformed Materials

Jiří Malášek, *FME BUT*

15.1 Introduction

An important possibility of using below-mentioned methods can be found at adjustments, optimization and regulation of technological processes with transformation – deformation of various materials.

Examples of these technological processes with deformation of materials are: mixing, mixture, compacting, transport, stocking.

Examples of these materials are: powdery materials, granular materials, particular materials, cohesive materials, pastes, viscous fluids, suspensions, dispersions.

Continuum-physical characteristics of these materials can be changed at processes with transformation, these materials can be only in parts connected continuums, eventually they have no continuum characteristics at all.

Generally speaking, these materials cannot be regarded as continua, these materials are in parts continuous spaces, and the properties of these parts, including their size and shape, are unstable in time (Malášek, 2005).

The common reality at deformation of these materials is a zone of transformation – deformation, as a cubic formation determined by system shear curves and streamlines. Streamlines and shear curves are identical - in the zone of transformation – deformation - in case gradient of velocity exists in this zone.

Boundaries of this zone are established by machine parts – for example by mixer blades, compact-machine jaws, sides of bunkers, they are established by a zone with an untransformed – undeformed rest of materials, too.

When processing these materials, the materials are being deformed by mechanical effects. As a result of the transformation – deformation, the formed stress state determines the stress of machine parts being in the contact with the deformed material. It is possible to determine stress tensors in selected points of shear curves from a form and position of short sections of shear curves only, where the selected points are located, and from a limiting dependence of shear and direct stresses – so called material characteristics $\tau = \pm f(\sigma)$. At last those material

16

Mathematical Modelling of Dynamic Characteristics of Vehicles

Ivan Mazůrek, *FME BUT*
Petr Porteš, *FME BUT*
František Pražák, *FME BUT*
Ondřej Blaťák, *FME BUT*

16.1 Introduction

The aim of the project is to improve tools for modelling of handling qualities of cars. Our primary focus is to extend utilization of mathematical models. Nowadays, mathematical models are employed above all as the so-called virtual prototypes used for simulation of behaviour of products before they are physically manufactured. However, mathematical models might be very useful in other stages of the product development. Development of a car, for example, goes on intensively even after the prototype is manufactured. Prototypes undergo many tests that monitor behaviour of the car during selected manoeuvres. On the basis of analysis of measured physical quantities and driver's perception, many parameters of car chassis mechanism and electronic systems are modified (ESP, ABS etc.). Application of mathematical models in these stages of car development can result not only in a more complex picture of the monitored processes (manoeuvres), but can be also used for subsequent calculation of new setting of car parameters.

Car mechanical system is in fact non-linear. This is caused by the fact that (1) vehicle body and parts of wheel suspension make large movements (such as rotation) while the slip curves of tyres are non-linear; and (2) that many non-linear elements (e.g. rubber stops, non-linear characteristics of dampers, progressive springs etc.) are used to satisfy many contradictory needs. Today, modelling of these systems is done using the so-called multi-body programs such as ADAMS, DADS, Simpack etc. These programs offer user-friendly interface of modelling of mechanical systems or even provide users with dedicated car modelling applications via e.g. preset models of various types of axles. Although these programs are often very advanced, in general they do not offer tools to integrate mathematical models with behaviours of physical quantities measured during car tests. This hinders both the process of model verification and the utilization of these software programs for analysis of the real measured process. Such integration is therefore necessary to employ software programs during testing and fine-tuning the product. Model verification process is one of the most important stages of mathematical model development. Unfortunately, evaluation of model identity is often performed vaguely, as model outputs are compared with measured values by

17

CFD Approach to Stirling Engine Virtual Design Process

Václav Píštěk, *FME BUT*
Pavel Novotný, *FME BUT*

17.1 State of thermodynamic cycle in computational models of external heat supply engines

The zero order analysis is based on experience and is difficult to justify from any other viewpoint. William Beale from Sunpower, Inc. appears to be the first to note - in the 1970's – that the actual performance of many Stirling engines could be expressed in terms of a very simple equation. The Beale equation is particularly useful for quick back of the envelope calculations to determine the size, output or viability of a new Stirling system. The Beale equation was specifically concerned with the customary temperature regimes for Stirling engines of about 1 000 K for hot parts (stainless steel heater) and 300 K for cooled parts (cooling water or air). The analysis of ideal Stirling cycle could also be classified as the zero order analysis.

First order analysis: Gustav Schmidt, a German engineering professor, between about 1860 and 1870, developed what has become the classical analysis of the actual Stirling machine. The analysis provides for:

- harmonic sinusoidal motion of the piston or other reciprocating elements;
- swept volumes of expansion and compression spaces to be different;
- phase angle, which enables volume variations between expansion and compression space, to be varied over a wide range;
- dead space in the working space, i.e. some void volume of heat exchangers, regenerator and interconnecting passages and ducts, as well as clearance space in the compression and expansion cylinders.

The Schmidt theory represents a much closer approximation to the way of how a real Stirling engine operates in comparison with the ideal Stirling cycle. Nevertheless the Schmidt cycle is still highly idealized. The network output (of the Stirling power system) or the net work input (of the Stirling refrigerator or a hot pump) will be twice or three times less at best.

Second order analysis: In the mid 1960's Joseph Smith, a professor of mechanical engineering at the Massachusetts Institute of Technology, pioneered the technique of decoupled second order analysis. In this process, the results calculated by first order Schmidt type isothermal or Finkelstein type adiabatic analyses (Finkelstein, 1960) are adapted to allow various parasitic losses that arise in actual Stirling engines to be included.

18

Virtual Model of Stirling Engine

Michal Sikora, *FME BUT*
Radek Vlach, *FME BUT*

18.1 Introduction

In relation to worldwide increasing consumption of energies, the engines capable of using heat from external sources are often point of discussion. The Stirling engine is the most significant representative of such engines.

It is rather difficult task to achieve the highest possible parameters and efficiency in real operation. Simple models (Schmidt, 1862) that are based on the theory of ideal cycles only do not provide sufficiently relevant results, which would be applicable for designing of real engines. A significant improvement may be achieved if relations describing all heat transfers, incl. heat losses (Píštěk & Kaplan & Novotný, 2005a), are incorporated in the model. Such a model (supplemented by a mechanical part) can already be used for approximate estimation of suitable parameters. It is good compromise between the accuracy and the theoretical exigence of the model. Another – much more complex – improvement represents the simulation of the gas flow by means of the Finite Element Method (FEM) (Píštěk & Kaplan & Novotný, 2005b).

18.2 Model Character

Properties of the developed Stirling engine model (γ-modification) are as follows:

- The Stirling engine model is represented by a system of several non-linear differential equations, which is solved by numerical integration with a fixed time step. It is therefore a numerical model.
- The whole volume of the working gas is divided into three sub-areas. The properties of their volumes in time depend on actual piston and displacer positions. The "dead" volumes are adjoined to these three volumes and are not further considered.
- The model so far does not include the re-generator of the working gas temperature.
- The ideal gas, for which the state equations apply, is considered as working medium.
- The working gas temperatures in individual volumes are considered to be constant.
- The leakages of the gas from engine working part are not considered.

V

Modelling of Biomechanical Systems Characteristics

19

Device for Experimental Modelling of Biomechanical Systems Properties

Tomáš Březina, *FME BUT*
Zdeněk Florian, *FME BUT*
Pavel Houška, *FME BUT*
Lubomír Houfek, *FME BUT*
Vít Ondroušek, *FME BUT*
Martin Houfek, *FME BUT*
Lukáš Březina, *FME BUT*
Tomáš Návrat, *FME BUT*

19.1 Introduction

The end of the 20th century is characteristic of fast development of computer technology. On one hand, this development of hardware and software made it possible to find the answer to very extensive and complex tasks. On the other hand, it facilitated data processing in real time, which can be very well used in the area of control. The following part of our project covers plan of implementation of devices which are important from the point of view of solution to two significant clinical problems where device control in real time is essential. The first of them is related to the spine problems, the second one is connected to the most frequently applied complete endoprosthesis in term of their malfunctioning in consequence of abrasion.

1. The spine problems are ranked to the biggest problems of current health service because they usually afflict people in the active period of their lives. These problems are mainly caused by the changes of lifestyle (sedentary jobs, using cars, risk free-time sport activities, sitting in front of computer) and they lead to traumatological and degenerative changes of spine. In some cases they can be reduced by using implant (fixator, …). In this respect doctors are interested in correlation of clinical experience with mechanical properties of these implants which are determined experimentally on testing device. Physiological spine enables rotary and translation motion on all three axes. There is no technical, commercially manufactured, testing device which could make it possible to simulate the spine motion and loading in physiological extent. As a result, design of such a testing device, which would match the above-mentioned requirements, is included in this paper. In 2005 the concept based on Steward platform was chosen. This year the work focused on the construction and control of this device. Next year the work will focus on realization of experiments with spine implants.

2. In clinical practice there are a lot of problems connected to ensuring utility of endoprosthesis of all human big joints. The most numerous group is formed by the problems connected to endoprosthesis loosening, which is caused by the products of

20

Computational Modelling of the Biomechanical Systems Properties

Zdeněk Florian, *FME BUT*
Vladimír Fuis, *FME BUT*
Tomáš Návrat, *FME BUT*
Martin Štekl, *FME BUT*
Milan Koukal, *FME BUT*

20.1 Introduction

The subject of computational modelling is the computational determination of mechanical properties of systems examined via experimental modelling described in chapter 18. Computational modelling enables determination of mechanical properties which are hard to determine using experimental modelling and it also enables to generalize the results of experimental modelling.

In clinical practice there are a lot of problems connected to ensuring utility of endoprosthesis of all human big joints. The most numerous group is formed by the problems connected to endoprosthesis loosening, which is caused by the products of abrasion. These microscopical particles cumulate on the boundary between endoprosthesis and bone. They are conducive to negative reaction of organism which first develops edge and complete endoprosthesis loosening. Endoprosthesis manufactures together with doctors and biomechanics try to minimize the wear of articulation areas. Solution to this problem is of a complex character. The size of abrasion is influenced by the processes in living organism. However, it mainly depends on mechanical relation in the connection between the acetabulum and the head of complete endoprosthesis. The aim of this part of the project is to determine relation between wear and mechanical properties of complete endoprosthesis or more precisely in the contact with complete endoprosthesis. The size of abrasion for a particular type of endoprosthesis can be determined only in an experimental way. That is why one part of this project concerns the device development, which is described in details in the part (Březina, 2005). On the contrary, mechanical quantities describing the features of the contact between two bodies (process of contact pressure, size of contact area, size of contact area when moving) can be determined effectively only by calculation.

Computational modelling enables to generalize given results and thanks to that it raises their importance for clinical practice. Therefore the computational modelling of distribution of contact pressure at philological hip joint and its comparison with the case, when the surface artificial joint was used, were implemented (see Chapter 20.3). At surface artificial joint the

1

Modern Mathematical Methods in Control Theory

Josef Šlapal, *FME BUT*
Jan Čermák, *FME BUT*

1.1 Introduction

Mathematical methods of control theory are among those fields of mathematics that can be thought of as classical while currently undergoing rapid development. Even if a number of key ideas of these methods (non-integer order derivative of a function, time-lag differential equations, etc.) were already known to the 18th and 19th century mathematicians, it is only in recent decades that these fields have really been developing. Such development was spurred most of all by the formulation of a number of engineering problems and it was their mathematical formalization that led to the use of some of these methods. A prominent part was played by the problems thematically belonging to control theory.

In the sequel, we will specifically deal with several fields of this theory that were the object of our research in 2006. They include dynamic optimization of controlled systems, analysis of time-lag and fractional differential equations, which entails studying algebraic methods suitable for finding solutions to such equations, algebraic control theory based on the properties of polynomial rings and matrices and on the behaviour of linear diophantine equations and, finally, studying closure operators to be used in image data processing.

Let us first consider a controlled system whose dynamics can be described by the differential equation

$$f(t, y(t), y'(t), \dots, y^{(n)}(t)) = u(t) \qquad (1)$$

where f *is* a (generally non-linear) function of n+2 variables, y is a state variable and u is a control variable. In a linear case, this equation acquires the following form

$$a_n(t)y^{(n)}(t) + \dots + a_0 y(t) = u(t). \qquad (2)$$

One of the essential questions of control theory is the problem of finding among all feasible controls $u(t)$ transforming the system from an initial state y_0 into a target state y_f (or a target set K) such a control $\hat{u}(t)$ for which an object functional $J = J(u(t))$ reaches its global minimum. This control is then called optimal and the corresponding state variable $y(t)$ is called an optimal state trajectory. Different approaches can be used to find a solution to a problem formulated in this way. Dynamic programming is a rather general and widely used method of solving optimization and decision problems of control theory. It is based on Bellman's principle of optimality and, mathematically, is represented by a non-linear partial differential equation as a necessary condition of optimality. Our goal is to present the application of Pontryagin's maximum principle, another very efficient method of solving

2

Physical Engineering: Research Support of Mechatronic Models

Jaroslav Pokluda, *FME BUT*
Pavel Šandera, *FME BUT*
Miloslav Ohlídal, *FME BUT*
Miroslav Doložílek, *FME BUT*
Anna Ryndová, *FME BUT*
Bohumil Vlach, *FME BUT*

2.1 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., 2005), the investigations performed by the group of the Institute of Physical Engineering (IPE) of FME come under three categories. The first category represents a basic research focused on extending knowledge in physical properties of materials considered either as appropriate for modelling of mechatronic systems or as “model” materials of similar but simpler crystalline structure. The second category concerns an applied research closely associated with mechatronic models under development. The third category represents a direct collaboration of IPE with the industry in the development of mechatronic systems. A part of the investigation was accomplished in a close collaboration with prominent domestic and foreign universities and research institutes. Moreover, industrial partners were also involved in some research phases. The results achieved by these structurally rich and interdisciplinary themes are hereafter successively presented according to these categories.

2.2 Modelling of Mechanical Properties and Testing of Surface Roughness of Eligible Materials

First-principles modelling of fcc metals and Nitinol

In addition to previous calculations of theoretical shear strength and its dependence on the stress applied perpendicularly to slip planes on Al and Cu, our study was extended to several other fcc metals (Au, Ir, Ni and Pt). The obtained results were presented at *14th international Conference on Strength of Materials* in Xi’an, China. The contribution passed the review procedure and was accepted for publication in a highly impacted journal Materials Science & Engineering A that will appear in the next year (Černý & Pokluda, in print).

II

Modelling of Systems with Electromechanical Energy Conversion

3

Mechatronic Systems with Magnetic Transmission Force and Magnetic Levitation

Josef Lapčík, *FEEC BUT*
Tomáš Láníček, *FEEC BUT*
Petr Huták, *FEEC BUT*

3.1 Introduction

The main aim of this work was the drive design of the mechatronic system consisting in extra corporal pumps for the artificial heart assist device or possible total artificial heart, including pump's electrical drive and modern control system for motor and magnetic bearing.

The mechanical part, solved in the Victor Kaplan Department of Fluid Engineering, deals with the principle of the rotating pump, whose parameters should be the same as the parameters of the human heart and the rotating speed is about 2000 rpm. The blood properties and related problems are not considered.

The work was focused on the design of the drive system consisting of the slot-less permanent magnet synchronous motor, magnetic active bearing and modern control system design for motor torque and bearing rotor position. Two ways conception was concentrated on the extra corporal and intra corporal pump systems, used as a heart assist device or total artificial heart.

The results of the analysis realized on the different types of pump's systems show that the blood degradation can be decreased by low vasotonia The pump's design concept was based on this. For the blood flow the most dangerous are those 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 the concept design for both the pumps (extra-corporal and intra-corporal).

The total artificial heart (TAH) systems can only use miniature pumps and drives. For the latest systems are mostly used high speed drive's motors and consequently high value of the vasotonia. Thus the design for this pump's system must follow the design requirements for the small size, acceptable speed and power output.

When the design is made for an extra-corporal heart assist device, the size is not a priority and the hydraulic design is simpler and we can find the construction where is not disproportion with the heart characteristic. Design problems could be made simpler when using non-wet able materials with respect to the blood. In the Victor Kaplan Department of Fluid Engineering the following pump's principles were designed:

4

Control of Active Magnetic Bearing

Milan Turek, *FME BUT*
Tomáš Březina, *FME BUT*

4.1 Introduction

Active magnetic bearing (AMB) inhibits a contact between the rotor and the stator and so it eliminates the limitations of a classic bearing. Therefore it is possible to use the AMB in specific and extreme circumstances where a classic bearing is inapplicable. The electromagnets located in the stator of the bearing create a magnetic field. The force caused by the magnetic field keeps rotor levitating in the desired position in the middle of air clearance. So the control of the magnetic field is necessary.

Nonlinearity of the magnetic force behavior makes the control difficult. Although a nonlinear controller can be designed (Charara, De Miras & Caron, 1996), its design is complicated. Much easier is to develop a linear model describing the magnetic force approximately. The problem is that such model describes the behavior of the magnetic force only near the operational point. The linear model is usually developed for the case when both opposite electromagnets are switched on and the difference in feeding current is controlled. But in this case, there exists high power consumption (Cho, Kato & Spilman, 1994). Another approach is to recalculate the desired action to the corresponding input voltage of the electromagnets to linearize the response of the AMB to the action.

The LQ design can be used for the optimal controller design of the linearized AMB afterwards. The common problem of the optimal control design methods is the fact that they are not robust. Furthermore, the model of the AMB used to controller design is approximate only. CARLA method can be used to improve the performance of the designed controller. The resulting controller is simple and can be easily implemented. But the AMB is a very quick and unstable system, so hardware with high performance is needed to implement more complicated control methods. Such hardware has a high cost and so a slowing down and stabilization of the AMB's response would be extremely useful. It can be achieved by a state control of the AMB.

5

Control of Stator Winding Slot Cooling by Water

Radek Vlach, *FME BUT*

5.1 Introduction

The project is concerned with computational and experimental simulations of stator winding heating of a synchronous machine. The synchronous machine operates as a high-torque machine with maximal torque 675 Nm at 50 rpm.

The aim was to find an algorithm for pump drive to keep the temperature of stator winding below the safe limit.

Software MATLAB/SIMULINK was used for computational simulation of water cooling drive. Computational simulations describe direct stator winding cooling by water.

Experimental device was used to verify the computational simulations and the drive algorithm.

5.2 Computational model

The computational model geometry is based on a real synchronous machine. It describes heat of a part of the synchronous machine mainly stator winding. The machine has 36 pairs of winding slots and permanent magnets on the rotor. Rotor with magnets is not modeled, because the heat loss can be found in the stator winding only, and the rotor effect on the heating of stator is not significant. The brass tubes were comprised in the middle of each winding slots. Cooling water flows in the brass tube. The machine was assumed as symmetrical, so only one pair of winding slot is modeled.

The thermal network method (Hak & Oslejsek 1973) was used for description of machine heating. Thermal networks (Fig. 1) consist of eight nodes. Last three nodes (6, 7 and 8) are used to describe heating of cooling water. Thermal model represents a transient state, because the load of the machine varies.

6

Optimal Design of Vibration Generator Function Product and Verification of Model

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

6.1 Introduction

The aim of this project is development of the vibration generator, which generates electrical energy from an ambient mechanical vibration. This generator will feed wireless sensors without the use of primary batteries. The generator extends the lifetime of the wireless sensor that can be mounted without any problems inside engineering's constructions or can be placed inside embedded structures. The design of the vibration generator is tuned up to the frequency and amplitude of the excited vibration. The appropriate vibration generator can produce the required power.

The designed vibration generator will be used as a source of energy for wireless sensors developed within the framework of the WISE project that studies the use of wireless sensors in aeronautics applications.

The vibration generator is tuned up to the stable resonance frequency (34 Hz) of the ambient vibration. The generator is capable of generating electrical energy with output power around 5 mW and output voltage of 2.5 V. The generator is excited by vibration with the amplitude range 50 - 150 μm; i.e. the level of vibration 0.2 - 0.7 G. The size of generator is not limited, but the aim is to design a very small device; the size depends on the possibilities of manufacture.

6.2 Electromagnetic vibration generator

The generic electromagnetic vibration generator consists of:

- **Resonance mechanism** is tuned up to the frequency of excited vibration and it provides a relative movement of magnetic circuit.
- **Magnetic circuit** provides a magnetic flux through coil. The magnetic circuit is a part and major mass of resonance mechanism.