INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

SELECTION OF DESIGN CONCEPTS USING VIRTUAL PROTOTYPING IN THE EARLY DESIGN PHASES

Mikko Seppälä[1], Andrea Buda[1] and Eric Coatanéa[1]
(1) Aalto University, School of Engineering, Finland

ABSTRACT
One of the challenges in the early phases of a product development process is the need to make fundamental decisions regarding the selection of design concepts. The use of virtual prototyping right from the early stages provides a means to rapidly develop design variants that can be analyzed in order to support these decisions. This article presents a systematic method for the evaluation of design concepts based on the performance assessment of dynamic virtual prototypes. The implementation alternatives for different functions are summarized in a Zwicky matrix. To manage the testing process and to analyze the results we use the Taguchi design of experiments method. The results are finally used to select the best design concept out of the Zwicky matrix. The details of the proposed method are presented and applied for the development of a vacuum cleaner robot. In order to describe the dynamic behavior of each concept immersed in its environment, our approach leverage on a 3D physics simulator connected in closed loop with a finite state machine control logic. This approach provides a technique improving the objectivity of the early decision process without being obliged to develop costly and time consuming real prototypes.

Keywords: Concept selection, Virtual Prototyping, Early design, Design of Experiments, Robotics

1 INTRODUCTION
Design and product development processes starts with the formalization of a set of requirements. Once these requirements are validated, the next step is to find potential design options that would meet these requirements. At the end of this creative process the design-team usually has several possible concepts and it is necessary to make a decision which concept or concepts should be selected for further study and development. For making this choice several methods have been suggested: Pugh’s concept selection [1], weighted rating method (WRM) [2], analytic hierarchy process (AHP) [3] and Electre method [4]. Honkala et al. [5] had compared these four commonly used methods. They concluded that the ranking order of the concepts is the same regardless of the method used; only in certain cases the choice of a selection method can have a significant effect on the result. They suggest to start with simpler methods like Pugh or weighted rating method, and if the results show only small differences, another method should be used in order to get a wider perspective on the results.
These methods are useful in systematically managing the data related to the decision. However, the data used in making the decision is usually subjective. The designers select the factors that are taken into account and evaluate them based on their own knowledge or intuition, since by traditional methods it is impossible to prototype all the concepts. Furthermore, in the very beginning of every project only a limited amount of information is available to support the selection process. A wrong decision at this stage can seriously compromise the success of a product. Thus, any additional information that can reduce the risk of certain choices is extremely valuable. Gaining information using traditional development methods might require a significant amount of time; for this reason the capability of modeling meaningful virtual prototypes rapidly is a crucial aspect of our approach.
The use of virtual prototyping tools provides a mean to rapidly create dynamic models of the product concepts in their intended use environments. In this way the performance of different concepts can be analyzed more objectively. Many aspects of virtual prototyping are similar to conventional simulation. Conventional simulation is understood as only to gain the understanding of a particular product aspect [6], while virtual prototyping has a bigger scope as it attempts to address all of the related product aspects in order to substitute physical prototypes [7].

What is not addressed by the previous definitions is the level of detail requested from the virtual representation of the system. An important point of our work is the development of models that are just detailed enough to support the immediate need. The same model can be further expanded by using specialized CAE tools, if a higher level of fidelity is required.
In this article we propose a systematic method for the evaluation of different design concepts based on the performance assessment of dynamic virtual prototypes. The proposed method can be used alongside the traditional concept selection methods to obtain more objective information of the system in early design stages. Starting point for this method is the Zwicky matrix [8], where the implementation alternatives of the different functions of the system under development are summarized. To evaluate the effect that each alternative has on the performance of the product and to keep the number of test runs manageable, we applied the Taguchi design of experiments (DOE) method [9]. The key phases of the suggested method are shown in Figure 1. The details of the proposed method are presented and applied for the development of a robotic vacuum cleaner.

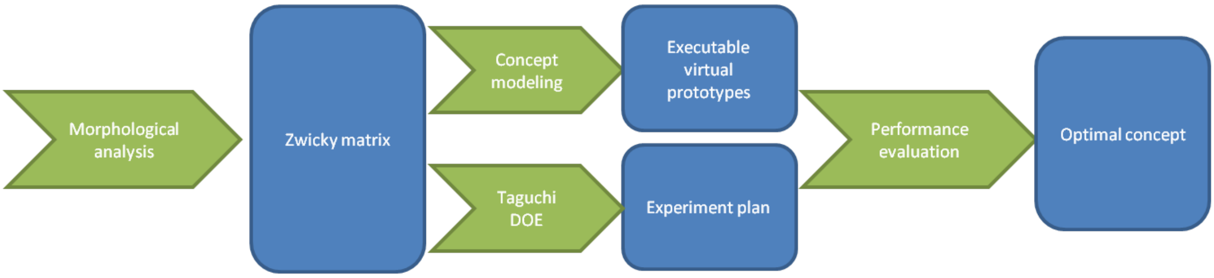

Figure 1: The suggested process for VP based concept selection

2 PREVIOUS RESEARCH

The advantages of using digital models, instead of physical prototypes, have been analyzed from different perspectives by a large number of researchers. In literature most of the approaches intend virtual prototyping to be a static 3D representation of the system, used to evaluate form and fit, ergonomics, assembly-disassembly capability and manufacturability [10], [11]. In the field of robotics and mechatronics the use of simulated environments in the early phases of the development is a growing trend. A virtual prototype can also assist in different stages of a product development process of complex aerospace systems [12].
Virtual prototyping (VP) has been used to provide access to cost prohibitive or unavailable sensors and components [13]. Also, physical prototypes may be limited in availability, while a virtual prototype can be easily replicated enabling concurrent engineering [13]. Additionally, the simulated environment is always available, making testing very cost and time efficient [14]. Examples of successful adaptations of this approach can be found in [15] and [16]. Our approach uses a virtual prototyping environment similar to the ones described in [17] and [18]. However, we are not focusing on the technical detail of such kind of environments, but on the exploitation of these tools in design concept selection.

3 SUGGESTED METHOD

3.1 Concept Generation and Morphological Box

General morphological analysis (GMA) is a method developed by Zwicky [8] for structuring multi-dimensional, non-quantifiable problem complexes. The method was developed to analyze problems in the fields of astronomy and space technology, but it is applicable to all kinds of problems where different solution alternatives and their relations have to be identified and investigated. The GMA is based on the concept of a morphological box, which is also known as a Zwicky box. To form the box first the solution parameters of the problem or system investigated have to be identified. For each parameter a range or selection of values is selected. From the n parameters a n-dimensional matrix can be derived, where each cell corresponds to a different combination of the solution parameters forming a unique solution to the problem. Here we use the Zwicky matrix as the starting point of the concept selection process.

To present our concept evaluation and selection method we present a robotic vacuum cleaner as a sample case. We want to find a design for the robot that would be most efficient in cleaning a room. As designing the robot we consider three functionalities it should have:

1. Move in a room.
2. Navigate as large area as possible as fast as possible.
3. Sense and avoid obstacles in the room.

In the Zwicky matrix shown in Figure 2 we present different possible implementation options for these functions. This representation is very limited to keep the example simple and informative. Also we are not going into details about selecting the options *for* the Zwicky matrix, but will focus on selecting the best concept from the known options *in* the matrix.

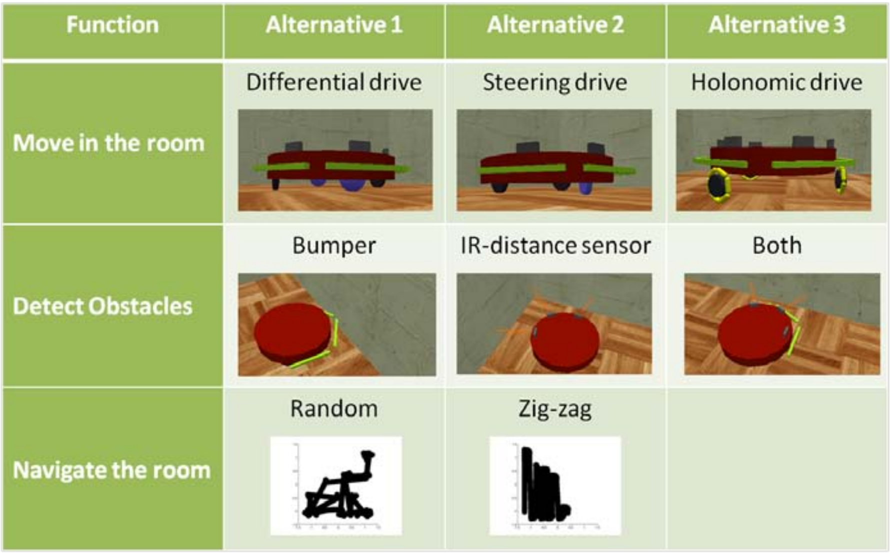

Figure 2: Zwicky matrix of the possible vacuum cleaner concepts

In the Zwicky matrix we have listed options for the robots movement system structure, sensors and algorithm used for navigating the room. For movement we consider the traditional differential drive, an omni-wheel based holonomic drive and steering drive system with a steerable front wheel. Different robot wheel configurations have been discussed in detail e.g. by Batlle and Barjau [19]. For navigation we consider two algorithms: random navigation where the robot turns to random direction whenever it encounters an obstacle and a more controlled algorithm where the robot drives in a zig-zag pattern with the aid of a compass sensor. To sense the obstacles we are interested in testing IR-distance sensors, micro-switch bumpers and a combination of the two.

3.2 Virtual prototype for robot performance evaluation

In the field of robotics several 3D simulation tools have been introduced in the academia [17], [20] and also as commercial products [18]. These simulation environments have many similarities with modern 3D video-games and some are actually based on video game engines. We selected to use a commercially available robot simulator Marilou by the AnyKode Inc [21]. The simulator is based on the Open Dynamics Engine physics library, so the properties discussed in [22] apply also to it. The Marilou software provides a graphical user interface for creating virtual environments with real-time dynamic physics simulation, including gravity and collision simulations for the objects in the virtual world. The objects consist of geometric primitives like cubes, cylinders etc. Between the objects different types of joints can be created to form mechanisms. To the joints and objects one can add programmable actuators and sensors to create automated devices, such as robots.

With a graphical user interface it is very fast to create a virtual representation of a typical room that the vacuum cleaner robot could be used in. We created a virtual 3m by 3m room shown in Figure 3, with dynamic objects. The room has a carpet that is slightly elevated from the floor and has an increased friction coefficient. To model typical obstacles the robot might encounter in a living room, tables and chairs with thin legs were added, as well as children’s toys: a ball and some building blocks. All these objects react dynamically to the robot.

Figure 3: The virtual test room

The different structures of the robot were modeled as well, using simple geometric primitives and the simulated actuators and sensors that the modeling tool provides. To rapidly develop a dynamic and functional prototype the robots control software needs to be developed with efficient tools. Here we suggest the use of finite state machine (FSM) models and code generation. This feature is supported by MATLAB Simulink, which can be easily interfaced with the Marilou virtual prototyping environment. An example FSM implementation of the robots random navigation algorithm is shown in Figure 4. The goal of our virtual prototype is not to be an accurate representation of the final robot, but rather a way to make rough estimates of the performance of different high level implementation options.

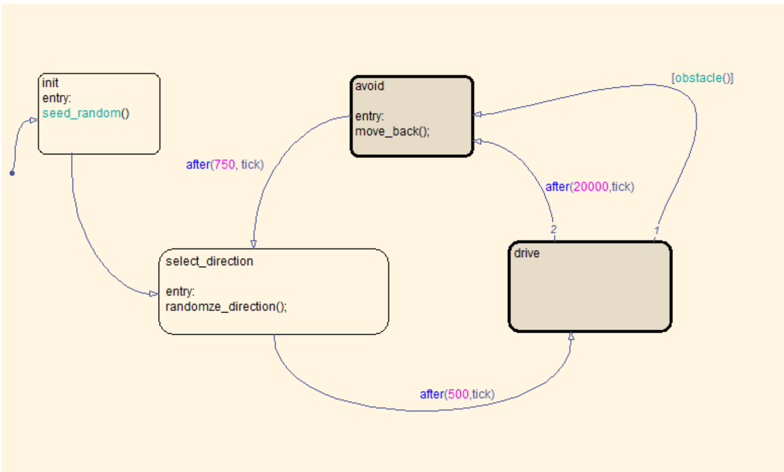

Figure 4: The FSM implementation of the robot's random navigation algorithm

3.3 Finding the Best Concept

If a Zwicky matrix has a lot of cells the number of different concepts that can be derived out of it gets fast out of hand. Thus, we suggest the use of Taguchi design of experiments [8] to test only some of the possible designs. The Taguchi method is based on the use of special orthogonal arrays to select only certain combinations of design parameters for testing. From these test runs the effect that each design parameter has on the overall performance can be calculated. Traditional way of applying Taguchi method to design is to tune design parameters in the detailed design phase, where the high level system concept is already fixed. Applying it to the virtual prototypes in the early design stages provides experiment based knowledge to support decision making when it is needed the most.

In the case of the vacuum cleaner robot, the three rows of the Zwicky matrix can be considered as the design variables or factors for the Taguchi method. For each factor we have two or three levels, which are the possible implementation solutions. As a performance measure of the concepts we use the percentage of test room area that the virtual robot can cover during a 300 second test period. To run the Taguchi experiments we select the smallest orthogonal array that can handle three variables with three levels; that is the array L9 [8]. With the experiment setup in the L9 array we need to run nine experiments to analyze the effect of each design variable to the concept. This is only half of the 18

possible concepts that can be formed from the original Zwicky matrix. With a larger Zwicky box the benefit would be even greater. Since the L9 array is designed for four factors with three levels each we need to do small adjustments. The fourth column in the array can be neglected since we have only three factors. Also the navigation factor only has two levels. Thus, when the table requests the third level for the navigation factor, a random selection between the two available levels was made.
Table 1 shows the experiments conducted with the virtual prototyping toolchain, as well as the results obtained on each run as percentages of room area covered. Each experiment was repeated three times to study the robustness of the designs, since the algorithms used contained random elements and the simulator generated noise to the sensors.

Table 1: The nine Taguchi experiments conducted and their results

	Navigate	**Move**	**Detect**	**Run1**	**Run2**	**Run3**	**Mean**
1	*Random*	*Differential*	*IR*	27,45	34,21	17,26	26,31
2	*Random*	*Holonomic*	*Bumper*	39,28	26,37	36,24	33,97
3	*Random*	*Steering*	*Both*	13,04	18,77	15,81	15,88
4	*Zigzag*	*Differential*	*Both*	21,00	31,18	28,92	27,03
5	*Zigzag*	*Holonomic*	*IR*	32,28	21,74	34,62	29,55
6	*Zigzag*	*Steering*	*Bumper*	34,47	36,71	36,04	35,74
7	*Random*	*Differential*	*Bumper*	20,36	31,13	19,63	23,71
8	*Zigzag*	*Holonomic*	*Both*	27,36	27,83	33,01	29,40
9	*Random*	*Steering*	*IR*	13,70	15,62	31,55	20,29
Mean				25,44	27,06	28,12	26,87

To analyze the results Taguchi suggests the use of special signal to noise ratios. However, in the early design phases we don't know the system parameters well and the experiments conducted here give only very approximate results. Thus, we are only interested in analyzing the main effects that each factor has to the performance. To do this we simply average all performance results of each factor level. For example, to evaluate the effect that selecting differential drive system would have on the final performance, we average the results of experiments 1, 4 and 7. To analyze the robustness of each alternative we calculated the range of performance (ROP) for each level by calculating the difference between the maximum and minimum performance result. The results of this analysis are shown in Table 2.

Table 2: The analysis of experiment results

	Mean	**ROP**
Random	24,03	26,24
Zigzag	30,43	15,71
Differential	25,68	16,95
Holonomic	30,97	17,54
Steering	23,97	23,67
IR	25,38	20,92
Bumper	31,14	19,65
Both	24,10	19,97

From these results we can conclude that the robot would perform best when using holonomic drive system, bumpers and the zig-zag navigation algorithm. Since this combination is not included in the original nine experiments, a confirmation experiment is required, where the factors are set to these levels. We conducted this experiment with the results shown in Table 3 and as expected this configuration performed better than any of the previously tested ones. There are no big differences in the robustness of the alternatives, with the exception of the random navigation algorithm, which naturally gives quite non-uniform results.

Table 3: Results of the confirmation experiment

	Navigate	Move	Detect	Run1	Run2	Run3	Mean
C	*Zigzag*	*Holonomic*	*Bumper*	35,34	34,12	38,65	36,04

4 DISCUSSION

When considering early design decisions, the process is usually characterized by a lack of quantitative data supporting an objective decision process, a poor level of measurability of the performance parameters and a poor level of repeatability of the decision taken by different engineers.

In order to tackle these issues, two main approaches can be considered; first, develop real prototypes and second develop models that can be simulated. The first approach is fitting well with simple artifacts or simple machines, but is difficult to apply for complex systems due to the cost, time and risk aspects associated with this early prototyping. Another approach consists of developing models that can lead to simulations as presented in this article. Modern tools, such as the physics engine used in the case study, allow fast VP with intuitive user interface and using rough estimates of the system geometry.

VP merely based on CAD provides only a static geometrical representation of the system. To take objective decisions we need to gain information regarding the dynamic behavior of the system. In the case study we relied heavily on the Marilou simulator. This kind of simulator is of course most suitable for mechanics or mechatronics oriented design and it has limitations, e.g. it can only model rigid bodies systems with basic joints, springs and dampeners. The Marilou simulator relies on the Open Dynamics Engine (ODE) for its physics calculations. This kind of engine has simplified solving algorithms for multibody systems (MBS) when compared with commercial MBS solver like MSC Adams. For this reason it is not suitable for accurate mechanism design and optimization. However, fine tuning and optimization are not the goal of conceptual design. Thus, the ODE can still provide valuable information to support main architectural decisions in the early stages. In conclusion regarding ODE we would like to highlight the fact that engineers must understand its limitations and carefully decide if certain decision can be taken upon simulations performed with this kind of solving engine.

Systems which require different kind of physics modeling, such as fluid dynamics or electromagnetic fields, are out of the scope of ODE. However, by selecting a suitable simulation tool that allows rapid development with limited knowledge of the system parameters, the outline of the method can be applied to design projects with a scope not related to mechanics at all.

By applying the Taguchi method to the VP based concept selection, the design team can get a simple numeric value for the performance of each design concept. It should be noted, however, that this value is representing only the performance of the specific virtual implementations of the concepts and not the abstract performance of the high level concepts. When the virtual prototypes are implemented in the early design stage, the detailed design parameters cannot be optimized. In the case study we were interested in the wheel configuration of the robot and wanted to test that. To simulate the concepts, many detailed parameters need to be set, e.g. the wheel diameter or friction coefficient. These cannot be taken to account in the Taguchi DOE, but they may still affect the performance. For now we provide no solution to this problem; setting these parameters to sensible values is the responsibility of the designer. Also, the suggested concept selection method takes only to account the technical performance of the system. It is hard to use this kind of VP to analyze economic or manufacturing aspects that are important in the final concept selection.

The amount of design parameters that needs to be considered and that can potentially influence the simulation results might be extremely important and cannot be considered entirely using the Taguchi approach. For this reason in future work another approach needs to be considered in order to determine by an analysis taking place before the modeling and simulation process described in this article the set of variables that might potentially affect the behavior of the system under study. It will also be necessary to define an approach to rank the relative importance of these variables beforehand using a more qualitative approach. For this reason the authors of this work consider that a deeper analysis of the resources provided by graph theory might be a valuable method to tackle these issues and limitations of the present research work.

5 CONCLUSIONS AND FUTURE WORK

This paper has presented a systematic method for the selection of optimal design concept based on the performance assessment of dynamic virtual prototypes. With this method and the aid of modern virtual prototyping tools, the concept selection decisions can be based on experimental knowledge instead of the subjective views of the design team. Our view is, however, that the traditional concept selection methods are still needed to filter the design options generated during the GMA process. Our method comes into play when the design team is not able to make a decision due to lack of knowledge or if a disagreement arises among them.

An increasing number of research groups and industries recognize how virtual prototyping provides a significant improvement to the current product development process. In our work we exploited the flexibility of the digital models to provide objective results in order to support decision making in the early design phases. Future work and development should point on the same direction: systematic exploitation of digital models. Our example focused on using the simulation tools in the field of robotics. The possibilities of these tools should be studied further to explore their usability also in other fields.

Furthermore, the experiment carried out in our case study has been performed “manually”. A simple enhancement consists on writing a script that can run all the tests overnight and automatically analyze the results. Future development might include a link with the requirement engineering discipline. Since the virtual prototypes are essentially pieces of software they could be automatically tested using advanced practices borrowed from software engineering providing a significant enhancement on the traceability of the design decisions taken.

In conclusion we suggest the adoption of virtual prototyping throughout the entire development process, both in the early phases and later during detailed design. Specialized CAE software can be used to deeply understand a particular aspect or domain of the system under development. In our view the virtual prototype is much more than a simple 3D representation of the system; it represents the ´knowledge repository´ of the project.

REFERENCES

[1] Pugh S. Concept Selection: A Method That Works. In *International Conference on Engineering Design,* Rome, 1981

[2] Ulrich K.T. and Eppinger S.D. *Product Design and Development,* 2nd ed., 2000 (McGraw-Hill, New York)

[3] Saaty, T.L. *The Analytical Hierarchy Process,* 1980 (McGraw-Hill, New York)

[4] Roy, B. The Outranking Approach and the Foundation of ELECTRE Methods, *Theory and Decision*, 1991, 31, 49-73

[5] Honkala, S., Hämäläinen, M. and Salonen, M. Comparison of four existing concept selection method In *International Conference on Engineering Design, ICED'07,* Paris 2007

[6] Thompson, J. R. *Simulation: A Modeler’s Approach*, 2000, (John Wiley and Sons, Inc., New York)

[7] Wang, G. G. Definition and review of virtual prototyping. *Journal of Computing and Information Science in Engineering (Transactions of the ASME),* 2002, 2(3), 232-236.

[8] Taguchi, G. *Introduction to quality engineering: Designing Quality into Process*. 1986, (Asian Productivity Organization, Tokyo).

[9] Schaaf Jr.,C. J. and Thompson, F. L. System Concept Development with Virtual Prototyping in *Proceedings of the 1997 Winter Simulation Conference.* 1997.

[10] Choi, S.H. and Chan, A.M.M., "A virtual prototyping system for rapid product development", *Computer-Aided Design*, 2004, 36, 401- 412.

[11] Bennett G.R., *The application of virtual prototyping in the development of complex aerospace products.* 1997, Aircraft Engineering and Aerospace Technology, Vol. 69 Iss: 1, pp.19 - 25

[12] Pepper C., Balakirsky S., Scrapper C., Robot simulation physics validation, Proceedings of the 2007 Workshop on Performance Metrics for Intelligent Systems, p.97-104, August 28-30, 2007, Washington, D.C.

[13] Paredis, C.J.J., Diaz-Calderon, A., Sinha, R. and Khosla, P.K. Composable Models for Simulation-Based Design. *Engineering with Computers*, 2001, 17(2), 112-128.

[14] Bacs, C. New datahandling and rapid virtual prototyping approch for mechatronic systems. In *International Conference on Engineering Design, ICED'07,* Paris 2007.

[15] Bruno, F., Caruso, F., Falbo, L, and Muzzupappa, M. A co-simulation based design methodology for mechatronic product. In *International Conference on Engineering Design, ICED'07,* Paris 2007.
[16] Laue T., Spiess K., Röfer T., SimRobot - A General Physical Robot Simulator and Its Application in RoboCup, (In A. Bredenfeld, A. Jacoff, I. Noda, Y. Takahashi (Eds.), RoboCup 2005: Robot Soccer World Cup IX, No. 4020, pp. 173–183, Lecture Notes in Artificial Intelligence)
[17] Michel O., Cyberbotics Ltd - WebotsTM: *Professional Mobile Robot Simulation. International Journal of Advanced Robotic Systems*, 2005, pp. 39-42.
[18] Zwicky F., *Discovery, Invention, Research - Through the Morphological Approach* (Toronto: The Macmillian Company, 1969)
[19] Batlle J.A., Barjau A., Holonomy in mobile robots. Original *Research Article Robotics and Autonomous Systems*, Volume 57, Issue 4, 30 April 2009, Pages 433-440.
[20] Carpin, S., Lewis, M., Wang, J., Balakirsky, S. and Scrapper, C., *USARSim: a robot simulator for research and education.* In Proceedings of 2007 IEEE Conference on Robotics and Automation, pp. 1400-1405, Roma, Italy.
[21] AnyKode Inc., Simulate your Robotics Applications 2010. online: http://www.anykode.com/index.php, referenced: 18/1/2011.
[22] Drumwright, et al. Extending Open Dynamics Engine for Robotics Simulation. *Simulation, Modeling, and Programming for Autonomous Robots*. Springer 2010.

Contact: Mikko Seppälä
Aalto University, School of Engineering
Department of Engineering Design and Production
PL14100, 00076 Aalto Finland
Tel: Int +358 9 470 26272
Email: mikko.seppala@tkk.fi
URL: http://edp.tkk.fi/en/

Mikko Seppälä is a research assistant and master student in the research group of systems engineering and early design in Aalto University. He received his B.Sc. from Aalto University School of Science and Technology in 2010 in the field of Automation and Systems Technology. The method presented in this article is developed further in his master's thesis.

Andrea Buda is researcher and doctoral student in the research group of CAD/CAM/CAE in Aalto University. He received his M.Sc. from the University of Milan in 2009 in the field of Computer Science. He is Mikko Seppälä's master's thesis instructor.

Eric Coatanéa received his doctoral degree in engineering design, conceptual modeling of life cycle design in 2005 from Helsinki University of Technology and University of West Brittany. Prof. Coatanéa was Marie-Curie Fellows from 2005 to 2007. Currently he is Full Professor of Machine Design and Product Development at Aalto University.