4th International DAAAM Conference
"INDUSTRIAL ENGINEERING – INNOVATION AS COMPETITIVE EDGE FOR SME"
29 - 30th April 2004, Tallinn, Estonia

MECHATRONICS SYSTEM DESIGN IN CONCEPTUAL STAGE

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Abstract: *In today's modern world increasing demands exists for mechatronics system design process. Therefore it is important to pay more attention for optimisation of the design process, especially for conceptual stage. It is important to employ new promising technologies for effective design process as the conceptual stage plays important role of the final cost of the product. The paper is a survey of product development process focusing conceptual stage, methodologies and techniques in it. The methodologies used and methodologies under the research in this field are studied. New promising techniques like genetic algorithms, neural networks, intelligent agents, etc. are described and idea of the new methodology based the combination of these techniques is considered.*

Key words: *mechatronics system conceptual design, artificial intelligence.*

1. INTRODUCTION

Decisions made during conceptual design stage have significant influence of a final product. It has been estimated that more than 75% of final product cost is settled in conceptual stage. Different methodologies for detail product design have been proposed and applied, but even the highest standard of detailed design cannot compensate for poor design concept formulated at the conceptual design stage. In spite of this, the automation of the conceptual design phase development becomes more important, also because the complexity of the mechatronics system and rising of new techniques together with increase of computational power as well as time and cost saving demands in today's rapid world. Many efforts are still needed to develop industry proved semi-automated tool for conceptual design phase. To archive this goal we need to define problem in unified way in the phase where very big uncertainty is common feature. This is not trivial task concerning that it must be easily understandable for product designers and other engineering people as well as customer. Later, semi-automated algorithm can be developed based on new techniques. An interactive process between engineer and software tool can lead for optimal design concept with effective consumption of time and cost. Together with interactive engineering process the semi-automated software tool makes easier development of conceptual design process and optimal conceptual solution.
In this objective the paper gives a survey of design process in conceptual phase and techniques for this phase. The survey covers resent research in problem abstraction, algorithm generation and new modelling techniques as well.

2. PRODUCT DESIGN

Product design in general can be described as certain phases, need to be passed, although products are very different, even in single domain. These phases can be formulated as specification definition, conceptual design, product design and product support (Fig. 1.)

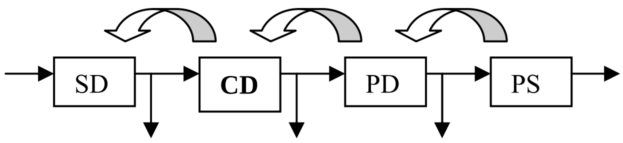

Fig. 1. Product design phases, where SD - Specification definition, CD - Conceptual Design, PD - Product Design & PS - Product Support.

In the specification phase the main goal is to completely understand the design problem what correspond to the customer requirements. The biggest problem here is that there is very little information about design problem. The result of this stage is engineering specification and measurable behaviours of the future product that will help to measure the quality, later on the design process.
The next stage, conceptual design, is very important as decision made here affects most the overall design process. In this stage uncertainty and limited knowledge, but big design freedom as well, are major keywords. The danger here is that designers take the first idea and start to refine it towards a product. This is a weak methodology because there is great possibility that this idea is not optimal or best one at all. Therefore it is very important to generate more than one or two design candidates. Then it's much more plausible that designer may find good solution (Ullman, 2002).
One goal of this stage is to choose best alternatives with the least expenditure of time and other resources. Techniques generating concepts and making decisions are used interactively as knowledge is increasing with new ideas (Ullman, 2002). The iteration is much less expensive during this phase than on the following phases. The result of this stage is usually system architecture, functional and behavioural specification of the future product.
In conceptual design process, designer takes statement of the problem and generates broad solution to it in the form of schemes, block diagrams, etc. In this stage engineering science, practical knowledge, commercial aspects, product methods and others relevant aspects need to be brought together, and the most important decisions are taken (French, 1999).
Techniques and methods for conceptual design are not for replacing designer or generate complete solutions. They are intended to improve the quality and speed of the design process and to help designers at following ways:

- by increasing insight into problems, and speed of acquiring insight,
- by reducing the size of mental step required in the design process,
- by diversifying the approach to problems,
- by generating design philosophies for the particular problem in question,
- by documenting design process progress,
- by improving communication between designers and/or other relevant people (French, 1999).

The product design phase is most time and labour consuming part of design process. Here the concept generated and evaluated in last stage, will be fully developed and manufactured.
The product support phase covers all activities related with support: support for manufacturing/assembling, support for vendors, support for customer, etc. Techniques for conceptual design (Ullman, 2002).

2.1. Construction of Table of Options, Functional Analysis

Construction some sort of table of option is usually used for combinative methods. Since the number of different options is often too large, only separate options are usually displayed. The option can be viewed in different ways and main possibilities to construct a table are followings:

- alternative means of performing essential functions,
- alternative solutions to various smaller design problems or sub-problems arising within the main problem,
- a classification derived from a study of known solutions of the same or allied problems,
- alternative spatial arrangement, configurations or orders,
- mix of previous (French, 1999).

The choice depends on the nature of the problem and the preference of the designer.
An important tool for constructing table of options is a functional analysis, which sets out the essential functions that the designer is required to perform. Comparing these functions, compatible combinations can be figured out.
Basic steps of functional analysis:

- parametric mapping of options,
- alternative configurations,
- elimination procedures, reduction ,
- evaluation of options,
- grouping functions,
- amalgamation or condensation,
- elimination of a single options,
- synthesis – kernel table (French, 1999).

2.2. Mathematical models

Even mathematical models are quite obvious in product design process, it not always used in conceptual stage. Here some simple mathematical model and calculations can be used. Sometimes the best is way to devise mathematical model of his own, what is not a trivial task, but shows good competence of the designer (French, 1999).

2.3. The search for alternatives

The search of alternatives is very common technique in conceptual design stage and should be always considered. A great help for solving design problem, as well as getting better overview of the problem is comprehensive list of known engineering means. One particular alternative that can always be considered and occasionally leads to a profitable idea is to dispense a function altogether. Another type of alternative easily found by a systematic approach is that involving inversion, either in the narrow sense or in a wider sense (French, 1999).

2.4. Logical chains

A device sometimes leading to a unique practical solution is logical chains of reasoning. Here logical statements and deductions are made and linked. The weak point of this device is that in most case relevant logical reasoning can be made as hindsight (French, 1999).

2.5. Past practice

Past practice is definitely most widely used, as it is natural for human being. The problem here is that designers sometimes takes automatically previous solutions for new design problem, and this solutions may not be good solution in current circumstances and maybe even not the best solution at all for this kind of problem. It is important to realise this issue and always consider other solutions, for example by a systematic review of the logic behind the scheme in question and a diligent search for viable alternatives (French, 1999).

2.6. Problem Solving and Analytical Techniques

Creative thinking and problem solving techniques are widely use not only engineering field. As conceptual design stage is very creative in its nature these techniques are important to know and use. Most known techniques are:

- Brainstorming - generating options,
- Critical Path Analysis - planning and scheduling complex tasks,
- Decision Trees - powerful quantitative analysis of decision impact,
- Force Field Analysis.

Detailed information about problem solving and creative techniques can be found from reference (Higgins, 1993) and (Dombroski, 2000).

2.7. Use of CAE tools

As described previous section the design process is divided into stages, starting with specification analysis to the product retirement. Successful computer aided tools have been developed and used many years to support product design stage, namely parametric design, configuration design, product analysis, layout design or Computer Aided Design (CAD), Finite Element Method (FEM), and supporting tools like Product Data Management (PDM), Enterprise/Electronic Document Management (EDM), Virtual Reality (VR) and so on. But only limited work has been done to support conceptual stage of product development process. At recent years considerable attention is paid for this area. New concepts and ideas have been developed, but only some of them has been expanded to the test product and are used for testing purpose. Tools to support conceptual design stage have been limited in their expertise because of the variety of physical concepts that need to be represented. Another difficulty is the lack of knowledge how the conceptual design stage interacts with the product design stage (Madhusudan, 1995). Additionally great creativity must be ensured in tremendous indeterminate environment.
There are many promising new techniques that can improve the design process in conceptual design phase. These techniques are described in next section.

3. STATE-OF-ART

Many non-traditional techniques and methods on engineering problem solving domain have been come to the fore recently. One of the reasons is definitely increase of the computing power. These opportunities allow us to solve the engineering tasks, which can’t be described with linear differential equations and are non-deterministic. The techniques for more advanced mechatronics system modelling, which is taken into account, are followings:

- Artificial neural networks,
- multi-agent systems,
- genetic algorithms,
- fuzzy planning,
- etc.

3.1. Artificial Neural Networks

Artificial neural networks (ANN) are collections of mathematical models that emulate some of the observed properties of biological nervous systems and draw on the analogies of adaptive biological learning. The key element of the ANN paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements that are analogous to neurons and are tied together with weighted connections that are analogous to synapses.

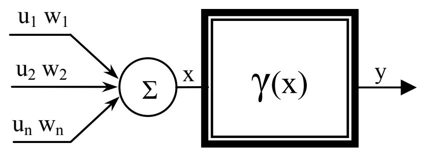

Fig. 2. Neuron structure

Learning of ANN typically occurs by example through training, or exposure to a truthed set of input/output data where the training algorithm iteratively adjusts the connection weights (synapses). These connection weights store the knowledge necessary to solve specific problems (Battelle Memorial Institute 1997).
Neural networks are designed to work with patterns - they can be classified as pattern classifiers or pattern associators. The networks can take a vector (series of numbers), and then classify the vector (Matthews, 2000).
Neural Networks are usually used for classification (i.e. market profiles, medical diagnosis, image recognition, etc), forecasting (i.e. future sales, production requirements, energy requirements, weather, etc.) and modelling (i.e. process control, systems control, dynamic systems, signal compression, robot control, etc.)
The problems with neural networks are the lack of defining rules to help construct a network given a problem - there are many factors to take into consideration: the learning algorithm, architecture, number of neurons per layer, number of layers, data representation and much more (Matthews, 2000).

3.2. Genetic Algorithms

Genetic Algorithms (GA) are basically algorithms based on natural biological evolution. The architecture of systems that implement genetic algorithms is more able to adapt to a wide range of problems. A GA functions by generating a large set of possible solutions to a given problem. It then evaluates each of those solutions, and decides on a "fitness level" for each solution set. These solutions then breed new solutions. The parent solutions that were more "fit" are more likely to reproduce, while those that were less "fit" are more unlikely to do so. In essence, solutions are evolved over time. This way you evolve your search space scope to a point where you can find the solution (Hsiung & Matthews, 2000).
A GA needs to know only two things about a problem:
1. The set of possible solutions needs to be coded as a set of strings,
2. For each string (solution) there must be a way of measuring how good it is compared to the other strings.
The function that performs this task is the “fitness function”.
The Fundamental Theorem of Genetic Algorithms:

$$M(H,t+1) \geq M(H,t)\frac{f(H)}{F}(1-p_1-p_2)$$

where
M(H, t) number of strings in population 't' with the schema 'H'.
f(H) average fitness of the strings with the schema 'H'.
F average fitness of the entire population.
p_1 probability of the schema being destroyed by crossover.
p_2 probability of the schema being destroyed by mutation.
This equation describes exponential like growth of 'good' schema from one generation to the next. GAs are designed to search for, discover, emphasise and breed good solutions (or "building blocks") to a problem in a highly parallel fashion (Hsiung & Matthews, 2000).

3.3. Multi-Agent Systems

A multi-agent system (MAS) is a loosely coupled network of problem-solver entities that work together to find answers to problems that are beyond the individual capabilities or knowledge of each entity (Durfee, et al., 1989). More recently, the term multi-agent system has been given a more general meaning, and it is now used for all types of systems composed of multiple autonomous components showing the following characteristics:

- each agent has incomplete capabilities to solve a problem,
- there is no global system control,
- data is decentralised,
- computation is asynchronous (Jennings, et al., 1998).

4. SOLUTION IDEAS UNDER THE RESEARCH

As mentioned above, conceptual stage of product development process is extremely important for optimal solution of final product. Although there are methodologies for modelling conceptual design stage, most work is done respectively designer experience and personal predilections. In last decade many non-traditional techniques have been got widely available, because of rapid increase of computational power. Therefore the great interest for exploiting new techniques for modelling purpose have been arisen. Few attempts to combine non-traditional techniques for early stage modelling are described in this chapter.

4.1. Mechatronics conceptual design supported by Multi-Agent system

Rzevski introduces the concept of mechatronic systems conceptual design with multi-agents technology. Intelligent agent technology for designing mechatronics system in conceptual phase is used. Introduced technology can be used to design small intelligent units capable of competing and/or co-operating with each other on specified task and making decisions under the condition of uncertainty through a process of negotiation. The major elements of these systems are intelligent agents, which are software objects capable of communication with each other, as well as reasoning about received messages (Rzevski, 2003).

4.2. Mechatronics system design together with bond graphs

Many concepts of modelling early design stage are based of exploiting the bond graphs (BG). A bond graph is a domain-independent representation of a physical system. By this approach, a physical system can be represented by symbols and lines, identifying the power flow paths. The lumped parameter elements of resistance, capacitance and inertance are interconnected in an energy conserving way by bonds and junctions resulting in a network structure. From the pictorial representation of the bond graph, the derivation of system equations is so systematic that it can be algorithmised (Samantaray, 2001).

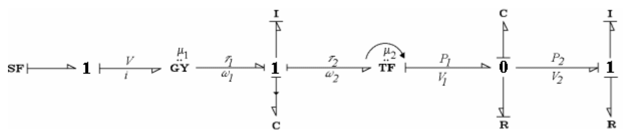

Fig. 3. Example of the Bond Graphs

Genetic Algorithms Research and Applications Group (GARAGe) has developed method using bond graphs and genetic algorithms. They suggest a unified and automated design methodology for synthesising designs for multi-domain systems. The approach described will evolve new designs (represented as BGs) with ever-improving performance, in an iterative loop of synthesis, analysis, and feedback to the synthesis process.

The approach combines bond graphs (BGs) for representing the mechatronic system models with genetic programming (GP) as a means of exploring the design space. The flow of the entire algorithm is shown in Fig. 4. The user must specify the embryonic physical model for the target system (i.e., its interface to the external world, in terms of which the desired performance is specified). That determines an embryonic BG model and corresponding embryo (starting) element for a GP tree. From that, an initial population of GP trees is randomly generated. BG analysis is then performed on the BG specified by each tree. This analysis consists of two steps—causal analysis and (if justified) state equation analysis. Based on those two steps, the fitness function is evaluated. For each evaluated and sorted population, genetic operations—selection, crossover and mutation—are performed. This loop of BG analysis and GP operation is iterated until a termination condition is satisfied. The final step in instantiating a physical design would be to realise the highest-fitness BG in physical components (Seo, et al., 2003).

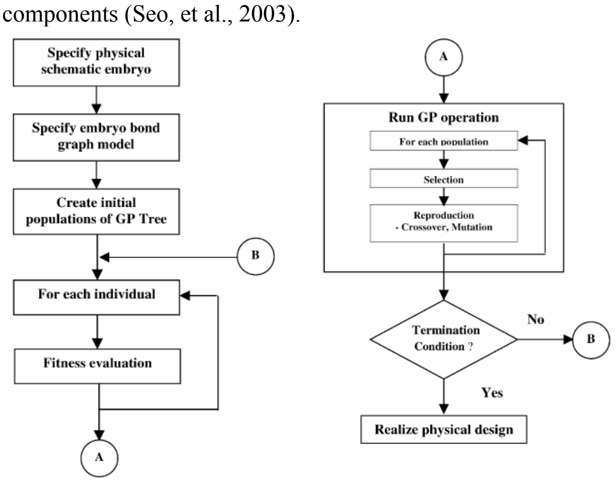

Fig. 4. The GARAGe BG/GP algorithm (Seo, et al., 2003)

The approach developed by Granda integrates theoretical principles of bond graph modelling and graphical software tool called Computer Aided Modeling Program with Graphical input (CAMP-G). The tool implements the theoretical principles of bond graphs and then the models are transformed into MatLab/Simulink. The system generates first order state space differential equations, symbolic transfer functions and Simulink S functions in source code from such as MatLab .m or .s files, which Simulink can process. The idea is to generate automatically the differential equations from the bond graph model. This means the generation of the system A, B, C, D matrices to produce the state space representation and also the computer generation of transfer functions and output equations in symbolic form. For non-linear systems this implies a set of equations where the individual non-linear constitutive relations can be accomplished as well as any conditional switches, non-linear time dependent effects and of course a form suitable for logical execution of all these by MatLab and the non-linear S functions of Simulink (Granda, 2002).

5. FUTURE WORK

Modelling complex mechatronic systems like most of the real-life products are, there is not reasonable to concentrate only to the one particular method. The mechatronics problem needs more complex approach and one of the possibilities is to combine different suitable techniques and methods.

The ongoing research is studying the best way to combine techniques and methods described above. The research result so far is the specification of the methodology for effective early design process.

6. CONCLUSIONS

Important question of design process is: what the customer actually needs. The problem, how to put together customer need and design result where big uncertainty and lack of requirements specification is present, must be solved quickly and effectively. Here the new systems, based on artificial intelligent methods can play a significant role.

A shot overview of techniques and methods for advanced mechatronics modelling is studied and described. This work is the base of the current research project, aimed to develop new methodology for mechatronics system design on the conceptual stage. To develop new methodology, complementary solutions have to be further evaluated. Several state-of-art techniques have to be combined for automated and optimised mechatronics design methodology.

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8. ACKNOWLEDGEMENTS

This work is supported by Estonian Science Foundation Grant No 5908.