Automated Conceptual Design of Mechatronic Systems

Since many years the need for controlled electro-mechanical systems with more flexibility, higher performance and higher reliability is increasing. It was recognised that these systems require coherent design activities of several disciplines. These developments led to the introduction of mechatronics. Especially in the conceptual design stage of electro-mechanical systems, a mechatronic design approach can be applied successfully. Automated design support for this approach has been developed on basis of an existing design method for a large class of mechatronic systems. This method determines the functional interaction between different domain specific subsystems. Automated model reduction and model simplification algorithms are applied to convert the system model of a proposed design to a standard form required by this method. The functional interaction is implemented by means of constraints. Dependencies between the subsystems can be visualised in several ways, using constraint satisfaction techniques. The resulting support puts emphasis on the interpretation of the results instead of the application of procedures. It quickly provides insight in the design problem and estimates feasible goals and required design efforts at an early stage.

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1 Introduction

In this research, a particular class of controlled electro-mechanical systems is considered, as depicted in figure 1. A path generator indicates the trajectory or the point to point motion of the end-effector. The actuator drives the end-effector through a transmission. The controller processes the information from the (position) sensors, that are generally located at the actuator or the end-effector, such that the desired motion of the end-effector is obtained.

This paper discusses the development of computer-based support, that assists in finding realisations of the subsystems of figure 1, using a mechatronic design approach; i.e. an approach where the system is designed as a whole instead of subsequent design of domain specific subsystems.

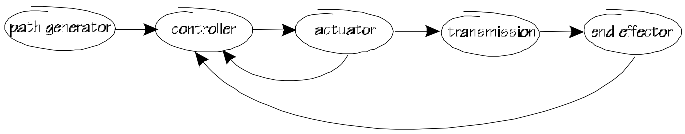

Fig. 1. Controlled electro-mechanical system

The mechatronic design environment **20-sim**, which now incorporates what was formerly known as MAX [5], supports conceptual mechatronic design from a modelling perspective. Within this environment model simplification and reduction algorithms have been implemented, together with an automated design method proposed by Groenhuis [3].

2 Conceptual Design

In the conceptual design stage “a rough idea is developed of how the project will function and what it will look like” [9]. For mechatronic systems this "rough idea" is expressed as a somewhat detailed version of figure 1. The conceptual design stage is an early stage in the design process, that is well suited to determine the functional interaction between different subsystems.

Design decisions bring a system from the initial design state, through several other design states, to the goal of the design process. Both the initial state and the design goal are generally described in vague terms, that are not definitive. Therefore during conceptual design of mechatronic systems the explorational mode is dominant. In this mode "activities are not really planned, but initiated instantaneously, on the basis of local information about the state of the design process" [5].

Controllers developed during the conceptual design stage, are designed on basis of a model of the system to be controlled. These models should have the following characteristics [8]:

- simple, low order;
- small number of parameters,

such that the model of the controlled-system provides:

- reliable estimates of dominant dynamic behaviour;
- reliable estimates of attainable bandwidth of controlled system.

Models with these characteristics will provide an easy to understand, sufficiently accurate and fastly available framework for continuation of the design.

As the mechatronic design process is complex, tools are needed to support the designer. Specific problems that occur during conceptual design of mechatronic systems and that should be addressed by design tools are:

– functional interaction between domain specific subsystems;
– consequences of solutions and alternative solutions in other do-mains;
– prediction of guaranteed performance of a particular solution.

For fourth-order electro-mechanical system models Groenhuis [4;7] developed a design method for the minimisation of the positional error after a change in the input function (point to point motion) when using a PD-controller. This design method takes into account the interaction between the design of the controller, the electro-mechanical plant and the determination of the input function of the path generator. It is a powerful method, that can be applied in several ways, as it advocates a true mechatronic design approach [3].

In the conceptual design stage one generally comes up with a model with too many parameters and too little knowledge to estimate appropriate parameter values. Model simplification and reduction techniques can be applied to reduce the number of parameters and the model order. Subsequently, the Groenhuis design method can be used to find parameter values for the controlled system.
To allow fast and correct model reduction, computer-based support has been developed that can reduce models of mechatronic plants to fourth-order models. The outcome is a model where the representations of the sub-systems are generally reduced to a mass for the end-effector, a compliance for the transmission and a mass with an applied force for the actuator (figure 7). The parameters in this reduced order model are a combination of the parameters of the original model. The algorithm consists of two separate steps, a simplification and a reduction step, that are applied iteratively.

3 Automated model simplification

The simplification algorithm minimises the number of elements in a model by eliminating transformations and by joining elements. It is assumed that the user is familiar with bond graphs. Bond graph models are being used, because simplification rules have been formally described and are applicable in any energetic domain [1]. A short list of common simplifica-tion rules is given below. The **20-sim** procedure implementing the rule is indicated; the procedure returns *true* whenever it actually has performed a simplification.

– junctions can eliminate themselves if energy flow is not branched and can join themselves if there is exactly one power bond between identical junctions (*simplifyJunctions*);
– a junction can join two similar single-port elements connected to itself (*simplifyElements*);
– two transmissions (transformer/gyrator) connected by one bond can be composed into one transmission (*simplifyTransmissions*).

The parameter of a simplified element is a combination of the parameters of the elements it is composed of. All elements have a variable that contains the transformation factor (*c*) of the parameter, such that a controller developed for the simplified model can immediately be connected to the original non-simplified model; i.e. input and output variables of the original plant model are preserved.

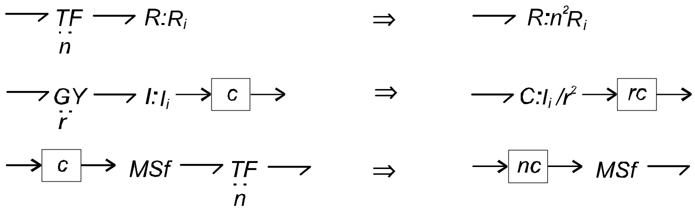

Fig. 2. Composition of a transmission and an element

A transmission can be eliminated from the model by joining it with a single-port element, figure 2. The parameter value and the type of element may change by this simplification.

Transmissions can be propagated over junctions, as shown in figure 3 (*propagateTransmissions)*. Propagation of transmission and composing of transmissions will lead to a model without transmissions and dependent elements, if the model does not contain power loops.

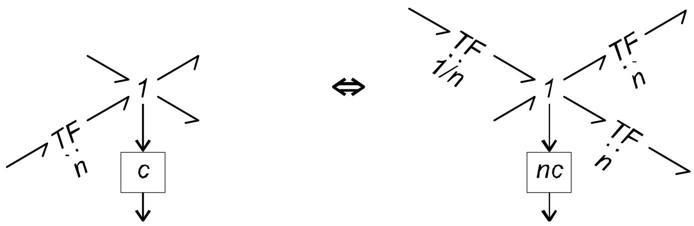

Fig. 3. Propagation of a transformer

As design specifications are generally given in terms of the end-effector, it is convenient to use the co-ordinates of the end-effector as a reference. Transmissions are propagated away from this reference point, as shown in figure 4, using an existing propagation machine [2].

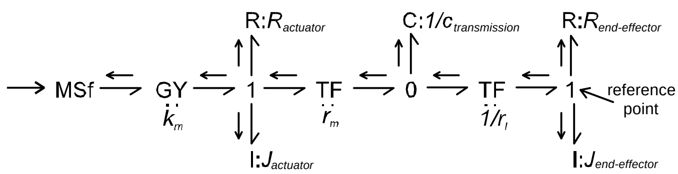

Fig. 4. Determination of direction of propagation

The simplification algorithm for a bond graph model is:

```
simplify
    begin
    determineDirection.
    repeat  [    (simplifyJunctions)   or
                 (simplifyElements)    or
                 (simplifyTransmissions) or
                 (propagateTransmissions)
            ]     whileTrue.
    end.
```

Application of the simplification algorithm to the model of figure 4 results in the bond graph model of figure 5, where the transformation factors are omitted. It can be seen that the complexity of the structure decreases, while the complexity of the parameter increases.

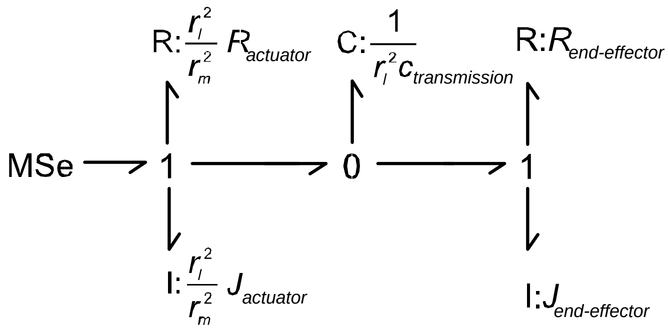

Fig. 5. Simplified bond graph model (without transformation factors)

4 Automated model reduction

Reduction algorithms reduce the order of the system to four, such that only the lowest (undamped) natural frequency is modelled. For two common types of model structures an order-reduction algorithm has been developed: the *chain* structure (figure 6) and the *fork* structure [10]. The fork structure consists of three chain structures connected by a 0-junction. Reduction of fork structures is similar to reduction of chain structures, therefore the only the latter is described. Reduction is applied to chains by dividing the follower part into two sub-chains that are equally stiff. The masses in both sub-chains then reflect the mass-ratio of the system. A simple search algorithm is used for this purpose (*splitChain)*. The two sub-chains are reduced to second order representations and finally combined to a fourth-order model. Three different reduction techniques for sub-chains (*reduceSubChains*) will be discussed, that assume the lowest natural frequency of the model to be dominant, i.e. other natural frequencies are at least twice as large [10].

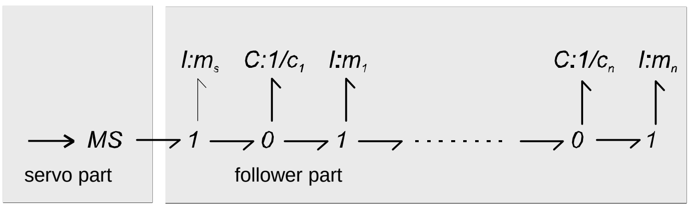

Fig. 6. Chain structure

Intuitive reduction method

Very small masses and compliances can be removed from the model as they do not contribute to the lowest natural frequency. For fourth-order chain structures it has been investigated when a compliance or a mass can be considered very small. The natural frequencies of both non-reduced systems and reduced systems have been calculated and compared. Where the difference between these frequencies was lower than 4%, the reduction was assumed valid. It was concluded that for a fourth-order sub-chain a mass or compliance can be removed if it is approximately 15 times as large as another mass or compliance. When the order of the chain structure increases, the relative difference in compliance and mass must be larger.

Rayleigh's reduction method

According to Rayleigh's method [6], the natural frequency can be approximated by:

$$w = \sqrt{\frac{c_c}{m_{eq}}}$$

with the overall stiffness c_c, equal to the overall stiffness of the non-reduced model and m_{eq} the equivalent mass:

$$c_c = \left(\sum_{i=1}^{n} \frac{1}{c_i} \right)^{-1} \qquad m_{eq} = \sum_{i=1}^{n} \left[m_i \left(\sum_{j=1}^{i} \frac{c_c}{c_j} \right)^2 \right]$$

Errors in the approximated lowest natural frequencies are less than 4% if the sum of the mass contributions to m_{eq} of the intermediate masses does not exceed 25% of the end-mass, on condition that the sum of the intermediate masses is less than three times the end-mass. These conditions implicitly assure that the lowest natural frequency is dominant.

Numerical reduction method

Instead of approximating the lowest natural frequency it can be calculated exactly. Once the overall stiffness c_c is determined the equivalent mass m_{eq} can be calculated. No approximation error will be made, but the same restrictions as in Rayleigh's method exist to ensure the lowest natural frequency to be dominant.

The reduction algorithm for a bond graph chain structure is:

```
reduceChain
  begin
    removeDamping.
    splitChain.
    reduceSubChains.
    combineSubChains.
  end.
```

In either of the reduction methods the total mass of the reduced model is usually lower than the total mass of the original model. The servo parameters in the Groenhuis design tool are made proportional to the total of the mass of the non-reduced model, to allow to use Groenhuis' results to the original model [10].

5 Automated Groenhuis design method

Constraints are used to represent the dependencies between variables, design parameters and diagrams. If a constraint variable changes, other variables are immediately updated by constraint satisfaction techniques, such that the relations defined by Groenhuis are always valid [3].

If, for example, the motor mass is increased by dragging the slider, the icon of the motor mass in figure 7 will also increase, the natural frequency will decrease and the error will increase for a given reference function. These changes are represented numerically and graphically in Bode diagrams and a time response.

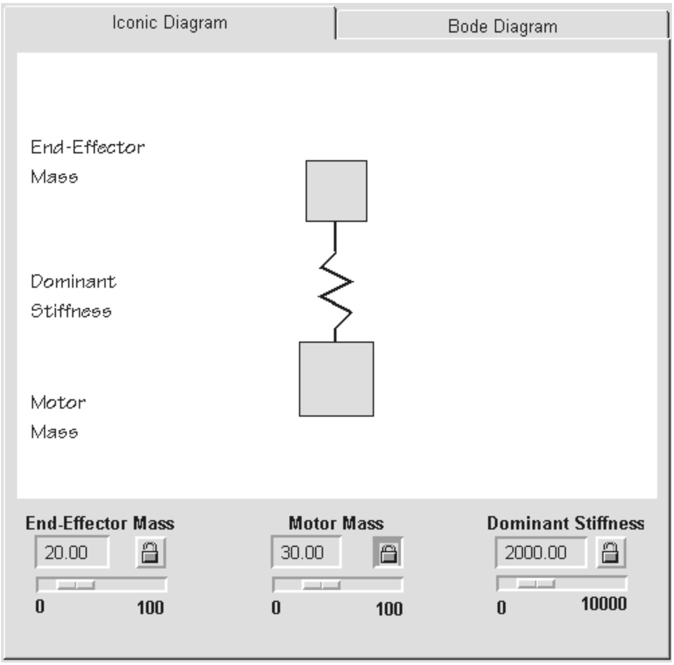

Fig. 7. Iconic diagram with variables

Section 2 identified specific problems, which occur during conceptual design of mechatronic systems, that are addressed by this design tool. Functional interaction between domain specific subsystems and conse-quences of solutions and alternative solutions in other domains, are dealt with by the machinery of the Groenhuis design tool. The computer support provides the designer with transparency in the relations between the design parameters; sliders and locks can be used to (not) change the parameters. If one parameter is changed, others will change automatical-ly according the underlying constraints, so the designer can evaluate the interaction between different subsystems in an explorational design mode. Local design goals can easily be changed, while information about the consequences of this change is readily available.

6 Conclusions

Interactive computer-based support is developed for conceptual design of mechatronic systems, using constraints, such that it:

- supports the complete conceptual design stage for mechatronic systems;
- supplies design automatons for fast and correct model simplification and order reduction;
- provides transparency in the relations between different design parameters;
- supports application of the Groenhuis design tool in an explorational design mode;
- puts emphasis on the interpretation of the results instead of the application of procedures.

The principal benefits are that it quickly provides insight in the design problem and that feasible goals and required design efforts can be estimated at an early stage.

References

1. Breedveld, P.C. and J. van Amerongen, “Dynamische Systemen: modelvorming en simulatie met bondgrafen (in Dutch)”, Dictaat Open University, Heerlen, The Netherlands, ISBN 90-358-1303-0, 1994.
2. Breunese, A.P.J., “Automated Support in Mechatronic Systems Modeling”, PhD thesis, University of Twente, Enschede, The Netherlands, 1996.
3. Coelingh, H.J., T.J.A. de Vries and J. van Amerongen, “Automated Conceptual Design of Controllers for Mechatronic Systems”, Lancaster International Workshop on Engineering Design CACD'97, Lancaster, U.K, 1997.
4. Coelingh, H.J., T.J.A. de Vries, P.B.T. van Lochem and J. van Amerongen, “Automated Optimal Controller Design in Mechatronics”, Proc. IFAC Symposium on CACSD'97, Gent, Belgium, p.157-162, 1997.
5. De Vries, T.J.A., “Conceptual design of controlled electro-mechanical systems”, PhD thesis, University of Twente, Enschede, The Netherlands, 1994.
6. Den Hartog, J.P., “Mechanical vibrations”, McGraw-Hill, New York, U.S.A., 1956.
7. Groenhuis, H., “A Design Tool for Electromechanical Servo Systems”, PhD thesis, University of Twente, Enschede, The Netherlands, 1991.
8. Oelen, W., “Modelling as a tool for design of mechatronic systems”, PhD thesis, University of Twente, Enschede, The Netherlands, 1995.
9. Ullman, D.G., The mechanical design process, McGraw-Hill, New York, U.S.A., 1992.
10. Van Lochem, P.B.T., “Towards automated mechatronic system design”, MSc thesis, University of Twente, Enschede, The Netherlands, 1997.