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Automated Performance Assessment of Mechatronic Motion Systems During the Conceptual Design Stage

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Abstract: In the conceptual design stage of electro-mechanical systems, a mechatronic design approach can be applied successfully. Automated mechatronic design support 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 into the standard form required by this method. The results of this design method, feasible parameter values for the proposed design, can be assigned to the components in the model in an interactive way. The developed design 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.

1. Introduction

Since many years the need for controlled electro-mechanical systems with more flexibility, higher performance and higher reliability is increasing. It was recognized that these systems require coherent design activities of several disciplines. These developments led to the introduction of mechatronics. 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 flexible 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.

Early in the design process the designer has to find possible realizations 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.

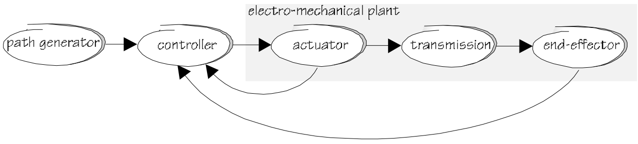


Figure 1: A class of controlled electro-mechanical systems

This mechatronic design process is complex, therefore tools are needed to support the designer. Specific problems that occur during conceptual design of mechatronic systems are (Coelingh et al, 1997a):

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

This paper will describe a computer-based design tool for conceptual design of mechatronic motion systems that addresses these problems and that will give a feasible design proposal that is likely to meet the desired performance.

2. Conceptual Design

For the development of the design tool, knowledge is required about the design activities during the conceptual design stage. Ullman (1992) states that in this stage "a rough idea is developed of how the project will function and what it will look like". It is an early stage in the design process, that is well suited to establish 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" (De Vries, 1994). A design tool should allow the designer to work in an explorational way.

A typical result of the first steps in the conceptual design of an A0-plotter may be the sketch of Figure 2. The plotter has to move a pen (1) across a sheet of paper that is placed in the x-y-plane. The pen moves across a shuttle (2) in the y-direction. The shuttle can move in the x-direction, supported by two guidances (3 and $3^{*)}$ and driven by a motor (12) through a transmission (8, 9 and 10), another transmission (6 and 6^*) and four timing belts (4, 4^*, 5 and 5^*). The motion of interest is the motion in the x-direction. The technical specification (task) for this motion is that the pen should be able to move over a distance h_m = 0.5 [m] within the motion time t_m = 1 [s]. The maximum positional error after the motion time is u_0 = 0.1 [mm].

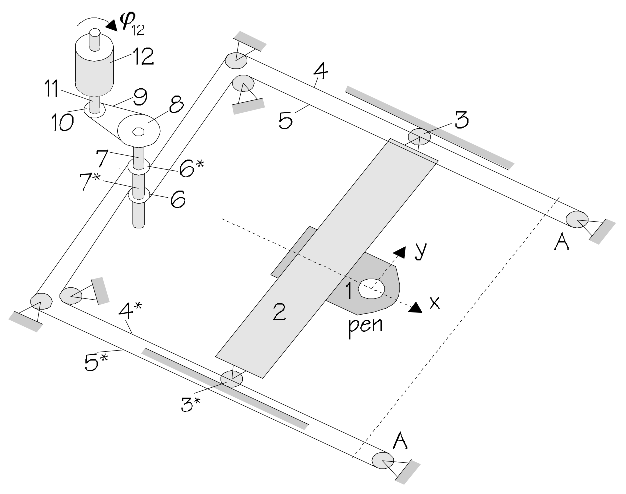


Figure 2: Sketch of the A0-plotter to be designed

To verify whether this is a feasible specification, an indication of the dynamic behavior of the controlled system is required. Controllers are designed on basis of a model of the plant. In the conceptual design stage these models should have the following characteristics (Oelen, 1995):

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

such that the model of the controlled system provides:

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

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

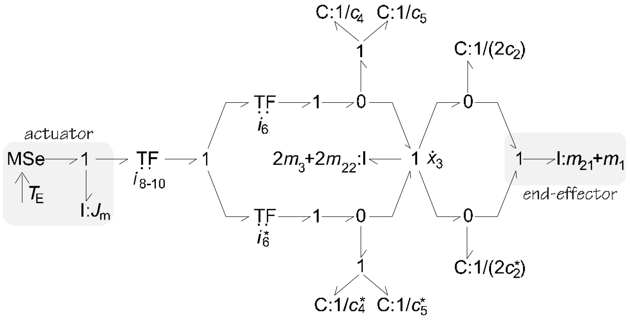


Figure 3: Initial bond graph model of A0-plotter

A bond graph model of the design proposal of Figure 2 is shown in Figure 3. Note: it is assumed that the shuttle cannot rotate, such that the velocities of guidances 3 and 3* are equal. The definition and initial estimates of the parameter values in the model are given in the appendix. Initially timing belts of type 1 are used. In a later stage of the design process more accurate and more definitive parameter values have to be determined.

The specifications have to be met for the worst case situation, i.e. the situation where the shuttle (2) is in position AA and the penholder is located at the center of the shuttle.

For fourth-order electro-mechanical system models Groenhuis (1991) developed a design method for the minimization of the positional error after a change in the input function (point-to-point motion) when using a PD-controller. This design method provides recommended values for the combined parameter set of the controller, path generator, plant and motion specification. Hence, this method takes into account the interaction between the domain specific subsystems. It is a powerful method, that can be applied in several ways, as it advocates a true mechatronic design approach (Coelingh et al, 1997a).

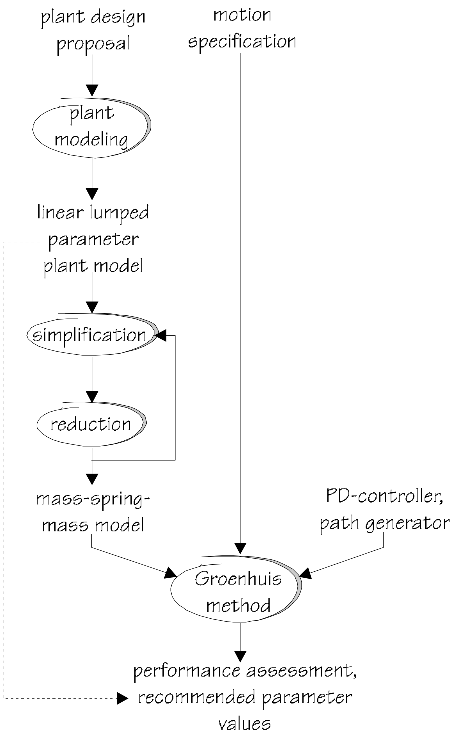


Figure 4: The automated conceptual design process

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 iteratively 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, as shown in Figure 4.

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 (mass-spring-mass model). The parameters in this reduced-order model are a combination of the parameters of the original model.

3. Automated model simplification

The simplification algorithm minimizes the number of elements in a model by eliminating transformations and by joining elements. Bond graph models are being used, because simplification rules have been formally described and are applicable in any energetic domain (Breedveld and Van Amerongen, 1994). It is assumed that the user is familiar with bond graphs. A short list of common simplification rules is given below. The procedure implementing the rule is indicated; the procedures return *true* whenever it actually has performed a simplification.

- junctions (0, 1) can eliminate themselves if energy flow is not branched and can join themselves if there is exactly one power bond between identical junctions; double differences can be eliminated in most situations (De Vries, 1994). (*simplifyJunctions*)
- a junction can join two similar linear single-port elements (R, I , C, S) connected to itself. The parameter of the simplified element is a combination of the parameters of the elements it is composed of. (*simplifyElements*)
- two transmissions (TF, GY) connected by one bond can be composed into one transmission. Additionally a transmission can be eliminated from the model by joining it with a single-port element (Figure 5). The parameter value and the type of element may change by this simplification. All elements contain a special factor (*c*) that indicates the transformation ratio of the parameter, such that a controller developed for the simplified model can instantly be connected to the original non-simplified model; i.e. input and output variables of the original plant model are preserved. (*simplifyTransmissions*)

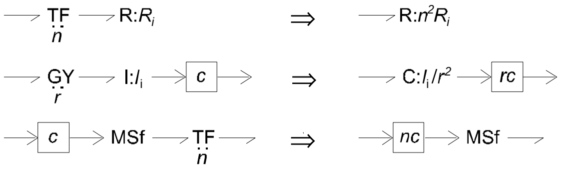


Figure 5: Composition of a transmission and an element

- Transmissions can be propagated over junctions, as shown in Figure 6 (*propagateTransmissions).* As design specifications are generally given in terms of the end-effector, it is convenient to use the coordinates of the end-effector as a reference in the simplified plant model. Transmissions are propagated away from this reference point using an existing propagation machine (Breunese, 1996). The resulting direction of propagation is indicated by the arrows along the bonds in Figure 7. Each time a single transmission is propagated over a junction, the procedure *simplifyTransmission* is applied, within the procedure *propagateTransmissions*, to enhance simplification.

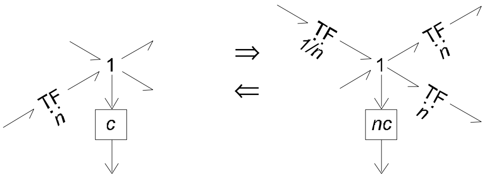


Figure 6: Propagation of a transformer

The simplification algorithm for a bond graph model is:

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

Figure 7 shows a possible intermediate step of the simplification where the transmissions are collected just after the actuator, to allow the choice of transmission ratios according to inertial match (Koster et al., 1994).

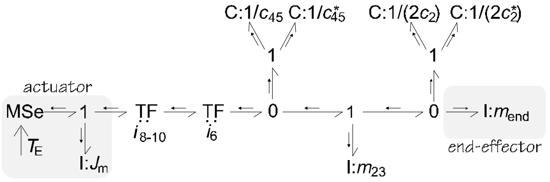


Figure 7: Intermediate step in simplification procedure

Some parameters in Figure 7 are a composition of parameters in the initial bond graph of Figure 3. The dependency between these parameters is maintained in the software by means of parameter relations. The parameter relations for Figure 7, including their values, are:

$$c_{45} = c_4 + c_5 = 1.0 \cdot 10^4 \ [\mathrm{Nm}^{-1}] \qquad (1)$$

$$c^*_{45} = c^*_4 + c^*_5 = 1.0 \cdot 10^4 \ [\mathrm{Nm}^{-1}] \qquad (2)$$

$$m_{23} = 2m_3 + 2m_{22} = 0.474\,[\mathrm{kg}] \qquad (3)$$

$$m_{\mathrm{end}} = m_1 + m_{21} = 0.47\,[\mathrm{kg}] \qquad (4)$$

If the model does not contain power loops, further propagation of transmission and composing of transmissions will lead to a model without transmissions. The final plotter model after completion of the simplification algorithm is shown in Figure 8.

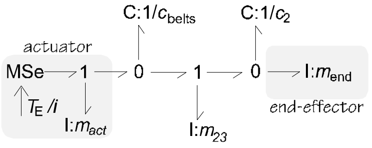


Figure 8: Simplified bond graph model

The parameter relations in this figure are:

$$c_{\text{belts}} = c_{45} + c_{45}^{*} = 2.0\cdot 10^{4}\ [\text{Nm}^{-1}] \tag{5}$$

$$i = i_{8-10}\cdot i_{6} = 1.65\cdot 10^{-3}\ [\text{m}] \tag{6}$$

$$m_{\text{act}} = \frac{J_{\text{m}}}{i^{2}} = 0.92\,[\text{kg}] \tag{7}$$

Figure 8 shows that the model simplification algorithm decreases the complexity of the model structure. Simultaneously the complexity of the parameter relations in the model increases, as shown by the equations. What is gained in this procedure is that the composite parameters are more easily interpreted and related to the controller, path generator and motion specification.

4. Automated model reduction

The resulting model after application of the simplification procedure, is generally not in the form of the mass-spring-mass system required by the design method of Groenhuis. To reduce the order of the model and convert it to the required form, a reduction algorithm has been developed for two common types of model structures: the *chain* structure (Figure 9) and the *fork* structure. 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 only the latter is described. Reduction of the chain structure is performed by dividing the follower part (see Figure 9) into two sub-chains that have equal stiffness. The masses in both sub-chains reflect the mass ratio of the system. A simple search algorithm is used for this purpose. The two sub-chains are reduced to a mass-spring model and finally combined to a mass-spring-mass model. Three different techniques for reducing sub-chains will be discussed. The lowest natural frequency of the model is assumed to be dominant, i.e., other natural frequencies of the sub-chains are at least twice as large.

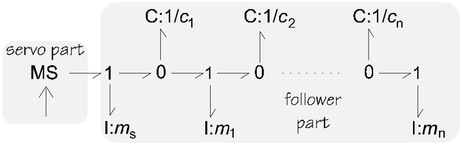


Figure 9: Chain structure

Intuitive reduction method

Relatively small masses and compliances can be removed from the model as they do not contribute to the lowest natural frequency. For spring-mass-spring-mass 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 a mass or compliance can be removed if it is approximately 15 times smaller than the other mass or compliance. When the number of masses and springs in a chain structure increases, the relative difference in compliance and mass must be larger.

Rayleigh's reduction method

According to Rayleigh's method (Den Hartog, 1956), the natural frequency can be approximated by:

$$w = \sqrt{\frac{c_{\text{c}}}{m_{\text{eq}}}} \tag{8}$$

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

$$c_{\text{c}} = \left(\sum_{i=1}^{n}\frac{1}{c_i}\right)^{-1} \qquad m_{\text{eq}} = \sum_{i=1}^{n}\left[m_i\left(\sum_{j=1}^{i}\frac{c_{\text{c}}}{c_j}\right)^{2}\right] \tag{9}$$

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 (Koster, 1973). 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 will be applied to the 3-DOF model that is obtained after simplification of the plotter model. This model has a chain structure. First the follower part is split up in two parts (A and B) that have equal stiffness.

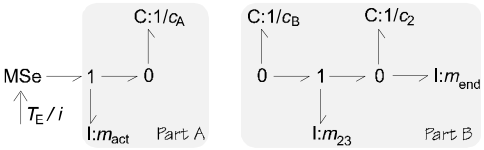


Figure 10: Split plotter model

The overall stiffness of model is:

$$c_{\text{tot}} = \left(\frac{1}{c_{\text{belts}}} + \frac{1}{c_2}\right)^{-1} = 1.93\cdot 10^{4}\ [\text{Nm}^{-1}] \tag{10}$$

so the stiffness c_A and c_B are:

$$c_{\text{A}} = \left(\frac{1}{2}\frac{1}{c_{\text{tot}}}\right)^{-1} = 2c_{\text{tot}} = 3.86\cdot 10^{4}\ [\text{Nm}^{-1}] \tag{11}$$

$$c_{\text{B}} = \left(\frac{1}{2c_{\text{tot}}} - \frac{1}{c_2}\right)^{-1} = 4.15\cdot 10^{4}\ [\text{Nm}^{-1}] \tag{12}$$

Part A is a mass-spring model and needs no reduction. Part B has to be reduced. The natural frequencies of this part are:

$$\begin{aligned} w_1 &= 2.08\cdot 10^2 \text{ [rad s}^{-1}\text{]} \\ w_2 &= 1.54\cdot 10^3 \text{ [rad s}^{-1}\text{]} \end{aligned} \tag{13}$$

Modeling the lowest natural frequency, using the numerical reduction method results in the following values for the stiffness and equivalent mass:

$$\begin{aligned} c_c &= 2c_{tot} = 3.86\cdot 10^4 [\text{Nm}^{-1}] \\ m_{eq} &= \frac{2c_{tot}}{w_1^2} = 0.89\,[\text{kg}] \end{aligned} \tag{14}$$

Connecting part A and the reduced part B results in the reduced-order model of Figure 11.

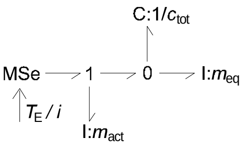


Figure 11: Reduced order model of the plotter

5. Design

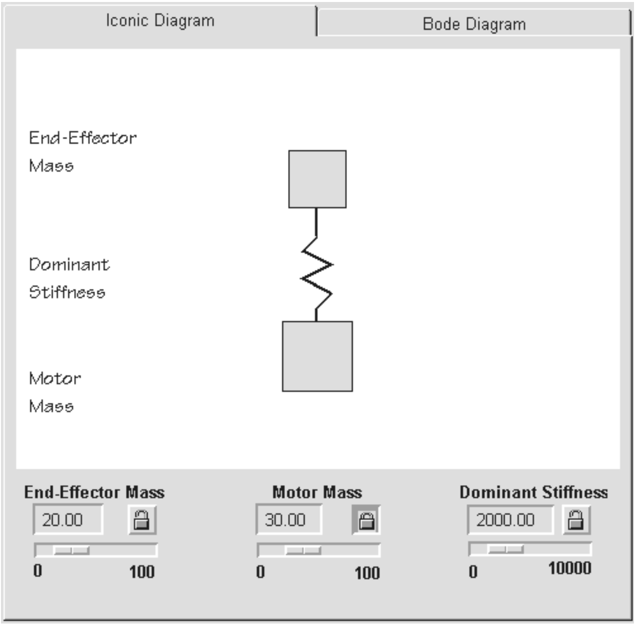
A special editor has been developed that allows explorational design of controlled fourth-order systems. Constraints are used to represent the dependencies between variables, design parameters and diagrams. If a constraint variable changes, other variables are immediately updated by constraint satisfaction techniques, such that the relations defined by Groenhuis are always valid (Coelingh et al, 1997a).

If, for example, the motor mass is increased by dragging the slider, the icon of the motor mass in Figure 12 will also increase, the natural frequency will decrease and the error will increase for a given reference path. These changes are represented numerically and graphically in an open- and closed-loop Bode diagram and a time response.

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 the application of Groenhuis' results to the original model.

A possible application of this editor to the reduced-order model of the A0-plotter may consist of the following (partially automated) steps:

1. The parameter values of the masses and dominant stiffness of Figure 11 are automatically entered in the editor of Figure 12.
2. The specifications (task), describing the desired point-to-point motion in terms of the movement h_m and motion time t_m are entered in an editor similar to Figure 12. This editor graphically shows the reference path.



End-Effector Mass 20.00

Motor Mass 30.00

Dominant Stiffness 2000.00

Figure 12: Iconic diagram with variables

3. The location of the position sensor is indicated. For the A0-plotter it is located on the motor axis.
4. A second-order reference path is selected, i.e. a parabolic path.
5. The design tool now automatically indicates the values for the PD-controller, using constraint satisfaction techniques on the rules proposed by Groenhuis (1991).
6. An estimate of the positional error for the specified task is indicated. For the A0-plotter this error u_0 equals 0.18 mm, which is larger than the desired positional error of 0.1 mm.
7. The designer may use sliders and locks (as in Figure 12) to find out the consequences of changes in the physical parameters or the design parameters in an explorational way.
8. It is possible to determine what the value of the dominant stiffness c_{tot} has to be when the maximum positional error is 0.1 mm. This stiffness equals 3.5×10^4 N/m.

Simulations of the PD-controlled plotter will show that the specifications are met in case the plant is represented by the model of Figure 11, with the new value for the dominant stiffness c_{tot}. However the specifications have to be met when using the model of Figure 3 for the plant and the new value of c_{tot} has to be mapped onto stiffnesses in this initial model. A possible continuation of the design consists of the following steps:

9. The dominant stiffness in the reduced-order model consists of the sum of the stiffnesses of the four timing belts and the shuttle. These stiffnesses can be assigned a new value in an explorational way using sliders and

locks as in Figure 12, using constraint satisfaction techniques.

10. Changing the stiffness of the shuttle c_2 possibly requires modifications to the proposed construction. It is easier to chose for a different type of timing belt. The required stiffness per timing belt equals 9.4×10^3 N/m, therefore belts of type 3 are selected.

6. Evaluation

Now we have a feasible design proposal for the A0-plotter that is likely to meet the desired performance. A simulation of the controlled system, with the plant model of Figure 3, is shown in Figure 13. This simulation shows:

A the reference path.
B the position of the penholder (1).
C the error between the reference path and position of the penholder.

The positional error, i.e. the maximum error after the motion time $t_m = 1$ [s], is $u_0 = 0.06$ [mm] for $h_m = 0.5$ [m].

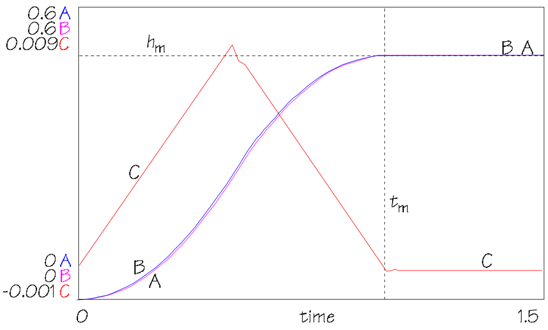


Figure 13: Simulation of the controlled plotter model

The specific problems that occur during conceptual design of mechatronic systems are addressed by the presented design tool. Functional interaction between domain specific subsystems and consequences 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 automatically 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.

7. Conclusion

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;
- can apply the results of the Groenhuis design tool to the initial model in an explorational way;
- puts emphasis on the interpretation of the results instead of the application of procedures.

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

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9. Appendix: properties of the A0-plotter

Mass of the penholder (1)	$m_1 = 0.2$	[kg]
Mass of the shuttle at (1)	$m_{21} = 0.27$	[kg]
Stiffness of the shuttle (2)	$c_2 = 5.5\times10^5$	[Nm^{-1}]
Mass of the shuttle at (3 and 3*)	$m_{22} = 0.137$	[kg]
Mass of the guidances (3 and 3*)	$m_3 = 0.1$	[kg]
Stiffness per timing belt:		
Type 1	$c = 0.5\times10^4$	[Nm^{-1}]
Type 2	$c = 1.0\times10^4$	[Nm^{-1}]
Type 3	$c = 1.5\times10^4$	[Nm^{-1}]
Radius of pulleys (6 and 6*)	$r_6 = 5\times10^{-3}$	[m]
Transmission	$i_{8\text{-}10} = 0.33$	
Motor inertia	$J_m = 2.5\times10^{-6}$	[kg×m^2]