SNE SIMULATION NOTES EUROPE

EUROSIM 2016

9th EUROSIM Congress on Modelling and Simulation

City of Oulu, Finland, September 16-20, 2016

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SNE EUROSIM Congress Issue

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- *Education Note* – modelling and simulation in / for education and e-learning; 6 - 8 pages
- *Short Note* – recent development on specific topic, max. 6 p.
- *Software Note* – specific implementation with scientific analysis, 4 – 6 4 pages
- *Benchmark Note* – Solution to an ARGESIM Benchmark; commented solution 4 pages, comparative solutions 4-8 pages

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Editorial

Dear Readers – *This second SNE issue of the year 2016, SNE 26(2) is a 'special' special issue – the first 'SNE EUROSIM Congress Issue'. The EUROSIM Executive Board has initiated this special issue in order to promote EUROSIM and the EUROSIM Congress, which this year takes place in Oulu, Finland, organized by SIMS, the Skandinavian Simulation Society. Print copies of this issue will be distributed to participants of the congress and to EUROSIM societies for promotion. Special issues usually emphasize on a special area in modelling and simulation, but this issue intends to show (i) the development and (ii) the broad variety of modelling and simulation. Editorial board members of EUROSIM societies have tried to find authors who prepare and submit contributions following this aim, and after careful selection and review this first SNE EUROSIM Issue could be compiled. The contributions show also the different types of contributions SNE foresees – Overview Notes, Technical Notes, Short Notes, and Benchmark Notes. Indeed the contributions show the development and the challenges for modelling and simulation, and it will be of interest to compare with the second SNE Congress Issue SNE 29(2), which is planned on occasion of the next EUROSIM Congress 2019 in La Rioja, Spain.*

I would like to thank all authors for their contributions, and especially the editorial board members who have stimulated authors for this issue and who took care on the contributions. And last but not least thanks to the Editorial Office for layout, typesetting, preparations for printing, and web programming for electronic publication of this SNE issue.

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Scope: Technical Notes, Short Notes and Overview Notes on developments and trends in modelling and simulation in various areas and in application and theory; benchmarks and benchmark documentations of ARGESIM Benchmarks on modelling approaches and simulation implementations; modelling and simulation in and for education, simulation-based e-learning; society information and membership information for EUROSIM members (Federation of European Simulation Societies and Groups).

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Editorial 'SNE EUROSIM Congress Issue'

Dear Readers, dear EUROSIM Congress Participants

On occasion of the **9th EUROSIM Congress on Modelling and Simulation** in Oulu, September 2016, the EUROSIM executive board has initiated this special SNE issue – the **SNE EUROSIM Congress Issue**

- as promotion for modelling and simulation as important method and tool in the forthcoming challenges for research and development,
- as promotion for **EUROSIM**, the Federation of European Simulation Societies / Simulation Groups,
- as promotion for **EUROSIM**'s scientific journal **SNE Simulation Notes Europe**, an open access journal for rapid publications on 'simulation', which also ties together the **EUROSIM** member societies,
- and as promotion for the **EUROSIM Congress** itself – this year with the 9th edition in Oulu, organised by **SIMS**, the Scandinavian simulation society, and in 2019 with the 10th edition in La Rioja, Spain, organised by **CEA-SMSG**, Spanish simulation society.

Not only modelling and simulation, but also **EUROSIM** and the journal **SNE** have taken interesting developments in the last years, from the first **EUROSIM** Congress 1992 in Capri, until now. **EUROSIM**, in the beginning a nation-based federation, has opened itself to a federation for simulation societies and simulation groups, which have different structures and work nation-wide, or itself as federation across countries, or as simulation council of another society, etc.

The journal **SNE Simulation Notes Europe** has developed from EUROSIM's newsletter **SNE Simulation News Europe** to a scientific journal for rapid publication of contributions on 'simulation', with open access, but with special benefits for the **EUROSIM** member societies and for their personal and institutional members. **SNE** ties together **EUROSIM**, by post-conference publication of contributions to conferences of the **EUROSIM** member societies, by news and information in the news chapter of the **SNE** issues, and by mirroring this information on the **EUROSIM** web www.eurosim.info.

The **EUROSIM Congress** can be seen as constant within these developments – each three years simulationists from all over the world gather in one European country to exchange information on development in modelling and simulation.

For this **SNE** issue, the first **SNE EUROSIM Congress Issue**, member societies have selected and reviewed contributions, which reflect the broad area and the development of modelling and simulation.

The issue starts with an *Overview Note* on testing and validation of simulation models (D. Murray-Smith, **UKSIM**). The *Technical Note* by D. Zimmer, **ASIM**, addresses the developments in modelling along Modelica, the 'European' modelling standard. The second *Overview Note* by J. I. Latorre-Biel and E. Jiménez-Macías, **CEA-SMSG**, represents Petri nets as modelling and simulation tool for decision making. Next, a *Technical Note* presents an implementation for design, simulation and operation of task-oriented multi-Robot applications (B. Freymann et al; **ASIM**). The following *Technical Note* gives an overview on modelling and simulation of the melting process in electric arc furnace (V. Logar, **SLOSIM** – Slovenian simulation society). Two *Short Notes* by **UKSIM** authors sketch applications: 'Applying Gamification Principles to a Container Loading System in a Warehouse Environment), A. Remi-Omosowon et al. and 'Anatomical Joint Constraint Modelling with Rigid Map Neural Networks', G. Jenkins et al.). The fourth *Overview Note* by E. K. Juuso, **SIMS**, introduces to modelling and simulation in adaptive intelligent control – to some extent announcing also the **SNE Special Issue SNE 26(4)** *Modelling and Simulation in Modern Control* edited by **SLOSIM**. The issue closes with a *Benchmark Note*, defining the **EUROSIM/ARGESIM** Benchmark C21 'State Events and Structural-dynamic Systems' (A. Körner, F. Breitenecker, **ASIM** – Sim. Soc. Germany, Austria, CH).

We hope, readers and congress participants enjoy this issue – for further information on societies and on publication we refer to the EUROSIM and SNE web page or to the web pages of EUROSIM's member societies, and we hope to welcome you again on occasion of the **10th EUROSIM Congress on Modelling and Simulation** in La Rioja, Spain, 2019.

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Borut Zupančič , SLOSIM, EUROSIM Secreary
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Issues of Transparency, Testing and Validation in the Development and Application of Simulation Models

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Abstract. The importance of verification, validation and documentation of simulation models is widely recognised, at least in principle. However, in practice, inadequate model management procedures can lead to insufficient information being available to allow a model to be applied with confidence or for it to be re-used without difficulty and much additional effort. The ease with which a model can be understood by someone not involved in its development depends on the transparency of the model development process. This paper reviews ideas associated with transparency and model management. It also includes discussion of some related issues that are believed to be particularly important, such as identifiability and experimental design for model validation. Some recent developments in engineering applications and in physiological and health-care modelling are discussed, along with the responsibilities of the academic community in giving more emphasis to simulation model testing and transparency.

Introduction

The testing, validation and detailed documentation of simulation models are all important issues in every field in which modelling and simulation techniques are used. It is also well-established that the development of simulation models involves an iterative process and that model testing is inseparable from all other aspects of model development. One very important milestone was the production in 1979 of the ground-breaking recommendations of the SCS Technical Committee on Model Credibility [1].

This provided a useful set of conventions and definitions for use in discussing the development of models and the main message about the importance of model testing and the iterative nature of modelling and simulation processes has since been emphasised repeatedly by many others, such as Sargent (e.g. [2]), Ören (e.g. [3]), Balci (e.g. [4]) and Brade (e.g. [5]).

Transparency in simulation model development is another closely-related issue and is concerned with the ease with which a model, its associated simulation software and testing procedures, can be understood by someone not involved in its development. This relates to questions of model management in general and to documentation in particular.

In the context of engineering applications, a simulation model that is used in the design of a new product may well have a continuing and significant role throughout the complete life-cycle of that product. The continuing value of a model will depend on how that model is managed from the outset, including the testing strategy, verification and validation processes, and the availability of useful information about all aspects of the model and its development [6].

In all application areas the increasing use of object-oriented software, the integration of simulation tools with other forms of specialist software, the availability of libraries of sub-models and the development of generic simulation models intended for use in a number of different applications are typical of ways in which modelling and simulation methods have been changing in recent years [6-8]. These changes of approach should have been accompanied by determined efforts to ensure transparency within the development process, through careful and systematic documentation, together with more rigorous procedures for testing, verification and validation.

However, there is clear evidence that these issues are still not being given appropriate attention by some model developers, users and also those involved in education [8-11]. Issues relating to model quality, such as the range of applicability of a given model, how the behaviour of a model can be compared with the behaviour of the corresponding real system, the precise experimental conditions used in comparing simulation reults with real-world data and availability of of documentation are seldom emphasised in published material.

This situation is made worse by the fact that many published journal papers and reports dealing with modelling and simulation applications lack real transparency in terms of the model and the simulation methodology being used and also include little about testing and validation results. How can students be expected to give more attention to these issues when they see that their lecturers and professors are still successfully publishing research papers in which scant attention appears to be given to these topics?

Another related issue is that, in some organisations, simulation modelling is often treated in a different way from other software development processes. Simulation models are often developed without the benefits of version control procedures that are a central feature of most software development environments. Should methods of approach to version control that have been used successfully in the software engineering field be applied to the development and management of simulation models?

There is also a clear need to consider why rigorous and systematic testing techniques that are currently available are not being applied more widely and why the documentation of models is too often superficial or non-existent. The consequent problems that follow on from these failings also need to be considered, together with consideration of the added short-term costs of adopting a more rigorous approach of this kind.

1 The Need for Good Model Management

As mentioned above, quality assurance mechanisms and model management procedures are often notably absent from the modelling and simulation processes within many organisations.

Whether models are developed from first principles, or reinstated from previous projects, or acquired from other organisations, appropriate strategies need to be in place to make sure that model quality issues are addressed properly and that all aspects of the modelling and simulation activities are managed in an appropriate fashion [5], [8-11]. This is important in all scientific, medical and decision making application areas as well as in engineering.

One important aspect of model management involves the establishment of a suitable plan for model verification, validation and approval and this needs to be started at the earliest stages of a model development project. Such a plan should lay down clear quantitative requirements for the validation for each element of the model, but with flexibility in terms of methods to be used. For example, preliminary assessment of a model on the basis of face validation may be followed by the application of a more quantitative approach as confidence increases. Where model libraries are being applied, validation information about sub-models should be brought together using the available documentation and reviewed in a critical fashion in the context of the intended application. The plan has to provide guidance for every aspect of model testing and has to be recognised as being quite different and distinct from the model specification. In addition, the plan for verification, validation and approval should outline the methods to be adopted and provide information about resources available from previous projects, such as fully-tested simulation models or sub-models.

Since the modelling process is iterative, the verification, validation and acceptance plan may itself have to be modified and fine-tuned as the work progresses. For example, as experience grows from analysis of test results from the real system, trade-offs may become necessary between the validation requirements and the quantity of additional validation data needed. Even if collection of test data from the real system is the responsibility of others, those involved in the model development process should be able to contribute to the planning of the model testing process since early experience with a simulation model may provide insight that influences the design of experiments. An example of this is the fact that understanding of parameter sensitivity issues built up during the model development process can contribute significantly to experimental design and to questions relating to model uncertainties.

On the other hand, the management system should ensure that, wherever possible, the assessment of test results and model results should involve blind comparisons. Initially, experimentalists should provide the simulation developers only with measured input data and other relevant information about test conditions. The simulation group would then use the input data provide by the experimentalists to make predictions of corresponding output variables. Experimental and simulation results could then be compared by members of both groups working together and conclusions reached about the adequacy, or otherwise of the model.

Documentation is another area where strict management procedures are important. Awareness of model limitations in the minds of users inevitably fades with time and accurate and easily accessible documentation is essential. This should deal with all aspects of the model including its purpose, assumptions and simplifications, details of verification and validation tests and an assessment of the range of conditions for which the final accepted model can be used. The documentation should also include information about the model variations developed during the project, together with reasons for accepting or rejecting each of these [8].

1.1 Model management practices

Reliable and easily-used methods for model version control are essential for large and complex models. This is particularly important when models are developed and maintained by a team rather than by an individual. Interactions between models of different types can also be an important feature of a project and it is important to ensure that no data transfer errors can occur between models. In addition, it is essential to ensure through an appropriate management system that whenever changes are made all of the relevant models are updated at the same time.

It has been suggested that model documentation should always be divided into two distinct sections (e.g. [8]). The first would involve non-technical documentation and would be accessible by all having some interest in the model and its applications. This section of the documentation would include an overview of the model in terms of its purpose, intended applications, variables, equations, parameters etc, together with a summary of the verification and validation procedures, detailed verification and validation results and resulting recommendations in terms of the range of conditions over which the model could be used. The second section would provide all the additional information that would be required by someone wishing to make use of the model or to reconstruct the model and reproduce results that had been obtained previously. Splitting the documentation in this way means that aspects of a model regarded as being in some way confidential could be held back while still providing interested parties with a broad ouline of the model and its capabilities.

The choice of software tools to assist in the management of models, simulation programs and the documentation depends on the computing environment being used. Details of the systems for keeping track of model versions, simulation programs, parameter values, validation data sets and results are also going to be different for different types of organisation. For example, in academic environments, large research groups may benefit from relatively rigid and centralised systems for model version control. On the other hand, an individual researcher working with one or two research students may find advantages in a simpler and less formal approach which just involves establishing a systematic way of keeping track of different model versions, of linking them to the appropriate data sets and to the corresponding simulation programs. Results of verification and validation tests must also be readily available and be easily linked to each model version. In large organisations the way in which this control can be achieved are clearly very different, especially when teams are geographically dispersed, when a more formal system of management becomes really important.

1.2 Benefits versus costs in model management

One ever-present issue that has to be considered in any organisation, whatever its size, concerns the costs of establishing systems of model management which involve comprehensive verification and validation procedures and large amounts of documentation. The recurrent expenses associated with such systems can be considerable. However, the costs resulting from failure to establish appropriate systems for the management of models can be much greater. In an engineering application, for example, the use of an inappropriate model for design purposes may lead to very large amounts of unplanned expenditure when re-design becomes necessary. The later in the design project that the problems are discovered the larger the costs of rectification.

Prototypes that fail to meet performance specifications inevitably lead to time-consuming and expensive changes to hardware and software. Similarly, in areas such as scientific research, the use of an inappropriate model can result in false conclusions and possibly incorrect decisions in terms of subsequent directions of research or policy recommendations.

Proper model management procedures, model transparency and documentation are also very important because knowledge about models which resides only in the heads of model developers is likely to be lost as soon as those individuals move on to new areas of responsibility or to a different organisation. Such a loss is clearly very wasteful. The academic world particularly weak in this respect because work carried out by graduate students at Master's degree and PhD level is recorded mainly though dissertations and these seldom include the level of detail about models that is necessary to build upon what has been achieved. Where modelling forms an important aspect of the work being reported, some separate archiving system should be required to supplement and support the information provided in the published thesis and this should be accessible by all who have access to the thesis.

One way of attempting to control the costs of model validation is through the establishment of a link between the verification, validation and acceptance plan and the more general requirements analysis document that details the purpose of the model, its accuracy requirements and defines the broad strategy for its development. That requirements analysis document can then provide the basis for a project plan which includes estimates of the human effort and can indicate how tasks involved in the model development process can be split between individuals. Establishment of a plan of this kind that places due emphasis on model validation should also allow confidence to be built up about the fitness of a model for its intended application while, at the same time, allowing the overall cost to be monitored continuously.

It is always difficult to obtain information about procedures for model management adopted elsewhere and this is especially true in commercial organisations. However, a number of studies have been carried out. One of these is an investigation by Foss et al [12] which relates to system modelling and simulation activities within the chemical industry. The modelling process receives close attention, including issues of verification, validation and documentation, using information from 16 experienced modellers and simulation specialists in organisations in several different countries. Suggested developments as a result of that investigation relate mainly to improvements in modelling technology and the use of advanced modelling tools. Foss et al also provide some useful insights about how modelling and simulation activities are carried out within the industry [12]. A second investigation focussed its attention on the helicopter manufacturing industry and involved responses to a questionnaire which sought views on the use of system identification and parameter estimation techniques for tasks such as the validation of physically-based flight mechanics models [13]. Eight companies from North America and Europe responded and the answers to the questions posed showed considerable interest in model validation and in the use of these specific techniques, while emphasising the need for physically-based interpretations at all times.

Cost predictions in terms of a model-based approach to engineering design also receives attention in a document by Pace [10] which discusses large projects in the aerospace and defence sector. A case is put forward for more sharing of information about the costs of modelling and simulation activities in order to allow the development of more reliable costing procedures. Another factor is that models can only be maintained properly if they are seen to be important, either in economic terms or in terms of their future potential. The difficulties and costs of maintaining models over the complete life-cycle of the system or product have to be considered explicitly and it appears that some engineering organisations and companies are establishing technology groups which are tasked with maintaining models, their software and documentation and translating these to new software environments as necessary.

2 The Testing of Simulation Models

There are two distinct and separate aspects to the testing of simulation models. One of these is termed 'validation'" and this is concerned with the process of establishing how well (or otherwise) the mathematical and logical description gives behaviour in the model that agrees with the observed behaviour of the system that it describes [1].

When a real system is available for testing and direct comparisons can be made of the time histories of key variables, the process can be carried out using a range of different quantitative methods and measures. Examples of methods that have been successfully applied in the past include graphical comparisons of various kinds, the use of methods based on system identification and parameter estimation, parameter distortion methods and evolutionary computing methods such as Genetic Programming (see e.g. [6], [8] for outlines of these different approaches). 'Face' validation methods, in which the model behaviour is assessed by someone who has expert knowledge of the real system but was not involved in the development of the model, provide a useful alternative (see e.g. [8]). A model can never be 'valid' for all applications and must be assessed in terms of its suitability for some specified use. Often a combination of quantitative and face validation approaches are used and subjective and objective evidence has to be combined in some way in establishing whether or not the model is fit for purpose. Acceptance of a model for its application requires statements of the range of conditions over which it can be used and the associated accuracy of model predictions

The second aspect of testing is termed 'verification' and relates to the process of establishing that a computer implementation of a model corresponds to the underlying mathematical and logical structure for that model [1]. This involves systematic checks of simulation code to ensure that no errors are present and also algorithmic checks to establish that appropriate computational methods have been applied [8]. This is a simpler process than validation and it has been suggested that formal methods (and especially 'lightweight' formal methods) could be used [14].

Both aspects of the model testing process are vitally important and must be considered in a systematic way in any application of modelling and simulation techniques. In essence, validation is concerned with the question 'Is this the right model to describe the given system?', while verification deals essentially with the question 'Is the software implementation of the simulation correct?'. Each time a model and the associated simulation are changed in any way the procedures of verification and validation must be repeated and the whole procedure of model formulation, model testing and model updating must be regarded as iterative process which may have to be repeated many times during the life of a simulation model.

Although, as mentioned above, there are many different approaches to model validation there is one overriding aspect of testing that is relevant whatever method is adopted. This relates to questions of experimental design. In many engineering applications (and also in dealing with many physiological and biomedical modelling applications) testing includes the use of input signals to perturb the system. This is of fundamental importance because the choice of test input signal has a direct bearing on the amount of information available about the system under investigation. It thus also has an important influence on the effectiveness of tests carried out for the purposes of validating a model.

3 Issues of Identifiability and Test Input Design

Dynamic responses measured from experiments involving the application of test inputs can provide a great deal of information that is not available from the analysis of steady-state conditions or from responses resulting from some imposed set of initial conditions. Experiments involving test input signals also provide a basis for many well-established techniques of system identification. This is an inverse modelling procedure in which the structure and parameters of a model are estimated from sets of measured input-output data from the real system. Such techniques may be important in the development of physically-based simulation models if significant uncertainties exist in terms of the model structure or parameter values. Note that this 'model identification' type of inverse problem has to be distinguished from the 'causation' type of inverse problem where, for a given model, one seeks to find inputs that produce a specified response [15]. This causation type of approach also has relevance for model validation, as discussed elsewhere (e.g. [8]).

One very important concept that is closely linked to parameter estimation and model testing is model 'identifiability'. There are two types of identifiability problem and these can be classified as:

a) 'global', 'structural', 'deterministic' or 'a priori' identifiability

and b) 'pathological', 'numerical', 'practical' or 'a posteriori' identifiability.

As the names suggest, the first type of identifiability problem arises because of the structure of the model.

Such issues arise when, for example, a model has too many parameters to allow all of them to be found independently from any identification experiment involving any combination of test inputs. Identifiability of this kind is the minimum condition necessary to obtain estimates of all model parameters. Thus, if a model is found to be structurally unidentifiable certain parameters cannot be estimated independently of others and this has important implications for model validation since sets of independent values cannot be assigned to those parameters. The second type of identifiability problem is encountered when a structurally identifiable model is being investigated using data sets that are too short in relation to the dynamic characteristics of the model or where measured response data sets are corrupted by significant measurement noise. Measured response data sets thus have to be long enough to capture the essential characteristics of the system if they are going to be useful for model validation and also have to be relatively noise free.

In the case of linear models, methods for the investigation of structural identifiability are well known and many relate to a transfer function type of approach proposed by Bellman and Åström [16], to methods based on Taylor series expansions or to a Markov parameter matrix approach [17]. In the case of nonlinear models two approaches are currently available. The first involves linearisation of the model about suitable operating points to reduce the nonlinear problem to a series of linear problems for which one of the linear approaches may be used. The second approach involves a Taylor series expansion of observations [17], although it is recognised that this is difficult to apply in the case of complex models.

Test inputs that are good for the purposes of system identification are those that excite the dominant modes of the system and also cover a range of amplitudes that are appropriate for characterising possible non-linear behaviour. Test inputs that are judged to be good for the purposes of system identification and parameter estimation are also generally good test inputs for the purposes of model validation. This fact is well-established but is often overlooked within the modelling and simulation community.

Specific techniques of test input design that have been found to be particularly useful in the context of model validation include those based on the D-optimal criterion (where equal emphasis is placed on all the relevant parameters) and the truncated D-optimal criterion (where a sub-set of the relevant model parameters is emphasised) [18]. The use of these test-input design techniques within simulation model validation, together with discussion on the use of frequency-domain measures (such as spectral energy and coherence functions) in comparing the effectiveness of different inputs is attracting renewed interest and details of these methods may be found elsewhere, along with relevant case studies (see e.g. [6], [8]).

4 Developments in Some Specific Application Areas

4.1 Engineeering developments

It is very clear that in safety critical application areas, such as aircraft design, the automotive industry, railway systems, the nuclear industry and in many areas of defence, models are now subjected to a thorough process of development that involves version control, testing and documentation. Careful selection of test inputs for the purposes of model validation is also typical of work in these application areas. This, in many cases, is due partly to requirements imposed by external regulators and safety authorities.

In recent years the importance of using modelling techniques in large projects has become a central part of the philosophy of the US Defense Science Board (DSB) in the context of the DSB Model-Driven Architecture [19-20]. Closely associated with the ideas of a Model-Driven Architecture is the concept of a ‘model as a specification’ This was promoted very actively by Terry Ericsen and his colleagues at the US Office of Naval Research, as part of a drive for major enhancements in the use of modelling and simulation techniques in the context of ship design, construction and operation (e.g. [21-23]).

The approaches used in other, less controlled and less safety-critical areas can sometimes be equally rigorous. However, there is still plenty of evidence that in many contexts simulation models are being developed and used in ways that lack extensive testing and involve documentation that is inadequate for anyone attempting to re-use a model. The documentation also often lacks transparency and may be inadequate for supporting and maintaining the system represented by the model over its complete lifecycle.

The justification for this rather haphazard approach to modelling and simulation activities is often that the more rigorous approach adopted in safety-critical application areas cannot be afforded and that the approach adopted is ‘what has always been done’.

Such negative views of the significance of model testing and documentation fail to take proper account of the costs that could possibly be saved in the development and management of new products through a more rigorous approach. Although such savings are difficult to quantify, it is interesting to note that in some areas of industry and science new approaches to computational models are becoming well-established.

In the Unkited Kingdom one important example of this is the decision that all major new building and infrastructure projects funded by central government from 2016 must adhere to Building Information Modelling (BIM) Level 2 requirements. Level 2 BIM provides a common single and coordinated source of structured information for consultants, contractors and all other parties engaged in a large and complex project [24]. It involves the use of computer-based models and associated databases for visualisation, information retrieval, documentation and life-time maintenance and support, and promotes consistency and transparency. It is already being used for the Crossrail project in London and is an essential feature of the planned HS2 high-speed rail construction project between London, Birmingham and cities further north. Although not concerned primarily with dynamic system simulation, BIM can provide data for dynamic simulations, in terms, for example, of building energy simulations and optimisation.

Future developments lie with Level 3 BIM and will require full collaboration between all parties involved in a project through the use of a single, shared project model held in a central repository. Everyone involved will then be able to access and modify that same model, and the benefit is that it eliminates risks associated with conflicting information. Industry concerns about commercial sensitivity and copyright issues are being resolved through robust documentation and software control procedures.

This requirement from the UK government is one aspect of a plan for reducing waste in the construction industry by 20%. It is believed that discrepancies, mistakes and inefficiencies in the information supply chain are major contributors to this waste and that collaborative working can significantly reduce it. Further BIM developments (at Levels 4D, 5Dand 6D) involve the use of BIM data to analyse time, for purposes of cost management and for facilities management.

It is interesting to note that BIM Level 3 has features that can be linked to the concepts of a ‘model as a specification’. The central and closely managed computer-based model of BIM Level 3 should provide a common reference point for all engaged in a project.

4.2 Some developments in the modelling of physiological and health-care systems

Just as in engineering applications, the development of models of complex physiological systems needs to be made transparent to users. A systematic and properly managed approach is of great importance for the specification of a model, for development of model equations (including the choice of variables, parameters, model boundaries, assumptions and simplifications), for verification, for validation and for documentation. One interesting example from the biological sciences is the Human Physiome Project of the International Union of Physiological Sciences [25]. This is an initiative which is concerned with establishing a central repository of databases of experimentally-derived information and related computational models. The term ‘Physiome’ comes from ‘physio’ meaning ‘life’ and ‘-ome’ which means ‘as a whole’. The project aims to bring together, within one self-consistent framework, all the experimental and modelling elements of current physiological research. Contributors to the Human Physiome Project are from all parts of the world and simulation programs accepted for publication through this project may be downloaded and used by others. It is important to note that, within the Physiome Project, the word ‘model’ can be used to describe anything from a schematic diagram that suggests relationships between elements of a physiological system to a fully-tested and documented computer simulation model. Any model that is accepted is regarded as a ‘working hypothesis’ and has to form an internally self-consistent statement of the available information. What is especially interesting is that, through the processes of publication in the Physiome Project, the models and associated data sets provide an important stepping-stone to new experiments on the real system and thus to new models. Understanding of a given system should be enhanced in a step-by-step fashion through this type of collaborative procedure which involves an iterative process of modelling, simulation, testing and comparison.

One important feature of the Physiome Project is that all models have to pass through a ‘curation pipeline’ prior to being accepted and made available publicly. This procedure is similar to an independent review process for a conventional publication and is a form of ‘accreditation’. Within the curation procedure the submitted simulation model is tested to ensure that it is semantically sound and results obtained from it are consistent with the available published information about the corresponding real system.

In the health care systems modelling field one significant development in 2012 was the publication of seven papers prepared by the Good Research Practices in Modeling Task Force. This group was established in 2010 by the International Society for Pharmacoeconomics and Outcomes Research (ISPOR) and the Society for Medical Decision Making (SMDM). The Task Force produced a set of recommendations and seven articles were jointly published by both societies in their respective journals. A summary of the articles was presented as a plenary session at the ISPOR 16th Annual International Meeting in May 2011 and again at the SMDM 33rd Annual Meeting later that year and [26] provides an overview. Of the six other papers published by the Task Force members, the two most directly relevant to the theme of this paper focus on parameter estimation and uncertainties [27] and on ‘best practices’ in terms of model transparency and validation issues [28]. Many of the best practice recommendations are directly relevant to modelling and simulation in general and are not limited to applications involving health care. Most correspond to general issues of model management, testing and documentation discussed in this paper.

5 Discussion and Conclusions

Model management procedures should ensure that the model development process is reliable and robust. Good documentation standards should lead to high levels of transparency in the models created within such a management system.

Helpful insight in terms of good practice can be obtained from work on safety-critical and defence-related projects but issues of national or commercial secrecy limit transfer of knowledge from these fields into other areas of application. On the other hand, some very positive developments have also taken place recently in a number of areas of biomedical and healthcare modelling and interesting recommendations have followed in terms of transparency and validation.

Recent developments in areas such as ship design and civil engineering also suggest that, with some external pressures initially, good modelling practice can produce significant benefits and potential cost savings in large projects. Current trends in those areas need to be considered to establish whether or not the ideas behind such developments could be transferred to other fields.

Education and training undoubtedly has an important influence. Many students encounter the ideas of mathematical modelling and computer simulation but relatively few graduates appear to be fully aware of the importance of testing their models. The emphasis in many courses is on the development of models from the underlying laws of physics, chemistry and other areas of science and then on the numerical methods for finding solutions. An examination of syllabus information from a wide range of universities suggests that, in many courses involving simulation, the topics of model testing, validation and documentation do not receive sufficient attention.

Another interesting point that relates to a number of scientific disciplines (e.g. the biological sciences) is that the convention in publication of experimental or computational results in a journal or conference proceedings is that a ‘methods’ section is traditionally included. The inclusion of the methods section is intended to provide enough information to allow readers to fully understand the techniques used to obtain the published results and, ideally, to allow readers to follow the processes used and thus repeat the results independently and be able to reproduce the published findings. Unfortunately, this is not a convention that is widely followed, at present, in most published work on modelling and simulation applications but has clear benefits in terms of establishing transparency and reproducibility.

Clearly, there are several areas in which there is scope for improvement in the processes of developing, implementing, documenting and applying simulation models within many organisations. It is clear that recent developments in some specific fields have led to interesting and helpful ideas and to recommendations in terms of best practices. Many of these ideas are transferable to other areas and are worthy of careful consideration by all engaged in modelling and simulation and especially by those involved in education.

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Equation-Based Modeling with Modelica – Principles and Future Challenges

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Abstract. Modelica is a well-established, open standard for the modeling and simulation of cyber-physical systems. Since it is based on equations, this modeling language is applicable to a multitude of physical domains and especially suited for complex physical systems and their control. This paper provides a brief introduction on the kind of equation-based modelling promoted by Modelica and its underlying core principles. The paper then describes its current state in development and outlines the most important technology trends for its future development.

Introduction

Modelling and simulation is today one of the most prevalent methods for the design of systems and their control. A large variety of specialized tools have been developed and are continually improved that take into account the specifics of each physical domain.

However, many systems combine components of different physical domains. Their design consequently represents an optimization process that cannot be mastered by any domain-specific tool alone. Fortunately, many methods for modelling and simulation of physical systems build on the same principals and can be shared across different physical domains. This is what has led to a multitude of generic simulation languages for physical systems such as MIMIC, ACSL, CSMP, gPROMS, VHDL-AMS, Matlab-Simulink, etc. [16].

This paper presents one of the more recent and meanwhile well-established languages: Modelica. This is an openly standardized modelling language, primarily aimed at the modelling and simulation of physical systems and their control.

From its founding in 1997, the language developed with a steadily growing user-base both in academia and industry.

Being a discussion paper, this text presents the author’s view on Modelica:

- How to introduce Modelica with its basic principles?
- How has Modelica matured and established itself?
- What will be the future challenges and main development trends?

Each of these questions is addressed in a separate section. Going through these questions aims at providing a concise overview on Modelica.

1 Basic Principles of Modelica

There are five core principles that define the design of the Modelica modelling language:

- It is an **equation-based** language.
- It enables the **acausal** formulation of systems.
- It uses **physical connectors** to connect different components of a model.
- It is an **object-oriented** language that enables the reuse of once developed models.
- Although being a textual language, it embraces a second layer of **graphical modeling**.

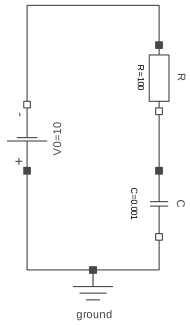
This list represents the author’s choice. There are many other factors that have influenced Modelica and that need to be taken into account when designing a language. Nevertheless, these 5 principles cover the most vital aspects. Let us go through them one by one.

1.1 Equation-based Modeling

As an equation-based language, Modelica enables the modeller to formulate the system directly by the means of differential algebraic equations (DAEs). The following Listing represents the equations of a simple RC circuit in a corresponding Modelica model.

A Modelica model has a header that contains declarations of parameters (constant over simulation time) and variables. The subsequent equation part then contains algebraic and differential equations. The operator `der()` represents the time derivative:

```
model SimpleCircuit
  parameter Real C;
  parameter Real R;
  parameter Real V0;
  Real i;
  Real uC;
equations
  V0-uC = R*i;
  der(uC)*C = i;
end SimpleCircuit;
```



Listing 1: A simple Modelica model for an RC circuit.

Listing 1 presents basic elements of a Modelica model: parameter, variables, and equations. None of these elements is bound to physics in any way. Yet, it is meaningful, to use variables of physical quantities where applicable and to add description texts. This makes the code far easier to understand and safer to use:

```
model SimpleCircuit
 ″A simple RC circuit″
 import SI = Modelica.SIunits;
 parameter SI.Capacitance C=0.001
 ″Capacity″;
 parameter SI.Resistance R = 100
 ″Resistance″;
 parameter SI.Voltage V0 = 10
 ″Source Voltage″;
 SI.Current i ″Current″ ;
 SI.Voltage uC ″Capacitor Voltage″;

initial equation
  uC = 0;
equations
  V0-uC = R*i;
  der(uC)*C = i;
end SimpleCircuit;
```

Listing 2: Polished version of listing 1, using description texts and physical units.

The equations in the examples of this paper are only used to describe continuous processes but Modelica also contains means to deal with events and conditional expressions which enable the formulation of discrete processes.

1.2 Acausality

Modelica uses acausal equations and not causal assignments. This means that the modeller can focus on what he wants to model and does not need to state how to compute the system. For instance, Ohm's law of Listing 1 can also be formulated in either of the following forms:

- `uC + R*i = V0;`
- `(uC-V0)/R = -i;`

Acausality is however more than the freedom on how to form an equation. It becomes an essential feature as soon as equations are reused, as typical for object-oriented modelling. Let us consider the following electric circuit that contains two instances of Ohm's law (Figure 1)

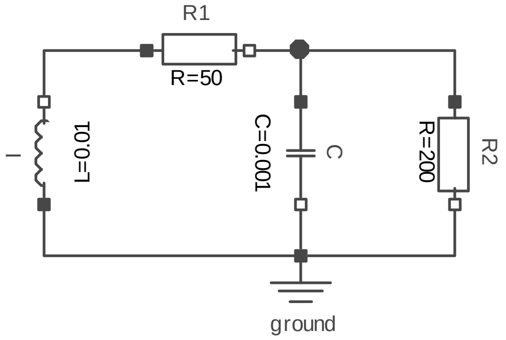


Figure 1: An electric circuit with two resistors R1 and R2 both representing Ohm's law.

and its corresponding computational realization in Matlab Simulink® (Figure 2):

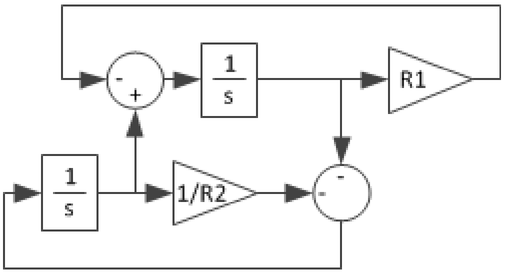


Figure 2: Computational realization of the electric circuit in a Simulink Block Diagram.

Evidently, R1 is used to compute the voltage out of the current, while R2 is used to compute the current out of the voltage. In Modelica, you do not have to care about this. Ohm's law is valid for both resistors.

More formally, within Modelica you describe systems according to the implicit DAE form:

$$\mathbf{0} \;=\; \mathrm{F}(\boldsymbol{x_p}, \dot{\boldsymbol{x}}_{\boldsymbol{p}}, \boldsymbol{u}, t)$$

It is then the task for a Modelica tool to bring this implicit DAE form into an explicit ODE form, typically more suitable for simulation:

$$\dot{\boldsymbol{x}} \;=\; \mathrm{f}(\boldsymbol{x}, \boldsymbol{u}, t)$$

where $\boldsymbol{x}$ is a subset of $\boldsymbol{x_p}$. This transformation is called index-reduction [3], with the index denoting the complexity of the transformation. Many physical systems, such as multibody systems typically are higher-index systems.

Index reduction is also useful for more advanced applications. It enables model inversion: instead of prescribing the forces and computing the trajectory, the modeller can prescribe the trajectory and compute the required forces. Such inverted models can then be used in a non-linear control loop to derive modern model-based control laws [12].

1.3 Physical connectors

The example of listing 2 contains a complete model, with as many equations as variables. This approach however is only feasible for very small models. For larger models with thousands of equations, an object-oriented approach is mandatory. Here, a model is composed out of sub-models, also denoted as components. The sub-models contain fewer equations than variables. The missing equations then are added by connecting the components. For example, Figure 3 displays the model diagram of an electrical actuated inverted pendulum.

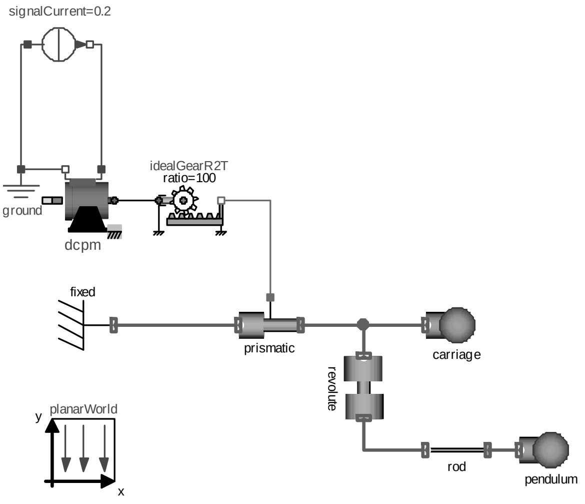


Figure 3: Modelica model diagram of an electric driven inverse pendulum.

The individual components of this diagram feature domain-specific connectors (green squares for translatory mechanical hinges, blue squares for electric pins, etc.). These connectors are declaring pairs of potential and flow variables. By connecting them with lines, a junction is formed. For each of these junctions, equations are generated: potential variables are all set to be equal whereas the sum of flow variables has to be zero.

The modeller is free to use whatever variables for potential and flow as desired. For many physical domains however, Table 1 already provides suitable pairings:

Domain	Potential	Flow
Translational Mechanics	Velocity: v [m/s]	Force: f [N]
Rotational Mechanics	Angular velocity: ω [1/s]	Torque: τ [Nm]
Electrics	Voltage potential v [V]	Current i [A]
Magnetics	Magnetomotive force: Θ [A]	Time-derivative of magnetic flux: Φ [V]
Hydraulics	Pressure p [Pa]	Volume flow rate V [m^3/s]
Thermal	Temperature T[K]	Entropy flow rate S [J/Ks]
Chemical	Chem. potential: μ [J/mol]	Molar flow rate v [mol/s]

Table 1: Pairs of potential and flow variables for different physical domains inherited from bond graphs

These pairings of potential and flow variables are known from bond graph modelling [7]. The product of each this pairs represents the flow of energy. Hence the connection via these pairings will represent flows of energy going in and out of components.

The typical use in Modelica may partly deviate from this table. For instance position may be favoured over velocity, and specific enthalpy maybe more practical than temperature. Modelica is hence less dogmatic than bond graphs but nevertheless still profits from the same underlying thermodynamic principles.

1.4 Object Orientation

The combination of physical connectors with pairs of potential and flow and the ability to formulate acausal DAEs then enables a fully object-oriented modelling approach.

The equations are distributed over several components. Components of any domain such as resistors, dampers, wheels, joints, batteries can be declared in the same way as simple variables. Listing 3 presents the object-oriented code corresponding for the following electric circuit.

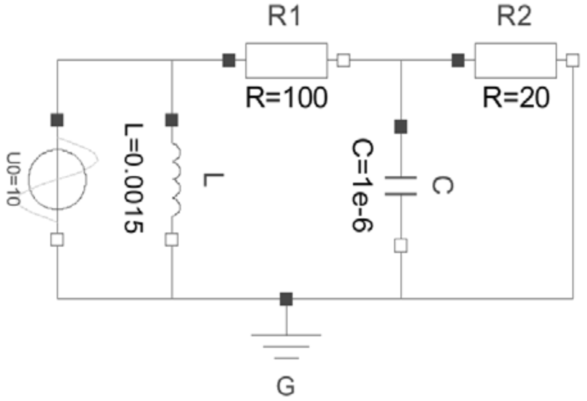


Figure 4: An example electric circuit.

```
model Circuit
  import E = Modelica.Electrical.Analog
  E.Basic.Resistor R1(R=100);
  E.Basic.Resistor R2(R=20);
  E.Basic.Capacitor C(C=1e-6);
  E.Basic.Inductor L(L=0.0015);
  E.Sources.SineVSource S(Ampl=15, Freq=50);
  E.Basic.Ground G;
equations
  connect(G.p,S.n)
  connect(G.p,L.n)
  connect(G.p,R2.n)
  connect(G.p,C.n)
  connect(S.p,R1.p)
  connect(S.p,L.p)
  connect(R1.n,R2.p)
  connect(R1.n,C.p)
end Circuit;
```

Listing 3: Modelica Model of Figure 4.

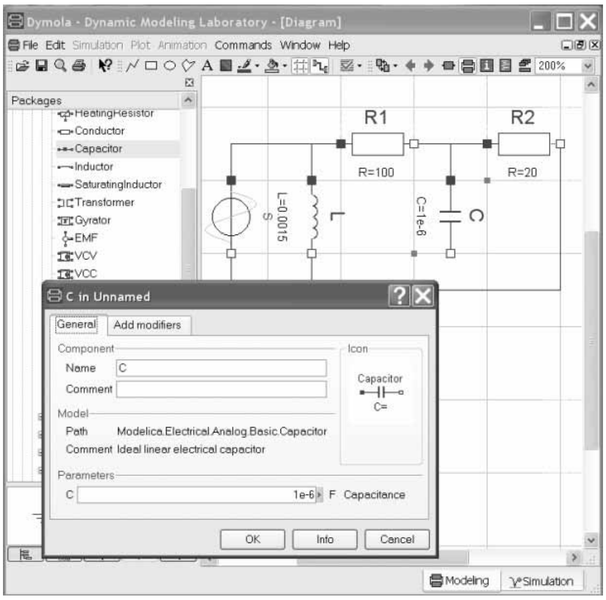
Models for one domain can be collected in packages, Modelica's name for its software libraries. The package for analogue electrical components is imported in the listed example. The components of this package are then accessed by dot notation and declared just as variables. The equation section does not contain direct equations anymore but just the connect statements.

There is more to object-orientation than the basic use of components and its collection in packages. Modelica supports concepts of inheritance, even multiple inheritance. Partial models are the counterpart to abstract classes in equation-based models and can be used to define component interfaces.

The structural type system then enables a flexible replacement of models or model classes.

1.5 Graphical modelling

The manual coding of physical systems as presented in Listing 3 is a laborious and potentially error-prone task. Instead, engineers prefer to model graphically. Most Modelica modelling tools hence offer a diagram editor that can be used to compose systems such as in Figure 1, 2, or 4 in a purely graphical way by using drag and drop.



Name C
Comment
Path Modelica.Electrical.Analog.Basic.Capacitor
Comment Ideal linear electrical capacitor
C 1e-6 F Capacitance

Figure 5: GUI of Dymola, one possible Modelica tool, used to model the circuit of Figure 4.

The Modelica language provides annotations that act as a container for the resulting meta-information. These are used to store the graphical information about the position, orientation and scale of the components in the diagram layer. Most Modelica editors hide the content of annotations by default so that the modeller can focus on the essential parts.

1.6 Resulting modelling style

What results of the 5 principles is a declarative modelling language that enables the creation of self-contained models.

Declarative means that the modeller can focus on *what* he wants to model rather on *how* to compute it.

Self-contained means that the models alone are valuable information source, even without any simulation tool at hand.

2 Establishment of Modelica

2.1 Language and tools

Modelica is not the first language to be based on the outlined principles. Many academic predecessors or tools such as OMOLA, or 20-sim have helped to path the way. Yet it is one of the few openly specified languages that meanwhile found significant industry acceptance and tool support. Table 2 provides an incomplete list of commercial and free tools supporting the Modelica standard.

Tool	Developer	Type
Dymola	Dassault Systèmes	commercial
OpenModelica	OSMC /Linköping Univ.	free
SystemModeller	Wolfram	commercial
JModelica.org	Modelon AB / Lund Univ.	free
SimulationX	ITI GmbH	commercial
MapleSim	MapleSoft	commercial
LMS Imagine Lab Amesim	Siemens PLM	commercial
MWorks	Suzhou Tongyuan	commercial
CyModelica	CyDesign Labs /ESI	commercial
Modelicac	SciLab Enterprises	free

Table 2: List of Modelica simulation environments. Complete tool list available at [1].

Whereas Listings 1-3 only presented toy examples, many realistic models of various application fields have been created, often with more than 100,000 equations.

Automotive companies were among the early adopters. Models for vehicle dynamics but also for cabin climatization and powertrain modelling are in use at the automotive industry. Also motorcycles, trucks, trains and heavy equipment of all kinds are frequently modelled in Modelica.

Meanwhile also the conservative aviation business is increasingly using Modelica. Especially the design of energy systems for modern more electric aircraft is a demanding application field.

The energy sector in general is highly relevant for Modelica. Models of various power plants (from solar thermal to coal fired) have been created and their integration into a common energy grid is studied. In this way, a substantial amount of intellectual property has meanwhile been encoded in Modelica.

It would, however, be wrong to reduce Modelica just to the language and its tools. Equally important are the available Modelica libraries, especially the extensive, free Modelica Standard Library (MSL). Furthermore there is the Modelica Association. This is a non-profit association that engages in development of the standard, corresponding libraries and the scientific and industrial community.

The Modelica language, the Modelica libraries and the Modelica Association consequently form a powerful triangle that has enabled the recent success of this technology.

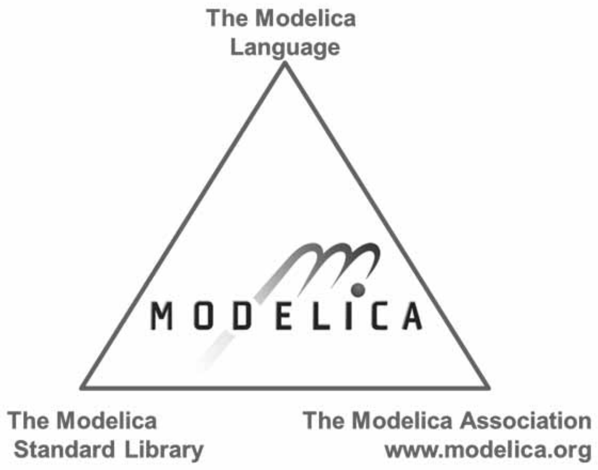


Figure 6: Illustration of Modelica's version of trinity: combining an open language, with open libraries and an open association.

2.2 Modelica Standard Library

Most modelling tasks do not start from scratch but build upon pre-existing models. The Modelica Standard Library provides therefore suitable building blocks. For the most relevant domains in physics and control it offers ready-to-use components, corresponding documentation and explanatory examples.

The recent development of the MSL has undergone steady growth. So has the number of code lines doubled to more than 250,000 from MSL v2.2.2 (2008) to MSL v3.2.1 (2013) (including comments and meta-data).

Where the MSL proves to be insufficient, the modeller can choose from a long list of free and or commercial Modelica libraries. The Modelica website [1] lists all these libraries together and offers compliance checkers. For the collaborative development of free libraries, GitHub offers a popular and well suited platform.

2.3 Modelica Association

The Modelica Association is a non-profit organization formed out of more than 20 organizational and more than 100 individual members. This community organizes its work in internal projects. Two of them are devoted for refinement and development of the language specification and for the development of the MSL.

Since both the specification as well as the MSL have meanwhile reached a high level of complexity, further development or request for changes or clarification build upon dedicated processes. To illustrate this, Figure 7 shows the size of the specification document (in terms of page number). From roughly 50 pages the size almost 6-folded to 300. The specification of Modelica is in plain text and in most parts not formal. Hence, the rise of specification length does not only express the growing complexity of the language but also the stronger need for clarifications. The larger number of tools supporting Modelica fortifies this need.

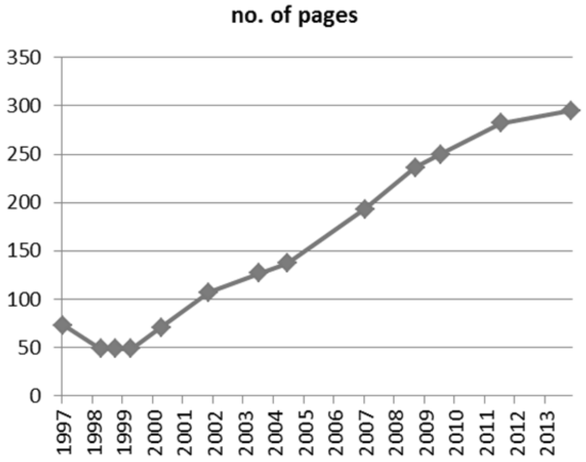


Figure 7: Length of the Modelica Specification Document in number of pages from 1997 (v1.0) to 2014 (v3.3rev1).

Furthermore, the Modelica Association is also organizing the development of the FMI Standard which goes beyond Modelica in its applicability (see chapter 3).

Internal meetings are organized in form of regular design meetings, roughly 4 times a year. To reach out to a larger community, international Modelica conferences are organized every one or two years. These conferences bring together industry and academia. Their scope ranges from concrete modelling applications to new language concepts. For newbies to Modelica, these conferences are an excellent learning and networking opportunity.

3 Modelica – Future Challenges

Being a naturally readable and openly standardized language, Modelica has established itself as an excellent storage format for mathematical models. This alone is of major importance. Model libraries often contain the result from years of development, validated data from expensive test rigs and in general models often represent key intellectual property of industrial companies. Hence, it is vital that the format of these models is a tool-independent and mature standard that guarantees ongoing usability.

This usability of a system dynamics model is also what generates the upcoming demands on the Modelica language and its tools. The primary and established application fields are the early design optimization of systems and the corresponding design of controllers.

These two fields form the seeds for two corresponding development trends in today’s industry. The first trend is the increasing use of models within systems engineering also frequently denoted as model-based systems engineering (MBSE). The second trend of cyber-physical systems is where controllers and the physical system are modelled as a whole and the models are used more directly for the controller development.

Figure 8 provides an overview of typical tasks arising from a stronger integration of Modelica in either systems engineering or cyber-physical systems.

3.1 Towards MBSE

In system engineering, the use of Modelica and its models is not an isolated activity but part of a larger product development process. The trend is to use more and more models for this. This confronts Modelica with new demands for the use of its models such as the formulation of requirements or the need for failure analysis.

Additionally, the term systems engineering correlates often with the on-going bureaucratization of engineering. The trend is hence driven by large industrial companies, often part of even larger conglomerates in the need to cooperate with each other. Since these large entities, are strongly bureaucratic [6], so their engineering processes become. For Modelica, this means that generic interfaces are needed to integrate the models or the tools within the foreseen (if not prescribed) industrial tool-chains. The key development in this direction was the development of the functional mock-up interface (FMI) standard [2].

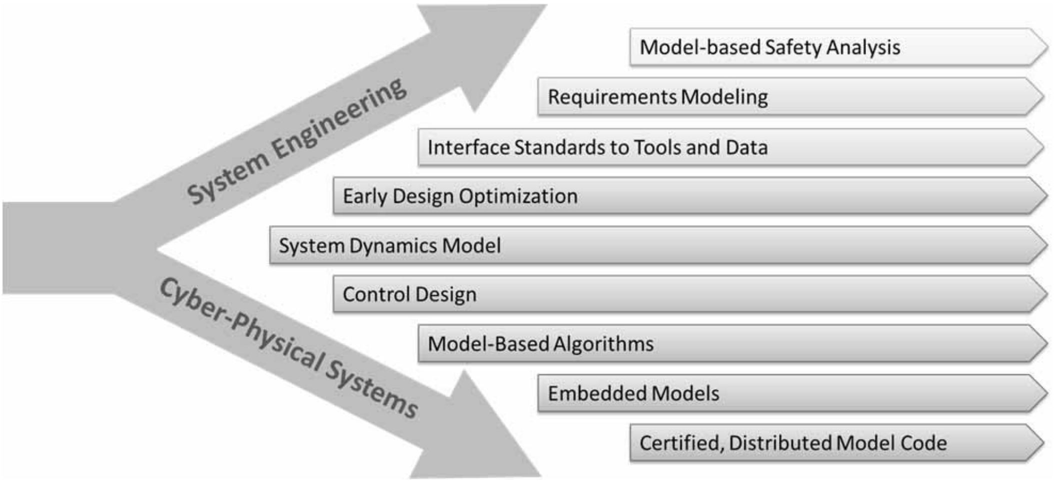


Figure 8: Illustration of two major development trends and their sub-topics.

FMI offers a tool independent standard for model exchange and co-simulation. The difference between these two forms is whether or not the code of the numerical ODE solver is included or not. Model-exchange is (simplistically) based on the mathematical form:

$$(\dot{\boldsymbol{x}}, \widehat{\boldsymbol{h}}, \boldsymbol{y}) \;=\; \mathrm{f}(\boldsymbol{x}, \boldsymbol{h}, \boldsymbol{u}, t)$$

with $\boldsymbol{x}$ being the continuous states, $\boldsymbol{h}$ the discrete states, $\boldsymbol{u}$ the input, $\boldsymbol{y}$ the output and t the time. The FMI then offers a suitable application programming interface that enables the connection to other models and the application of any hybrid ODE solver. In co-simulation, the numerical solver for the advance of time is already included in the exchanged code. This is suitable for non-stiff couplings between sub-systems and is also an option to combine classic tools for system simulation with 3D tools for fluid dynamics or finite elements.

One important aspect of FMI is that models do not need to be exchanged as white boxes. The model code can be obfuscated either by compilation or even by more effective means. In many cases, this represents a sufficient level of protection of intellectual property that companies are willing to mutually exchange some of their models, a process needed for the early design of today’s systems. For instance, within the research project Clean Sky, the environmental control system model of an aircraft, the corresponding cabin model and the electrical system model could be exchanged by FMI and a total system simulation was performed [14].

The exchange of models is also important for other reasons. Models can also represent requirements.

In this way a company can communicate its specification to a supplier and the supplier can test his models against these specifications.

Ready-to-use libraries [8] help the Modelica developer to formulate its requirements and future language extensions [4] may ease the binding of requirements to the corresponding models in the near future.

The FMI does not only offer a standardized API, it also contains a standardized XML format for the description of hierarchical, object-oriented models. This format can be used to import or export meta-information for the corresponding models. Enhancements of the Modelica standard enable to include this or other meta-information directly within Modelica models [15]. In combination this allows advanced model-based methods to be performed using multiple tools.

For instance, models can be tagged with possible fault modes and corresponding failure rates. A tool can then extract this information and perform a series of simulation for a safety and reliability analysis. By extracting information about the connection structure of the model, this analysis can cover all relevant fault cases within reasonable effort [10]. Special Modelica libraries for fault modelling may help the modeller perform such a task [13].

In summary, the integration of Modelica into the processes of MBSE is an on-going process. However, the formulation of interface standards such as FMI has led to significant higher industry acceptance. New, practically explored language concepts support this development by enabling a better handling of meta-data within models.

3.2 Towards Cyber-Physical Systems

Cyber-Physical systems denote mechanisms in interaction with model-based algorithms. The goal is hence to develop model-based algorithms such as controllers, health-monitoring, fault-detection, etc. within Modelica, test these algorithms (also in discretized form) in a virtual environment with Modelica models. Ideally, code for the distributed embedded control units shall then be automatically generated in a certified form similar to standards such as DO-178. In its entirety this represents hence a challenging goal.

In order to better support this trend, Modelica 3.3 has been extended by Modelica Synchronous [5]. This language extension enables the modelling of clocked synchronous processes. In this way, controllers can be modelled in a discrete form and discrete control effects can properly be taken into account.

To generate code for the embedded control units, code generation of Modelica tools may require improvement. Also here the FMI standard may be useful to serve as a container for light-weight model and simulation code. The use of FMIs on rapid-prototyping hardware has meanwhile substantially improved [2].

Finally, for many safety critical applications in aviation, transport or energy, the certification of the applied controller code is of key importance. This will only be realistically possible with a well-defined subset of the Modelica language. First definitions in these directions have been undertaken by [9] and [11]. Nevertheless, the vision to automatically generate certified code for embedded systems out of Modelica models is still a far reaching goal but definitely worth pursuing.

4 Conclusions

Being solely based on equations with no pre-implemented physics, Modelica is a truly generic and universal modelling standard. Much freedom is given to the modeller and after almost 20 years of establishment, it is fair to say that modellers of many different backgrounds have endorsed this freedom. For the future development of Modelica, the resulting amount of variety in its usage and the rising complexity represents a vital challenge – a challenge worth to be taken.

About the author

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Modeling, Simulation, and Optimization with Petri Nets as Disjunctive Constraints for Decision-Making Support. An Overview.

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Abstract. A panoply of modeling formalisms, based on the paradigm of Petri nets is overviewed and their application to modeling, simulation, and optimization of discrete event systems with alternative structural configurations is discussed. This approach may be appropriate for the development of decision support systems for the design process of discrete event systems. The motivation, definition and an example of application is provided for several formalisms that include a set of exclusive entities. A practical methodology and the main advantages and drawbacks of the application of these formalisms to the calculation of quasi-optimal values for the freedom degrees in the structure of discrete event systems in process of being designed is addressed.

Introduction

The application of discrete event systems (DES) to a broad variety of fields of technological interest is growing from day to day [1], [2].

Petri nets (PN) consist of a paradigm widely used for the modelling, simulation, and optimization of DES. Many theoretical results related to the PN contribute to the body of knowledge that can be applied to the construction of models, their simplification and verification by structural analysis, their validation, as well as the implementation of performance analysis [3], [4].

Simulation consists of another very productive methodology for many operations related to PN. In particular diverse decision-making support methodologies rely upon the simulation of the evolution of the Petri net model of an original DES [5], [6], [7].

Several methodologies for decision-making support based on the simulation of Petri net models proceed by means of the following steps:

a) Obtaining a Petri net model of a DES with freedom degrees or controllable parameters.
b) Defining the objectives to be achieved by the DES and the way to evaluate their degree of achievement, also called quality, in its Petri net model.
c) Making a guess on a feasible (and promising) set of values for the different freedom degrees of the model, or solution of the decision-making problem, including the initial state or marking of the Petri net.
d) Configuring the parameters of the simulation, for example the stop criterion. In some cases, such as for a manufacturing process, this criterion might be the completion of a certain period of simulated time.
e) Developing the evolution of the Petri net, while gathering the information necessary for evaluating the quality of the tested solution.

These methodologies reach a significant potential if the previously mentioned steps from (a) to (e) are iterated for different solutions or values for the controllable parameters of the model. After a number of solutions have been simulated, regarding the availability of time and computer resources, it is possible to provide a set of selected solutions to the decision maker [8], [6], [9], [10].

Depending on the way of choosing the feasible solutions to be simulated, several methodologies can be defined, since an exhaustive exploration of the complete solution space is not possible for the majority of cases. This limitation arises from the construction process of the set of feasible solutions for the freedom degrees of the Petri net. This may be carried out by a combinatorial process, where different values for the diverse controllable parameters are combined for building up solutions.

As a consequence, the size of the solution space might be huge and, since the simulation of a single solution may consume significant computer resources, the simulation of all the solutions might not be a realistic option [6], [9], [10].

In particular, a linear augmentation of the size of the set of controllable parameters implies an exponential growth of the size of the solution space.

Once the exhaustive search for solutions is discarded, a guided search of the most promising solutions is a practical approach. Nevertheless, due to the fact that the exploration is reduced to a small region of the solution space, the optimum is not always found. However, a good solution, quasi-optimal, is enough for practical purposes.

This search for promising solutions can be a manual process, such as a “what-if” analysis, where small changes on tested solutions seek to deduce the influence of variations of one or several freedom degrees’ values in the outcome of the simulation [11], [12]. Alternatively, an automatic procedure for exploring feasible solutions may use of metaheuristics for exploring local optima in the search for the global optimum [5] to [10].

This approach has been applied to the operation of a DES [5] to [8], [10]. That means that the makespan, yield, utilisation rate of the equipment, or level of stocks have been considered to evaluate the quality of solutions for the scheduling or routing of systems such as a manufacturing facility or a supply chain, just to give an example.

Another common and complex case, where decision making support can be applied is the design of a DES [13], [9]. One of the key steps in the design of a system is the analysis of different alternative solutions for choosing the best one and proceed with the following design stages. It is very common that different alternative solutions for the design of a DES can be modelled by PN with different static structures [13], [9].

The design of a DES is not the only application dealing with a variety of static structures. It is the case of systems, whose structure varies over time on a controllable process, i.e. a decision maker should find the best sequence of transformations to achieve its goals. An example is the problem of preventive maintenance, where a manufacturing facility should stop sequentially its different installations, without a restriction on the sequence to follow but with strong constraints on the period of time each installation is stopped, the resources used in the operations of maintenance, the overall loss of production and the impact on the service provided to customers [14].

The way to build up the alternative structural solutions to these decision problems might be based in the combination of feasible subsystems of the model [15]. This is especially true, when the DES to be designed is composed by differentiated and real subsystems, such as machines or production lines. The number of feasible alternative solutions arisen from this combinatorial process may be very large; thus, manual selection of the best alternative solution by expensive experts in manufacturing management is not always an efficient perspective.

A decision problem can be stated with a set of alternative PN modelling the structural configurations, which are exclusive constraints; hence, they constitute a disjunctive constraint to the decision problem [16].

Four approaches for solving the problem are addressed in this document, as well as their advantages and drawbacks. Main difference between these approaches is the Petri net formalism chosen for modelling the DES. In brief, the formalism drives the methodology applied to state and solve the decision problem [17], [9].

In Section 1, the formalism of the alternative PN is discussed, while in Section 2, it is considered the compound PN. The following two sections address the alternatives aggregation Petri nets (AAPN) and the disjunctive coloured Petri nets, respectively. Section 5 focusses on the comparative of the methodologies arisen from the different formalisms, while the following section is devoted to the combination of different formalisms in a single PN model. Section 7 describes the common steps of the methodologies for solving a decision problem using these formalisms. Section 8 presents the conclusions and the last section lists the bibliographical references.

1 Alternative Petri nets

This formalism has been used in diverse applications and can be considered a classic approach for solving decision problems with PN as disjunctive constraints. A definition and contextualisation is provided in [18].

1.1 Motivation

This formalism is a classic approach, used in diverse applications, such as [11], [19], and [12]. It is a natural, yet inefficient way to represent a disjunctive constraint in terms of PN [9]. This intuitive way to describe a set of alternative models for designing a DES consists of developing independent models for every alternative structure.

This simple idea is behind a set of alternative Petri nets, which contains so many nets as alternative models have been considered in the process.

1.2 Definition

A set of alternative Petri nets is a collection of models with different structure, i.e. incidence matrix, where any of them is able to describe the same DES. These models can be represented by any Petri net formalism.

Definition 1. Set of alternative Petri nets.

$S_R = \{ R_1, \ldots, R_n \}$, set of PN, is a set of alternative Petri nets if

i) $\mathrm{card}(S_R) = n > 1$.

ii) $\forall\ i, j \in \mathbf{N}^*$ such that $1 \leq i, j \leq n$, $i \neq j$, $R_i, R_j \in S_R$, then $\mathbf{W}(R_i) \neq \mathbf{W}(R_j)$, incidence matrices of R_i and R_j.

iii) $\exists!\ R_k \in S_R$, such that $\mathbf{m_0}(R_k) \neq [0\ \ 0\ \ldots\ 0]^T$, where $\mathbf{m_0}(R_k)$ is the initial state or initial marking of R_k. □

In other words, given a set of alternative Petri nets associated to a DES, the choice of any of them as solution for the structure of the system's model implies that the initial marking of all the non-chosen alternative Petri nets contains zero tokens in every place. Only the chosen PN can be simulated at a given time. The simulation of any other PN requires discarding the previous choice.

1.3 Examples

Some examples of sets of alternative Petri nets are:

A decision problem for deciding the best structural configuration of a manufacturing facility among a set of three alternative Petri nets is stated in [18]. A second example is provided just to illustrate the statement of an optimization problem with such a disjunctive constraint.

Four different topologies of manufacturing facilities, with diverse degrees of production flexibility, are discussed in [12]. Their Petri net models, developed for simulation, constitute a set of four alternative Petri nets.

An assembly line is modelled in [19] under three different manufacturing strategies. The resulting alternative Petri nets are simulated for choosing the best control policy: push, "on demand", or Kanban.

A manufacturing facility is presented in [11], such that the combination of diverse production strategies and lot sizes lead to a set of alternative Petri nets.

2 Compound Petri Nets

This formalism is well known under the name of parametric Petri nets or parameterized Petri nets. An application of this formalism to decision problems with PN as disjunctive constraints is described in [20].

2.1 Motivation

In design problems, the alternative Petri nets might be an inefficient option to construct a Petri net model appropriate for simulation because of the following reasons:

a) Different alternative solutions might share common subsystems; hence, a complete set of alternative Petri nets may contain a large amount of redundant information. The larger the model, the more computational resources might consume its simulation.

b) Each alternative PN defines an independent problem of searching good solutions. Hence, computer resources should be devoted to every alternative Petri net, no matter if it leads to good solutions or not.

c) To avoid the statement of a large number of search problems, a manual pre-selection of a small set of feasible solutions is usually carried out. This process might skip high quality solutions.

A compound PN tries to remove these limitations by:

a) Removing redundant information in the static structure of the PN that defines the disjunctive constraint.

b) Allowing a single search process. Non-promising solutions can be skipped, devoting more computer resources to promising regions of the solution space.

c) A single search problem is stated; hence, a manual pre-selection of feasible solutions is not necessary.

2.2 Definition

The static structure of a PN is described by its incidence matrix; hence, a compound Petri net presents freedom degrees or controllable parameters in its incidence matrix [21]. Moreover, every alternative structural configuration (ASC) of the model is associated to a feasible set of values for these parameters. Even though it might be possible to construct ASC from different combinations of values for these controllable parameters, in general, not all the combinations are valid sets.

Definition 2. Compound Petri net.

A marked compound Petri net is a 7-tuple

$R^c = \langle P, T, \mathrm{pre}, \mathrm{post}, \mathbf{m_0}, S_{str\alpha}, S_{valstr\alpha} \rangle$, where

i) P and T are disjoint, finite, non-empty sets of places and transitions respectively.

ii) pre: $P \times T \rightarrow \mathbf{N}$ is the pre-incidence function.

iii) post: $T \times P \rightarrow \mathbf{N}$ is the post-incidence function.

iv) $\mathbf{m_0}(R^c)$ is the initial marking of the net.

v) $S_{str\alpha} \neq \varnothing$ is the set of structural parameters of R^c.

vi) $S_{valstr\alpha}$ is the set of different feasible combinations of values for the structural parameters of the net.

2.3 Examples

[21] illustrates the main concepts of a compound PN, while two examples in [20], describe a transformation of a set of alternative PN into one compound PN.

3 Alternatives Aggregation Petri Nets

AAPN is a formalism proposed as a tool for describing disjunctive constraints in the form of a Petri net model.

3.1 Motivation

Similarly to compound PN, AAPN aim at removing the limitations of a set of alternative models for a DES. The construction process and specific parameters of the formalism itself are discussed in [18].

3.2 Definition

An AAPN integrates in a single Petri net model a complete set of ASC. A set of choice variables allows choosing one of the ASC. A function of choice variables is associated to some transitions as guards. Only one choice variable can be active at a given time [16].

Definition 3. Alternatives aggregation Petri net.

An AAPN system, R^A, is defined as the 7-tuple:

$R^A = \langle P, T, \mathrm{pre}, \mathrm{post}, \mathbf{m_0}, S_A, \mathrm{f_A}\rangle$, where,

i) *P, T,* pre, and post are explained in Definition 2.

ii) $\mathbf{m}_0$ is the initial marking representing the initial state and is usually a function of the choice variables.

iii) $S_A = \{a_1, a_2, \dots, a_n \mid \exists!\, a_i=1$, where $i \in \mathbf{N}^*$, $1 \le i \le n \wedge \forall\, j \neq i$ then $a_j=0\}$. S_A is a set of choice variables, such that $S_A \neq \varnothing$ and $|S_A| = n$.

iv) $\mathrm{f_A}: T \rightarrow \mathrm{f}(a_1, \dots, a_n)$ is a function that assigns a function of the choice variables to each transition t such that type[$\mathrm{f_A}(t)$] = Boolean. □

3.3 Examples

The application of an AAPN to the design of a manufacturing facility is shown in [18]. Different strategies for solving this problem by means of distributed computation are presented and their computation time compared. The transformation algorithm from a set of alternative Petri nets into a single AAPN is illustrated in [16].

4 Disjunctive Colored Petri Nets

Coloured Petri nets consists of a formalism, closely related to the AAPN [22], [9].

4.1 Motivation

Even though AAPN can be very efficient, when describing a model of a disjunctive constraint, simulating the evolution of a model might require specific *ad hoc* tools.

Coloured Petri nets are conceptually similar to the AAPN, but the formalism contains the same elements than the commonly used coloured Petri nets. For this reason, tools developed for simulating coloured Petri nets or the more general high-level Petri nets, can be used for simulating disjunctive coloured Petri nets.

4.2 Definition

A disjunctive coloured Petri net presents a static structure which is the same as an equivalent AAPN. The main difference is associated to the mechanism used to decide the chosen alternative structural configuration. In the case of a disjunctive coloured Petri net, it is possible to define a choice colour in different ways [22].

Nevertheless, a choice colour allows for the tokens of a certain structural configuration to describe the evolution of the Petri net [9]. An important characteristic of the choice colour is that it should be monochrome, i.e. it is not possible to mix tokens from different choice colours for analysing the evolution of the Petri net by simulation. This limitation prevents the exploration of unreal states for the Petri net model.

Definition 4. Disjunctive colored Petri net

A disjunctive colored Petri net $R = \langle N, \mathbf{m}_0\rangle$ is a 9-tuple

$CPN = \langle P, T, F, \mathbf{m}_0, \Sigma, V, \mathrm{cs}, \mathrm{g}, \mathrm{e}\rangle$, where:

i) P and T are disjoint, finite, non-empty sets of places and transitions respectively.

ii) $F \subseteq P\times T \cup T\times P$ is a set of directed arcs.

iii) $\mathbf{m}_0$ is the initial (monochrome) marking.

iv) Σ is a finite set of non-empty color sets, such that verifies one of the following two conditions:

a. $\exists\, S_C$ set of Boolean choice colors such that $S_C \in \Sigma$.

b. $\exists\, (c, C)$ a natural choice color such that $C \in \Sigma$ and C is the number of ASC, while $c \in \mathbf{N}$ and $1 \le c \le C$.

v) V is a finite set of typed variables such that type[v] $\in \Sigma$ for all variables $v \in V$.

vi) $\mathrm{cs} : P \rightarrow \Sigma$ is a color set function that assigns a color set to each place.

vii) $\mathrm{g} : T \rightarrow EXPR_V$ is a guard function that assigns a guard to each transition t such that type[g(t)] = Boolean.

viii) $\mathrm{e} : F \rightarrow EXPR_V$ is an arc expression function that assigns an arc expression to each arc a such that type[e(a)] = $\mathrm{c}(p)_{MS}$, where p is the place connected to the arc a.

4.3 Examples

A decision problem on the choice of the best production strategy for a manufacturing facility is given in [9]. In this example a set of 24 alternative Petri nets are transformed into a single disjunctive coloured Petri net. An optimization problem is stated and a comparison between a classic solving strategy by means of the set of alternative Petri nets and the use of the single disjunctive coloured Petri net is shown.

In [22] an application of the disjunctive coloured Petri nets to the design of a manufacturing facility is presented. The modelling process from a set of diverse alternative Petri nets is detailed.

5 Advantages and Drawbacks

The main purpose of the four Petri net formalisms presented in this paper, consists of minimizing the size of a Petri net model with a set of ASC. Nevertheless, there are other considerations that may be considered as advantages or drawbacks of these formalisms. In particular, the following features are interesting ones:

a) Size rate, or quotient between the size of the model, measured by the size of its incidence matrix and the size of an equivalent benchmark, usually a set of alternative Petri nets.
b) Easiness of modelling. Simulation can be considered as an inexpensive methodology for experimentation, when compared with practising the real system. However, constructing models fast and with absence of errors may make feasible a decision making support tool.
c) Availability of theoretical and practical tools for analysing, simplifying, and simulating a model of a DES.

It is interesting to realize that the compactness of the Petri net model, allowed under certain conditions by some formalisms presented in this document, does not compromise the usefulness of the model to explicitly represent and show the structure of the modelled system. In fact, the removal of redundant data present in the model of the system tends to point out the key information that determine the structure of the system itself.

Some of the features mentioned in the present section depend on the DES to be modelled. In particular, if there are similarities between the ASC it is likely that certain formalisms might lead to reductions in the size of the model. Of course, it is necessary to specify what means similarity in this context.

The concept of similarity depends on the formalism that is intended to be applied.

For example, a compound Petri net may present a small size rate, corresponding to a large amount of removed redundant data, when the incidence matrices of the alternative Petri nets present a reduced number of different elements. As a consequence, in the context of a compound Petri net, similarity is a concept that can be quantified in inverse proportion to the number of different elements between the incidence matrices of and equivalent set of alternative Petri nets.

Nevertheless, similarity in the case of AAPN or disjunctive coloured Petri nets can be quantified as a parameter proportional to the number and size of shared subnets. This parameter also depends in inverse proportion to the elements of the model that do not belong to any shared subnet. It is not unusual in a design process that the different ASC are built up by means of combining in different ways a given set of subnets [17], [15].

It is also possible to say that if the similarity of the alternative Petri nets that model a DES is not high, the size of the set of alternative Petri net may be smaller than the size of an equivalent model described by any other of the formalisms presented in this document.

Regarding other important feature, such as the modelling easiness, it is possible to say that the alternative Petri nets may lead to a very intuitive way of modelling, since an independent model is developed for any of the ASC. Nevertheless, a faster approach for the modelling stage might be carried out, in cases characterised by high similarity between the alternatives, by other formalisms. For example, in the case of a family of machines with small structural differences, a compound Petri net may be an appropriate formalism, not only for obtaining a small model but also for constructing the model in a productive way, by developing the common structure and particularizing the details of every alternative by means of a set of parameters and the associated set of values for them.

Analogously, the AAPN or the disjunctive coloured Petri net might lead to an easy modelling process when the ASC are obtained by different combinations of a set of subnets.

The last important feature of the formalisms that will be considered in this document is the availability of tools for modelling, analysing, and simulating the models.

In particular, the tools should permit including in the model the elements that allow representing the exclusiveness between alternatives: parameters in the case of compound Petri nets and guard functions for certain transitions in the case of the AAPN.

	Size rate	Modelling easiness	Practical tools
Set of alternative PN	Usually largest	Intuitive	No restrictions
Compound PN	Small with similar incidence matrices	Easy with similar incidence matrices	For parametric Petri nets
AAPN	Small with shared subnets	Easy with shared subnets	Allowing guards in transitions
DCPN	Small with shared subnets	Easy with shared subnets	For Colored Petri nets

Table 1: Summary of main characteristics of the formalisms presented in this document with regard to three key concepts.

Disjunctive coloured Petri nets require to model choice colours, which are supported by any coloured Petri net tool. A summary of the previous considerations is provided in Table 1.

6 Polytypic Sets of Exclusive Entities

This section is devoted to abstracting the feature of the Petri net formalisms able to represent a set of ASC. As a result of this process, a characterisation of all this kind of formalisms will be stated.

6.1 Motivation

All the formalisms presented in this paper as tools for modelling DES with ASC can be applied to the construction of disjunctive constraints in decision problems.

There is a different feature in every one of these formalisms to describe the exclusive nature of each alternative structural configuration. This feature is a set of exclusive entities, whose cardinality is the same as the number of ASC.

In the case of a set of alternative Petri nets, every pair of nets are mutually exclusive, while in the case of a compound Petri net, the set of exclusive entities is a set of feasible combination of values for the structural parameters of the net. The AAPN presents a set of choice variables and a disjunctive coloured Petri net includes a set of choice colours.

6.2 Definition

The examples that have been shown in this document include Petri net models with a monotypic set of exclusive entities, meaning that a single formalism has been chosen for constructing the whole disjunctive constraint in the form of a Petri net [22].

Let us consider a DES D, whose structure is not completely defined. Let us consider that there are n ASC for D, able to determine completely the structure of D. It is possible, although not necessary in this context, to obtain a different alternative Petri net model for D from each one of the different structural configurations. As a result, it would be possible to obtain a set of n alternative Petri nets $S_R = \{ R_1, \ldots, R_n \}$.

Definition 5. Monotypic set of exclusive entities.

A monotypic set of exclusive entities related to a DES D is a set $S_x = \{ X_1, \ldots, X_n \}$, such that

i) The elements of S_x are exclusive, i.e. only one of them can be chosen as a consequence of a decision.

$\forall\, i, j \in \mathbf{N}^*, i \neq j, 1 \leq i, j \leq n$

ii) $X_i \neq X_j$

iii) type[X_i] = type[X_j].

iv) $\exists$ f: $S_x \rightarrow S_R$, where $S_R = \{ R_1, \ldots, R_n \}$ is a set of alternative Petri nets, feasible models of D, such that f is a bijection, meaning that $\forall\, X_i \in S_x\ \exists!\ \mathrm{f}(X_i) = R_i \in S_R$ and $\forall\, R_i \in S_R\ \exists!\ \mathrm{f}^{-1}(R_i) = X_i \in S_x$. □

Nevertheless, it is also possible to combine different formalisms for modelling a given DES. The reason for following this strategy may arise from the conclusions presented in section 5, where a comparative of the advantages and drawbacks of the formalisms is performed. In fact, a set of alternative Petri nets can be decomposed into different subsets, whose elements might present differences regarding the similarity between the ASC of the DES. In this case, the associated set of exclusive entities is not a monotypic one anymore but a polytypic set [20], [18].

Definition 6. Polytypic set of exclusive entities.

A polytypic set of exclusive entities associated to a DES D is a set $S_x^p = \{ X_1, \ldots, X_n \}$, which verifies that

i) The elements of S_x^p are exclusive, i.e. only one of them can be chosen as a consequence of a decision.

ii) $\forall\, i, j \in \mathbf{N}^*, i \neq j, 1 \leq i, j \leq n$ then $X_i \neq X_j$.

iii) $\exists\, S_x , S_x' \subseteq S_x^p$, such that $\forall\, X_i \in S_x , X_j \in S_x'$ it is verified that type[X_i] $\neq$ type[X_j].

iv) $\exists$ f: $S_x^p \rightarrow S_R$, where $S_R = \{ R_1, \ldots, R_n \}$ is a set of alternative Petri nets, feasible models of D, such that f is a bijection, meaning that $\forall\, X_i \in S_x^p\ \exists!\ \mathrm{f}(X_i) = R_i \in S_R$ and $\forall\, R_i \in S_R\ \exists!\ \mathrm{f}^{-1}(R_i) = X_i \in S_x^p$. □

6.3 Examples

In [22] the modelling of a manufacturing facility with a number of alternative structural configurations is carried out by two monotypic set of exclusive entities in the form of a set of alternative Petri nets and a disjunctive coloured Petri net respectively.

Furthermore, [20] is a document devoted to exploring some modelling possibilities of the polytypic sets of exclusive entities. This reference presents an example, where the same model is transformed to be represented by three different formalism. In two of the representations a monotypic set of exclusive entities has been used, while in the third case, a polytypic set has been considered as a set of diverse alternative compound Petri nets.

The configuration of a set of exclusive entities as a polytypic one is the basis of the potential that this methodology presents for using distributed computation to speed up the solving methodology of the decision problems with disjunctive constraints. This topic has been addressed in [18].

7 Optimization with Petri Nets as Disjunctive Constraints

Section 1 discussed a general algorithm for decision making support based on simulation, which can be found extensively in the scientific literature. This algorithm is applicable under several approaches for cases where there is not any disjunctive constraint in PN form.

The introduction of formalisms able to model sets of exclusive entities requires the adaptation of the decision making methodology to the special features of a disjunctive constraint represented by one or several of these formalisms [17].

In fact, it is desirable not to modify the steps of the algorithm presented in the introduction, due to its success in diverse applications, as well as the existence of tools developed to apply this procedure. The main difference of the classic approach with the proposed methodology to be applied using the formalisms with exclusive entities (others than a set of alternative Petri nets) is to reduce the number of instances of decision problems to be solved, from $k \in \mathbf{N}$, where $1 \leq k \leq n = \mathrm{card}(S_R)$, to just one. However, if several independent processors are available, this objective can be adapted [18].

In other words, instead of dodging the disjunctive constraint of the decision problem by choosing a subset of k promising alternative Petri nets and solving k independent decision problems, a single decision problem is tackled with the disjunctive constraint represented in the form of a single Petri net with exclusive entities.

The only requisite to perform this reduction in the number of instances of the decision problem is to include in any solution to the problem a mechanism to choose one exclusive entity prior to the development of a simulation. This additional information has two purposes:

a) The solution itself bears the necessary information to simulate the model of the system under a single structural configuration, thus, regarding the structure of the system, performing a deterministic simulation.
b) Once the decision making problem has been solved, the solution(s) furnishes the decision maker with a suggestion on the most promising ASC.

As a conclusion, when applying this proposed methodology for decision making support, all the three drawbacks of the classic methodology, highlighted in section 2.1 have been overtaken [9].

8 Conclusions

In this document, a systematic approach for the description of disjunctive constraints represented by PN models is addressed. In particular, four formalisms have been presented: a set of alternative Petri nets, a compound Petri nets, an AAPN, and a disjunctive coloured Petri net.

All these formalisms have in common the inclusion of a mechanism to represent a set of exclusive entities, which are the main feature of the disjunctive constraint. Moreover, this approach allows the combination of different Petri net based formalisms to describe diverse parts of the same Petri net model, with the purpose of profiting from the nature of the system to be modelled and the features of the formalisms.

An application of this approach can be found in the statement of decision problems based on the simulation of the model of a system with ASC. This methodology proves that splitting the problem in a pre-selected number of subproblems may a less effective strategy. A decision making support problem with a set of ASC for the system of interest can be very common in a design process.

The research line presented in this document seems promising. However, there are open research questions that should be solved. On the one hand, more applications should be performed to get information on its suitability and success for the decision making in diverse fields and processes.

On the other hand, more effort should be devoted to the characterization of a given DES to decide which combination of formalisms to choose for describing it and how to minimise the size rate of the final model.

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Design, Simulation and Operation of Task-oriented Multi-Robot Applications with MATLAB/Stateflow

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Abstract. Robot programming software is mostly proprietary and cannot be used for other manufacturers' robots. Nevertheless, there is a desire to allow interactions between robots being developed by different manufacturers in order to set up a *Multi-Robot System* (MRS). An MRS refers to a team consisting of interacting industrial robots which share skills to increase performance. The mapping of classical control development methods for *Single-Robot Systems* (SRSs) to MRSs is difficult. Based on a classification of interactions within MRSs, a *Task-Oriented Control* (TOC) approach is suggested and examined. Furthermore, with *Simulation Based Control* (SBC) an approach for continuous development of event-driven multi-robot controls according to the *Rapid Control Prototyping* (RCP) is presented. SBC supports TOC and the mapping of interactions via tasks. Based on SBC and MATLAB/Stateflow a prototypical, task-oriented model library for interacting robots is developed and tested.

Introduction

New fields for applied robotics are made up continuously, something which increases the need for research. For example, current research focus on mobile robotics, service robotics and human-robot interaction is referred to as *Collaborative Robots* (Cobots) [1]. In manufacturing, industrial robots are often used as flexible handling and production units.

In the context of Industry 4.0, there is a desire for intelligent and networking factories [2]. Among other things, these are characterized by a flexible and versatile production of individual parts up to mass production. A *Single-Robot System* (SRS) mostly does not have sufficient skills to meet these requirements. Therefore, *Multi-Robot Systems* (MRSs) are proposed as a key technology.

In an MRS, the robot systems which are involved form a team by sharing skills in order to enhance performance. In this work, an MRS consists of commercially available SRSs with a shared central control computer.

In contrast to an SRS the involved robot systems for an MRS always influence each other, which is called interaction. One motivation for the use of an MRS is to increase the efficiency of the robot team, thus reducing the production time and costs. Nevertheless, the use of an MRS presents new challenges, because classical industrial robots and their software tools are usually not designed to be used in a team.

For an SRS, different design methods for control development are known [3,4] but the transfer to an MRS is difficult [5]. In particular, the use of robots from different manufactures represents a major challenge. Industrial robots are mostly programmed in proprietary development environments, which do not support third party robots. Some of these environments are already supporting a control development for MRSs, but usually only for small team sizes, a limited number of predefined interactions and exclusively for robots of the particular manufacture. Also the integration of sensors and actuators is usually restricted to vendor specific products.

Proprietary development environments are based on vendor-specific robot programming languages. Attempts to standardize robotic programming languages, such as the *Industrial Robot Language* (IRL) and its successor, the *Programming Language for Robots* (PLR), are usually ignored by robot manufactures. However, the ongoing spread of the *Robot Operating System* (ROS) [6], an open source project to provide cross-vendor robot programming and process visualization, shows that there is an unbroken interest in unified development methods and environments.

In the context of control development, different demands exist [7]. In this work the following issues will be considered in more detail: (i) flexible adaptation to new problems and quick commissioning (ii) testability, maintainability (iii) cross-vendor interactions between robots and (iv) support of vendor-independent hardware and software.

In order to meet these demands, the software and conceptual foundation are presented. At first a non-vendor-specific control of industrial robots is shown, using the *Robotic Control & Visualization* (RCV) Toolbox for MATLAB as middleware with associated interface. Then the concept of *Task-Oriented Control* (TOC) development [4,8] is described for an SRS. For MRS control development, the *Simulation Based Control* (SBC) procedure model is proposed which follows the *Rapid Control Prototyping* (RCP) approach by Abel [9]. SBC enables continuous control development from the early planning phase to the operational control use and defines a framework for practical implementation. In addition, the investigations in [10–12] show that the SBC approach supports TOC. Furthermore a classification of interactions between industrial robots is introduced based on [13]. Based on a case study, the mapping of interactions to tasks is examined. The implementation of the SBC approach is realized in the MATLAB/Stateflow environment.

1 Fundamentals

In this section, the necessary basics for the development of a *Multi-Robot System* (MRS) control are explained. The methods described and the tools are already used for *Single-Robot Systems* (SRSs) and will be applied to MRSs.

1.1 Robotic Control & Visualization Toolbox for MATLAB/Simulink

As mentioned before, the programming of robotic systems is affected by vendor dependent languages and proprietary development environments. Existing standards are mostly ignored by manufacturers, which makes control development for multi-robot controls difficult or even impossible. In engineering, control development is often associated with *Scientific and Technical Computing Environments* (SCEs), such as MATLAB. To close the gap between vendor-specific robotic environments and common SCEs, the *Robotic Control & Visualization* (RCV) Toolbox for MATLAB/Simulink was developed [14,15].

The RCV Toolbox consists of three modules: (i) a set of generalized robot-oriented MATLAB functions, (ii) a set of MATLAB functions for process visualization and (iii) robot-specific command interpreters. The basic structure of an RCV based control is shown in Figure 1. The *Control PC* runs a MATLAB instance which processes the control program on the basis of functions of the module (i). The *Visualization PC* runs another instance of MATLAB and visualizes the process based on functions of the module (ii). The communication with real robots is performed by the robot controllers and specific command interpreters according to the module (iii). A detailed description of the RCV Toolbox can be found in [16].

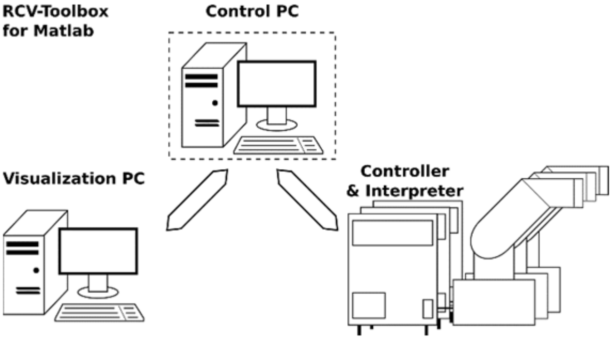

Figure 1: Principle structure of an RCV-based multi-robot application.

It should be noted that the use of an SCE, such as MATLAB, simplifies the integration of additional sensors and actuators to the control.

1.2 Task-oriented control design

Task-Oriented Control (TOC) design [4,8] is already known for SRSs [17,18]. The principle is to divide the complex control problems into a set of tasks and their couplings.

Tasks are logical, mostly independent, abstract operations. Once identified, tasks are coupled together to map the control problem. Couplings can be carried out sequentially, conditionally or in a loop. Some problem descriptions mean it is necessary to use tasks multiple times or to work them off in parallel. The general procedure corresponds to the human way of thinking in solving complex problems.

Figure 2 shows the TOC approach on the example of a transportation problem. The problem can be divided (decomposition) into the two tasks *PickPart* and *PlacePart*.

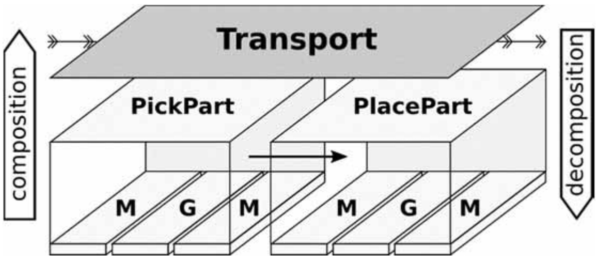

Figure 2: Tasks and subtasks of transport problem.

The task *PickPart* specifies the grasping of a component at a defined position and the task *PlacePart* corresponds to placement at a new location. The task *PickPart* has to be executed before the task *PlacePart*, which corresponds to a serial execution. Furthermore, the figure shows that a task can be composed of other (sub-) tasks. For example, the task *PickPart* can be described by the serial linking of the tasks *Move* (M), *GripperAction* (G) and *Move* (M). According to [10], TOCs can be realized using *Top Down* (decomposition) or *Bottom Up* (composition) principles.

A TOC specification is not directly executable, because tasks are an abstract description of operations. A task describes '*what*' but not '*how*' something has to be solved. To perform tasks, a transformation method is required, as shown schematically in Figure 3.

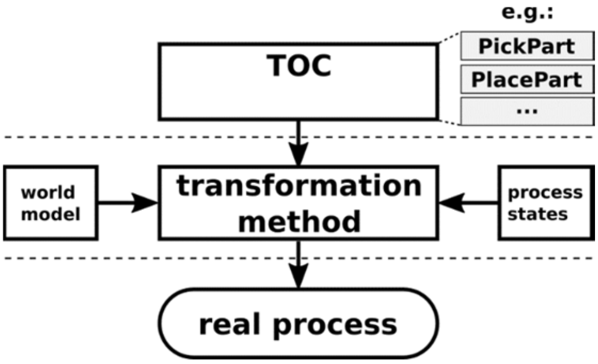

Figure 3: Processing of a TOC according to [8].

All tasks have to be transformed into control commands in order to execute them. To perform the transformation it is either possible to use a world model or a process model.

Early TOCs used a compilation approach which produces an executable control program in advance. The transformation was carried out before the commissioning by using a world model. More recent works [8,17] understand the transformation step as a function of the operational control.

This has the advantage that current process states can be used instead of the world model. Thus, reactive controls can be realized, which can flexibly adapt to current process states and, for example, respond to faults by alternative processing of individual tasks. Here, the task transformation has to keep pace with the process dynamics.

Another extension of classical TOC is parameterized tasks. These allow the grouping of similar tasks into a common task. Thus, the reusability in repositories increases which also reduces development times, costs and errors.

1.3 Simulation based control approach

The *Simulation Based Control* (SBC) approach [11] is a methodology for control development and defines a framework for practical implementation. The main goal of SBC is to provide a systematic way for *Rapid Control Prototyping* (RCP) [9].

Accordingly, a gradual and consistent model-based control development from the early planning phase to real operational use is supported (Figure 4). The control designs can be successively tested by simulation and supplemented by additional requirements. To enable this form of step-wise control development, an appropriate software environment or tool chain is required.

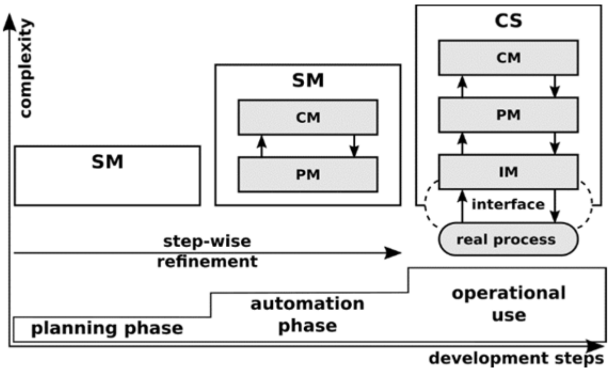

Figure 4: The SBC approach.

The consequent usage of simulation in all phases of the development process is key for detecting design errors as early as possible. The *Simulation Models* (SMs) are step-wise refined. During the transition from planning to the automation phase, a separation of the SM into a *Control Model* (CM) and a *Process Model* (PM) is introduced. Within the automation phase the SM is completed by an *Interface Model* (IM).

In this stage the SM can be used for system simulation (in conjunction with an appropriate physical process model), or for *Software-in-the-Loop* (SiL) simulation.

During the transition from the automation to the operational phase, the SM becomes real *Control Software* (CS). This transition is usually known as *Code Generation*. Depending on the real-time requirements of the control application, the SBC approach distinguishes between explicit and implicit code generation. The first type is the classical method for high real-time requirements in conjunction with mostly embedded controller hardware. In this case, the explicit code generation is done by an appropriate compiler. For applications with rather slow timing, implicit code generation is suitable. That means the last SM of the design process is used as CS without modification. This is possible due to the IM. It provides a process interface enabling SiL but also operational use.

Following the SBC approach the CS always includes a PM. Thus, observer concepts can easily be realized. In the case of poorly or not measurable process states, the PM can provide at least estimated values.

In [11,17] the SBC-Framework has been successfully applied for SRS control development for different manufacturers. Furthermore, it is shown that SBC supports a task-oriented control specification (Figure 5).

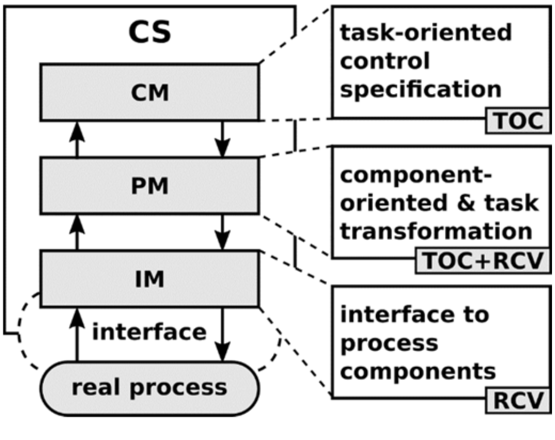

Figure 5: Use of TOC and RCV Toolbox within the SBC Framework.

In this case, the CM contains the task-oriented control specification. The PM still has a component-oriented structure according to the elements of the real process. With a task-oriented CM on top, the PM is also the place of task transformation as described in Section 1.2.

The tasks are mapped onto the generalized commands of the RCV Toolbox (Section 1.1). Thus, the PM remains independent according to concrete robots. The vendor-specific mapping is subject of the IM.

Below, the mapping of interactions in MRS to a task-based control specification using the SBC framework is shown after, the term interaction is discussed.

2 Interactions in MRS

In the previous sections, methods and tools for control design of *Single-Robot Systems* (SRSs) were introduced, which should be applied to *Multi-Robot Systems* (MRSs). A fundamental element of an MRS is interactions. This section treats characteristics and classification of interactions in MRSs.

2.1 Discussion

In MRSs, the robots usually support each other in order to improve the team performance. The term interaction describes the mutual influence of the robots. An interaction often requires the sharing of a limited resource, such as a robot's workspace (Figure 6). For example, if two robots need to pass a workpiece, their workspaces must overlap. This implies that the robots have to coordinate the handover to avoid a collision. One possibility for realizing the coordination is to exchange information between the robot systems.

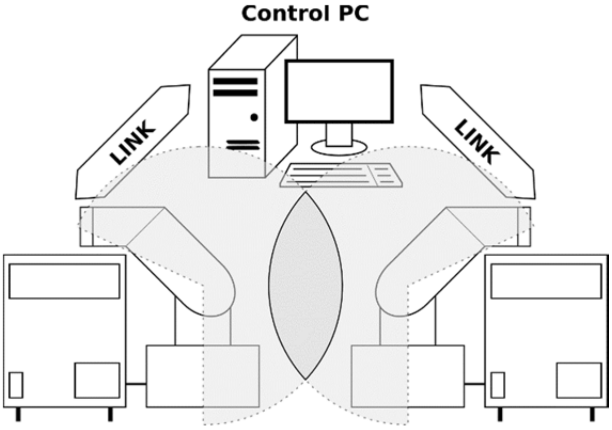

Figure 6: Example of an MRS with two industrial robots.

2.2 Classification

Based on the general classification in [13], interactions of industrial robots can be divided into six classes. Figure 7 shows the example of a transportation problem for better illustration. Parts have to be transported from an *Input Buffer* to an *Output Buffer*. *Class 0* starts with an SRS and hence involves no interaction.

Class 1 to *Class 6* solve the same problem with an MRS. The complexity of the transportation problem can increase from one class to another class. For example, new part types are introduced with special requirements. To solve the problem, the necessary level of interaction will increase too.

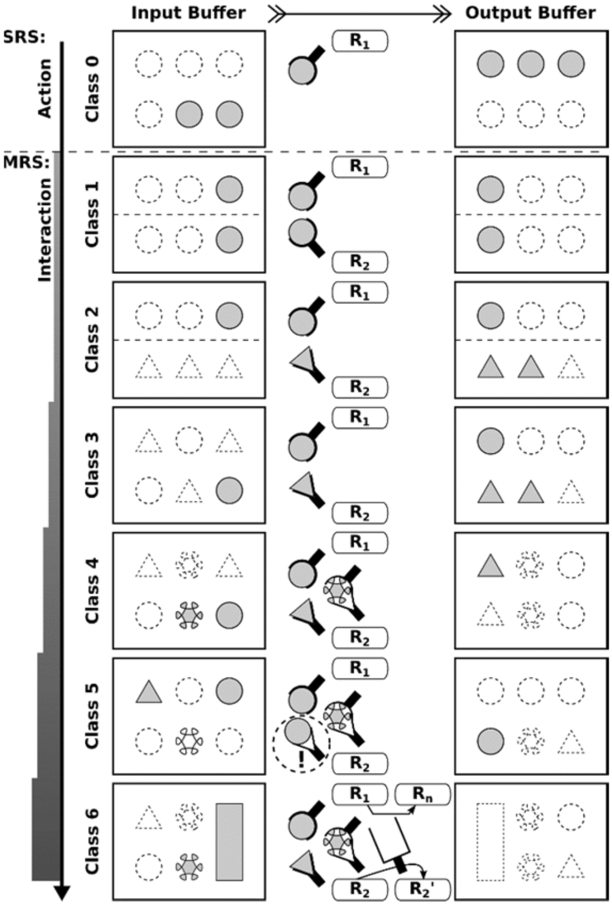

Figure 7: Classification of interacting robots based on [13] – with level of interaction.

Class 0. One type of part has to be transported by an SRS. The robot's tool is adapted to the part. The task is completed when all parts have been transported from the *Input Buffer* to the *Output Buffer*. There is no interaction.

Class 1. An MRS consisting of two robots (R_1, R_2) with separate workspaces. Both robots have identical tools. No exchange of information between the robots is required. The interaction refers to the collective solution of a problem by two or more robots.

Class 2. As for *Class 1*, supplemented by a new type of part, which requires the exchange of one robot tool.

Regarding the interaction there is no change compared to *Class 1*. The robots still solve one problem and have separate workspaces. Therefore, *Class 1* and *Class 2* have the same degree of interaction.

Class 3. As for *Class 2*, but the robots share a common workspace. To avoid collisions the robots have to coordinate their motions. Therefore, the degree of interaction is increased compared with *Classes 1 & 2*.

Class 4. As for *Class 3*, but another type of part leads to a stronger interaction. The new type can only be moved by the two robots together. Thus, the degree of interaction is increased compared to *Class 3*.

Class 5. One robot supports the other one, even if the tool is not ideal for this purpose. This form of interaction is used to compensate for the overload of one robot by irregular arrival of parts.

Class 6. A new type of part which cannot be handled by the robot team requires the replacement of a robot or the tool. Interaction refers to the modification of team members.

3 Case Study

In the following, the control development for a *Multi-Robot System* (MRS) is examined by a handling and assembly problem. Different interactions are implemented using a task-oriented control design. Based on the above described methods and tools, the control will be developed in the MATLAB/Stateflow environment.

3.1 Layout and workflow

The experimental setup is illustrated in Figure 8. It consists of two robots (R_1, R_2) and two cameras (C_1, C_2). Each robot has a separate *Input* (I_1, I_2) and *Output Buffer* (O_1, O_2) in its workspace. Furthermore, both robots share a portion of the workspace by a *Common Output Buffer* O_C. The two *Input Buffers* are externally stocked up with parts of type A or B.

Each robot randomly picks up a part of its respective *Input Buffer*. The position of the parts is assumed to be known. The gripped part can either be of type A or B which makes identification by a corresponding camera necessary. The result of the identification dictates how to proceed with the part. If the gripped part is of type A, it can be directly placed in the *Output Buffer* of the robot. Then the robot picks up another part from the *Input Buffer* and the procedure is repeated until a part of type B is identified. Two parts of type B always have to be assembled with each other by both robots before they are stored in O_C.

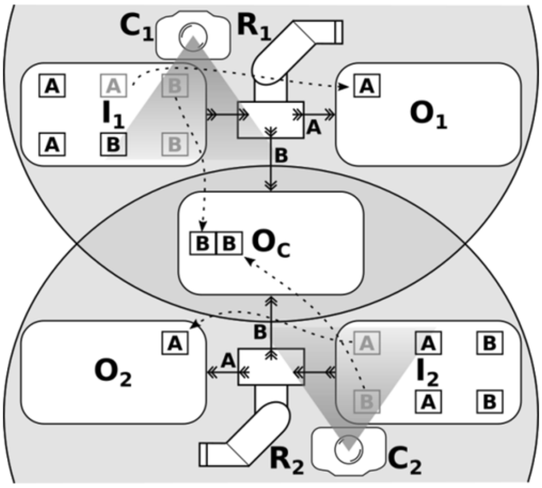

Figure 8: Experimental setup of the case study.

Figure 9 shows the subtasks which have to be done to solve the task *CommonPlacePart* (CPP). If a robot picks up a part of type B, he moves to a mounting position above O_c and is blocked then (field a) until the second robot also picks up a part of type B and reaches its mounting position (field b). Both robots proceed with a synchronous motion (field c) in order to place both parts in O_C (click mounting, field d). Subsequently, a new cycle takes place

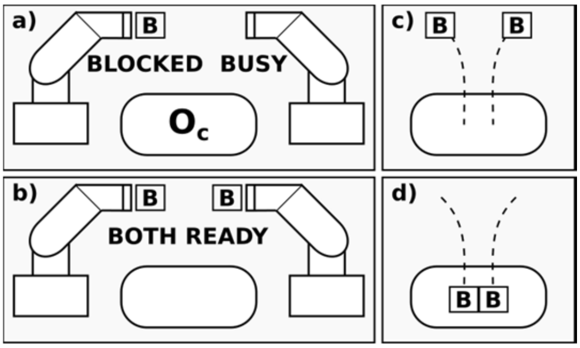

Figure 9: Workflow of two robots doing task *CommonPlacePart* (CPP).

3.2 Task-oriented analysis

A task-oriented description of the workflow is shown in Figure 10. The notation is based on *Harel statecharts*.

The figure shows the first step of the task-oriented control design. The problem description is done using the tasks *PickPart*, *IndentPart*, *PlacePart*, *MoveToPos* and *CommonPlacePart* (CPP). The control logic is identical for both robots and can be mapped by two identical parallel states (AND states), drawn as dashed lines.

As long as no part of type B is identified, both robots work independently and in parallel.

The task sequence is: (i) grip a part (*PickPart*), (ii) identify the gripped part with the camera (*IndentPart*) and (iii) place the part in the *Output Buffer* (*PlacePart*).

If a part of type B is identified, the task sequence changes. Instead of *PlacePart*, the task *MoveToPos* will be executed. In consequence, the robot moves to its mounting position above O_C. The subsequent task *CPP* blocks the robot (Figure 9a) until the second robot also executes the task *CPP* (Figure 9b). Both robots coordinate the motions until the task *CPP* ends (Figure 9c, d). The independent handling of type A parts by a sequence of tasks corresponds to a *Class 1* interaction. The interaction can be modeled by parallel execution of task sequences. The mapping of the assembly process of type B parts corresponds to a *Class 4* interaction because it necessitates the coordination of both robots. The necessary time synchronization and coordination is mapped in the form of a separate task (*CPP*).

3.3 Implementation aspects

The implementation of the control is based on the *Simulation Based Control* (SBC) approach and realized in the MATLAB/Stateflow environment. In accordance with SBC, the control consists of a *Control Model* (CM), *Process Model* (PM) and *Interface Model* (IM) (Figure 4, 5). The CM shown in Figure 11 implements the *Task-Oriented Control* (TOC) logic according to Figure 10. The task sequences of both robots are implemented as parallel states. The task *CPP* in both parallel states (tasksR1, tasksR2) is signaling a standby for assembling.

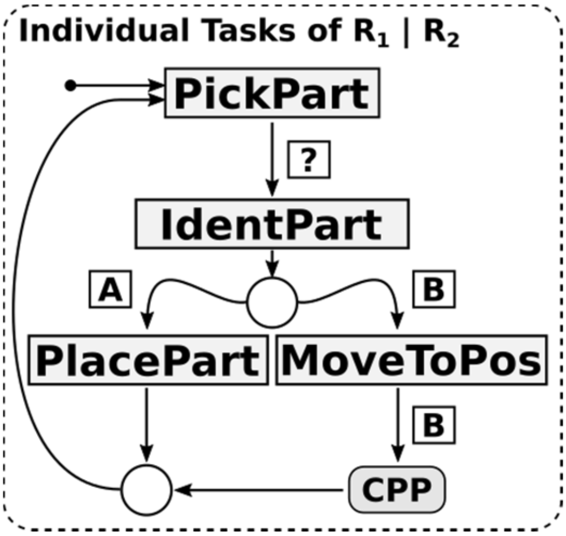

Figure 10: Task composition for both robots.

The implementation of the control is based on the *Simulation Based Control* (SBC) approach and realized in the MATLAB/Stateflow environment. In accordance with SBC, the control consists of a *Control Model* (CM), *Process Model* (PM) and *Interface Model* (IM) (Figure 4, 5). The CM shown in Figure 11 implements the *Task-Oriented Control* (TOC) logic according to Figure 10. The task sequences of both robots are implemented as parallel states. The task *CPP* in both parallel states (tasksR1, tasksR2) is signaling a standby for assembling.

The implementation of the necessary interaction Figure 9c, d) was modeled as a separate task *CPP* in another parallel state. Thus, the interaction principle is mapped to a common, reusable task.

The PM is modeled analogously to fulfill the requirements of the SBC and the TOC and is illustrated in Figure 12. Each process component is represented as a parallel state and with two sub-states, *idle* and *execTask*. The state *idle* indicates that the component is on standby. The state *execTask* implements the process depending on task transformation. Because the task transformation is more clearly implemented procedurally it has been transferred to a MATLAB function call. The input parameter is a numeric value and represents the decoded task.

The IM, shown in Figure 13, is realized analogously to the PM. It defines a parallel state with two sub-states for each process component, which needs to be controlled. Communication with the real process components is implemented, in each case, as a MATLAB function. To control the robot, the function *execTask( )* is used which is based on the *Robotic Control & Visualization* (RCV) Toolbox (Section 1.1).

For the control of other peripherals, such as the cameras, MATLABs *Instrumental Control Toolbox* [19] can be used.

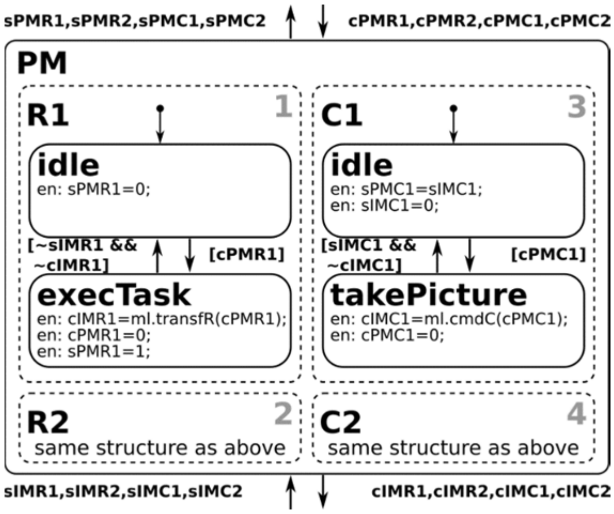

Figure 12: Statechart of PM based on SBC Framework.

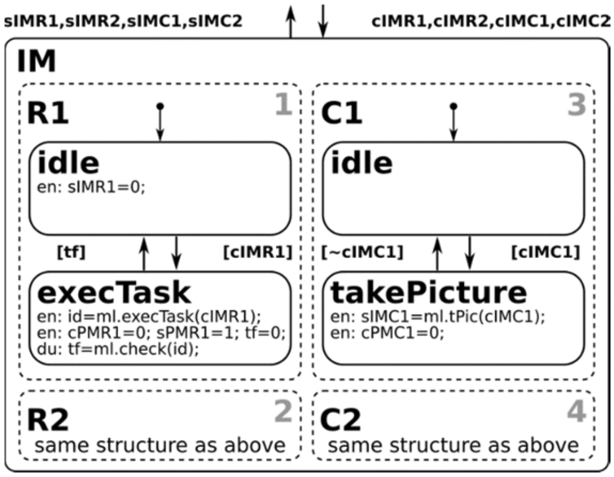

Figure 13: Statechart of IM based on SBC Framework.

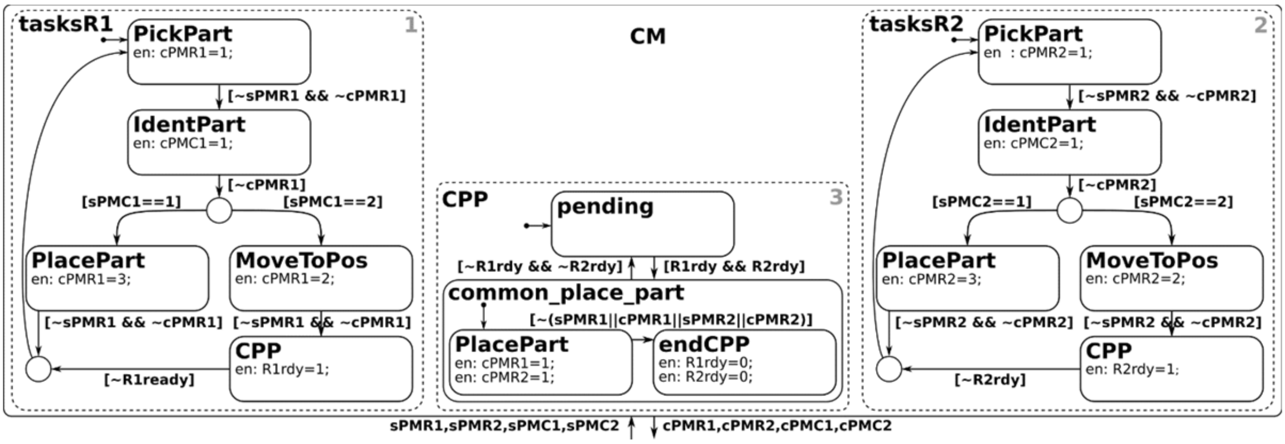

Figure 11: Statechart of CM based on SBC Framework.

The SBC based control development in the MATLAB/ Stateflow environment supports a gradual, simulation-assisted development of control software.

4 Summary and Outlook

Based on methods and tools, which are established in the control development for *Single-Robot Systems* (SRSs), an approach for *Multi-Robot Systems* (MRSs) was developed. In contrast to SRSs, interactions must be considered in MRSs. For this purpose, a characterization and classification of interactions in MRSs was introduced. An example demonstrating two interaction classes showed how interactions can be modeled as a general, reusable task, according to the task-oriented robot control paradigm.

The prototypical implementation was based on the *Simulation Based Control* (SBC) approach in the MATLAB/Stateflow environment and used the *Robotic Control & Visualization* (RCV) Toolbox for MATLAB. It was demonstrated that the control development of an MRS can be realized vendor independently, analog to an SRS and with simulative tests throughout the control development cycle.

At the beginning, defined requirements are largely fulfilled by prototypical implementation. The next step will be to examine if other identified interaction classes can be mapped to reusable tasks. Additionally, a proof of concept for a more advanced application will be provided in the future.

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Modelling and Simulation of the Melting Process in Electric Arc Furnace: An Overview

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Abstract. Increasing market demands on quality of the steel, steel price and production times are leading to introduction of many technological innovations regarding the electric arc furnaces (EAFs). One of the areas with significant potential is also advanced computer support of the EAF process, which allows data acquisition, advanced monitoring and proper control of the EAF.

In the most advanced form of such system, its basis can be represented by mathematical process models, capable of online estimation of the crucial process values, which are otherwise not measured, such as chemical compositions and temperatures of the steel, slag and gas.

In this paper, idea and development of all key EAF-process models (electrical, thermal, mass-transfer and chemical), which are used for estimation of the unmeasured values, are presented.

The validation results that were performed using operational EAF measurements indicate high levels of estimation accuracy, which allows the usage of these models in broader environments, for either soft sensing and monitoring or process optimization and decision support.

Introduction

Current market demands on steel quality, price and production times dictate an introduction of several technological innovations regarding the electric arc furnace (EAF) steelmaking.

An emerging field with huge potential, but yet rather unexplored, is also advanced software support of the EAF operation. Running in parallel to the EAF process such systems allow online monitoring, fault detection and even model-based control of the process.

Using such systems in parallel to the actual EAF process can have several advantages in comparison to the manual EAF operation, arising from the nature of the steel-melting process. As known, several crucial process values are hard to measure continuously, such as temperatures and chemical compositions of the steel, slag and gas etc. Using EAF process models, which integrate all significant EAF phenomena and use available EAF data to calculate the missing process values, results in a system, which is able to estimate the process values with sufficient accuracy. In this manner, better insight to the melting process can be established and consequently a more optimal operation of the EAF can be performed.

The paper presents an overview of the proposed EAF model, including electrical, hydraulic, mass-transfer, heat-transfer and chemical submodules in terms of modelling approach, modelling detail and schematic representations of the model structure. Since the mathematical models of the EAF have already been developed, validated and extensively described [1], [2], [3], [4]; the paper presents only the key characteristics of each separate submodule and its importance for the overall accuracy of the calculations. Furthermore, the paper discusses possible and necessary upgrades of the models to implement them in process-optimization and decision-support frameworks.

The aim of those is to present an EAF operation-support tool, which will be running in parallel to the EAF process and will be used for enhancement of the operation, such as:

- a) EAF operation monitoring based on soft-sensing technology, allowing a better insight to the melting process and consequently more optimal control of the EAF;
- b) process-optimization based on process models, optimizing the melting programs, according to the current state in the EAF;
- c) operator decision support, combining the advantages of model-based soft sensors and process optimization in one solution, representing the highest level of EAF software support.

1 Modelling of the EAF Processes

Literature review in the field of modelling, optimization and control of the electric arc furnaces shows that many different models and engineering approaches studying the EAF processes have been developed. Most of these are focused on particular processes of the EAF and were developed for the purpose of the field research or simulation of the EAF operation. A few models were designed especially for their implementation into industrial applications as an operator-support tool for monitoring of the recycling process and thus easier decision making and control of the processes.

First models associated with the EAF processes were introduced back in 1980s and were functionally extremely limited. Modern models have progressed in their complexity, usability and accuracy and are also used in industrial applications for monitoring of the EAF during the steel-melting process. Below, some of the most relevant research and practical applications in the field of modelling, optimization and control of the EAF processes are described.

Woodside [5] introduces a concept for optimal EAF control, based on Pontryagin approach and uses it for optimization of the energy input during coke injection. The simplified model was introduced in 1970 and was able to estimate bath temperature and carbon concentration. Montanari [6], Tseng [7], Collantes-Bellido [8] introduce mathematical models describing the electrical part of the EAF and the impact of the EAF operation on electrical grids in terms of disturbances (flickers) and their elimination.

In 1999, Bekker [9] develops a mathematical model implementing thermodynamic relations for the purposes of EAF-process simulation. The model is simplified and assumes that all available heat is transferred directly to the steel bath and further from the bath to the solid steel.

Although it addresses some important chemical reactions and the released energy, the presented simulation results are not validated and thus applicable only with limitations. Nonetheless, the Bekker model represents one of the first attempts to model all crucial processes of the EAF. Additionally, Bekker [10] introduces a concept of model-predictive EAF control (MPC).

Oosthuizen [11, 12] designs a mathematical model of the EAF processes derived from the Bekker model [9].

Using a more complex modelling approach, the proposed model gains on estimated offgas temperature accuracy and allows a calculation of the slag foaming. Furthermore, optimal controller is introduced, which should control the furnace in a manner to reduce its operational costs. Similarly to Bekker [10], a simulation study involving a model-based control (MPC) is performed on the model for the purposes of cost reduction.

One of the most sophisticated EAF models up to 2005 was introduced by MacRosty and Swartz [13, 14] and used for optimization of the EAF process. The model considers the complete EAF and includes chemical, mass- and heat-transfer processes. Due to modelling simplifications, the EAF layout is divided into four zones with similar physical characteristics. Chemical reactions in each zone are based on molar-mass equilibria, while the overall model is based on energy and mass equilibrium.

The model was validated using the measured operational data and can be used to estimate bath temperature, bath composition and slag composition. Further on, the model is implemented in a simulation study to optimize the operational costs of the EAF. The authors report of several issues regarding the optimization procedure and its unreliability.

Logar [1 - 4] introduces complex EAF models, including electrical, hydraulic, chemical, heat- and mass-transfer processes. The models are based on fundamental physical laws and are validated on measured operational data of the EAF. The results show high levels of similarity between the measured and the simulated data. The combination of all developed models in one functional model represents the most complex approach to EAF modelling found in literature.

Many studies have been performed in the field of numerical modelling of the EAF. The field has been established as a new, fast emerging science and engineering discipline that encompasses computational solid mechanics [15] and fluid mechanics [16], connected with solidification phenomena [17, 18], allotropic transformations phenomena [19], and put into the context of computational microstructure evolution [20] in processes like casting [21], heat treatment [22] etc. The use of numerical modelling proved to be an efficient approach for modelling the relations between bath stirring, fluid flow and electromagnetic (EM) forces.

Due to the complex coupling between flow and EM forces, numerical modelling is the most economical way of analyzing, optimizing and developing new applications.

Many modern industrial processes, such as electrical arc furnaces, rely on findings of EM, heat-, mass-transfer and metallurgical science. Their interconnections are currently not sufficiently understood and computationally modelled.

Furthermore, modelling approaches to gas-phase phenomena [23, 24] and EAF off-gas heat recovery have been proposed [25].

The implementation of the mathematical models in industrial applications can be found at renowned EAF manufacturers and users, such as Tenova, Siemens VAI, SMS Siemag, Centre de Recherche Métallurgiques (CRM), ArcelorMittal and BFI [26 - 30]. The developed models vary in modelling approach, modelling detail, usability, accuracy and types of input data used for estimating the process values.

Reviewing the available literature, most of these models are based on static calculations using statistical or regression methods, i.e. SMS Siemag, BFI and Tenova. The model, based on dynamic modelling approach was introduced by CRM. It relies on fundamental laws of thermodynamics and is used to estimate the end-point bath temperature. It is claimed that the accuracy of the model is +/- 50 K, which indicates that further improvements of the model are possible.

The literature review reveals that all models used in industrial applications are designed solely for estimation of the process values, while no support to the operators in the sense of optimal control is given. Thus, the main challenge in EAF operation, i.e. determination of optimal melting programs, times and amounts of charged materials, is therefore still left to the operator and his experience.

Regarding the literature review, a design of the overall EAF process model was initiated, incorporating all crucial EAF processes and focusing on accuracy and usability of the obtained solution for further development and its inclusion to several other software environments.

2 Modelling Technique

2.1 General

The models as presented in this paper have been developed according to the fundamental physical laws by means of non-linear, time-variant, first order differential equations; although, several other approaches could be implemented as well.

The selected approach has its advantages and drawbacks when compared to other possibilities; however, the possibility to use the developed models with as many EAF designs as possible was the main aim of the study and for this reason the models are based on fundamental mathematical/physical approaches. The model can be presented schematically as in Figure 1.

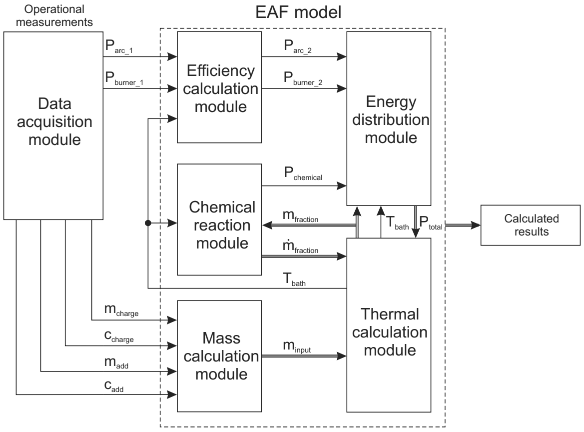

Figure 1: Schematic presentation of the developed EAF models.

The presented model as shown in Figure 1 comprises mathematical descriptions of all main physical processes appearing during the steel-recycling process, i.e. electrical, hydraulic, thermal (including radiation), chemical and mass transfer. As shown in Figure 1, the model for estimation of the EAF process values is composed of several modules, which contain mathematical relations describing the physical properties of the EAF steel melting process and the corresponding model parameters.

The calculations are grouped in submodules in order to simplify the model structure and assure low computational loads.

Due to complexity of the modelled processes and in order to simplify the obtained models, the EAF layout has been divided into several zones, assuming that each zone is homogenous and possesses equal physical characteristics, such as temperatures, densities, heat transfer coefficients etc. The zones used in the model are solid steel, liquid steel, solid slag, liquid slag, gas, roof and walls, as shown in Figure 2.

According to the above, calculations of a separate submodule are limited only to certain zones, i.e. electrical and hydraulic models appear in no zone directly, heat-transfer model appears in all zones, mass transfer model appears in solid steel, liquid steel, solid slag, liquid slag and gas zones, and the chemical model appears in liquid steel, liquid slag and gas zones.

2.2 Model properties

Each of the above models utilizes different physical laws and mathematical equations in order to obtain the values needed by other models or as an end result/estimation.

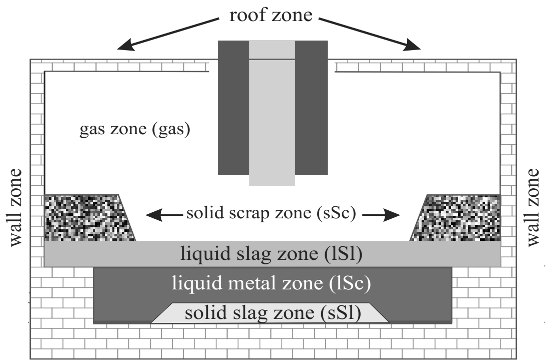

Figure 2: Division of the EAF layout to different zones.

The electrical and hydraulic models can be characterized by the following:

- all electrical values are calculated using harmonic analysis, i.e. in complex space,
- Cassie-Mayr arc model (1st order ODEs) is used with additional variable Lorentz noise,
- the models utilize transformer and reactor taps, resistances/reactances of lines, transformer, arcs and steel, all electrical values (voltages, currents, powers, energies, power factors, impedances etc.),
- electrode control is carried out using a hydraulic model and three independent PI controllers,
- the model parameters are variable for different stages of the melting process, i.e. electrode bore-down, melting, flat bath.

The heat-transfer model can be characterized by the following:

- the melting process is divided to different phases of the melt-down (electrode bore-down, exposing panels, flat bath etc.)
- 1st order ODEs are used to calculate the temperatures based on energy input/output balances
- heat-transfers are utilized to each zone from: arcs, burners, chemical reactions, volatile oxidation, electrode oxidation and other zones,
- heat losses are utilized due to cooling of the furnace, offgas extraction, steel and slag enthalpy,
- implementation of geometry supported (view-factor based) radiative heat exchange,
- taking into the account temperature-dependent burner efficiency and continuous transitions between the zones (geometry supported).

The mass-transfer model can be characterized by the following:

- the melting process is divided to different phases of melt-down (electrode bore-down, exposing panels, flat bath etc.)
- 1st order ODEs are used to calculate mass transfers based on temperature levels (melting) and energy input/output balances,
- elements and compounds which are taken into the account in calculations are:
  - steel zone: Fe, C, Si, Cr, Mn, P
  - slag zone: FeO, SiO_2, MnO, Cr_2O_3, CaO, MgO, Al_2O_3, P_2O_5
  - gas zone: N_2, O_2, CO, CO_2, CH_4 (gas burners),
- implementation of reversible dynamics (cooling and solidification of the steel),
- calculation of mass transfers due to: melting, charging and slag addition, oxygen-fuel burners, oxygen lancing, carbon injection and chemical reactions.

The chemical model can be characterized by the following:

- implementation of all main chemical reactions appearing in the steel-melting process (oxidation/reduction of Fe, FeO, Si, SiO_2, C, CO, Mn, MnO, Cr, Cr_2O_3, P and P_2O_5),
- 1st order ODEs are used to calculate rates of change of elements/compounds based on molar equilibria with reaction equilibria constants dependent on molar composition of the zone,
- utilization of chemical energy exchange due to exothermic and endothermic reactions,
- calculation of foaming slag height based on slag density/viscosity/surface tension and superficial gas velocity (CO) including slag decay,
- calculation of online and endpoint steel/slag/gas compositions and relative pressure.

The parameters of the model (approximately 100) were obtained using known data or conclusions of different studies (transformer taps, resistances/reactances, furnace dimensions, heat capacity coefficients, densities, emissivities, enthalpies of formation, reaction rates, molar masses etc.) or were determined experimentally using the available initial, online or endpoint operational EAF measurements (cathode voltage drops, arc temperatures, arc conductances, arc cooling constants, slag-reactance coefficients, heat-transfer coefficients, specific area coefficients, arc-energy distributions etc.). The validation of the models was carried out using operational EAF measurements, which were obtained during different melting scenarios. In this manner, an accurate model of the actual EAF recycling process was obtained.

3 Results

The displayed results show the most important estimations of the process values while operating the EAF, i.e. bath temperatures, steel compositions and slag compositions. Figure 3 shows the comparison between measured and model simulated values for initial steel mass, endpoint steel mass, power on time and bath temperatures. The results were obtained from several heats and are represented in a form of a mean value with standard deviation.

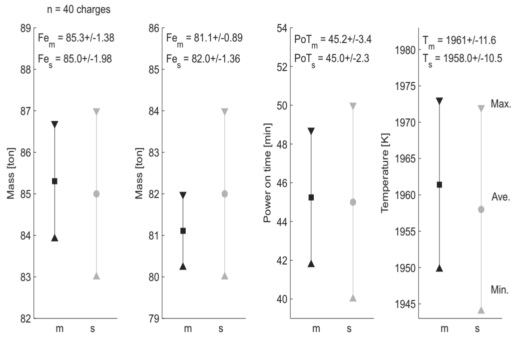

Figure 3: comparison between measured and simulated values for initial (1st) and enpoint (2nd) steel mass, power on time (3rd) and bath temperatures (4th). Black squares and grey circles represent measured and simulated mean values, while black and grey triangles represent measured and simulated standard deviations, respectively.

As can be seen in Figure 3, all measured and simulated values are similar, both in mean values and in standard deviations. The most important validation values from Figure 3 are steel yield (difference between the initial and endpoint steel masses) and steel bath temperature. Bath temperature is usually measured one to three times before tapping, while steel yield is determined at tapping. Neither of these values is measured continuously during the EAF operation.

Figure 4 shows the comparison between measured and model simulated endpoint steel composition in a form of a mean value with standard deviation.

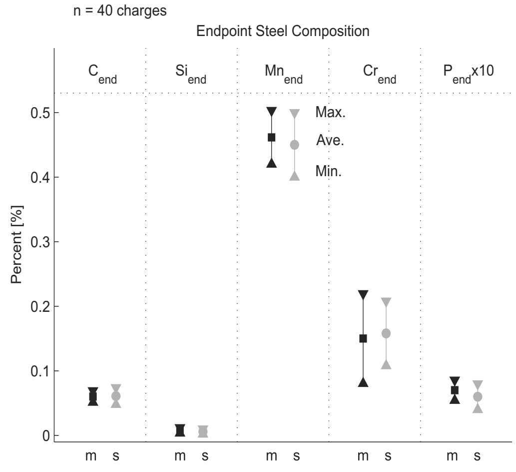

Figure 4: comparison between measured and simulated endpoint chemical compositions of the steel.

As can be seen in Figure 4, all measured and simulated values are similar, both in mean values and in standard deviations. The most important validation value from Figure 4 is the carbon content in the steel, since carbon percentage is (among others) directly linked to different steel grades produced and has to be determined and contained in proper amount. Complete steel composition is determined at tapping and is otherwise not measured continuously.

Figure 5 shows the comparison between measured and model simulated endpoint slag composition in a form of a mean value with standard deviation.

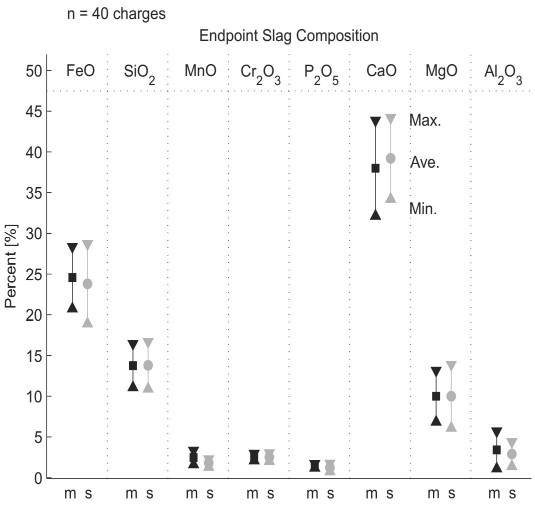

Figure 5: comparison between measured and simulated endpoint chemical compositions of the slag.

As can be seen in Figure 5, all measured and simulated values are similar, both in mean values and in standard deviations. The most important validation value from Figure 5 are FeO, SiO2, MnO, CaO and MgO contents in the slag, since these compounds define the properties of the slag, which are linked to its foaminess and protective characteristics.

Figure 6 shows the energy balance as calculated by the proposed model.

As can be seen in Figure 6, total energy input required to produce 1 ton of steel is approximately 760 kWh. More than a half of this energy is represented by electrical energy, while other important sources of energy are oxygen burners and chemical reactions.

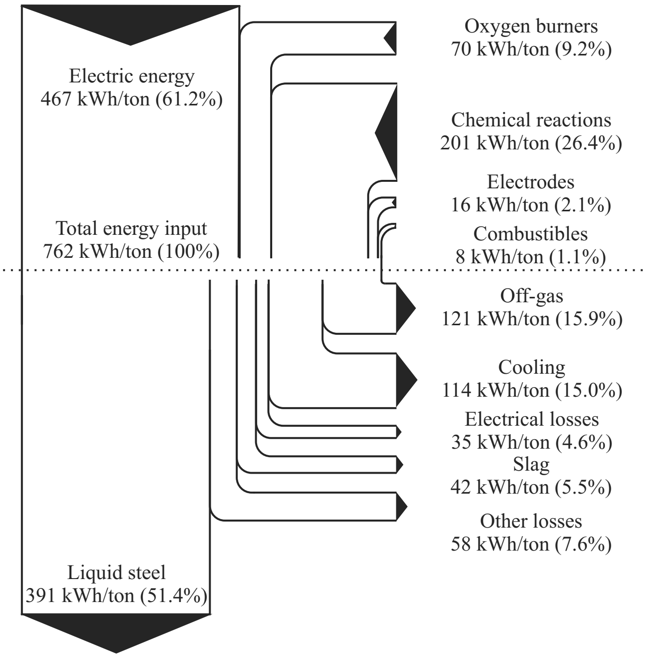

Figure 6: energy balance of the EAF as obtained by the proposed model.

Regarding the losses of energy, approximately 390 kWh of energy is held by steel enthalpy due to its high temperature. This energy is later lost to the environment as the steel cools down. Furthermore, off-gas extraction and cooling of the furnace vessel also represent an important sinks of energy.

4 Practical Applications of the Model

Due to the nature of the EAF steel-recycling process (high temperatures and electric currents), performance of the crucial process measurements is difficult.

Consequently, monitoring and control of the melting process is performed using the operator's experience and is based on indirect measurements (e.g. power-on time, consumed energy, arc stability etc.) and not on the actual conditions in the EAF (e.g. stage of melting, bath composition, bath temperature), which leads to suboptimal operation, i.e. lower energy and raw material efficiency, increased off gas and CO2 emissions, decreased quality of the steel; and consequently higher operational costs.

Furthermore, operational efficiency is influenced also by variable composition of the input materials (steel scrap, non-metallic additives). The fluctuations in EAF operation can be resolved using a combination of EAF process models, optimization techniques and decision support methods.

The combination of these methods together with available process measurements forms a supporting system for operation of the EAF. Such a system uses process measurements as inputs, in order to provide a better insight into the current EAF conditions and to suggest the most appropriate action, leading to more efficient operation of the EAF.

Using mathematical models, which are designed in compliance with the physical laws and using available measurements as inputs, crucial process values, which are not measured, can be estimated in parallel to the EAF process with high accuracy.

In this manner, an optimal operation of the EAF can be established, leading to higher steel yield, lower energy, raw material and additive consumption, shorter production times, higher steel quality etc. The introduction of such operation indirectly leads to improved economic, ecological and technological aspects of the mills, with such system installed.

5 Conclusion

In this paper a brief explanation of the modelling approach to crucial EAF processes as well as its potential use in higher-level applications is presented. Furthermore, some key comparisons between the measured and the simulated values are presented, showing the overall accuracy of the calculations.

The objective of developing a complete EAF model is to use it in application frameworks for different purposes, such as online monitoring, process optimization or operator decision support.

Since the description and modelling details are far too great and extend the frame of this paper, all interested readers can refer to the reference list (Logar et al.) for further information.

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Applying Gamification Principles to a Container Loading System in a Warehouse Environment

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Abstract. Gamification is a recent phenomenon that emphasizes the process of incorporating game elements, for a specific purpose, into an existing system in order to maximise a user's experience and increase engagement with the system. In this paper, we discuss the effects of the introduction of the principles of gamification to a system for solving real-world container loading problems in a warehouse environment. We show how user engagement and confidence increases over time during interaction with the 'gamified' system, and we propose subsequent work for the thorough application of gamification to the system that completely abstracts the complicated container loading algorithms running in the background.

Introduction

Gamification is a phenomenon that has in the last few years garnered a lot of attention with numerous applications particularly focusing on productivity and health fitness. It is defined as the use of game design elements in non-game contexts [1] and is mostly introduced into a system to increase user experience and user engagement [2], or to act as the means of actual user engagement where there is none. The increase in experience and engagement is considered to be the result of the effects obtained when leveraging people's natural desire for learning and accomplishment.

In this paper, we discuss the application of the principles of gamification to a container loading system used to assist warehouse operatives during container loading in a real world warehouse environment.

We discuss the effects this has on the adoption of the container loading system, and show a systematic build-up of trust and familiarity over time of the system by the operatives. We then propose a fully gamified system as an abstraction that provides an interactive environment for the engagement of warehouse operatives with what would be otherwise complicated algorithms that solve container loading problems.

1 Background

Information technology systems have long since been introduced into the workplace to bring about an increase in business performance [3,4, 5,6, 7]. The phenomenon of introducing gaming elements in a nongaming context in order to increase engagement, is generally referred to as gamification [2]. This can be illustrated by our case study of a real world problem in a UK distribution centre (henceforth known simply as the UKDC) of one of the largest industrial bearing suppliers in the world.

The problem the UKDC faces is that of optimally selecting and loading groups of palletised goods onto containers. The palletised goods, typically spread across different locations in a warehouse, are heavy and require the use of fork-lift trucks to move, stack and load them. The goods are made up of boxed bearings which are packed into cartons that are arranged on any of several different pallet types, which are then shrink-wrapped and treated as individual units. Several practical constraints must be satisfied in order to produce a feasible solution to the problem.

To solve this important problem optimally, the UKDC have invested in research towards a computerised loading optimisation system in a bid to: i) increase overall loading speed: ii) reduce the cost of hiring containers by optimally maximising the capacity of every loaded container to reduce overall number of containers used for loading; iii) reduce damage to goods that might occur because of non-optimal packing in the container, therefore reducing costs that might arise from replacing damaged goods, or customer fines for the receipt of damaged goods; iv) provide greater customer satisfaction by speedily processing and loading customer orders for safe and prompt delivery, and v) increase warehouse throughput: the more goods that are loaded and sent out from the warehouse, the higher the warehouse's capacity to process new customer orders with the existing space, which could lead to more business for the company.

We refer the reader to [8] [9] for the more fulfilling aspects of the jobs of the warehouse operatives who currently perform the planning and loading operations. It did not help that the output of the initial system prototype was plain text data (Figure 1), with numbers tersely showing item dimensions, weight, group membership, coordinate point locations, etc., that was difficult to interpret by the operatives. It also did not help that almost all the solutions produced from initial test runs consistently obtained 100% container utility (compared to the average of 85% utility from manual loading).

Related Work. As gamification research is still in its infancy, several varied definitions exist for it in literature: Deterding, Nacke, Dixon and Khaled in [1]; Zichermann and Cunningham in [10]; Huotari and Hamari in [11]; and Werbach and Hunter in [12]. The important point in this definition is the presence of a purpose; the game elements incorporated into a system must have a specific purpose if an improvement in user engagement and motivation is expected [7].

Li, Grossman and Fitzmaurice in [13] gamified a tutorial system to help new users learn AutoCAD. McDaniel, Lindgren, and Friskics in [14] introduced gamification, through the use of badges as a sign of achievement, into a learning management system to motivate students towards certain behaviours desired by teaching staff. De-Marcos, Garcia-Lopez, and Garcia-Cabot in [15] studied the effects of gamification on learning performance in an undergraduate course.

2 Gamification Approach and Experiments

Our main goal was to ensure and increase user engagement in the loading system. We identified from literature that the application of gamification principles was a good fit for this goal, and we set about identifying areas in the underlying system that could benefit from such principles. Table 2 shows the gamification sub-goals we set and the eight strategies we identified for tackling them. In the rest of this section, we discuss our implementation of some of these strategies and outline some of the observations resulting from the exposure of the resulting gamified system to the warehouse operatives. The remainder of our observed results are discussed in the following section.

```
Best Solution:
---------------
Selected Groups: 0002, 0004, 0005, 0015, 0029
Total Weight: 25948kg
Summary (54 items): E-TYPE (12), S-TYPE (22),
     N-TYPE (20)
GROUP0002/00001, W: 294kg, LBH: 80/70/74, STK:0
GROUP0002/00002, W: 592kg, LBH: 105/75/71, STK: 1
GROUP0002/00003, W: 391kg, LBH: 80/70/92, STK: 1
GROUP0002/00004, W: 279kg, LBH: 80/70/72, STK:0
GROUP0002/00005, W: 401kg, LBH: 120/81/76, STK:0
GROUP0002/00006, W: 495kg, LBH: 105/75/69, STK: 1
GROUP0004/00001, W: 292kg, LBH: 80/70/58, STK:0
GROUP0004/00002, W:700kg, LBH:120/81/60, STK:0
GROUP0004/00003, W:676kg, LBH:120/81/76, STK:1
GROUP0004/00004, W:816kg, LBH:120/81/76, STK:0
GROUP0004/00005, W:503kg, LBH:120/81/60, STK:1
GROUP0004/00006, W:601kg, LBH:80/70/92, STK:1
GROUP0004/00007, W:700kg, LBH:120/81/76, STK:1
GROUP0004/00008, W:660kg, LBH:120/81/76, STK:0
GROUP0004/00009, W:661kg, LBH:120/81/92, STK:0
```

Figure 1. Example text output from initial loading system.

2.1 Defining conventions for visual layout representation

Our first steps involved building a visualisation for the text data output of the loading system (Strategy 1). The visual representation is provided as a container layout that shows the exact placement of colour-coded palletised goods within a container (Figure 2). In subsequent interaction with the loading system, all loading operation results were presented using this visual representation.

Problem	Goal Strategy	Goal Strategy
System adoption is low and system output is dull, non-engaging and difficult to interpret	A. Engage users visually with an intuitive interface	1. Present an interface with intuitive loading representation that is easy for users to use and understand
	B. Retain user engagement and make system fun	2. Ensure the interface is simple and can make loading tasks fun
		3. Provide loading 'challenges' that can be rewarded with special badges or trophies
	C. Encourage user learning, improvement and knowledge sharing	4. Implement a scoring system to leverage user competiveness which makes users want to do better than others at loading tasks
		5. Provide repeatable tasks, which can be used in conjunction with score feedback, to reinforce learning
		6. Record completed user tasks that other users can easily access and learn from
		7. Provide users with a way to interact with the results from the loading system in order to allow modifications that result in new solutions
		8. Provide an interface that allows one to quickly and easily check if a particular load layout will fit in a container

Table 2. Identified gamification strategies and goals for the system.

Our observations of these interactions revealed that our conceived visual representation, while a step in the right direction, came across as rigid and final to the operatives. This observation informed the need for a more flexible interactive interface, and became the basis for the identification and implementation of Strategy 2 and Strategy 7.

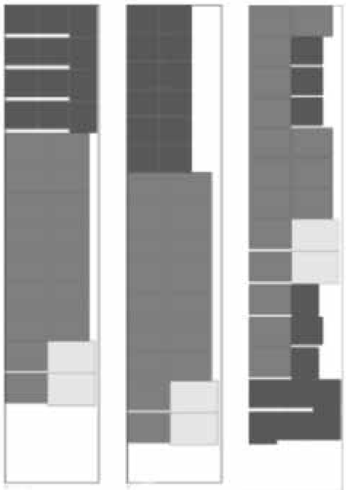

Figure 2. Visual representations for loading system output.

2.2 Providing an interactive simulation interface

In other to provide an interface that would be fun and interesting (Strategy 2), we decided to build a simulation interface that would incorporate the same visual representation conventions we had previously defined (Figure 3a).

We made this interface accessible on a tablet because of its ubiquity and mobility; the idea being that the warehouse operatives would find it very familiar and easy to operate. We then presented the simulation interface in a manner that vaguely resembles the game 'Tetris'. This helped loaders check and reinforce their own loading knowledge. As part of our continuous evaluation of the system, this observed interaction helped further inform the gamification goals and became the basis for the identification and implementation of Strategy 8.

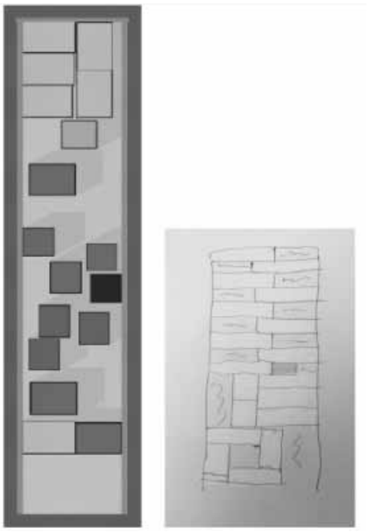

Figure 3: (a) Interactive simulation interface for the loading system. (b) An operative uses our colour scheme when sketching a suggested layout.

Pallet name	Pallet dimension ratio	Colour
E-Type	12 x 8	Yellow
S-Type	8 x 7	Blue
N-Type	10.5 x 8	Red
E2-Type	8 x 6	Green

Table 1. Defined convention for layout representation.

3 RESULTS AND DISCUSSION

Our visual representation convention has now been internalised so much that it is used in the day-to-day discussion of general loading activities, not necessarily related to the loading system, in the warehouse (Figure 3b).

In our initial gamified representation of the loading system output, users were presented with loading layouts as seen in Figure 2. This feature alone caused a significant increase in user engagement with the system.

3.1 Use Case: Loading Feasibility Checker

The system can be used to check if a load can fit completely into the simulated container.

As the simulation is built to scale, if the load fits in the simulation, it will most likely fit in the real world. We remind the reader that the real world loading operations involve using fork-lift trucks to move around heavy goods; it is easier, faster and safer to plan out such activities first in the simulation and then loading, rather than directly proceeding with physical loading and trying to rectify any issues that develop as they manifest. This particular complementary behaviour of the system has proven to be very useful to the operatives.

3.2 Use Case: Knowledge discovery tool

The system has sometimes generated and presented loading layout patterns that the loaders have never experienced or implemented before. A common comment received from the users regarding this behaviour is “I never would have thought to do it that way”. Some of these interesting loading layouts allow the loaders to pack more goods onto the container than they previously thought possible; others introduce entirely new ways of packing loads efficiently. The loaders have adopted these new patterns and started to apply them practically to their loading operations in the real world (Figure 4 and Figure 5).

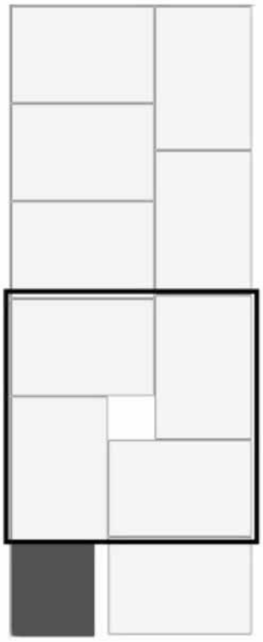

Figure 4. Loading system representation of an interlocking arrangement of boxes.

Figure 5. A loader's real-world representation of a loading plan using the same interlocking arrangement.

3.3 Use Case: Training aid

The system can be used as a training aid for teaching new or inexperienced loaders about loading and how to perform loading activities. Overall, the application of gamification principles and the manner of our approach has had a very positive effect on the use of the underlying loading system to which we applied the principles. The gamified system has increased, and continues to retain, user engagement and has provided a fun and engaging environment for performing serious loading tasks and activities.

4 Conclusion and Further Work

The majority of the studies on gamification tend to generally indicate a positive effect on the system that is gamified; this is however highly dependent on the context in which the gamification is applied, and on the users of the gamified system [16,17].

Our next steps will involve setting up a scoring system and implementing a high scores table into the interactive simulation.

As gamification is an ongoing process that should be constantly evolved over time to improve the nature of the interaction with users [18], much of this investigation will be focused upon continuous capture and analysis of data such as how easy it is to use the system, how effective the learning experience is, how much faster an inexperienced loader learns using the gamified system compared to the traditional means, how inexperienced loaders' performance in the gamified system compares to that of experienced loaders, how much performance obtained in the gamified system reflects actual real-world performance, and how much correlation there is between loading performance in the gamified system and loading performance in practice. This will help refine the user engagement process and ensure that the system has a direct impact on users, ultimately resulting in an increase in the performance of warehouse operatives in their day-to-day loading activities.

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Anatomical Joint Constraint Modelling with Rigid Map Neural Networks

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Abstract. The development of anatomical models both for individuals and groups are important for applications in animation, medicine and ergonomics. Recent approaches have utilised unit quaternions to represent orientations between limbs which eliminate singularities encountered in other rotational representations. As a result a number of unit quaternion based joint constraint validation and correction methods have been developed. Recent approaches harness machine learning techniques to model valid orientation spaces and has included the use of Kohonen's Self Organizing Maps (SOMs) to model regular conical constraints on the orientation of the limb. Recent work has considered a derivative of the SOM, the Rigid Map, applied in the same context which we extend here.

Introduction

Anatomically correct joint models are essential to ensure realistic movement during simulation for applications in animation, medicine and ergonomics [1, 2, 3]. Many current approaches are limited by their underlying representation of rotation or abstraction of the joint function [4], while in others, accuracy is linked to compulational cost [5]. This work builds on previous research exploring the use of machine learning to model joint constraints; specifically using unsupervised neural networks to model unit quaternion based phenomenological [6] joints (whose behaviour can be modelled without reference to the underlying joint anatomy).

Rigid Maps [7], similar to Kohonen's Self Organising Map (SOM), are used to implicitly model the boundary between valid and invalid orientations by modelling a group of valid rotations, expressed as unit quaternions. The SOM produces a topography preserving projection of the prototypes from the n-dimensional input space onto an m-dimensional output space [8], while the Rigid Map [7] uses a fixed output space of uniformly distributed unit quaternions. Competitive learning is employed to train a Rigid Map to represent a group of valid unit quaternion orientations. In response to an input orientation, the output is the weight of the output node which best matches the input, this can be used to provide a target for correction.

This paper considers constraints on the rotation of the limb (or swing [9]) with regular (circular) bounded constrained regions. Irregular boundaries and rotation around the limb (or twist [9]) are the subject of future work.

1 Background

Joint constraints can be expressed using Euler angles: this box-limit model is popular in animation tools and file formats [4]. Such course representations fail to capture inter-dimensional dependencies [10] and can encounter singularities [11]. Inter-dimensional dependencies can be represented by geometric functions fitted to a given data set e.g. spherical [12] and conical polygons [1]. Alternative rotational parameterisations have been deployed to overcome singularities including special orthogonal matrices [2] and unit quaternion e.g [13].

Quaternions are an extension of complex numbers, a subgroup where all quaternions are of unit length (the unit quaternion group) and their associated algebra allows the representation of rotation without the presence of gimbal lock [11]. Unit quaternions occupy a three dimensional surface (a hypersphere) in four dimensional space. This mapping is redundant as the unit quaternion represent 4π rotations, polar opposites (q and $-q$) describe the same orientation [11].

Unit quaternion joint constraints can be modelled by decompositing the limb origination, as a unit quaternion, into conical and axial components (also unit quaternions) constrained independently [13] or related by a simple function fitted to sampled data [14]. A number of approaches remove the reduncancy in quaternion space and project one hyper hemisphere to three dimensional space. Sampled groups of valid orientations can then be represented and used as targets for correction. Approaches include bounded volumes created from sphereical primitives [15] and voxels [16] with an implicit surface representing the rotational limit. An iterative approach was employed in both cases to resolve invalid joint configurations, by rotating toward the nearest primitive (sphere or voxel,) until the orientation was valid. An alternative approach used the maximum deviation from the mean of the projected points [17] as a constraint. Iterative correction towards the mean, to within the constraint and reverse projection could then be used to correct an invalid orientation [17].

Artificial Neural Networks (ANNs) have been employed to model anatomical joint constraints represented using unit quaternions. Here, unlike other approaches [13, 15], unit quaternions can be used as input without decomposition or projection. ANNs have been trained using supervised learning approaches to implicitly model a joint constraint boundary [18]. Such approaches are difficult to apply to recorded data as they require both valid and invalid patterns for training. To overcome this issue, ANNs trained using unsupervised techniques such as competitive learning have been proposed. SOMs have been trained using competitive learning to implicitly model joint constraints using only valid orientations expressed as unit quaternions [19, 20]. The weights of the output nodes are trained via competative learning to represent the training data while preserving the topography of the input space. The network responds to a given input orientation with the closest orientation in its model of the input data. This can be used directly for correction [19] or as a target for an iterative approach [20].

The Rigid Map Network is a modified SOM proposed for pose estimation problems by Winkler *et al* [7]. In their approach self-organisation is abandoned, the output node topology is fixed and the nodes are uniformly distributed over the orientation space, in this case the S^3 hypersphere using regular polyhedra. The learning algorithm is modified such that during training the winning node is based on the proximity between the input pattern and the position of the output node, rather than its weight (as in the SOM), determined by the inner product. The updating of weights, however, remains unchanged with the weight of the winning node and its neighbours being moved some distance toward the input according to the learning rate [21]. Both the learning rate and the radius of the neighbourhood decay exponentially with time [21]. When fired, the network responds with the weight which is the shortest Euclidean distance from the input [21].

It is hypothesised that the Rigid Map Network will produce superior results to the earlier SOM approach as the orientation space is known and self-organisation can be abandoned. Exploratory work has considered the capabilities of the Rigid Map in modelling the orientation of the limb with a regular rotational boundary and no constraint on the rotation around the limb. Future work will explore more complex constraints including irregular boundaries and rotation around the limb.

The remainder of this paper is structured as follows: Section 3 provides a description of our methodology with reference to the techniques employed. Section 4 reports the results of the experiments undertaken with these discussed in Section 5. Finally Section 6 draws conclusions from this work and highlights areas for future investigation.

2 Methodology

The Rigid Map used consists of four input nodes and a number of output nodes joined by a weighted connection. The output nodes are placed into a topology each having a position on the unit quaternion hypersphere, arranged using a selection of regular polytopes in 4D-space, in this case the polydodecahedron and polytetrahedron. The polytetrahedron has 120 vertices and 600 tetrahedral cells, while its reciprocal, the polydodecahedron has 600 vertices and 120 dodecahedral cells [22]. Combining these results in the vertices of the polydodecahedron being placed at the center of the polytetrahedron [21].

The Rigid Map was trained according to the process defined by Winkler *et al* [21, 7]. Each experiment was repeated ten times to ensure the consistency of the results. The Rigid Map used in this work was based on that presented by Winkler [21] modified such that the output nodes occupy the whole hypersphere rather than a single hemisphere.

Experiments were undertaken with output nodes arranged as polytetrahedron, polydodecahedron and a combination of both with on datasets of between 500 and 6000 patterns. In experiments where the range was not varied, a constant range of 90° was used with other training parameters identified though experimentation. The training dataset contained only valid patterns, similar to those recorded from the movement of a human arm. A set of 'ideal' corrections (no correction for valid orientations and the nearest valid orientation for invalid,) were generated using Lee's [13] approach and provided a measurement of the Rigid Maps capabilities.

3 Results

The results show the effect of correcting the orientation to that suggested by the Rigid Map (the unit quaternion represented by the weight of the winning node), indicating successful training of the Rigid Map. An increase in the range (angle between the virtual limb and the z-axis) of the constrained region results in a decrease in performance, as shown in Figure 1. The resulting corrections, however, are inferior to those of the SOM (from our earlier work [19]) using the same training data, training iterations and a similar number of output nodes (625) as shown in Figure 1.

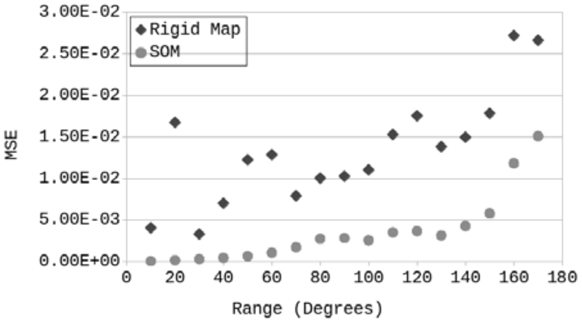

Figure 1: Performance of the Rigid Map with increasing constraint range compared to a similar SOM.

Increasing the number of training epochs produced an increases in performance, which attenuates rapidly as the number of epochs increases. The network error decreases as the number of output nodes is increased while the error appears independent of the number of training patterns.

4 Discussion

The results demonstrate that Rigid Maps are capable of identifying the nearest unit quaternion representing a valid orientation of a virtual anatomical limb, providing a representation of a region occupied by valid orientations in unit quaternions space. The Mean Squared Error (MSE) on the test set (containing invalid and valid orientations) is reasonably low, but higher than those for the SOM (shown in Figure 1). As in earlier work overcorrection is a problem; the limb is corrected to the orientation provided by the weights of the winning node, these being inside the valid region, while the testing process measures the MSE based on the distance from the boundary.

The results provide an insight into the effects of problem, network and training attributes on performance. It is clear that the network is capable of learning constraints of varying sizes, although larger constraints appear to demonstrate a higher error. This suggests an increase in overcorrection of valid points as output nodes are more dispersed over the valid region and an increase in overcorrection of invalid points as fewer output nodes occupy spaces near the boundary. Improvements resulting from the increase in output nodes can be ascribed to an increase in the density of output nodes over the valid region, reducing correction errors. Winkler [21], recommends an even distribution of output nodes, however no further polytopes exist [22]. This has implications for both small networks and large constraints due to the low density of output nodes in the valid region.

Previous results with the SOM [19] network showing improved results with an increase in the data set size are not echoed in the results for the Rigid Map, suggesting that the other factors (possibly the limited output node density) limit further improvements in performance.

5 Conclusion

Rigid Maps have been shown to be capable of representing a group of valid orientations in unit quaternion space to a degree of accuracy. However, this requires that the output nodes are uniformly distributed in the output space [21]. This initial research shows them to demonstrate inferior performance to the traditional SOM. Both approaches have similarities to non-machine learning based solutions [16, 17] with the advantage that no decomposition or reformatting of the unit quaternion orientation is required. Comparisons with other popular approaches in terms of accuracy and speed are now required.

Research is required into the tuning of the Rigid

Maps training parameters, along with the distribution and density of nodes in the output layer. A key limitation of this work, highlighted by the results, is an inability to explore larger output layers. Subdivision of the regular polytopes [7] along with other techniques [23] are being explored as part of our ongoing research.

Current results are encouraging and suggest that Rigid Maps are able to implicitly model constraints on the rotation of the limb with regular boundaries in unit quaternion space. They may have potential for modelling similar constraints with irregular boundaries and rotation around the limb while providing advantages over current approaches.

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Modelling and Simulation in Adaptive Intelligent Control

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Abstract. The linguistic equation (LE) approach uses the same compact structures are used for models and control systems. Inverse, internal and predictive control can be combined with switching and fuzzy set systems. Measurement levels, interactions and composite local models are analysed in a gradually refined way in the data-based modelling. In the applications, specific models and indicators are selected and constructed from similar building blocks. Intelligent analysers produce informative indirect measurements and indices for the controller which operates like an agent-based solution where all the actions are available for activation when needed. All subsystems are presented as parametric systems which can be tuned for wide operating areas by using a balanced set of process situations. The control solution has been tested in three different applications which use the same blocks in a process specific way.

Introduction

Model-based control is widely applied in industry [1]. *Phenomenological models* provide a useful process insight and understanding of the interactions and time delays inherent in the process [2]. However, the control of an industrial kiln requires adequately accurate models which are not easy achieve [3]. *Feedforward control (FF)* can be based on models, e.g. most of the controllers tested in the solar collector field use model-based feedforward control based directly on the steady state energy balance relationships [4]. A FF controller has been combined with different feedback controllers, even PID controllers operate for this purpose [5], and FLCs could be improved considerably [6, 7].

Internal model control (IMC) uses inverse modes to remove the difference between the measured and predicted outputs. The feedback controllers should cope with modelling errors and disturbances. In principle any types of models can be used, e.g. fuzzy models [8], models based on partial differential equations [9], and nonlinear models based on local linear models [10]. The classical IMC can operate efficiently in varying time delay conditions [9]. The IMC approach is a good solution if the model is not too complicated. The scheme can also contain on-line adaptation, e.g. a fuzzy model can be adapted and the consequent parameters are transferred to the inverse model [8].

In *model predictive control (MPC)*, models are used for predicting the process output over a prediction horizon [11]. Intelligent methods can be used at the modelling level, in optimisation and in the specification of the control objectives [8]. Stages in the development of modelling algorithms and incorporating fuzzy models into controllers are described in [12]. Fuzzy internal models have been used in the MPC approach [13]. A MPC using fuzzy TS models is discussed in [14].

Multiple model adaptive control (MMAC) allows different control structures, i.e. each mode corresponds to one model and one controller. Switching control strategies are based on selecting a controller from a finite set of fixed controllers, e.g. heuristic rules or predictions with models [15, 16, 17]. A combination of a switching algorithm and model predictive control (MPC) is presented in [18]. *Event based control*, also known as aperiodic or asynchronous control, uses sampling which is event-triggered rather than time-triggered [19, 20, 21]. It is close to a way a human behaves as a controller, and suits for distributed control systems.

Normal *feedback (FB)* and *feedforward (FF)* controllers can be extended to changing operating conditions with adaptation, model based approaches and high level knowledge based systems. Intelligent methods provide a good basis for handling nonlinear multivariable control systems, e.g. a large number of highly successful *fuzzy logic control (FLC)* applications are implemented in process industry. Fuzzy logic controllers can use normal state variables, $(x_1,\dots,x_n)$, instead of error, change of error and sum of error. Then the controller is presented by rules. An example of a FF controller based on an inverted fuzzy model is presented in [22]. For wide operating areas, accurate models are more difficult to develop than introducing intelligent controllers to run in the whole are. Fuzzy logic controllers are good examples of this.

Fuzzy controllers can be converted to linguistic equation form by replacing the symmetric parts of the rules with linguistic equations where linguistic levels for the error, error derivative and change of control are represented by linguistic values [23].

This paper classifies combined linguistic equation models and control methodologies and discusses about their applicability in three applications. The solution includes data-based LE modelling, intelligent LE control and model-based tuning.

1 Data-based LE modelling

Directions of interactions can usually be understood on the basis of domain expertise but the nonlinear effects may become hidden by various nonlinear effects. In the LE approach, the nonlinearities of the process are handled by the nonlinear scaling of the variables, which reduces the complexity of the models drastically [23]. Composite local models provide useful extensions for the linear models [24].

1.1 Data analysis

The parameters of the scaling functions are obtained by data analysis based on generalised norms and moments. The generalised norm is defined by

$$||^{\tau}M_j^p||_p = (M_j^p)^{1/p} = [\frac{1}{N}\sum_{i=1}^{N}(x_j)_i^p]^{1/p}, \qquad (1)$$

where the order of the norm $p \in R$ is non-zero, and N is the number of data values obtained in each sample time τ. The norm (1) calculated for variables x_j, $j = 1,\dots,n$, have the same dimensions as the corresponding variables. The norm $||^{\tau}M_j^p||_p$ can be used as a central tendency value if all values $x_j > 0$, i.e. $||^{\tau}M_j^p||_p \in R$. [25]. The norm can be extended to variables including negative values [26].

The orders, p, focus on different statistical properties of the dat distributions. The specific orders are chosen by using the generalised skewness,

$$(\gamma_k^p)_j = \frac{1}{N\sigma_j^k}\sum_{i=1}^{N}[(x_j)_i - ||^{\tau}M_j^p||_p]^k. \qquad (2)$$

The standard deviation σ_j is the norm (1) with the order $p = 2$. [27] The parameters can be recursively updated by using the norms with the spefied orders [26].

1.2 Nonlinear scaling

Scaling functions are monotonously increasing functions $x_j = f(X_j)$ where x_j is the variable and X_j the corresponding scaled variable. The function $f()$ consist of two second order polynomials, one for the negative values of X_j and one for the positive values, respectively. The corresponding inverse functions $x_j = f^{-1}(X_j)$ based on square root functions are used for scaling to the range [-2, 2], denoted linguistification. In LE models, the results are scaled to the real values by using the function $f()$.

The parameters of the functions are extracted from measurements by using generalised norms and moments. The support area is defined by the minimum and maximum values of the variable, i.e. the support area is $[\min(x_j), \max(x_j)]$ for each variable $j, j = 1,\dots,m$. The central tendency value, c_j, divides the support area into two parts, and the core area is defined by the central tendency values of the lower and the upper part, $(c_l)_j$ and $(c_h)_j$, correspondingly. This means that the core area of the variable j defined by $[(c_l)_j, (c_h)_j]$ is within the support area.

1.3 Interactions

The basic form of the linguistic equation (LE) model is a static mapping in the same way as fuzzy set systems and neural networks, and therefore dynamic models will include several inputs and outputs originating from a single variable [23]. External dynamic models provide the dynamic behaviour, and LE models are developed for a defined sampling interval in the same way as in various identification approaches discussed in [28].

Dynamic LE models use the parametric model structures, ARX, ARMAX, NARX etc., but the nonlinear scaling reduces the number of input and output signals needed for the modelling of nonlinear systems. For the default LE model, all the degrees of the polynomials become very low:

$$Y(t) + a_1 Y(t-1) = b_1 U(t-n_k) + e(t) \tag{3}$$

for the scaled variables Y and U .

1.4 Composite local models

The *composite local model* approach constructs a global model as a weighted sum of local models, which usually are linear approximations of the nonlinear system in different neighbourhoods.*Linear parameter varying (LPV) models*, where the matrices of the state-space model depend on an exogeneous variable measured during the operation, are closely related to local linear models. The models can be state-space models or parametric models. The model switches between different modes as the state variable varies over the partition [24].

Fuzzy set systems can be used when the operating areas of the local models can be overlapping (Figure 1). Also additional special phenomena can be added with fuzzy set systems [29]. The LE approach can be combined with several fuzzy modelling methodologies: the fuzzy arithmetics and extension principle introduce uncertainty processing and fuzzy inequalities can be used in selecting local models [30].

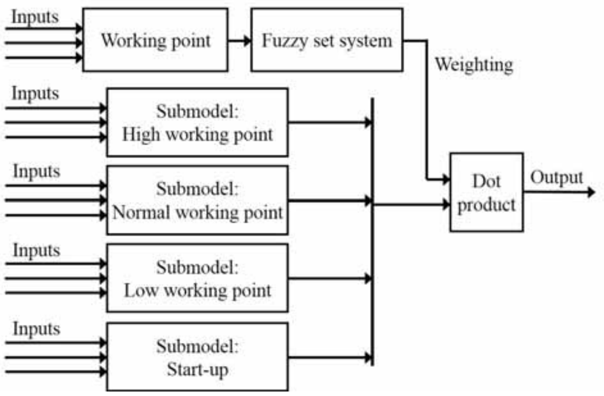

Figure 1: Composite local models of a solar collector field.

2 Intelligent LE control

The first direct LE controller was implemented in 1996 for a solar power plant [31, 32], and later the multilevel LE controller was installed in an industrial lime kiln [33]. The feedback LE control is enhanced with working point control and intelligent actions (Figure 2).

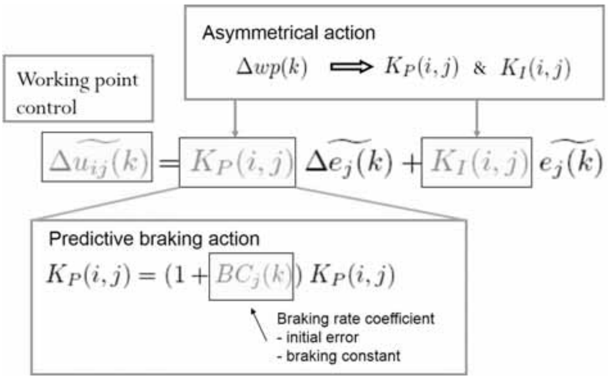

Figure 2: Adaptive LE controller.

2.1 Feedback control

Feedback linguistic equation (LE) controllers use error $e_j(k)$ and derivative of the error $\Delta e_j(k)$. These real values are mapped to the linguistic range $[-2,2]$ by nonlinear scaling with variable specific scaling functions in the same way as in LE models. The linguistic values of the inputs, $\widetilde{e_j(k)}$ and $\widetilde{\Delta e_j(k)}$, are limited to the operating range: outside the scaled values are -2 and 2 for low and high values, respectively.

A *PI-type LE controller* is represented by

$$\widetilde{\Delta u_{ij}(k)} = K_P(i,j)\, \widetilde{\Delta e_j(k)} + K_I(i,j)\, \widetilde{e_j(k)}, \tag{4}$$

which contains coefficients $K_P(i,j)$ and $K_I(i,j)$. The strengths of effects of $\widetilde{e_j(k)}$ and $\widetilde{\Delta e_j(k)}$ can be tuned by membership definitions $(f_e)_j$ and $(f_{\Delta e})_j$, respectively. However, the direction of the control action is fixed in (4). Different directions and strengths can be handled with this controller.

The output i of a single input single output (SISO) controller is calculated by adding the effect of the controlled variable j to the manipulated variable i:

$$u_i(k) = u_i(k-1) + \Delta u_{ij}(k). \tag{5}$$

2.2 Intelligent analysers

The LE control included predictive braking and asymmetry actions (Figure 2) already in the first implementations. The efficient handling of cloudy conditions intro-

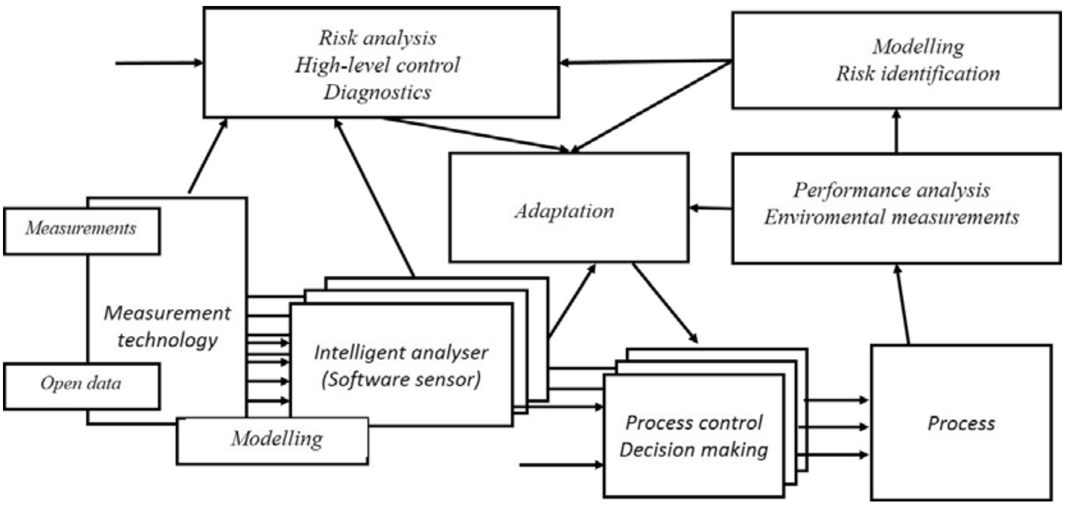

Figure 3: Intelligent analysers and control.

duced a fluctuation indicator [34]. Braking and asymmetry actions are not activated when fluctuations are high. There are additional safety actions for both drastic and accumulating effects. The intelligent analysers produce informative calculated variables for the controller (Figure 3). The indices can be interpreted in natural language.

Predictive braking indication. Braking is activated when a very large error is detected. The calculated braking coefficient, $bc_j(k)$ is used to emphasise the influence of the derivative of the error by means of the following equation:

$$K_P(i,j) = (1 + bc_j(k))\, K_P(i,j) \qquad (6)$$

A new solution has been introduced to detecting the large error.

The realisation of the braking action is process specific. In the solar plant, the control actions are large at the beginning of the correction and the braking is used in stopping the fast change. In the lime kiln, the braking is used in the beginning to start the correction with care.

Asymmetry detection. The action is activated only close to the set point if there are no strong fluctuations of the controlled variable evaluated by ${e_j}^-$ and ${e_j}^+$. The earlier calculation based on the solar noon operated well on clear days but they do not take into account actual irradiation changes in the solar application.

Fluctuation indicators. Detecting cloudiness and other varying situations is important in avoiding oscillations. The fluctuations are detected by calculating the difference of the high and the low values of the corrected irradiation as a difference of two moving generalised norms:

$$\Delta x_j^F(k) = ||^{K_s\tau}M_j^{p_h}||_{p_h} - ||^{K_s\tau}M_j^{p_l}||_{p_l}, \qquad (7)$$

where the orders $p_h \in \Re$ and $p_l \in \Re$ are large positive and negative, respectively. The moments are calculated from the latest $K_s + 1$ values, and an average of several latest values of $\Delta x_j^F(k)$ is used as an indicator of fluctuations. [34]

2.3 Adaptive control

Adaptive LE control takes into account process situation, manipulating variables and previous control actions in a predefined procedure. The correction factor is a weighted sum of the following scaling coefficients:

- working point wp_i is the deviation from the normal operating conditions;
- control power is calculated by a specific LE model for each manipulating variable;
- cumulative rate of control actions is used for avoiding the accumulation of a very large control action in slow processes.

Invidual scaling coefficients and the correction factor are are within the range $[-2,2]$. The correction factor modifies the final scaling of the change of control. Each manipulating variable needs to be constrained into the acceptable ranges defined by the physical constraints.

The adaptation uses indirect measurements provided by the intelligent analysers and weight factors and constraints defined by the high level control (Figure 3).

2.4 Model-based control

The LE model types summarised in Section 1 have linear interactions and can thus be used in the control as inverse process models. Feedforward controllers can also be based on heuristic LE systems and manually constructed scaling functions. The linear interactions make the highly flexible solution includes both switching between inverse models and using the weighted sums of inverse models.

The compact LE controllers can be used in the model-based predictive control if the operation is fairly smoothly. Strong fluctuations are harmful also for this kind of model-based control. Mainly the modelling part is embedded in the development of the intelligent analyses from measurements and open data (Figure 3). Online LE modelling could also be implemented, but it is not feasible in applications which have a lot of strong disturbances and fluctuations. The online modelling is restricted in performance and risk analysis.

3 Applications

Three applications of different kind are discussed in this section. Fast adaptation to changing operation conditions are needed in the solar plant. Several controlled and manipulating variables are needed in the lime kiln control where the FF actions are important. Two differently operating chemicals are essential in the control of water treatment which combines FF and FB actions.

3.1 Solar thermal power plant

Solar power plants should be designed to collect all the available thermal energy in a usable form within a desired temperature range. In cloudy conditions, the collector field is maintained in a standby mode ready for full-scale operation when the intensity of the sunlight rises again. Control is achieved by means of varying the flow of oil pumped through the pipes during the plant operation. For the solar collector field, the goal is to reach the nominal operating temperature 180 - 295 ^oC and keep it in changing operating conditions. The main challenge is to extend the operation to less favourable operating conditions.

Feedforward control. The *energy balance* of the collector field can be represented by expression [5]:

$$I_{eff} A_{eff} = (1-\eta_p) F \rho c T_{diff}, \tag{8}$$

where I_{eff} is effective irradiation (Wm^{-2}), A_{eff} effective collector area (m^2), η_p a general loss factor, F flow rate of the oil $(m^3 s^{-1})$, ρ oil density kgm^{-3}, c specific heat of oil $(Jkg^{-1}K^{-1})$ and T_{diff} temperature difference between the inlet and the outlet (^oC). The effective irradiation is the direct irradiation modified by taking into account the solar time, declination and azimuth. The volumetric heat capacity increases very fast in the start-up stage but later remains almost constant because the normal operating temperature range is fairly narrow.

Feedback control. The feedback controller is a PI-type LE controller (4) with one manipulating variable, oil flow F, and one controlled variable, the maximum of the outlet temperatures of the loops, or shortly denoted as the outlet temperature T_{out}. The original controller was defined by the coefficients $K_P(i,j) = K_I(i,j) = 1$ [31, 32] and extended to real-valued coefficients in [35]. The basic LE controller is defined for the normal working point $wp_i = 0$.

Adaptive control. The LE controller is adapted to different operating conditions by using a working point LE model

$$wp = \tilde{I}_{eff} - \tilde{T}_{diff}, \tag{9}$$

where $\tilde{I}_{eff}$ and $\tilde{T}_{diff}$ are obtained by the nonlinear scaling of variables: efficient irradiation I_{eff} and temperature difference between the inlet and outlet, $T_{diff} = T_{out} - T_{in}$. The working point, wp, represents a fluctuation from the normal operation.

The working point variables already define the overall normal behaviour of the solar collector field, $wp = 0$, where the irradiation $\tilde{I}_{eff}$ and the temperature difference, $\tilde{T}_{diff}$, are on the same level. A high working point $(wp > 0)$ means low $\tilde{T}_{diff}$ compared with the irradiation level $\tilde{I}_{eff}$. Correspondingly, a low working point $(wp < 0)$ means high $\tilde{T}_{diff}$ compared to the irradiation level $\tilde{I}_{eff}$. The normal limit $(wp_{min} = 0)$ reduces oscillations by using slightly lower setpoints during heavy cloudy periods. Higher limits, e.g. $(wp_{min} = 1)$, shorten the oscillation periods after clouds more efficiently.

Intelligent analysers. The working point (9) is an important intelligent analyser which is used all the time. Predictive braking indication (6) is activated when a very large error is detected, e.g. after a drastic setpoint change. The asymmetry detection is activated only close to the setpoint. Cloudy conditions detected with the indicator (7) are taken into account in selecting a suitable working point $wp_i = 0$ when needed. This overrides the manual settings of the working point to avoid oscillations. Since this set of indicators operate very well, the indicators for fast changes of temperatures (inlet, outlet and difference) or too high temperatures activate in the current system very seldom [36].

Intelligent analysers are essential in transforming the complex control system into an agent-based solution where all the actions are available for activation when needed.

3.2 Lime kiln

Feedforward LE controllers are important in the lime kiln control in keeping good operating conditions when process input changes: draught fan speed, kiln rotational speed and fuel feeds are controlled by an inverse model. The fuel feeds are adjusted with the feedback LE controllers. The FB control, which is required in order to maintain the hot-end temperature within the most favourable range for the lime quality, is used for the fuels: sawdust and oil. The controllers are PI-type LE controllers based on two controlled variables: the hot end temperature and the cold end temperature with weights 0.7 and 0.3, respectively. The error is calculated as difference of two moving average [33].

Adaptive scaling, braking action and the fuel quality analyser are the key parts in the FB control. The fuel quality indicator is the most important for the biofuel. Another important requirement is the need to cope with the long time delays. The cumulative rate of control actions is essential in avoiding excess control actions to one direction. The working point is defined by the production rate and the draught fan speed.

The more efficient control solutions reduce the fluctuations of the product quality and minimise the environmental impact through smooth operation close to the process operation constraints. This brings the process optimisation into real practise.

3.3 Water treatment

The adaptive FB controller of the faster effecting chemical reacts efficiently to the change of the water quality and to the halving of incoming flow: the setpoint is kept, and there is no offset. The FF controller of the slowly affecting chemical (Chem1) is needed for the fast changes of flow and water quality (Figure 4). LE controllers have been successfully implemented at a mill [37]. Pre-tuning facilitates a fast operation in changing process conditions: the controller does not need time for finding correct parameters, since the changes are detected by the water quality indicator.

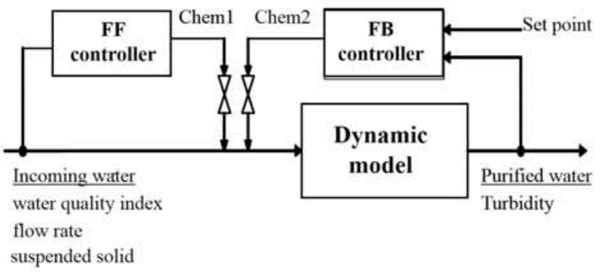

Figure 4: Dosing control in water treatment.

4 Model-based tuning

Dynamic LE models have been used for developing, testing and tuning the controllers in changing process conditions without disturbing the process.

A balanced set of different operating conditions is needed since the multilevel LE control system should operate in a wide operating area. The optimisation based on genetic algorithm can be used simultaneously for a large number of parameters, including

- parameters of the scaling functions for variables, errors and changes,
- model coefficients (working point, quality indices, cumulative rate, FF),
- correction factors, and
- weight factors.

In the applications, the number of parameters is from 40 to 100. Model-based predictive control is suitable for the tuning of the braking action.

In the water treatment, the dynamic simulator contains a dynamic LE model for the flotation basin, controllers for two chemicals and a soft sensor for the detection of incoming water quality. Simulation made the implementation faster without any re-tuning of control parameters was needed. [38]

5 Conclusions

The linguistic equation (LE) approach is an efficient solution for model-based intelligent control. Measurement levels, interactions and composite local models are analysed in a gradually refined way and the models and indicators are constructed from similar building blocks. The controller operates like an agent-based solution where all the actions are available for activation when needed. The parametric systems can be tuned for wide operating areas.

Acknowledgement

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State Events and Structural-dynamic Systems: Definition of ARGESIM Benchmark C21

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Abstract. Modelling and simulation of state events and of structural-dynamic systems is getting more and more important in advanced modelling theory and application. Therefore, the requirements regarding flexibility on modelling and on implementation in simulators is increasing.

To investigate, how modelling approaches and simulation environments deal with state events and structural-dynamic systems, the new ARGESIM Benchmark C21 'State Events and Structural-dynamic Systems' is defined. Three case studies should compare modelling and implementation of state events in dynamic systems, up to structural-dynamic systems governed by state events. The first case study, the almost classical bouncing ball dynamics investigates different kinds of bounce modelling and implementation with associated events. In the second case study, Switching RLC Circuit, different diode models result in simple switching state events or in in DAE systems. The third case study is structural-dynamic by itself: the rotating pendulum with free falling phase changes dynamics from swinging to falling (an vice versa) – switching between different degrees of freedom. These three case studies invite simulationists for providing 'solutions' – reports on modelling, implementation and specific investigations by of suggested experiments with the implemented model, to be published in SNE Simulation Notes Europe.

Development - Background

In, 1990, ARGESIM started in the journal SNE *Simulation News Europe* the comparison series *Comparison of Simulation Software* in order to compare features of simulators for classic system simulation. Since that, system simulation has developed further on (physical modelling, structural-dynamic systems, state charts, ...), and consequently also the comparisons developed further on towards *Benchmarks for Modelling Approaches and Simulation Implementations*.

Development of System Simulation

The classic explicit state space modelling has partly been replaced by 'higher' modelling techniques. Mainly the Modelica standard and the competitive VHDL-AMS standard have introduced physical modelling – component-based modelling with a-causal relations. Thereby, the components may be part of textual or graphical libraries in various domains [1], Figure 1. From mathematics' viewpoint, instead of explicit state models now implicit 'law-oriented' model descriptions have become basis for subsequent simulation, resulting in implicit differential-algebraic systems (DAEs).

In principle, the simulator now must translate the a-causal model description into a DAE system with proper structure of differential and algebraic equations, so that a 'modern' DAE solver can handle the implicit state space model with sufficient accuracy and sufficient convergence (index reduction problem).

Furthermore, more and more discrete elements were used in system simulation – not only sampled data, but also conditions and structural changes - so that also modelling techniques for discrete dynamic structures have become necessary – e.g. state charts with discrete and continuous dynamics.

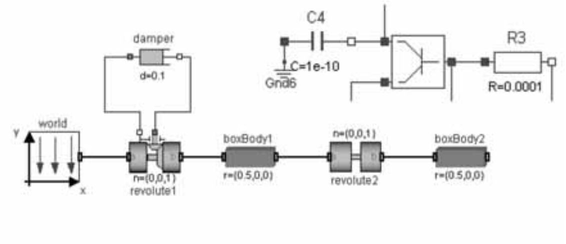


Figure 1: Modelica physical modelling for analog electrical domain and mechanics multibody domain.

Development of Comparisons / Benchmarks

ARGESIM / EUROSIM started in 1990 the series Comparison of Simulation Software in the journal Simulation News Europe (SNE). These comparisons are based on relatively simple, easily comprehensible processes.

In the beginning, simulationists were invited to prepare a ‘solution’ and to publish in SNE (1-page solution). Along with development of system simulation, also the comparisons developed further on. This development can be seen in definitions and solutions published from 1990 to 2016 in 87 SNE issues: 23 definitions (some revised), and about 350 comparison ‘solutions’. The following list of comparisons and benchmarks shows also the broad variety of the applications (including this new benchmark):

- C1 Lithium-Cluster Dynamics, SNE 0(1), 1990
- C2 Flexible Assembly System, SNE 1(1), 1991
- C3 Generalized Class-E Amplifier, SNE 1(2), 1991
- C4 Dining Philosophers I, SNE 1(3), 1991
- C5 Two State Model, SNE 2(1), 1992
- C6 Emergency Department SNE 2(3), 1992
- C7 Constrained Pendulum, SNE 3(1), 1993
- CP1 Parallel Simulation Techniques, SNE 4(1), 1994
- C8 Canal-and-Lock System, SNE 6(1), 1996
- C9 Fuzzy Control of a Two Tank System,
  SNE 6(2), 1996, revised SNE 16(3), 2006
- C10 Dining Philosophers II, SNE 6(3), 1996
- C11 SCARA Robot, SNE 8(1), 1998
- C12 Collision of Spheres, SNE 9(3), 1999
- C13 Crane Crab and Embedded Control,
  SNE 11(1), 2001; rev. SNE 17(1), 2007
- C14 Supply Chain, SNE 11(2-3), 2001
- C15 Clearance Identification, SNE 12(2-3), 2002
- C16 Restaurant Business Dynamics, SNE 14(1), 2004
- C17 Spatial Dynamics of SIR Epidemics,
  SNE 14(2-3), 2004; revised SNE 25(2), (2015)
- C18 Neural Networks vs. Transfer Functions,
  SNE 15(1), 2005
- C19 Pollution in Groundwater Flow, SNE 15(2-3), 2005, revised SNE 16(3-4), 2006
- CP2 Parallel &$_4$Distributed Simulation, SNE 16(2), 2006
- C20 Complex Assembly System, SNE 21(3-4), 2011
- C21 State Events and Structural-dynamic Systems,
  SNE 26(2), 2016

In 2006, a re-organisation of the comparisons has been started [2]. The comparisons developed towards *Benchmarks for Modelling Approaches and Simulation Implementations:*

- Revised definitions: SNE is publishing revised definitions of previous comparisons, updating models and tasks in order to continue them as benchmark.
- Extended solution documentation: SNE allows two (or more) pages for solutions of classic benchmarks.
- Extended Benchmarks: SNE introduces extended benchmarks, comparing modelling and simulation paradigms, or dealing with more complex models and experiments – as with benchmarks C19, CP2, C20 and C21.
  Documentation and publication in SNE of ‘solutions’ may take more pages – up to 10 pages SNE.

1 State Events and Structural – dynamic Systems

This section reviews some necessary mathematical background and modelling notations, in order to allow a better and comparable documentation of the investigations in this new benchmark C21.

1.1 DAE systems and state events

Mainly because of physical modelling techniques like sketched in Figure 1, the classical ODE state space description

$$\dot{\vec{x}}(t) = \dot{f}(t,\vec{x}(t),\vec{u}(t)), \qquad \vec{x}(t_0) = x_0, \qquad (1)$$

with $\vec{x}(t)$ state vector, $\vec{f}(t)$ derivative vector, $\vec{u}(t)$ input vector, $\vec{x}_0$ initial state vector and $\vec{p}$ parameter vector, was replaced by the (semi-) implicit state space description of DAE system type

$$\begin{aligned} \dot{\vec{x}}(t) &= \vec{f}(t,\vec{x}(t),\vec{z}(t),\vec{u}(t),\vec{p}), \qquad \vec{x}(t_0) = x_0 \\ \vec{g}(\vec{x}(t),\vec{z}(t),\vec{u}(t),\vec{p}) &= \vec{0} \qquad (2) \end{aligned}$$

The algebraic equations, e.g. constraints, are coming along with another new challenge, with structural dynamic systems. Constraints are very often coupled with state-dependent conditions for their validity – like loss of freedom, etc., requiring a conditional change of the model description.

Consequently the problem of state event description and state event handling becomes much more complex than in classic ODE models and raises new questions for proper model description.

Although mathematically incorrect, in models from application it is often necessary to model discontinuities in the model description, because a certain system phenomenon can only be described approximatively by a (discontinuous) change in the model,

These discontinuous changes are called *events*; if the time instant of the change is known in advance, the event is called a *time event*; if the event depends on a certain value or threshold for a state variable (which is not known in advance), it is called *state event*.

A state event is defined

- by an event function $h(\vec{x}(t),\vec{z}(t),\vec{u}(t),\vec{p})$, whose zero determines the time instant $\hat{t}$ of the next occurrence of the event,
- and by an event action $E(\vec{x}(\hat{t}),\vec{z}(\hat{t}),\vec{u}(\hat{t}),\vec{p})$, which performs the discontinuous change.

An event function h can cause the associated event action E several times, and there may be more than one event scheduled by an event function:

$$h^B(\vec{x}(t),\vec{u}(t),\vec{p}) \overset{!\,\pm}{=} \vec{0} \overset{\hat{t}^B}{\Rightarrow} E^B(\vec{x}(\hat{t}^B),\vec{u}(\hat{t}^B),\vec{p}) \quad (3)$$

$$\dots$$

$$h^Z(\vec{x}(t),\vec{u}(t),\vec{p}) \overset{!\,\pm}{=} \vec{0} \overset{\hat{t}}{\Rightarrow} E^Z(\vec{x}(\hat{t}^Z),\vec{u}(\hat{t}^Z),\vec{p})$$

The symbol $\left(\overset{!\,\pm}{=}\right)$ in equation (3) means, that the zero $\hat{t}^B$ of the event function $h^B(\vec{x}(t),\vec{z}(t),\vec{u}(t),\vec{p})$ responsible for the event 'B', is to be determined ('!'), whereby crossings in both direction cause the event ('±'), or only crossings in negative direction ('-'), or only crossings in positive direction ('+'). Event functions can be seen as classical output functions, but sometimes they are only locally defined, or sometimes the algebraic function becomes an event function and vice versa.

The associated event action $E^B(\vec{x}(\hat{t}),\vec{u}(\hat{t}),\vec{p})$ must now handle the discontinuous change in the model description, which ranges from simple to very complex. It makes sense to classify events with respect to their 'quality' of action of change [3], [4]:

- Parameter change event – SE-P
- Input change event – SE-I
- State change event – SE-X
- Function change event – SE-F
- Structure change event – SE-S
- Output trace event – SE-O
- Algorithm event – SE-A

A simple state event is a *parameter change event* SE-P. One or more parameters p_m of the parameter vector $\vec{p}$ change to a new value:

$$\text{SE-P:}\quad E^P(\vec{x}(\hat{t}),\vec{u}(\hat{t}),\vec{p}):\quad p_{m,prev} \overset{\hat{t}}{\rightarrow} p_{m,new} \quad (4)$$

The *input change event* SE-I is not a state event, it is 'only' a time event – in order to synchronize discontinuities in input $\vec{u}(\hat{t})$ with the stepsize of the DAE solver.

A *state change event* –SE-X- is a strange construct – one or more components of the differential state vector change discontinuously. From viewpoint of mathematics, that cannot happen, because the state vector $\vec{x}(t)$ results as 'integration' of the continuous derivative function. But usually events of this type itself model a dynamic behaviour, which for simplicity or other reasons is 'concentrated' into a timeless event.

$$\text{SE-X:}\quad E^X(\vec{x}(\hat{t}),\vec{u}(\hat{t}),\vec{p}):$$

$$x_{n,prev}(\hat{t}) \overset{\hat{t}}{\rightarrow} x_{n,new}(\hat{t}) \quad (5)$$

A *function change event* SE-F changes at event time components of the derivative function or of the algebraic function, not only with a jump in values, but with a new description:

$$\text{SE-F:}\quad E^F(\vec{x}(\hat{t}),\vec{u}(\hat{t}),\vec{p}): \quad (6)$$

$$f_{(prev)} \overset{\hat{t}}{\rightarrow} \check{f}_{(new)}\,,\, g_{(prev)} \overset{\hat{t}}{\rightarrow} \check{g}_{(new)}$$

State events of type SE-F and SE-X are 'simple' cases of structural model changes. The *structure change event* SE-S is the most complex one: in case of the event, another model is to be used; this new model may have a state space $\vec{x}^S(t),\vec{z}^S(t)$ of different dimension and type:

$$\text{SE-S:}\quad E^S(\vec{x}(\hat{t}),\vec{u}(\hat{t}),\vec{p}): \quad (7)$$

$$\vec{x}\,(t) \overset{\hat{t}}{\rightarrow} \vec{x}^S(t), \qquad \vec{z}\,(t) \overset{\hat{t}}{\rightarrow} \vec{z}^S(t)$$

$$\dot{\vec{x}} = \vec{f}(\vec{x},\vec{z},\vec{u},\vec{p}) \quad \overset{\hat{t}}{\rightarrow} \quad \dot{\vec{x}}^S = \vec{f}^S(\vec{x}^S,\vec{z}^S,\vec{u}^S,\vec{p}^S)$$

$$0 = \vec{g}(\vec{x},\vec{z},\vec{u},\vec{p}) \quad \overset{\hat{t}}{\rightarrow} \quad 0 = \vec{g}^S(\vec{x}^S,\vec{z}^S,\vec{u}^S,\vec{p}^S)$$

State events of type SE-D and SE-S are strongly related to structural-dynamic systems, which require dynamic change of state vector dimensions, e.g. cause by loss or addition of degrees of freedom.

A simple state event is the *output trace event* SE-O. At event time, a certain value given by an output function $g_{out}(t)$ is to be traced:

$$\vec{y}(t) = \vec{g}_{out}(t,\vec{x}(t),\vec{z}(t),\vec{u}(t),\vec{p})$$

$$\text{SE-O:}\quad E^O(\vec{x}(\hat{t}),\vec{u}(\hat{t}),\vec{p}):\quad \overset{\hat{t}}{\rightarrow} g_{out}(\hat{t}) \quad (8)$$

For completeness, the *algorithm event* SE-A is mentioned. Although model description and implementation should be independent, it can happen, that under some circumstances (mainly because of problems with accuracy) the algorithmic calculations must be 'influenced' – e.g. by changing ODE solver parameters:

$$\text{SE-A:}\quad E^A(\vec{x}(\hat{t}),\vec{u}(\hat{t}),\vec{p}):\quad \overset{\hat{t}}{\rightarrow} \begin{array}{l}\text{appropriate action}\\ \text{influencing the}\\ \text{algorithm}\end{array} \quad (9)$$

In general, an event function $h^{B,C,D,\dots}$ can cause more than one event, so that an event 'E' can belong to more than one type.

1.2 State Event Handling

The primary task for event handling are the synchronisation of the state event with the ODE/DAE solver, and the 'execution' of the event – i.e. the discontinuous change of parameters, inputs, and states, and the choice of new derivatives or new models.

State event algorithm requires the following steps:

- *Detection* of the event
- *Localisation* of event and solver stopping
- Event *Action*
- *Restart* of solver

Event detection is usually done by observing the algebraic sign of the event function during the time advance of the ODE/DAE solver. Localisation is usually superimposed to the DAE solver, by using an appropriate algorithm (iterative methods, interpolative methods). Iterative methods can give more accurate results. But in case of event functions with nearby roots, iteration may cause a deadlock, may let events vanish, etc. State event functions can be given by a state value itself – here the event localisation could be integrated into the DAE solver – but only few DAE solver implementations make use of this possibility.

1.3 Structural-dynamic systems

Systems with state events of essential types SE-F (5) or SE-S (6), often come together with a change of the dimension of the state space, then called *Structural-dynamic Systems*. In principle, for modelling structural-dynamic systems two approaches are meaningful:

- *maximal state space*: in a maximal state space, state events switch on and off algebraic conditions, which freeze certain states for certain phases, and state events 'act' within in the model (Figure 2, at left).
  hybrid decomposition: a global discrete state space controls local models with fixed state spaces, or with newly composed state spaces; state events 'schedule' different models (state chart in Figure 2, at right).

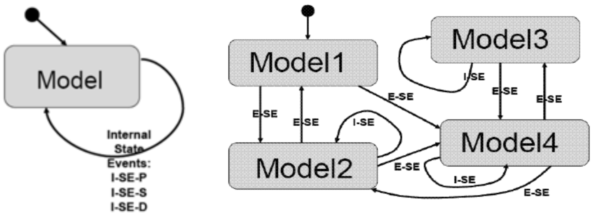


Figure 2: State chart model for -
maximal state space approach (at left)
and hybrid decomposition approach (at right)

The hybrid decomposition approach must be supported by a framework, which allows the switching between different models, and within one model – caused by state events – convenient are sate charts.

2 Case Study Bouncing Ball

When observing a bouncing ball, the ball is falling and jumping quite high, but bit by bit, position amplitude is decreasing, and bounce frequency is increasing. This physical process is well known as bouncing ball dynamics, met also in other applications. Figure 3 shows three classical examples – bouncing balls of different sizes, and a non-classical example, the pogo stick.

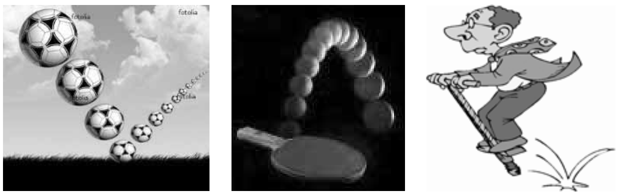


Figure 3: Various bouncing ball dynamics – football, ping pong, pogo stick

The bouncing ball dynamics allow various modelling approaches and incorporate events, where the dynamics change or the description of the dynamics must change.

2.1 Bouncing Ball Model - Event Contact

Following e.g. [6] the bouncing ball dynamics consist of two different phases, the free falling phase with or without air resistance, and a 'timeless' contact phase, where the bouncing ball hits the ground, and changes direction of movement (Figure 4).

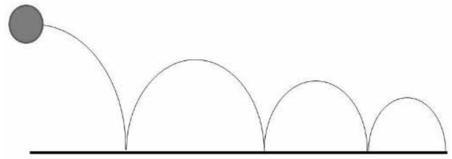


Figure 4: Idealized bouncing ball dynamics, sketch.

Free falling phase. The motion of a free falling mass in a gravitational field is given by the following two differential equations for position x and velocity v:

$$\dot{x} = v,\ \ \dot{v} = -g - \beta v^2 \mathrm{sign}(v) \tag{10}$$

with g acceleration of gravity, β air resistance coefficient, and state space $\vec{x}(t) = (x(t), v(t))^T$.

Neglecting air resistance gives the simple linear model

$$\dot{x} = v\,,\ \ \dot{v} = -g \tag{11}$$

Event contact model. The *contact phase* can be implemented using different models. The *event contact model* is a quite simple approach, using Newton's 3rd law, and a coefficient μ to describe the loss of energy in case of a 'timeless' bounce, neglecting any deformation, - modelled the event '*B' Bounce*.

The velocity $v_{prev}(\hat{t})$ of the ball right 'before' the contact (impact) with the ground 'jumps' to the velocity $v_{new}(\hat{t})$ by means of 'reflection' and energy loss, being a *state change event* SE-X (5) with event action E^B:

$$v_{new}(\hat{t}) \overset{\hat{t}}{\rightarrow} -\mu \cdot v_{prev}(\hat{t}). \tag{12}$$

The event function (13) for event action E^B (12) is simply the position x: the (bottom) position of the ball reaches ground, crossing zero into negative direction:

$$h^B(x,v) \overset{!-}{=} x \tag{13}$$

Mathematical analysis. The linear model (11) allows analytical calculation of the impact time instants $t_{\mathrm{B,m}}$. The linear model has a solution of type

$$x(t) = -\tfrac{g}{2}t^2 + b\,t + c,\ v(t) = -gt + b \tag{14}$$

With initial values $x_0 > 0$ and $v_0 = 0$, the first impact can be calculated using (14) as $t_{\mathrm{B},1} = \sqrt{2x_0/g}$.
Starting flight at $t_{\mathrm{B},1}$ with $x(t_{B,1}) = 0,$ and

$$v(t_{B,1})_{new} = -\mu \cdot v(t_{B,1})_{prev} = \mu \cdot g \cdot t_{B,1},$$

gives the next impact time $t_{B,2} = t_{B,1}(2\mu + 1)$. Continuing with the analytical solution (14) derives a recursion for impact time: $t_{B,m} = t_{B,m-1}(\mu + 1) - \mu t_{B,m-2}$.
This recursion allows calculating the time instant t_{m} of the m-th bounce by means of the geometric series

$$t_{B,m} = \sqrt{\frac{2x_0}{g}} \cdot \left(-1 + 2\sum_{i=0}^{m-1} \mu^i\right) \tag{15}$$

As $|\mu| < 1$, the above series (15) converges and gives the limit for the series of bouncing time instants t_∞:

$$t_{\mathrm{B},\infty} = \sqrt{\frac{2x_0}{g}} \cdot \frac{1+\mu}{1-\mu} \tag{16}$$

- being a finite number! These considerations proof, that in finite time infinite many bounces take place.

2.2 Bouncing Ball Model - Dynamic Contact

The model (10) or (11) with *event contact phase* works considerably good in case of contact with very little deformation and very short (neglectable) contact time, i.e. for a rather stiff bouncing on a rigid surface.

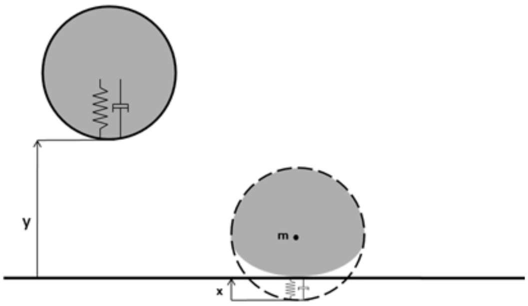


Figure 5: Ball deformation during contact phase, Kelvin-Voight model.

In case of a 'significant' contact phase, a more realistic model is necessary, which takes into account the elasticity in the contact region. The deformation can be modelled in first approximation by a spring-damper-element in parallel to the flying phase, as given in Figure 5, Kelvin-Voigt model, [5]).

Again the dynamics consist of two phase – free falling phase (or flying phase), and contact phase, but the contact phase is not any longer an isolated event, it consumes time and begin and end are controlled by state events; additionally, in both phases deformation is taken into account! In both phases three state variables characterize the dynamics: (bottom) position $x(t)$ of the not deformed ball, velocity $v(t)$, and deformation $w(t)$.

Free falling phase. For position and velocity again equation (10) or (11) is used, and a damping of first order describes the deformation $w(t)$ – during flight not coupled with position and velocity, but active:

$$\dot{x} = v,\ \dot{v} = -g - \beta v^2 \mathrm{sign}(v),\ \dot{w} = -\frac{k}{d} \cdot w \tag{17}$$

Figure 5 shows, that in model (17) the variable v is still the velocity, but $x(t)$ is now the distance from the ground to the virtual bottom point of the (not deformed) ball, which may become negative. $w(t)$ represents the deformation, so that the actual bottom position of the deflected ball, the distance $y(t)$ from the deflected ball bottom to ground is given by output equation

$$y(t) = x(t) + w(t) \tag{18}$$

Output equation (18) becomes now also the event function which terminates the free falling phase reaching the ground, i.e. reaching the threshold zero, causing event 'C' (*Contact*):

$$h^C(x,v,w) \overset{!-}{=} x + w \tag{19}$$

The associated event action E^C is switching to *contact phase*.

Dynamic Contact. In the *contact phase*, the (normalized) contact force $\mathrm{f_c}$ determines the dynamics:

$$f_c = -kx - dv \qquad (20)$$

In case of contact the dynamic equation (17) for velocity v gets the contact force f_c added as counterforce to gravity, and $\dot{w}$, change of deflection, equilibrates to velocity v. The dynamic equations in the *continuous contact phase* are consequently:

$$\dot{x} = v,\ \dot{v} = -\mathrm{g} + f_c = -g - kx - dv,\ \dot{w} = -v \quad (21)$$

The contact phase finishes, as soon as the contact force f_c get negative, and the ball starts flying again – event '*F*' – *Fly Restart* with contact force as event function:

$$h^F(x, v, w) \overset{!\,-}{=} f_c = -kx - dv \qquad (22)$$

Following the event classification in Section 1.1, the events '*C*' *Contact* and '*F*' *Fly Restart* are *function change events* SE-F. But as in *contact phase* the equation for deformation $w(t)$ is dependent on the others in (21), dimension – and consequently also structure of the model change – so that the events can be seen as *structure change events* SE-S. On the other side, the equations (17) and (21) are relatively simple and can be formulated together by using a boolean parameter, which switches parts in the derivative functions - so that a boolean parameter is controlled by simple *parameter change events* SE-P.

Figure 6 summarizes the evolving dynamics of the ball movement until second bounce: deformation happens also in the *flying phase*, except in the first *flying phase* (but only because of because of zero deflection at begin). After the first bounce, the deformation never goes down to zero, and the ball restarts flying in deformed status.

As deflection never reaches zero after the first impact, the number of bounces must be limited – after some bounces the ball stops flying and continues movement with decreasing deflection.

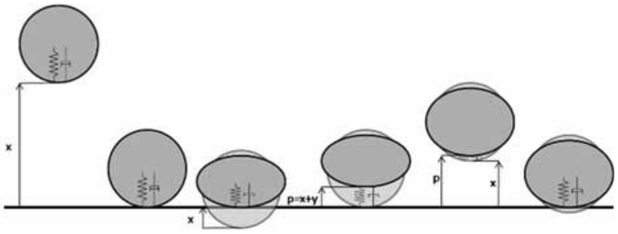


Figure 6: Phase sequence Flying – Contact – Flying for bouncing ball dynamics.

For both models it makes sense to define an additional event '*M*' *Maximium Height*, which determines the time instants where the ball reaches maximal height (zero velocity) – on first glance only an *output trace event* SE-O, but eventually of help in case of accuracy problems in the algorithm (*algorithm event* SE-A):

$$h^M(x, v, w) \overset{!\,+}{=} v \qquad (23)$$

2.3 Bouncing Ball Model – Benchmark Tasks

Generally, the tasks are model description, especially of event functions and event action, time domain analysis with model comparison and parameter studies, and especially of event handling, and comparison.

Modelling / Handling State Events with Event Contact Model

These tasks investigates modelling methods for state events of type SE-S - *state change event* (5), (12) in the *event contact model* and tests state event handling especially when handling frequent events and by comparing with analytical solutions.

Description of model implementation. Document implementation of continuous model parts (10) and (11), and of the event '*B*' –*Bounce* (12), (13), (textual model code snippets, (parts of) graphical model diagrams, etc.

Simulation until last bounce – scattering prevention. Simulate the *event contact model* (10-13) using the simulations system's event mechanism with and without air resistance and following parameters:

$$x(0) = x_0 = 10\,m, v(0) = v_0 = 0, \mu = 0.9$$
$$\beta = 0 \text{ or } \beta = 0.002\,\frac{1}{m}, \mathrm{g} = 9.81\,\frac{m}{s^2}, t_{end} = 30\,s$$

Event time for the 'last' bounce $t_{\mathrm{B},\infty}$. should be determined – by (16) and by simulation.

Straightforward implementation of events often have problems with event scattering – which happens definitely near to $t_{\mathrm{B},\infty}$ (16), Figure 7 – the ball 'falls' into the ground. Workaround is to stop bouncing before 'last' event, e.g. if maximal height of the flight period becomes too small.

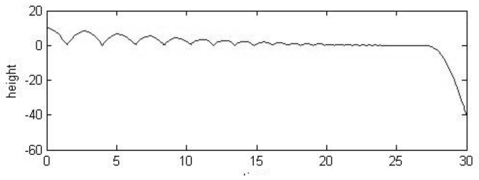


Figure 7: Scattering of *Bounce* events near the 'last' bounce due to missing error prevention.

In each flight period, the event '*M*' *Maximal Height* (23) can determine the maximal height, and below a critical maximal height further *Bounce* events are stopped by parameter change or by model change, or by change of solver parameters or accuracy of event detection, etc. Event '*M*' *Maximal Height* (23), first a simple *output trace event*, SE-O, becomes at a *parameter change event* SE-P or a *function change event* SE-F, or an *algorithm change event* SE-A.

Implement and document a proper strategy against event scattering, if necessary.

Testing accuracy of event handling. Using the linear model (11), the solution calculated by (14) gives the exact bounce times $t_{B,m}$ (15). Simulate the linear model with parameters given before (air resistance $\beta = 0$) tracks the 'numerical' bounce time instants $\hat{t}_{B,m}$.

Document results by comparison of entry times of the first 100 bounces by plotting bounce time differences $\Delta t_m := t_{B,m} - \hat{t}_{B,m}$ over number of bounces. Number of bounces can be determined easily in each bounce event by increasing a discrete output variable, so that '*B*', the *state change event* SE-X *Bounce* becomes also an *output trace event* SE-O. Again it might be necessary to prevent from event scattering!

Compensation of linear model deviation. In any case, air resistance is evident – but very small. Due to missing air resistance in the linear model, the event times are 'too late'. Simulate nonlinear and linear model with standard parameters below and try to compensate the 'too late' bounce times in the linear model by giving an initial velocity $v_0 = \delta$

$$x_0 = 10\,m,\ v_0 = 0 \text{ or } v_0 = \delta\,, \mu = 0.9$$
$$\beta = 0 \text{ or } \beta = 0.002\,\frac{1}{m}, g = 9.81\,\frac{m}{s^2}, t_{end} = 30\,s$$

Modelling / Handling State Events and Parameter Studies with Continuous Contact

These tasks investigate modelling approaches for events, tests cooperation of event location with different ODE solvers, and performs parameter studies. Standard parameters are:

$$x(0) = x_0 = 10\,m, v(0) = v_0 = 0, k = 10^6\,\frac{N}{m},$$
$$d = 500\,\frac{kg}{s}, g = 9.81\,\frac{m}{s^2}, \beta = 0.002\,\frac{1}{m}$$

Description of model implementation. Document implementation of continuous model parts (17) and (21), and of the events 'C' –*Contact* (20), and 'F' –Fly Restart (22), (textual model code snippets, (parts of) graphical model diagrams, etc.). Discuss the general modelling approach – maximal state space, hybrid decomposition, or switching model parts.

Dependency of results from algorithms. It might be necessary to choose specific ODE solvers or to tune ODE solver parameters and event detection parameters.

Simulate the d*ynamic contact model* using different ODE solvers, and / or tune parameters for ODE solvers and event detection, with $t_{end} = 30\,s$ and standard parameters.

Document of simulation results with plots or with tables indicating deviations for different algorithms, and discuss appropriateness of specific algorithmic properties (e.g. stepsize control vs event detection, or scattering prevention).

Investigation of contact phase. The proper implementation of the model (17), (21) and of the events '*C*' *Contact* (20) and '*F*' *Fly Restart* (22) can be seen in detail in the contact phase which is much shorter than the flying phase. Simulation results with standard parameters for first contact phase, the second flight phase, and the second contact phase should be given in separate time plots over $[t_{C,1} - \varepsilon_1,\ t_{F,1} + \varepsilon_1]$, $[t_{F,1} - \varepsilon_2,\ t_{C,2} + \varepsilon_2]$, and $[t_{C,2} - \varepsilon_3,\ t_{F,2} + \varepsilon_3]$, resp. ($\varepsilon_1, \varepsilon_2,$ and ε_3 being about a tenth of the length of the phase), showing all state variables, output variables, and the contact force (20) (in contact phase). Additionally, maximal height (event '*M*' *Maximal Height* (23)) in *flying phase*, and maximal deviation w in the *contact phases* – additional *output trace event* SE-O– should be determined.

Parameter studies. Variation of the spring constant k has big influence on the systems behaviour. Calculate simulation studies varying the stiffness-parameter $k = 10^6$ by a factor 100 while concurrently setting the damper constant to *d = 500*. Afterwards, vary *d* and finally document the relation of the parameters *k* and *d* by appropriate time plots and / or parameter plots (use standard parameters before).

Bouncing ball on Mars. It might be nice, to now about bouncing ball behaviour on Mars and to compare with behaviour on Earth. Let's simulate for 30 seconds, whereby for Mars we must use the different parameter values for gravity constant and air resistance: '$g_M = 3.69\,\frac{m}{s^2},\ \beta_M = 2.3 \cdot 10^{-4}\,\frac{1}{m}$. Document results as comparative plots for position and velocity.

3 RLC Circuit with Diode

The second cased study is the well-known classic serial RLC circuit, with a diode in parallel – Figure 8. Diode models are partly discrete models, and events control the switching of the diode. Physical modelling systems usually provide a library with circuit elements, but it is worth to have a closer look at diode implementation and consequence of the type of implementation.

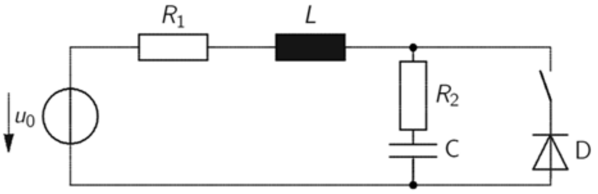


Figure 8: Serial RLC with diode in parallel

3.1 RLC model equations

Kirchhoff's laws and node equation first allow setup the physical model equations for the voltages:

$$u_C + u_{R_1} + u_L + u_{R_2} + u_C = u_0 \qquad (23)$$

$$u_{R_2} + u_C = u_D \qquad (24)$$

Inductor and capacitor have the constitutive equations,

$$\frac{di}{dt} = \frac{1}{L} u_L,\ \frac{du_C}{dt} = \frac{1}{C}(i + i_D) \qquad (25)$$

Classic 'manual' derivation of the system equations using (23), (24), and (25) will usually choose a differential state vector $\vec{x}(t)$ with RLC current i and capacitor voltage u_C, and an algebraic state vector $\vec{z}(t)$ consisting of diode current $i_D(t)$ and diode voltage $u_D(t)$ and result in the following 'general' a state space, with $\vec{u}(t) = (u_0(t)),\quad \vec{x}(t_0) = (i_0, u_{C,0})^T$
$\vec{x}(t) = (i(t), u_C(t))^T,\ \vec{z}(t) = (u_D(t), i_D(t))^T$:

$$\frac{du_C}{dt} = \frac{1}{C} i + \frac{1}{C} i_D \qquad (26)$$

$$\frac{di}{dt} = -\frac{R_1}{L} i - \frac{R_2}{L}(i + i_D) - \frac{1}{L} u_C + \frac{1}{L} u_0 \qquad (27)$$

$$0 = R_2(i + i_D) + u_C - u_D \qquad (28)$$

The diode is described by a 'switching' functional relation between current and voltage, in general

$$u_D = F(i_D),\ i_D = 0\ \ if\ \ u_D < 0 \qquad (29)$$

The diode has a locking phase with $i_D = 0$ for $u_D < 0$, and a conducting phase for $u_D > 0$ with i_D given by

$$0 = R_2(i + i_D) + u_C - F(i_D) \qquad (30)$$

3.2 Diode models and phase change

A diode is a mixed continuous – discrete element. It has two operational phases- a *locking phase* and a *conducting phase*, dependent on the diode voltage.

The mode change may be seen as simple switch (shortcut), or a conducting phase can be described by specific diode models.

Chang of phases - events

In any case, the diode voltage u_D controls the switching between *locking phase* and *conducting phase* due to equation (28). In *locking phase* with $u_D < 0$ and $i_D = 0$ equation (29) changes to $u_D = R_2 i + u_C$. A switching to *conducting phase* happens, if u_D becomes positive, which can be described by a state event '*C*' *Conducting Phase Start* with event function due to (3)

$$h^C(i, u_c) \overset{!\,+}{=} u_D = R_2 i + u_C \qquad (30)$$

with crossing from negative to positive diode voltage. In *conduction phase*, the diode voltage is given by equation (28) with nonzero diode current, calculating u_D as

$$u_D = R_2(i + i_D) + u_C$$

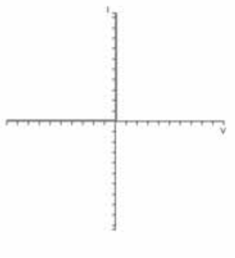
A switching to *locking phase* happens, if u_D becomes negative, which can be described by a state event '*L*' *Locking Phase Start* with event function due to (3)

$$h^L(i, u_c, i_D) \overset{!\,-}{=} u_D = R_2(i + i_D) + u_C \qquad (31)$$

with crossing from positive to negative diode voltage. Clearly, calculation of i_D depends on the choice of diode function description (29).

Shortcut diode model

The *shortcut diode model*, a simple diode model mimicries the dynamic behaviour as an ideal switch for the current depending on diode voltage u_D (Figure 9), so that the diode functional description, and also the model description (27-29) becomes simple.



$$i(u_D) = \begin{cases} 0, & u_D \le 0 \\ i(t), & u_D > 0 \end{cases}$$

$$u_D \cdot i_D = 0 \qquad (32)$$

Figure 9: Diode model as ideal switch

In *locking phase*, the general model description (27-29) simplifies to an explicit linear state space following (27) with $i_D = 0$ – the model for the RLC circuit alone.

In *conducting phase*, the shortcut simplifies the model descritption to a decoupled linear state space:

$$\frac{du_C}{dt} = \frac{1}{R_2} u_C,\quad \frac{di}{dt} = -\frac{R_1}{L} i + \frac{1}{L} u_0 \qquad (33)$$

The algebraic equations (29) and (29) become obsolete, the event functions (30), (31) become simple linear threshold function $h^C(i, u_c)$ and $h^L(i, u_c)$

The events ‘*C*’ *Conducting Phase Start* and ‘*L*’ *Locking Phase Start* generally are state events of type *function change event* SE-F; but as the model is linear, the changes are parameter changes in the state matrix, so they can be seen also as *parameter change event* SE-P.

Shockley diode model

A diode is a nonlinear element, and indeed the switching dynamics evolve nonlinear dynamics. One nonlinear model is known as *Shockley diode model*. The mathematical description is given by an exponential-like functional relation between diode current and diode voltage (Figure 11) given by

$$i(u_D) = \begin{cases} 0, & u_D < 0 \\ I_S \cdot \left(e^{\frac{u_D}{U_T}} - 1\right), u_D > 0 \end{cases} \tag{34}$$

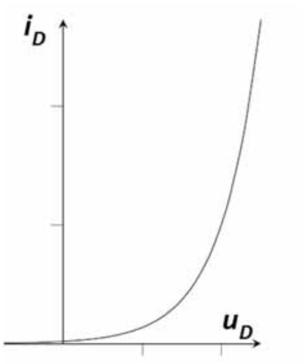


Figure 10: Diode model with Shockley characteristic

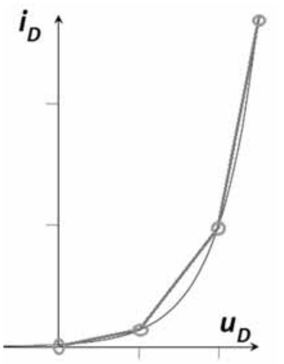


Figure 11: Diode model with interpolated Shockley characteristic

Inserting the description (34) into the algebraic equation (30) results in one algebraic equation for diode voltage:

$$I_S R_2 \left(e^{\frac{u_d}{U_T}} - 1\right) + u_c + u_d = 0 \tag{35}$$

Following notation in (3) $u_d(t)$ is an algebraic state $z(t) = u_d(t)$ and equation (35) is the corresponding algebraic equation due to (3). Alternatively, the functional relation in (34) can be inverted, so that u_d can be expressed as $u_d = U_T \ln\left(\frac{i_D}{I_S} - 1\right)$, resulting in an algebraic equation for i_D:

$$R_2(i + i_D) + u_C - U_T \ln\left(\frac{i_D}{I_S} + 1\right) = 0 \tag{36}$$

With *Shockley diode model*, the model description in *conducting phase* is governed now by a nonlinear DAE systems.

The state equation (27) becomes nonlinear when inserting the nonlinear expression (34) for i_D. The algebraic equations (35) or (36) are in any case nonlinear. The model description in *locking phase* is again the RLC model.

The events (30) and (31) for changing the modes remain unchanged – but they switch now between models with different number of states: in *locking phase*, an explicit model with two differential states, in *conducting phase*, a DAE model with two differential states and one algebraic state. Consequently, the events are of type *structure change event* SE-S, and the system is a structure-variable system.

Interpolated Shockley diode model

Characteristic curves are a classic way-around for algebraic equations. The curve for the diode’s operation (Figure 10) can be made a linear interpolated table function $i(t) = S_{LIN,j}(u(t); (u_j, i_j))$ with adequate breakpoints (u_j, i_j), $j = 1, .. n$. Inserting this interpolation into the algebraic equation (35) allows resolving with respect to u_D, giving a linear relation of type $i_D(t) = F_{LIN,j}(u_c(t); (u_{D,j}, i_{D,j})$.

As result, the state equations in *conducting phase* become a piecewise linear explicit system, and no algebraic equation is necessary:

$$\frac{d}{dt}\begin{pmatrix} i \\ u_C \end{pmatrix} = A^{C,j}\begin{pmatrix} i \\ u_C \end{pmatrix} \tag{37}$$

The model description in *locking phase* is again the RLC model.

Explicit Shockley diode model.

In Shockley diode model, in *conducting phase* a DAE system has to be solved. DAE solvers require iteration and state event detection requires backstepping in time, which is not suitable in case of real time simulation.

The DAE system (26), (27), (35) is an index-1 system. Index reduction can transform the algebraic equation (35) to an explicit ODEs. A straightforward method is to differentiate the algebraic equation (35) directly with respect to time, resulting in a relatively complicated ODE for $u_D(t)$ with initial value $u_{D,0} = 0$ at event ‘*C*’ *Conducting Phase Start*:

$$\dot{u}_D = -\dot{u}_C \left(I_S R_2 \left(e^{\frac{u_D}{U_T}}\right) \frac{1}{U_T} + 1\right)^{-1} \tag{38}$$

The model description in *locking phase* is again the RLC model.

The events (30) and (31) for changing the modes remain unchanged – but again they switch between different state dimensions: in *locking phase*, an explicit model with two differential states, in *conducting phase*, an explicit model with three differential states. Consequently, the events are of type *structure change event* SE-S, and the system is a structure-variable system.

3.3 RLC circuit with diode – tasks

Generally, the tasks are model description, especially of event functions/actions, and comparison of diode models.

Description of model implementations. Document implementation of the RLC model (26-30) and especially of the diode models (32), (33-36), (37), (38) with the phase changes and events (30), (31) (textual model code snippets, (parts of) graphical model diagrams, etc.). Discuss the general modelling approach – maximal state space, hybrid decomposition, or switching model parts, and possible model modifications for efficient modelling e.g. for comparing different diode models.

Dependency of results from algorithms. It might be necessary to choose specific ODE solvers or to tune ODE/DAE solver parameters and event detection parameters.

Simulate the *diode shortcut model* (32), (33) and the *Shockley diode model* (34), (35) using different ODE/DAE solvers, and / or tune parameters for ODE solvers and event detection, with standard parameters. Give plot results, indicate sensible solver parameters.

Comparison of shortcut and Shockley diode model. Compare results for *diode shortcut model* (32), (33) and for *Shockley diode model* (34), (35), with standard parameter, but timespan only two switching periods.

Document results with plots, and give a relative comparison of computation times.

Approximation of Shockley diode model. Investigate the approximation of the *Shockley diode model* (34), (35) by the *interpolated Shockley diode model* (37) with 3, 5 and 10 breakpoints for the interpolation (standard parameters, but timespan only two switching periods,

Document results with appropriate plots and with numeric deviation.

Relevance of choice of algebraic state. In case of *Shockley diode model*, either equation (34) for u_d or (35) for i_d can be used as algebraic state equation.

Simulate *Shockley diode model* with both variants, and check eventual differences – documented by plots or numeric deviations (standard parameters).

Investigation for real-time simulation. For real-time simulation, fixed step sizes and simplified event detection (without backstepping) must be used. With this premises, and with standard parameters, compare results for *diode shortcut model* (32), (33), *interpolated Shockley diode model* (37) and *explicit Shockley diode model* (38) by appropriate simulations. Document the implementation of the ODE for the diode voltage u_d .

Standard parameters (SI units):

$$R_1 = 1 \cdot 10^3, R_2 = 2 \cdot 10^1, L = 25.3 \cdot 10^{-6},$$
$$C = 100 \cdot 10^{-9}, I_S = 1 \cdot 10^{-8}, U_T = 26 \cdot 10^{-3}$$
$$t_0 = 0, \qquad t_{end} = 500 \cdot 10^{-6}$$
$$u_0 = -\sin(2\pi f \cdot t), \qquad f = 0.15 \cdot 10^{-6}$$

4 Rotating Pendulum with Free Flight Phase

This case study describes a classical idealized pendulum on a rope with damping. The pendulum body, which is considered a point mass, is connected to a fixed point in the space by a rope of given length. The rope is assumed to be non-elastic and without mass. As a simplification, it is presumed that the mass can move freely only in the plane, i.e. the area of a circle with a radius equal to the length of the rope.

The movement of the mass shows two phases:

- If the rope is tight, the mass is classically swinging (phase *swinging*); Figure 12a. Movement has one degree of freedom, usually described in polar coordinates.
- If the rope is loose, the mass is free falling (phase *falling*) until the rope is tight again (changing back in phase *swinging*; Figure 12b. Movement has two degrees of freedom, usually described in Cartesian coordinates

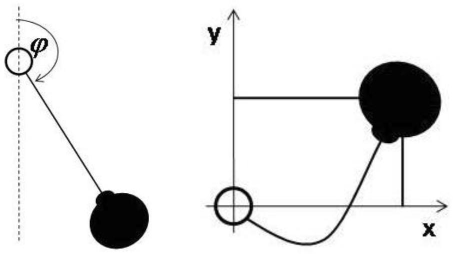


Figure 12: Left: Swinging pendulum – phase *swinging* (mass m, length l; angle φ as degree of freedom; Right: Free falling pendulum mass (phase *falling*) and Cartesian coordinates as degrees of freedom.

4.1 Model description

Equations for movement in phase *swinging* can be derived by using the angular momentum balance, resulting in the classic pendulum equation:

$$\ddot{\varphi} + \frac{k}{m}\dot{\varphi} - \frac{g}{l}\sin(\varphi) = 0 \tag{39}$$

with damping factor k, the mass m, rope length l and earth acceleration g. An explicit state space is given by

$$\vec{x}_S(t) = \big(\varphi(t), \dot{\varphi}(t)\big)^T \text{or } \vec{x}_S(t) = \big(\varphi(t), v(t)\big)^T \tag{40}$$

with $\dot{\varphi}$ angular velocity, v tangential velocity

The pendulum is swinging, as long as the force on the rope is bigger than zero.

$$F = -gm\,cos(\varphi) + ml\dot{\varphi}^2 \tag{41}$$

If this force $F(t)$, an output equation, becomes lower than zero, the gravitational force outweighs the centrifugal force: the pendulum is changing into phase *falling*.

In phase falling, the movement of the body has two degrees of freedom. The motion of the mass is derived by conservation of momentum in x- and y- direction:

$$\begin{aligned} m\ddot{x} &= -k\dot{x}, \\ m\ddot{y} &= -mg - k\dot{y}. \end{aligned} \tag{42}$$

An explicit state space is given by

$$\vec{x}_F(t) = \big(x(t), \dot{x}(t), y(t), \dot{y}(t)\big)^T \tag{43}$$

The distance d from rotation center

$$d^2 = x^2 + y^2 \tag{44}$$

indicates whether the rope is loose ($d < l$) or whether it gets tight again ($d = l$), forcing the body back on the circular path: the mass switches to phase *swinging*.

Figure 13 shows an overview of the two phases with the different models and with the criteria for the changes of phase. The overall system is a typical structural-dynamic system, and in modelling the change of degrees of freedom – the change of the dimension of the model – has to be mastered.

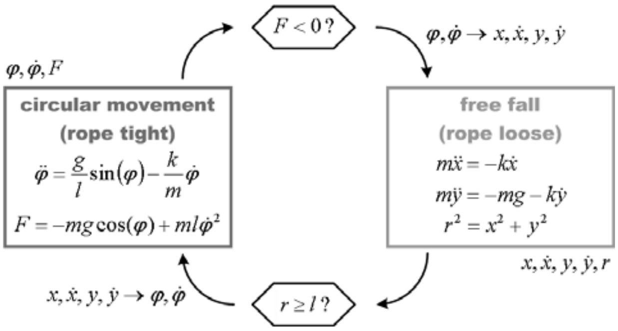


Figure 13: Summary of the two state models with criteria for the state changes

4.2 Change of phases – events

The change from phase *swinging* to phase *falling* can be described by the state event '*F*' *Falling*, which is given by a state event function using the formula (41) for the force on the rope:

$$h^F(\varphi, \dot{\varphi}) \overset{!\,-}{=} F = -gm\,cos(\varphi) + ml\dot{\varphi}^2 \tag{45}$$

A crossing into negative direction activates the event. The associated event action $E^F(\varphi(\hat{t}), \dot{\varphi}(\hat{t}))$ requires a change of the model – with change of degress of freedom, with calculation of new initial values. The state event therefore is a typical *structure change event* SES.

The change from phase *falling* to phase *swinging* is modelled by the event '*S*' *Swinging* which is activated, when the rope gets tight – measured by the distance (44) and described by the event function

$$h^S(x, \mathrm{y}) \overset{!\,+}{=} d^2 - l^2 = x^2 + y^2 - l^2 \tag{46}$$

A crossing into positive direction activates the event: the associated event action $E^S(x(\hat{t}), \dot{x}(\hat{t}), y(\hat{t}), \dot{y}(\hat{t}))$ requires a change of the model – with change of degrees of freedom. The state event therefore is a typical *structure change event* S-ES.

Structural-dynamic models can be implemented by hybrid decomposition, or by a maximal state space. A hybrid decomposition for this case study is sketched in Figure 13. A maximal state space approach would require a state space of dimension 6

$$\vec{x}_M(t) = \big(\varphi(t), \dot{\varphi}(t), x(t), \dot{x}(t), y(t), \dot{y}(t)\big)^T$$

where then depending on the event functions (45), (46) states are 'frozen' in the respective phases.

From physical modelling an alternative approach is suggested. The movement in the phase *swinging* can also be described in polar coordinates: the mass is moving freely, but a force $\lambda(t)$ forces the movement on a circle:

$$\begin{aligned} m\ddot{x} &= -k\dot{x} - \lambda x \\ m\ddot{y} &= -mg - k\dot{y} - \lambda x \end{aligned} \tag{47}$$

$$0 = x^2 + y^2 - l^2 \tag{48}$$

The above DAE system indeed describes the swinging of the mass, and it could be used instead of the model in polar coordinates (31). The events given by (45), (46) could now switch easier between the phases, because the differential state space is almost the same – so one state space with internal switching could be used (the model for the phase *swinging* must additionally solve an algebraic equation – with algebraic state $\lambda(t)$.

Interestingly, the algebraic state equation (48) in phase *swinging* is the same than the event function (46) (output equation) in phase *falling*. Unfortunately the DAE system (47), (48) is difficult so solve, because it has a differential index of 3 – which makes index reduction necessary.

4.3 Rotating pendulum – tasks

Tasks in this case study concentrate on the modelling approach and model implementation, and on few simulation.

Description of model implementations. Document implementation of the structural-dynamic system with phase *swinging* (39) and phase *falling* (42) the sate events (45), (46) which switch the phases. Alternatively describe the implementation of the 'common' DAE system (47), (48) (textual model code snippets, (parts of) graphical model diagrams, etc.). Discuss the general modelling approach – maximal state space, hybrid decomposition, DAE system with switching model parts, and possible modifications for efficient modelling.

Basic simulation of phases. Calculate and visualize a basic simulation run with the following parameters:

$$m = 1.5\,kg, k = 0.9\,\frac{kg}{s}, = 1\,m, = 9.81\,\frac{m}{s^2}$$

and the initial conditions

$$\varphi_0 = \varphi(0) = \frac{\pi}{4},\ \dot{\varphi}_0 = \dot{\varphi}(0) = 15\,\frac{1}{s}$$

Simulate beginning until the maximal oscillation does not exceed $\frac{\pi}{10}$ any longer (indicate time instant) – could be determined by adding an output event!

Dependency of results from algorithms. It might be necessary to choose specific ODE solvers or to tune ODE/DAE solver parameters and event detection parameters.

Perform simulations with standard parameters, timespan until begin of second phase *swinging* using different ODE/DAE solvers, and / or tune parameters for ODE solvers and event detection. Give plot results and indicate sensible solver parameters.

External energy supply. Due to physical constraints, only one phase *falling* can occur because of energy loss. In order to 'restart' the alternating movements, energy is supplied – as increase of the angular velocity (a 'kick').

Following the basic simulation of the second task, the angular velocity is increased by a factor, so that the pendulum reaches again the phase falling.

At the first zero crossing after angle did not exceed $\frac{\pi}{10}$, the angular velocity multiplied by a factor γ – a state event of type *state change event* SE-X

Determine factors γ so that

(i) the same movement than before results,

(ii) the next falling phase starts at $\varphi = \pi$, and

(iii) the swinging phase makes two rotations

5 Conclusion

This benchmark is a challenging one. We hope, that 'solution'sent in enrich the variety of modelling approaches and clarify some inconsistencies in state event modelling. We invite simulationist to provide a 'solution' – with publication of a *Technical Benchmark Note* (up to 10 pages) in SNE. Furthermore we ask for model source codes, for download by readers.

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EUROSIM 2016

9th EUROSIM Congress on Modelling and Simulation

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Web EUROSIM	Vitaly Bolshakov, *vitalijs.bolsakovs@rtu.lv*

Last data update June 2016

PSCS – Polish Society for Computer Simulation

PSCS was founded in 1993 in Warsaw. PSCS is a scientific, non-profit association of members from universities, research institutes and industry in Poland with common interests in variety of methods of computer simulations and its applications. At present PSCS counts 257 members.

→ *www.ptsk.man.bialystok.pl*
📧 *leon@ibib.waw.pl*
✉ PSCS / Leon Bobrowski, c/o IBIB PAN,
ul. Trojdena 4 (p.416), 02-109 Warszawa, Poland

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Secretary	Zdzislaw Galkowski, *Zdzislaw.Galkowski@simr.pw.edu.pl*
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Web EUROSIM	Magdalena Topczewska *m.topczewska@pb.edu.pl*

Last data update December2013

SIMS – Scandinavian Simulation Society

SIMS is the *Scandinavian Simulation Society* with members from the four Nordic countries Denmark, Finland, Norway and Sweden. The SIMS history goes back to 1959. SIMS practical matters are taken care of by the SIMS board consisting of two representatives from each Nordic country (Iceland one board member).

SIMS Structure. SIMS is organised as federation of regional societDjouaniies. There are FinSim (Finnish Simulation Forum), DKSIM (Dansk Simuleringsforening) and NFA (Norsk Forening for Automatisering).

→ *www.scansims.org*
📧 *esko.juuso@oulu.fi*
✉ SIMS / SIMS / Erik Dahlquist, School of Business, Society and Engineering, Department of Energy, Building and Environment, Mälardalen University, P.O.Box 883, 72123 Västerås, Sweden

SIMS Officers	
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Web EUROSIM	Vadim Engelson, *vadim.engelson@mathcore.com*

Last data update June 2016

SLOSIM – Slovenian Society for Simulation and Modelling

SLOSIM - Slovenian Society for Simulation and Modelling was established in 1994 and became the full member of **EUROSIM** in 1996. Currently it has 69 members from both slovenian universities, institutes, and industry. It promotes modelling and simulation approaches to problem solving in industrial as well as in academic environments by establishing communication and cooperation among corresponding teams.

→ www.slosim.si
📧 *slosim@fe.uni-lj.si*
✉ SLOSIM / Vito Logar, Faculty of Electrical
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SLOSIM Officers	
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Last data update June 2016

UKSIM - United Kingdom Simulation Society

The UK Simulation Society is very active in organizing conferences, meetings and workshops. UKSim holds its annual conference in the March-April period. In recent years the conference has always been held at Emmanuel College, Cambridge. The Asia Modelling and Simulation Section (AMSS) of UKSim holds 4-5 conferences per year including the EMS (European Modelling Symposium), an event mainly aimed at young researchers, organized each year by UKSim in different European cities.

Membership of the UK Simulation Society is free to participants of any of our conferences and thier co-authors.

→ *www.uksim.org.uk*

📧 *david.al-dabass@ntu.ac.uk*

✉ UKSIM / Prof. David Al-Dabass
Computing & Informatics,
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United Kingdom

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Last data update June 2016

RNSS – Russian Simulation Society

NSS - The Russian National Simulation Society (Национальное Общество Имитационного Моделирования – НОИМ) was officially registered in Russian Federation on February 11, 2011. In February 2012 NSS has been accepted as an observer member of **EUROSIM**, and in 2014 RNSS has become full member.

→ *www.simulation.su*

📧 *yusupov@iias.spb.su*

✉ RNSS / R. M. Yusupov,
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Deputy	B. Sokolov, *sokol@iias.spb.su*
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Last data update June 2016

EUROSIM OBSERVER MEMBERS

KA-SIM Kosovo Simulation Society

Kosova Association for Modeling and Simulation (KA – SIM, founded in 2009), is part of Kosova Association of Control, Automation and Systems Engineering (KA – CASE). KA – CASE was registered in 2006 as non Profit Organization and since 2009 is National Member of IFAC – International Federation of Automatic Control. KA-SIM joined EUROSIM as Observer Member in 2011. In 2016, KA-SIM has applied for full membership KA-SIM has about 50 members, and is organizing the international conference series International Conference in Business, Technology and Innovation, in November, in Durrhes, Albania, an IFAC Simulation workshops in Pristina.

→ *www.ubt-uni.net/ka-case*

📧 *ehajrizi@ubt-uni.net*

✉ MOD&SIM KA-CASE; Att. Dr. Edmond Hajrizi
Univ. for Business and Technology (UBT)
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KA-SIM Officers	
President	Edmond Hajrizi, *ehajrizi@ubt-uni.net*
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Web EUROSIM	Betim Gashi, *info@ka-sim.com*

Last data update June 2016

ROMSIM – Romanian Modelling and Simulation Society

ROMSIM has been founded in 1990 as a non-profit society, devoted to theoretical and applied aspects of modelling and simulation of systems. ROMSIM currently has about 100 members from Romania and Moldavia.

→ *www.ici.ro/romsim/*

🖃 *sflorin@ici.ro*

✉ ROMSIM / Florin Hartescu,
National Institute for Research in Informatics, Averescu
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ROMSIM Officers	
President	
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Last data update June 2016 (partly)

MIMOS – Italian Modelling and Simulation Association

MIMOS (Movimento Italiano Modellazione e Simulazione – Italian Modelling and Simulation Association) is the Italian association grouping companies, professionals, universities, and research institutions working in the field of modelling, simulation, virtual reality and 3D, with the aim of enhancing the culture of 'virtuality' in Italy, in every application area.

MIMOS has submitted application for membership in **EUROSIM** (Observer Member).

→ *www.mimos.it*

🖃 *roma@mimos.it – info@mimos.it*

✉ MIMOS – Movimento Italiano Modellazione e Simulazione; via Ugo Foscolo 4, 10126 Torino – via Laurentina 760, 00143 Roma

MIMOS Officers	
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Last data update June 2016

Albanian Simulation Society

At department of Statistics and Applied Informatics, Faculty of Economy, University of Tirana, Prof. Dr. Kozeta Sevrani at present is setting up an Albanian Simulation Society. Kozeta Sevrani, professor of Computer Science and Management Information Systems, and head of the Department of Mathematics, Statistics and Applied Informatic, has attended a EUROSIM board meeting in Vienna and has presented simulation activities in Albania and the new simulation society.

The society – constitution and bylaws are at work - will be involved in different international and local simulation projects, and will be engaged in the organisation of the conference series ISTI – Information Systems and Technology. The society intends to become a EUROSIM Observer Member.

🖃 *kozeta.sevrani@unitir.edu.al*

✉ Albanian Simulation Goup, attn. Kozeta Sevrani
University of Tirana, Faculty of Economy
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Last data update June 2016

EUROSIM Federation of European Simulation Societies

General Information. **EUROSIM**, the Federation of European Simulation Societies, was set up in 1989. The purpose of **EUROSIM** is to provide a European forum for simulation societies and groups to promote advancement of modelling and simulation in industry, research, and development.

Member Societies. **EUROSIM** members may be national simulation societies and regional or international societies and groups dealing with modelling and simulation. At present **EUROSIM** has 15 *Full Members* and 2 (3) *Observer Members*.

→ *www.eurosim.info*

EUROSIM Development

Not only modelling and simulation, but also **EUROSIM** and the journal **SNE** have taken interesting developments in the last years, from the first **EUROSIM** Congress 1992 in Capri, until now. **EUROSIM**, in the beginning a nation-based federation, has opened itself to a federation for simulation societies and simulation groups, which have different structures and work nation-wide, or itself as federation across countries, or as simulation council of another society, or as simulation society dedicated to a special area, etc.

Therefore EUROSIM is glad, that new societies and groups want to become EUROSIM members, and that inactive societeis have started a ‘relaunch’. On occasion of the EUROSIM Congress 2016 in September 2016 in Oulu, Finland, EUROSIM plans to welcome **MIMOS** - Movimento Italiano Modellazione e Simulazione – Italian Modelling and Simulation Association - as new member. The board will also discuss about the further membership potential.

Also the journal **SNE Simulation Notes Europe** has developed from EUROSIM’s newsletter **SNE Simulation News Europe** to a scientific journal for rapid publication of contributions on ‘simulation’, with open access, but with special benefits for the **EUROSIM** member societies and for their personal and institutional members. **SNE** ties together **EUROSIM**, by post-conference publication of contributions to conferences of the **EUROSIM** member societies, by news and information in the news chapter of the **SNE** issues, and by mirroring this information on **EUROSIM** web *www.eurosim.info*.

EUROSIM Congress

The **EUROSIM Congress** can be seen as constant within these developments – each three years simulationists from all over the world gather in one European country to exchange information on development in modelling and simulation.

EUROSIM 2016

9th EUROSIM Congress on Modelling and Simulation

September 12 - 16, 2016, Oulu, Finland

eurosim2016.automaatioseura.fi

In 2016, SIMS, the Scandinavian Simulation Society, organizes the EUROSIM Congress, together with Finnish Society of Automation and University of Oulu. The Congress is held in the City of Oulu, capital of Northern Scandinavia. The programme of the EUROSIM 2016 Congress will have a multi-conference structure with several special topics related to methodologies and application. The programme includes invited talks, parallel, special and poster sessions, exhibition and versatile technical and social tours.

The invited talks emphasize on the new challenges for modelloing and simulation:

- *Thermal Management Simulations within Power Engineering at ABB*, Rebei Bel Fdhila, ABB Corporate Research, Västerås, Sweden
- *Modelling and Simulation of the Electric Arc Furnace Processes*, Vito Logar, University of Ljubljana, Slovenia
- *Simulating the Composition of the Atmosphere*, Harri Kokkola, Finnish Meteorological Institute, Kuopio, Finland
- *Autonomous Driving and Levels of Automation*, Galia Weidl, Daimler AG, Böblingen, Germany
- *Situation Awareness and Early Recognition of Traffic Maneuvers*, Galia Weidl, Daimler AG, Böblingen, Germany

The EUROSIM congress series continues – the 10th EUROSIM Congress, EUROSIM 2019, will be organised by CEA-SMSG – Spanish Modelling and Simulation Group.

EUROSIM 2019

10th EUROSIM Congress on Modelling and Simulation

2019, La Rioja, Spain

ASIM
German Simulation Society
Arbeitsgemeinschaft Simulation

ASIM (Arbeitsgemeinschaft Simulation) is the association for simulation in the German speaking area, servicing mainly Germany, Switzerland and Austria. ASIM was founded in 1981 and has now about 700 individual members, and 30 institutional or industrial members.

→ *www.asim-gi.org* with members' area
✉ *info@asim-gi.org, admin@asim-gi.org*
🖂 ASIM – Inst. f. Analysis and Scientific Computing
Vienna University of Technology
Wiedner Hauptstraße 8-10, 1040 Vienna, Austria

ASIM and its working groups organize various conferences and workshops. These news sketch the mainly international events organized by ASIM.

Conference 'Simulation in Production and Logistics'

Every two years this conference new developments and interesting applications of simulation. This international conference is well balanced between research, development and industrial use. Scientific innovation is discussed as well as the successful application in every day's business. Companies, which have not been using simulation before, get first impressions and are enabled to estimate the benefits of simulation for their own enterprises, supported by the exhibition of relevant simulation tools and services.

Simulation users can exchange experiences, can evaluate new offers and can participate in special discussions. One important issue is the application of simulation, for example in the automotive industry, one-of-a-kind production, transport logistics, and supply chain management. Specific workshops and software tutorials intensify the discussion on current issues.

In 2015, this conference took place in Dortmund, Germany, with about 300 participants. The opening speech was given by David Kelton, University of Cincinnati *Irregular Simulation: Input Modeling and Applications.*

The next conference in these series is scheduled for September 2017.

18TH ASIM CONFERENCE
SIMULATION IN PRODUCTION AND LOGISTICS
September 20 - 22, 2017; Kassel, Germany
www.asim-fachtagung-spl.de

MATHMOD Conference. ASIM is also co-organizer of the MATHMOD conference series. The scope of tri-annual MATHMOD conference covers theoretic and applied aspects of the various types of mathematical modelling for systems of dynamic nature.

About 300 particpants enjoyed MATHMOD 2015 in Vienna. Next MATHMOD will take place in February 2018 in Vienna.

MATHMOD 2018
9th Vienna Conference on Mathematical Modelling
February 20 – 23, 2018, Vienna, Austria
www.mathmod.at

ASIM Symposium Simulation Technique. ASIM started in 1981 with an annual conference *ASIM Symposium Simulationstechnik*, which tried to cover all aspects of modelling and simulation – in German language. This conference has now developed to a conference on simulation approaches and methods, and special methodological simulation aspects in applications.

The *Simposium Simulation Technique* has become a bi-annual conference, mainly with English contributions. Next confenerence takes Place in Dresden, September 2016 ASIM

ASIM SST 2016
23th ASIM Symposium Simulation Technique
September 7 – 9, 2016; Dresden, Germany
www.asim2016.de

ASIM Workshops. The ASIM working groups *Simulation of Technical Systems*, *Methods in Modelling and Simulation*, and *Simulation in Environmental Sciences and Geosciences* organize annual workshops, partly with contributions and presentation in English language. Next workshop takes place March 2017.

ASIM STS/GMMS 2017
Workshop Simulation of Technical Systems –
Methods in Modelling and Simulation
March 9 – 10, 2017; Ulm, Germany
www.asim-gi.org

F. Breitenecker, *Felix.Breitenecker@tuwien.ac.at*

CEA-SMSG – Spanish Modelling and Simulation Group

General Information. CEA is the Spanish Society on Automation and Control and it is the national member of IFAC (International Federation of Automatic Control) in Spain. Since 1968 CEA (or CEA-IFAC) looks after the development of the Automation in Spain, in its different issues: automatic control, robotics, SIMULATION, etc. In order to improve the efficiency and to deep into the different fields of Automation.

The association is divided into national thematic groups, one of which is centered on Modeling, Simulation and Optimization, constituting the CEA Spanish Modeling and Simulation Group (CEA-SMSG). It looks after the development of the "Modelling and Simulation" in Spain, working basically on all the issues concerning the use of Modelling and Simulation techniques as essential engineering tools for decision-making and optimization.

→ *http://www.ceautomatica.es/grupos/*
→ *emilio.jimenez@unirioja.es*
simulacion@cea-ifac.es
✉ CEA-SMSG / Emilio Jiménez,
Department of Electrical Engineering,
University of La Rioja, San José de Calasanz 31,
26004 Logroño (La Rioja), SPAIN

General Activities.

The main usual activities of the group can be summarized as an annual meeting about modelling and simulation, inside the national CEA meeting on automation, an International Symposium on Modelling and Simulation since 2012, specialized courses, a distribution list, a periodic electronic report, technical books, a Journal (http://riai.isa.upv.es/) JCR indexed, a trade agreement with Pearson Inc. for a collection of books, an award for the scientific contribution in automation and a specific award for modelling and simulation, sponsorship of events, collaboration in international events, etc.

Past Events

Since 2012 the CEA-SMSG is organizing an International Symposium on Modelling and Simulation.

The activities include conferences from academia and industry, scientific and technical communications, courses, meetings, PdD presentations and selection of the best Thesis about M&S, and a session about the benchmark of the group about optimization by simulation. Last edition (III International Symposium on Modelling and Simulation of the CEA-SMSG) was held in Tudela (Navarre) 16-17 June 2016.

CEA IFAC celebrates every year the National Automatic Workshop (Jornadas de Automática), which includes the annual meeting of the CEA-SMSG. Last edition (XXXVI JA) was held in Bilbao (Spain) 2-4 September 2015.

The Group is collaborating in the last editions of the International Multidisciplinary Modelling & Simulation Multiconference, I3M. Most recent edition (12th I3M) was held in Bergeggi (Italy) 21-23 September 2015, including the following conferences: EMMS 2015, HMS 2015, MAS 2015, IMAACA 2015, DHSS2015, IWISH 2015, and SESDE 2015.

Coming Events

The Group will organize the IV International Symposium on Modeling and Simulation of the CEA-SMSG, which will be announced soon, and it is expected to be held in Tudela (Navarre), June/July 2017.

The group will celebrate its annual meeting, inside the 37th National Automatic Workshop (XXXVII Jornadas de Automática of the CEA-IFAC) 7-9 September 2016, Madrid (Spain).

The Group will collaborate with next edition of I3M (I3M2016) and will participate in next Eurosim conference (EUROSIM 2016):

Publications.

The journal of CEA, named RIAI (Revista Iberoamericana de Automática e Informática Industrial) and translated as "Latin American journal of Automation and Industrial Computing", was included in 2007 in the ISI Web of Knowledge of Thomson through its Science Citation Index Expanded, and since 2009 it is indexed in the Journal Citation Reports JCR of Thomson Reuters. It is the first journal of its issue in Spanish language included in that group, and constitutes the main reference for the national group as well as the ideal place for diffusion and collaboration with the Latin American community in this field (http://riai.isa.upv.es/)

Emilio Jiménez, *emilio.jimenez@unirioja.es*

LIOPHANT Simulation

General Information.

Liophant Simulation is a non-profit association born in order to be a trait-d'union among simulation developers and users. Liophant is devoted to promote and diffuse simulation techniques and methodologies. Liophant was originally established as Chapter of the Society for Computer Simulation International and it is currently actively cooperating with Eurosim and SCS.

→ *www.liophant.org*
✉ *info@liophant.org*

⌧ LIOPHANT Simulation, *c/o Agostino G. Bruzzone,*
DIME, University of Genoa, Savona Campus,
via Molinero 1, 17100 Savona (SV), Italy

General Activities.

Liophant promotes students exchange, sabbatical years, organization of International Conferences, courses and internships focused on M&S applications.

I3M, McLeod Workshops & User Group Meetings, WAMS

Liophant in actively involved in the I3M Mulficonference Organization. I3M runs since 2004 and is one of the major events in Europe. I3M activates often synergies with other organizations (e.g. NATO CAX Forum, Eurosim, Simulation Team and M&S Net) and represents an ideal framework for Project and User Group Meetings. In addition to thematic conference, the I3M McLeod Workshops provide an opportunity for establishing new co-operations and setting up joint proposals among international partners that are active in modeling and simulation. Moreover, Liophant supports WAMS - Workshop on Applied Modelling and Simulation. 2016 edition concentrates on Applications of Simulation and Computer Technologies

Coming Events

I3M 2017
International Multidisciplinary M&S Multi-Conference
September, 2017, Barcelona, Spain
www.liophant.org/conferences/

I3M includes 8 conferences addressing specific topics including Methodologies, Marine Domain, Logistics, Industrial Applications, Defense, Homeland Security, Medicine, Energy, Sustainability and Food. Indeed I3M provides valuable opportunities to the Authors to extend their scientific works for being published in several high quality International Journals (i.e. IJSPM, IJSCOM, IJMSSC, IJFE).

I3M: 14th Mediterranean Meeting
International Multidisciplinary Modelling & Simulation Multiconference

The I3M Multi conference is a consolidate International event devoted to promote M&S in Multidisciplinary Framework

I3M 2017
Barcelona
Spain

www.liophant.org/i3m

I3M A snapshot of the whole Event and Sponsors

Publications

Reports on activities are available online as well as details about SILENI - SImulation LEarning iNItiative. It promotes Seminars, Courses and Lectures on application of M&S with special attention to applications in Defense and Industry (*www.liophant.org/sileni/*).

Various

Liophant is actively involved in international activities for students such as ICAMES and SEE. In particular Simulation Exploration Experience (formerly Smackdown) is lead by NASA and aims to diffuse HLA technology. International Cultural and Academic Meeting of Engineering Students runs every year at the Bogazici University in Istanbul and focuses on a mix of cultural experiences and scientific achievements.

Figure 2. Liophanters at SEE and ICAMES

Marina Massei, *massei@itim.unige.it*

MIMOS – Italian Modelling and Simulation Association

General Information. MIMOS (Movimento Italiano Modellazione e Simulazione – Italian Modelling and Simulation Association) is the Italian association grouping companies, professionals, universities, and research institutions working in the field of modelling, simulation, virtual reality and 3D, with the aim of enhancing the culture of 'virtuality' in Italy, in every application area. MIMOS has submitted application for membership in **EUROSIM** (Observer Member).

→ *www.mimos.it*
✉ *roma@mimos.it*
✉ MIMOS – Movimento Italiano Modellazione
e Simulazione;
via Laurentina 760, 00143 Roma –
via Ugo Foscolo 4, 10126 Torino

MIMOS Network is composed by the main Italian Companies, Universities, Research Centre, Governmental Agency, Professionals, and Students dealing with Modelling & Simulation, Simulation & Training, and Virtual and Augmented Reality.

General Activities.

The main objectives of MIMOS are:

- Dissemination of the Simulation culture in Italy
- Experiences and competencies exchange
- Dialogue between University and Industry facilitation
- Wider Institutions involvement
- National and International agencies co-operation

The above objectives have been accomplished by

- MIMOS portal
- Monthly newsletter
- MIMOS Workshops
- MIMOS Award for best University and Doctorate thesis on simulation and virtual reality application
- MIMOS Academy

Past Events

In more than 15 years of activity MIMOS has organized several events around Italy on the full spread of simulation application, from Defence to Healthcare, from Industry to Cultural Heritage, from Food to Serious Games exploitation.

In the same time MIMOS has supported several other international events such as ITEC, MESAS; I3M, SIMUTOOLS and SIMULTECH.

Coming Events

The main objective of MIMOS is to create synergies among Industries, Academies and Institutional Agencies to foster new business opportunities going beyond the usual conference presentations. It can be done by means of specific multidisciplinary events where everyone can inform the audience, and stakeholders in particular, about its capabilities and projects in several fields of interest, allowing, at the same time, cross fertilization and networking possibilities.

MIMOS OPEN SIMULATION DAY

November 17th 2016, Rome, Italy

www.mimos.it

In this perspective, MIMOS will organize some Open Simulation Days to apply the above concept. He frist one of such event is planned for next 17th November. A dedicated newsletter will follow as soon as the organizational details have been defined.

The Open Simulation Days will be the approaching steps to the 15 Year Celebration of MIMOS on 2017 with a big event on Virtual Reality

MIMOS Award for Master and PhD Degrees on Simulation applications

MIMOS have launched the 7th edition of the Master and PhD Thesis on Simulation and Virtual Reality Award for Italian students degreed with a thesis on modelling, simulation, or virtual reality applications.

Aapplication from, contest rules and further information are published on
www.mimos.it/PremioMIMOS2016

MIMOS Academy

MIMOS Academy is a network of professional courses for the skill development on modelling, simulation and virtual reality fields, delivered by Universities and other Agencies

Paolo Proietti, *roma@mimos.it*

RNSS – Russian National Simulation Society

General Information.

RNSS - The Russian National Simulation Society was officially registered in Russian Federation on February 11, 2011. In February 2012 NSS has been accepted as an observer member of **EUROSIM**, and now it is full member.

→ *www.simulation.su*

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✉ RNSS / R. M. Yusupov,
St. Petersburg Institute of Informatics and
Automation RAS,
199178, St. Petersburg, 14th lin. V.O, 39

General Activities.

The society priority - to establish relations between experts in the field of Simulation in Russia, to define a circle of the organisations, institutes and the industrial enterprises using modelling as means of research and designing, to understand how much widely modelling and means of modelling are used in education.

We also want close and fruitful cooperation with foreign colleagues and we will be glad to any new contacts to the societies of Simulation promoting development of the theory and practice of Simulation.

Past Events

IMMOD-2015. Seventh National conference «Simulation. Theory and Practice' has taken place in Moscow, on October 21-23, 2015.

Conference was organized by V.A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences (Moscow), Institute for Informatics and Automation of the Russian Academy of Sciences, National Simulation Society, and JSC Shipbuilding and Shiprepair Technology Center (Saint-Petersburg). Sponsors of the conference were Russian Fund of Basic Researches, The AnyLogic Company, National Simulation Society and FGUP GosNIIAS (Moscow).

SCM MEMTS 2015. Third International conference «Simulation and complex modelling in marine engineering and marine transporting systems» took place in Saint Petersburg, on July, 01, 2015. Conference was the part of the International Maritime Defence Show (IMDS 2015 - www.navalshow.ru).

Organizers and founders of conference were Joint-Stock Corporation «Shipbuilding & Shiprepair Technology Center», Saint-Petersburg; St. Petersburg Institute for Informatics and Automation of Russian Academy of Sciences, Saint-Petersburg; Noncommercial Partnership «National Simulation Society», Saint Petersburg; United Kingdom Simulation Society (UKSIM); Latvian Simulation Society (LSM); International Mediterranean & Latin American Council of Simulation.

COMOD-2016. Annual International Scientific and Technical Conference «Computer Modeling 2016» took place on 5-6 July 2016 at St. Petersburg Peter the Great. Polytechnical University.

Coming Events

SCM MEMTS 2017. Fourth International Scientific-Practical Conference "Simulation and complex modelling in marine engineering and marine transporting systems" will take place on June 2017 in St.-Petersburg, Russia. Conference is an official event of International Maritime Defence Show - IMDS-2017.

IMMOD-2017. The Eight National Conference on Simulation and its Application in Science and Industry "Simulation. The Theory and Practice» will take place on October 2017 in St.-Petersburg, Russia.Within conference will be rewarding of the young scientists nominated on competition of a youth award of N.P. Buslenko founded by NP «NSS».

COMOD-2017. Annaul International Scientific and Technical Conference «Computer Modeling 2017» will be hold on July 2017 at the St. Petersburg Peter the Great Polytechnical University.

Publicatons.

The members of our society are usearly publish 7-8 monograph and textbooks yearly. This year they have published three textbooks by now.

Ivaskin Y.A. Multi-agent modeling in Simplex3: textbook. — M. : Binom.Laboratory of knwolege, 2016.—350 pp., ISBN 978-5-906828-72-9.

The textbook deals with theoretical and practical problems of multiagent modeling and simulation of different physical and social dynamical systems. Intelligent agents with own strategy of goal achievement and complex behavior and interaction with other agents and environment are considered. Different algorithms of agent behaviour, problems of identification and forecast of system's behavior are discussed and illustrated by models in Simplex3.

Kobelev N.B. Simulation Modeling of objects with haotic behavior: Textbook M.: KURS, INFRA-M, 2016. - 192 pp., ISBN 978-5-906818-20-1.

The textbook is devoted to problems of using simulation modeling for analysis and desingning large-scale systems with elements of haotic behaviour. Students of different specialities including «Business -Informatic» speciality may use it

Kolesov Y.B., Senichenkov Y.B. Object-Oriented modeling in Rand Model Designer 7: texbook —
M.: Prospect, 2016. — 256 pp.
ISBN 978-5-392-22360-2.

This is a practical guidance for modeling and simulation of event-driven complex dynamical systems in ***Rand Model Designer 7 (www.mvstudium.com)***. Rand Model Designer has object-oriented modeling language based on «standard de facto», that is Unified Modeling Language (UML). By using simple and intuitive examples, authers demonstrates different modern technologies of modeling multi-component system: «causal», «physical», «agent-based» approachers.

International co-operation.

International co-operation is one of planning activities of our society. Systematically we are going to joint conferences, scientific researchs, texbooks, and educational programs. This activity of Russian societies and researhers supports by goventment programs and grants (see *http://www.rfbr.ru/rffi/ru/active_contests*).

Figure 4. *COMOD's cultural program*

Let us consider annual conference COMOD in St. Petersburg as an example of international co-operation. Our first EUROSIM's guest of honour were Esko Juuso and Borut Zupančič. Later Alfonso Urquía and Carla Martín-Villalba visited our conference. The best papers of COMOD are published by Journals co-operated with conference.

Co-operation with Slovenia and Spain makes it possible to write proposal «Innovative Learning Environment, Modeling and Simulation in Engineering Education / ILEMOS» for ERASMUS Program and get money for it realization.

Now we are going to write joint book for Russian publishing house with our Spanish colleagues.

M. Yusupov, *yusupov@iias.spb.su*

LSS – Latvian Simulation Society

General Information. The Latvian Simulation Society (LSS) has been founded in 1990 as the first professional simulation organisation in the field of Modelling and simulation in the post-Soviet area. Its members represent the main simulation centres in Latvia, including both academic and industrial sectors.

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🖂 LSS / Yuri Merkuryev, Dept. of Modelling
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General Activities. The primary goal of the Latvian Simulation Society is to provide a platform for local modelling and simulation community to exchange expertise and knowledge of this domain. Each year LSS organises several meetings, seminars and workshops to present modern and advanced approaches to Latvian simulation experts. Furthermore Society helps to promote young researchers and PhD students of Latvian universities to successfully finish their education and to start successful career.

Past Events. The latest international event, where the Latvian Simulation Society has been actively involved, was the 2nd International Conference on Systems Informatics, Modelling and Simulation, SIMS2016, that took place in Riga on June 1-3, 2016. The conference was organized in cooperation with the IEEE Compter Society and IEEE Latvia Section. Its web site is located at http://sims2016.info.

Publications. In the near future the Latvian Simulation Society plans to issue own scientific journal in the field of simulation and modelling to promote scientific work of the Society members. This journal will provide an additional place for local scientists to publish their researches. It is planned that journal publications will be indexed in popular citation databases.

Various. The Latvian Simulation Society is actively working towards wide use of simulation and modelling in local industry and education. The Society widely involves in supplement of education of Latvian young researchers in the field of simulation and modelling.

Yuri Merkuryev , *merkur@itl.rtu.lv*

SIMS – Scandinavian Simulation Society

SIMS

General Information. SIMS is the *Scandinavian Simulation Society* with members from the five Nordic countries Denmark, Finland, Iceland, Norway and Sweden. The SIMS history goes back to 1959. SIMS practical matters are taken care of by the SIMS board consisting of two representatives from each Nordic country.

SIMS Structure. SIMS is organised as federation of regional societDjouaniies. There are

- FinSim (*Finnish Simulation Forum*),
- DKSIM (*Dansk Simuleringsforening*) and
- NFA (*Norsk Forening for Automatisering*).

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Past Events

OpenModelica Workshop

Annual OpenModelica Workshop 2016, February, Linköping, Sweden. *https://www.openmodelica.org/*

Modeling of Sustainable Economics Systems workshop (MOSES 2016), 16-20 May 2016, Linköping, Sweden. The workshop aims at defining new research directions for modeling and simulation-based explorations of viable transitions into a sustainable future, by bringing together world experts from many sustainability/related disciplines.

https://www.openmodelica.org/events/moses-2016.

Process Control Workshop

20th Nordic Process Control Workshop, 25-26 August 2016, Sigtuna, Sweden. Programme includes recent advances and future trends and cutting-edge developments in the field of process control, simulation and optimization. *https://www.kth.se/en/ees/omskolan/seminarium*

Coming Events

EUROSIM 2016 CONGRESS
9th Eurosim Congress on Modelling and Simulation
12-16 September 2016, Oulu, Finland
eurosim2016.automaatioseura.fi

The programme has a multi-conference structure with several special topics related to methodologies and application areas. The programme includes invited talks, parallel, special and poster sessions, exhibition and versatile technical and social tours. The 57th International Conference of Scandinavian Simulation Society SIMS 2016 is a part of EUROSIM 2016. Organised by SIMS, Finnish Society of Automation and University of Oulu. Technical sponsors IEEE and IFAC.

AUTOMATION SUMMIT
October 4, 2016, Gothenburg, Sweden
www.automationsummit.se

Focus on Automation solutions. Organised by Automation Region (SIMS) and Svenska Mässan.

AUTOMATION XXII
March 2017, Vaasa, Finland
www.automaatioseura.com

Organised by Finnish Society of Automation. Programme includes keynote, theme and regular presentations, as well as practical demonstrations and special sessions on modelling and simulation.

SIMS 2017
58th International Conference of Scandinavian Simulation Society
October 2017, Reykjavik, Iceland
www.scansims.org

Esko Juuso, *esko.juuso@oulu.fi*

SLOSIM – Slovenian Society for Simulation and Modelling

General Information. SLOSIM - *Slovenian Society for Simulation and Modelling* was established in 1994 and became the full member of **EUROSIM** in 1996. Currently it has 90 members from Slovenian universities, institutes, and industry. It promotes modelling and simulation approaches to problem solving in industrial as well as in academic environments by establishing communication and cooperation among corresponding teams.

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🖂 SLOSIM / Vito Logar, Faculty of Electrical
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General Activities.

SLOSIM society organizes various activities and events for its members as well as for broader audience. Among them are invited lectures of domestic and foreign researchers, active participation on modelling and simulation conferences including the cooperation in reviewing process, organization of special sessions and professional excursions.

Past Events.

Last year SLOSIM organized two modeling and simulation oriented sessions on the 24th ERK conference which took place from September 21st to 23rd, 2015 in Portorož, Slovenia. Seventeen papers were presented, while nine of them were contributed by the society members. The society also took an active part in some other sessions.

In the past year SLOSIM organized six professional lectures. Society members also participated in the traditional MathMod conference held in Vienna from Feburary 18th to 20th, 2015.

Furthermore, SLOSIM organized an educational excursion to Simulation center, University of Maribor, Faculty of medicine, which was among other society members also attended by students.

Slosim society is a co-organizer of an annual event – Automation Days and Lego Masters tournament organized at the Faculty of Electrical Engineering, University of Ljubljana every spring. The event is primarily intended for secondary schools and undergraduate students, allowing them to establish contacts with different potential employers in the field of automation. The Lego Masters tournament is a competition in autonomous mobile system design, where each team builds and programs their system, which is capable of solving a given task autonomously. Each year approximately 15 student and 20 secondary school teams attend the tournament.

A Slosim executive board meeting took place at the Faculty of Electrical Engineering, University of Ljubljana on July 29th, 2015, analyzing some past activities and future plans.

Coming Events.

In the following year some important events are schedulled. First is the EUROSIM 2016 congress in September where the SLOSIM members will participate with regular contributions and a key-note lecture. The next event will be the annual ERK 2016 conference, with active role of the society members. The next event will be general assembly of Slosim presumably in November 2016. Furthermore, society members will be co-organizing the next year Automation Days 2017. Slosim will also actively participate in the organization of the IEEE EAIS 2017 conference (IEEE International Conference on Evolving and Adaptive Intelligent Systems)

IEEE EAIS 2017

IEEE International Conference on Evolving and Adaptive Intelligent Systems

May 31st – June 2nd, 2016, Ljubljana, Slovenia

http://msc.fe.uni-lj.si/EAIS2017

Publications.

Slosim society is invited to organise a special issue of SNE (Simulation Notes Europe) on Modelling and Simulation for Control, planned to be issued in December 2016.

Vito Logar, *vito.logar@fe.uni-lj.si*

DBSS – Dutch Benelux Simulation Society

General Information. The Dutch Benelux Simulation Society (DBSS) was founded in July 1986 in order to create an organisation of simulation professionals within the Dutch language area. DBSS has actively promoted creation of similar organisations in other language areas. DBSS is a member of **EUROSIM** and works in close co-operation with its members and with affiliated societies.

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Mekelweg 4, 2628 CD Delft, The Netherlands

General Activities. The DBSS society have different activities throughout the year such as expert seminars, masterclasses in collaboration with Universities in the Benelux region and abroad, courses and industry and academic internships for students that want to get into the realm of simulation.

Coming Events

30TH ANNIVERSSARY SYMPOSIUM OF THE DBSS
The Influence and Use of Simulation
in Transport Industries
November 18, 2016, TUDElft, Delft, The Netherlands
www.DutchBSS.org

The next 18th of November the DBSS will celebrate the 30th anniverssary of its foundation. For such an important date a symposium will be held in TUDelft with the participation of Msc and PhD students, industry representatives and academics involved in the practice of simulation.

Publications. Some of our members recently published material that can be of interest for any practitioner:

-Dr. Mujica Mota recently published his book :”Applied Simulation and Optimization: In Logistics, Industrial and Aeronautical Practice”,ISBN 978-3-319-15032-1,Springer Book. This book deals with the combination of simulation with optimization techniques, the focus is put on applications of those techniques.

- Dr.Mujica Mota., Dr. C.Zuniga, MSc. P.Scala, Msc G. Boosten in June 2016 presented the study they made of the Mexican airport using simulation techniques: “IMPACT ANALYSIS OF REGULAR OPS OF A380 IN MEXICO CITY AIRPORT”, it was presented during the ATRS event in Rhodes, Greece.

- Dr. Mujica Mota and MSc Paolo Scala presented in Japan the methodology they developed for assessing the performance and optimization of Airport Systems: ”Methodology for Assessing and Optimizing Operation Performance in Airport Systems”, it was presented during the EIWAC in Tokyo, Japan.

Various. The steering committee of the DBSS has been renewed, and also a new webpage is online:

- DR. A.W. HEEMINK, TUDELFT, Chair
- Dr. MIGUEL MUJICA MOTA, Amsterdam Univ. of Applied Sciences---Vice-Chair, Treasurer
- MSc. PAOLO SCALA, Amsterdam University of Applied Sciences--- Secretary
- Dr. H. X. LIN, Leiden University ---Industry contact

Miguel Mujica Mota, *m.mujica.mota@hva.nl*

Albanian Simulation Society

At department of Statistics and Applied Informatics, Faculty of Economy, University of Tirana, Prof. Dr. Kozeta Sevrani at present is setting up an Albanian Simulation Society.

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University of Tirana, Faculty of Economy
rr. Elbasanit, Tirana 355 Albania

The society – constitution and bylaws are at work - will be involved in different international and local simulation projects, and will be engaged in the organisation of the conference series ISTI – Information Systems and Technology, which has a strong simulation track.

ISTI 2016
7th Information Systems and Technology Innovations
June 15 – 17, Tirana, Albania
http://www.conference.ijsint.org/

The scope of this conference is to bring important results regarding planning, analysis, design, construction, modification, implementation, utilization, evaluation, and management of information systems that use information technology to support and coordinate activities.

UKSIM - United Kingdom Simulation Society

General Information. The UK Simulation Society is very active in organizing conferences, meetings and workshops. UKSim holds its annual conference in the March-April period. In recent years the conference has always been held at Emmanuel College, Cambridge. The Asia Modelling and Simulation Section (AMSS) of UKSim holds 4-5 conferences per year including the EMS (European Modelling Symposium), an event mainly aimed at young researchers, organized each year by UKSim in different European cities.

Membership of the UK Simulation Society is free to participants of any of our conferences and thier co-authors.

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General Activities.

Members of the UKSim Board met in Cambridge at Emmanuel College during the period of their annual conference to reflect on past events and plan for new ones. Both past events and upcoming conferences are briefly presented in the following sections. For further information please visit the Society's website (*www.uksim.info*)

Past Events

UKSim's main activities in 2016 focused on:

i) its annual conference UKSim2016 in Cambridge, 6-8 April (*http://uksim.info/uksim2016/uksim2016.htm*),

ii) journal IJSSST (website *http://ijssst.info*),

and through its now well established links with the Asia modelling and simulation community (AMS) has co-organised several events including:

iii) The First International Conference on Micro and Nano Technologies Modelling and Simulation (MNTMSIM 2016) 1-3 March, Kuala Lumpur, Malaysia (*http://uksim.info/mntmsim2016/mntmsim2016.htm*),

iv) the IEEE 7th International Conference on Intelligent Systems Modelling and Simulation (ISMS 2016) 25-27 January, Bangkok, Thailand (website *http://uksim.info/isms2016/isms2016.htm*),

v) the second Interantional Conference on Systems Informatics, Modelling and Simulation (SIMS 2016) 1-3 June, Riga, Latvia (website *http://uksim.info/isms2016/isms2016.htm*)

vi) the 8th International Conference on Computational Intelligence, Communication Systems and Networks (CICSyN 2016) 25-27 July, Kuala Lumpur, Malaysia.

Coming Events

EMS 2016

European Modelling Symposium

October 24 – 26 (TBC), 2016, Pisa, Italy

www.uksim.info/ems2016/ems2016.htm

ASIA MULTI CONFERNECE

AMS 2016/ AIMS 2016/ CimSim 2016

Asia Modelling Symposium/ Artificial Intelligence Modelling and Simulation/Computational Intelligence Modelling and Simulation

December 5 – 7, 2016, Kota Kinabalu, Sabah, Malaysia

www.uksim.info/ams2016/ams2016.htm

www.uksim.info/aims2016/aims2016.htm

www.uksim.info/cimsim2016/cimsim2016.htm

Publications.

UKSim regurlary publishes the International Journal of Simulation Systems Science and Technology (IJSSST). The journal comprises of special issues on selected topics as well as extended papers from past conferences. Further information and submission guidelines may be found on the journal's website (*http://ijssst.info*).

Various

The UKSim 2016 conference was very well attended by delegates from many countries. The geographic distribution was as follows, with a total of 60 papers from 27 countries: United Kingdom-8. Saudi Arabia-7. Egypt, Germany: 4 each. Iran, Kuwait, Turkey, UAE: 3 each. China, India, Ireland, Lebanon, Norway, Russia: 2 each. Austria, Brazil, Denmark, Finland, Iraq, Italy, Jordan, Malaysia, Nigeria, Pakistan, Slovakia, Thailand, USA: 1 each.

UKSim 2016 Day 1: Delegates attending the conference at Emmanuel College, Cambridge.

The conference, as usual, received technical co-sponsorship by the IEEE: UK & RI chapters (Region 8 and Region 10) for supporting the event and UKSim activities in general.

On each day the conference hosted a well-established keynote speaker; on day 1, Prof Frank Wang: “Computing for Big Science: Gravitational Wave Detection”. On day 2, Prof Yong Meng Teo: “Modelling & Formalizing Weak Emergence”. On day 3 Prof Herman Hessling: “Analysing Large-Scale Data”.

The conference presentations and proceedings were organized according to the following tracks:

- Image, speech and signal processing.
- Energy, power, transport, logistics, harbour, shipping and marine simulation.
- Mobile/Ad hoc wireless networks, mobicast, sensor placement.
- Circuits, sensors and devices.
- Bioinformatics and bioengineering.
- Intelligent systems and applications.
- Performance engineering of computer and communication systems.
- Robotics, cybernetics, engineering, manufacturing and control.
- Internet modelling, semantic web and ontologies.
- Games, VR and visualization.
- Emergent technologies.
- Industry, business, management, human
- factors and social issues.

Alessandra Orsoni, *A.Orsoni@kingston.ac.uk*

KA-SIM Kosovo Simulation Society

KA-SIM

General Information. Kosova Association for Modeling and Simulation (KA – SIM, founded in 2009), is part of Kosova Association of Control, Automation and Systems Engineering (KA – CASE). KA – CASE was registered in 2006 as non Profit Organization and since 2009 is National Member of IFAC – International Federation of Automatic Control. KA-SIM joined EUROSIM as Observer Member in 2011, and has applied for full membership.

General Activities KA-SIM is organizing the international conference series International Conference in Business, Technology and Innovation, in November, in Durrhes, Albania, IFAC Simulation workshops in Pristina, and conferences in Tirana in collaboration with Univ. Tirana. Conference contributions are published in indexed proceedings, and postconference publication in scientific journals, e.g. SNE.

Coming Events

ICBTI 2016

5th International Conference for Business, Technology and Innovation

November 4 – 5, 2016, Durres. Albania

conferences.ubt-uni.net/2016/

It is our pleasure to invite to the 5th International Conference for Business, Technology and Innovation (ICBTI 2016) which will be in Durres, Albania, on 4-5 November, organized by UBT in collaboration with University of Vlora and University of Tirana.

Furthermore, KAS-SIM is co-organising the IFX TECS conference in Pristina / Tirana:

TECIS 2016

IFAC International Conference on International Stability, Technology and Culture

October 26-28, Durres. Albania

tecis2016.ubt-uni.net/

E. Hajrizi, *ehajrizi@ubt-uni.net*

EUROSIM 2016

9th EUROSIM Congress on Modelling and Simulation

City of Oulu, Finland, September 12 – 16, 2016

UNIVERSITY of OULU

EUROSIM Congresses are the most important modelling and simulation events in Europe. For EUROSIM 2016, we are soliciting original submissions describing novel research and developments in the following (and related) areas of interest: Continuous, discrete (event) and hybrid modelling, simulation, identification and optimization approaches. Two basic contribution motivations are expected: M&S Methods and Technologies and M&S Applications. Contributions from both technical and non-technical areas are welcome.

Congress Topics The EUROSIM 2016 Congress will include invited talks, parallel, special and poster sessions, exhibition and versatile technical and social tours. The Congress topics of interest include, but are not limited to:

Intelligent Systems and Applications
Hybrid and Soft Computing
Data & Semantic Mining
Neural Networks, Fuzzy Systems & Evolutionary Computation
Image, Speech & Signal Processing
Systems Intelligence and Intelligence Systems
Autonomous Systems
Energy and Power Systems
Mining and Metal Industry
Forest Industry
Buildings and Construction
Communication Systems
Circuits, Sensors and Devices
Security Modelling and Simulation
Bioinformatics, Medicine, Pharmacy and Bioengineering
Water and Wastewater Treatment, Sludge Management and Biogas Production
Condition monitoring, Mechatronics and maintenance
Automotive applications
e-Science and e-Systems
Industry, Business, Management, Human Factors and Social Issues
Virtual Reality, Visualization, Computer Art and Games
Internet Modelling, Semantic Web and Ontologies
Computational Finance & Economics
Simulation Methodologies and Tools
Parallel and Distributed Architectures and Systems
Operations Research
Discrete Event Systems
Manufacturing and Workflows
Adaptive Dynamic Programming and Reinforcement Learning
Mobile/Ad hoc wireless networks, mobicast, sensor placement, target tracking
Control of Intelligent Systems
Robotics, Cybernetics, Control Engineering, & Manufacturing
Transport, Logistics, Harbour, Shipping and Marine Simulation

Congress Venue / Social Events The Congress will be held in the City of Oulu, Capital of Northern Scandinavia. The main venue and the exhibition site is the Oulu City Theatre in the city centre. Pre and Post Congress Tours include Arctic Circle, Santa Claus visits and hiking on the unique routes in Oulanka National Park.

Congress Team: The Congress is organised by SIMS - Scandinavian Simulation Society, FinSim - Finnish Simulation Forum, Finnish Society of Automation, and University of Oulu.
Esko Juuso EUROSIM President, Erik Dahlquist SIMS President, Kauko Leiviskä EUROSIM 2016 Chair

Info: eurosim2016.automaatioseura.fi, office@automaatioseura.fi