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Automated Conceptual Design of Controllers for Mechatronic Systems

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Abstract

Especially in the conceptual design stage of electro-mechanical systems, a mechatronic design approach can be applied successfully. Automated design support is developed on basis of an existing design tool for a large class of mechatronic systems. This tool determines the functional interaction between different domain specific subsystems. The interaction will be implemented by means of constraints. Dependencies between the modules can be visualized in several ways, using constraint satisfaction techniques.

1. Introduction

Conceptual design of controllers for mechatronic systems requires a different approach than classic design of controllers for electro-mechanical systems. The mechatronic approach is described in section 2 for a particular class of systems with an end-effector, with an emphasis on the functional interaction between domain specific subsystems. The goal of our research is to develop computer-based support for this class of systems, such that it tackles specific problems occurring in the mechatronic design approach. This paper describes what has been developed so far.

2. Mechatronic approach to controller design

Since many years the need for controlled electro-mechanical systems with more flexibility, higher performance and reliability is increasing. It was recognized that these systems are the result of design activities of not just one discipline, but of several disciplines. Both developments lead to the introduction of *mechatronics*, "a technology which combines mechanics with electronics and information technology to form both functional interaction and spatial integration in components, modules, products and systems" [Buur, 1990]. This technology differs from classical design patterns for controlled electro-mechanical systems, where the design starts with the mechanical subsystems, then the electrical subsystems and finally the controllers, that are designed to obtain the specified performance.

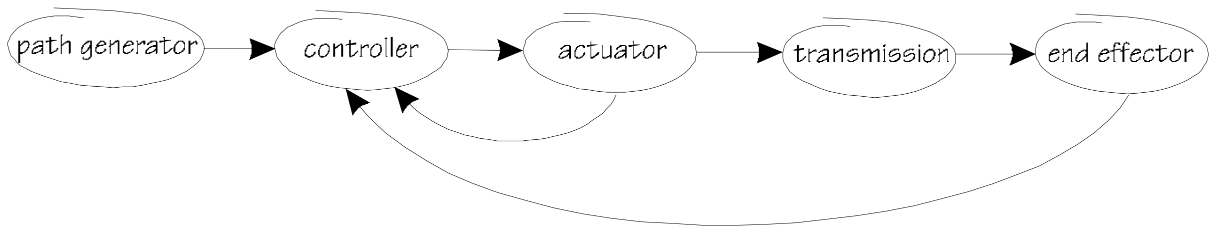

Figure 1: Controlled electro-mechanical system

This paper considers a particular class of controlled electro-mechanical system, as depicted in Figure 1, where 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 and (position) sensors are generally located at the actuator or the end-effector. The design problem is to find 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.

De Vries [1994] described specific problems, e.g. learning and communication problems, that occur during mechatronic design and showed that "a major cause of the problems is the lack of proper support for the *conceptual design task*". In the conceptual design stage "a rough idea is developed of how the project will function and what it will look like" [Ullman, 1992]. For mechatronic systems this "rough idea" is expressed as in Figure 1. As the conceptual design stage is an early stage in the design process it is very well suited to determine the functional interaction between the different subsystems. Or, as Isermann [1996] states, "the mechanical and the electronic components of a mechatronic systems must be considered as an integrated overall system from the beginning […], simultaneous engineering has to take place".

This can be illustrated by the design of a brushless permanent magnet linear motor, that is developed for high-accuracy motion control [Otten *et al.*, 1997]. High-accuracy can be obtained by spending most time and effort in the positioning of the magnets in the stator of the motor. An alternative is to choose for less accurate positioning of the magnets, but put the emphasis on controller design to obtain high-accuracy. The last option has the advantage that the effort needed for controller design has to be spent once, while accurate positioning of the magnets requires an expensive production process for every single linear motor. Thus similar performance can be obtained for a lower price per motor.

The design of a mechatronic system as in Figure 1 generally is a complex problem. Separating partial problems is a possibility to tackle such a complex design problem. Simon [1973] states that the design problem is "ill-structured in the large, but well structured in the small". The complex ill-structured design problem is split into small well-structured problems to which a local problem solver can be applied. These well-structured problems should not just be considered in a specific domain. Domain specific sub-problems should be solved by taking into account the consequences of a solution in other domains or by finding alternative solutions in other domains, refer Figure 2.

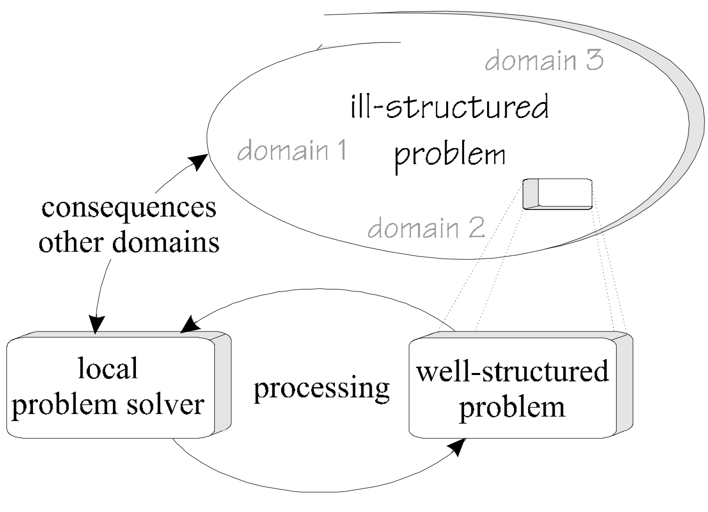

Figure 2: Schematic structure of solving ill-structured problems (Adapted from Simon [1973])

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]. In the explorational mode of designing the design object can pass a design state that has been passed before, but this time a different design decision is taken. Generally this is not a waste of time, as the designer has gained new insights by choosing a "wrong" path, that can be reused later. Simon [1981] generalizes this viewpoint to search processes and problem solving: "information that is obtained along any particular branch of a search tree may be used in many contexts besides the one in which it was generated".

Controllers which are developed during the conceptual design stage, are designed on basis of a model of the system to be controlled. Oelen [1995] states that the models in this design stage should have the following characteristics:

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

such that the model of the controlled-system provides:

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

Models with these characteristics will provide an easy to understand, sufficiently accurate and fast available framework for continuation of the design. System models should preferably be linear, unless their principle of operation depends on their non-linearity. For this kind of models, conventional controllers like PD or PID are normally appropriate to inspect how the design specifications can be met.

As the mechatronical design process is complex, tools are needed to support the designer. In the conceptual design stage these tools should consider the functional interaction between domain specific subsystems. Not many tools have this property, but in section 3 a design tool is described that is suited for conceptual design of most systems that are a member of the class of systems depicted in Figure 1. Design tools used in control engineering or (electro-mechanical) system design, that are domain specific, do not have this property and have to be adapted to this purpose, refer Figure 2.

Design tools that provide a guaranteed prediction of the performance are of great support in an explorational design mode, as they can tell the designer beforehand that a certain design decision leads to useful results or not, without using simulations or experiments to check if the design specifications are met.

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 domains;
- preservation of information after choosing a "wrong" path;
- prediction of guaranteed performance of a particular solution.

3. The Groenhuis design tool

A large group of electro-mechanical systems that contain an actuator and an end-effector can be represented competently, with a minimal number of elements, by a fourth-order model (Figure 3), as these models contain one dominant mechanical compliance [Oelen, 1994; Koster *et al.*, 1995]. Comparison of Figure 1 and 3 shows that the actuator is represented by a mass m_2 with an applied force, the transmission is flexible with stiffness c and the end-effector is represented by a mass m_1. For this class of systems, Groenhuis [1991] developed a design tool for the minimization of the positional error after a point to point motion. This mechatronic design tool provides the necessary interaction between the design of the controller, the electro-mechanical system and the determination of the input function. It ensures an upper bound for the positional error and guarantees a sufficient stability margin. So it tackles several specific problems, described in the previous section. The tool is based on the use of dimensionless quantities, which provides the opportunity to draw general conclusions for this class of systems, regardless of the particular problem setting.

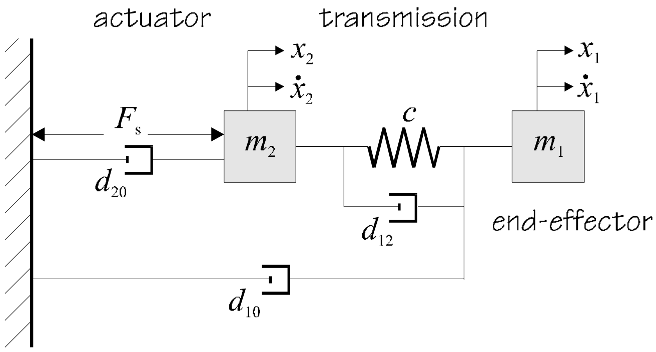

Figure 3 System with dominant compliance, where m_1 is generally referred to as the end-effector and m_2 as the motor

The Groenhuis method is attractive for mechatronic controller design, because little information about the plant is needed, while a reliable worst case performance is obtained.

Controlled system description

We consider a system consisting of a *plant*, a *controller* and a *reference path generator*, configured as shown in the scheme of Figure 4.

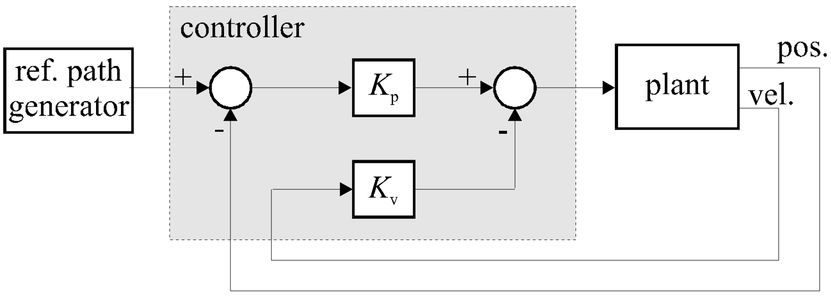

Figure 4 Controlled system configuration

The plant can be described as in Figure 3. The controller implements a proportional action K_p on a positional error and a proportional action K_d on one measured velocity. The positional error is obtained as the difference between one measured position and the reference path. The reference path is a smooth function. The smoothness is determined by an order number. If the reference path is of order 2, it involves two pieces of 2nd order polynomials (*i.e.*, it is a B-spline of order 3). If it is of order 3, it involves two pieces of 3rd order polynomials.

Determination of plant properties

Mass-ratio between actuator and end-effector mass:

$$a = \frac{m_2}{m_1 + m_2} \tag{1}$$

Characteristic plant frequency, which is the resonance frequency when actuator position is fixed:

$$w_\mathrm{m} = \sqrt{\frac{c}{m_1}} \tag{2}$$

Problem specification

The reference path specifies, in terms of the end effector m_1, a movement over a distance h_m in a time period t_m. The control goal is to guarantee an upper bound e_0 on the absolute value of the positional error after the reference path has reached the endpoint, refer Figure 5.

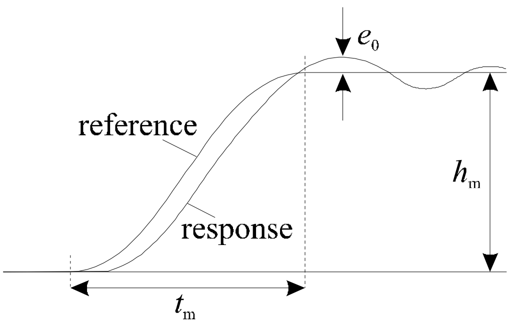

Figure 5 Reference path and a possible response

Determination of dimensionless problem specification

Maximal relative positional error:

$$E_0 = \frac{e_0}{h_\mathrm{m}} \tag{3}$$

Dimensionless problem–plant relations

Crucial is the periodic ratio t_m. This ratio can be calculated in two ways:

– from the characteristic plant eigen period and the movement period:

$$t_m = \frac{T_m}{t_m} = \frac{2p}{w_m t_m} \tag{4}$$

– from the maximal relative positional error:

Ref. path order	Periodic ratio	
2	$t_m = \sqrt{5E_0}$	(5a)
3	$t_m = \sqrt[3]{1.66E_0}$	(5b)

Table 1 Periodic ratio per path order.

Choice of sensor location

Four different configurations are possible. As we are interested primarily in load position, it is not sensible to feed back load velocity and motor position. Hence, three options remain (original labeling of Groenhuis has been maintained):

Label	I	III	VI
Feedback	$x_2, \dot{x}_2$	$x_1, \dot{x}_2$	$x_1, \dot{x}_1$
Condition	$0.1<a<0.8$	$0.1<a<0.5$	$0.1<a<0.12$

Table 2 Possible sensor locations.

Refer to Figure 3 for explanation of feedback signals. The conditions on the mass-ratio a are a consequence of a minimal required stability robustness. A choice of sensor position leads to optimal dimensionless controller settings, as given in table 3.

Label	I	III	VI
Ω_p	0.8	0.6	1.0
Ω_d	1.0	0.6	0.4

Table 3 Recommended dimensionless controller settings.

Recommended controller settings.

The values for the proportional control actions, for a particular problem setting are:

$$K_p = (m_1 + m_2) \cdot (w_m \cdot \Omega_p)^2 \tag{6}$$

$$K_d = (m_1 + m_2) \cdot (w_m \cdot \Omega_d) \tag{7}$$

Method of research.

The optimal dimensionless controller settings from table 3 are obtained by performing numerous simulations for a relevant set of the dimensionless quantities. The setting that results in the smallest positional error, after the reference path has reached the end-point, and that provides a sufficient stability margin is the optimal setting.

The relations in table 1 are obtained by another set of simulations, for a relevant set of dimensionless quantities and for the three sensor locations of table 2. For each member of this set a relation between the periodic ratio t_m and the relative positional error is determined. The equations in table 3 indicate upper bounds for all these relations.

Stability robustness.

To provide stability robustness a stability margin was introduced, that defines a minimal negative value d for the real part of the poles of the controlled system. The dimensionless version of this margin is defined as:

$$D = \frac{d}{w_m} \tag{8}$$

Sufficient stability margin was attained for D = 0.2.

Application of design tool

Relations (4) and (5) can be used in various ways, depending upon the specific design context. If plant characteristics and motion duration and distance have been chosen, (4) can be used to determine t_m, and (5) can be used to obtain the reference path order and corresponding e_0. If on the other hand e_0 and the motion distance are known, (5) can be used to determine t_m, and (4) may help to evaluate the required stiffness c for a particular motion duration, etc.

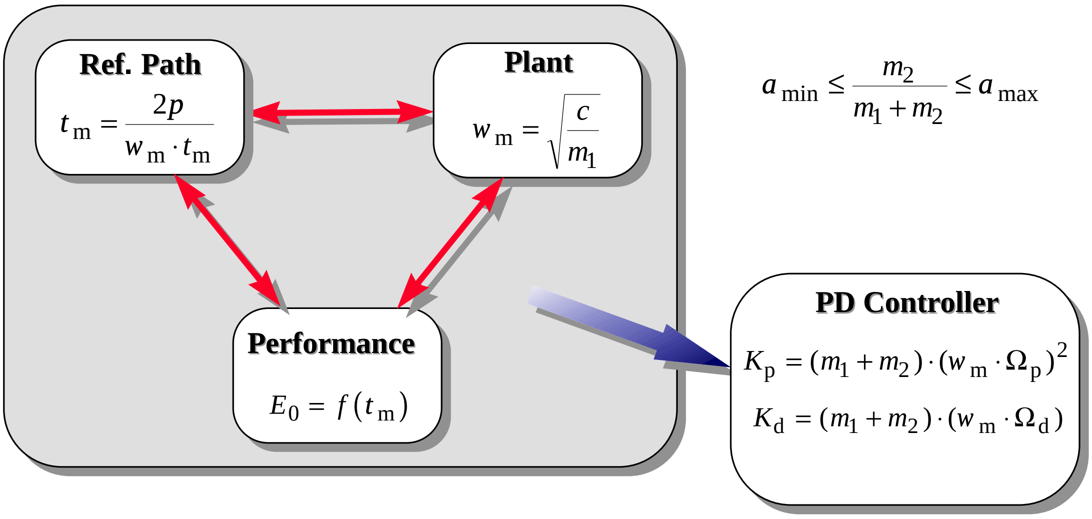

Figure 6 Possible applications of the Groenhuis design tool

These principles are shown in Figure 6. Once two of the three design parameters shown in this figure are chosen, the third one follows automatically. If the mass-ratio lies between it's lower and upper bound given in table 2, a PD-controller can be found, such that the controlled system fulfills all specifications.

The ratio between the bandwidth of the closed-loop system w_e and the natural frequency w_m for concept I is given in (9) and for concept III and VI in (10):

$$\frac{w_e^2}{w_m^2} = \frac{1 \pm \sqrt{1 - 4a\,\Omega_p^2)}}{2a} \tag{9}$$

$$\frac{w_e^2}{w_m^2} = \frac{(\Omega_p^2 + 1) \pm \sqrt{(\Omega_p^2 + 1)^2 - 4a\,\Omega_p^2)}}{2a} \tag{10}$$

4. Groenhuis design tool expressed in constraints

The Groenhuis design tool can be applied in several ways, as shown in Figure 6. This flexibility is both an advantage and a disadvantage of the tool. It allows for a true mechatronic design approach, but it does not provide transparent insight in the dependencies between different design parameters. Dependencies are the key factor for successful application of the tool, so computer-based support of the design tool should be focused on implementation of the relations between different design parameters. A change in one design parameter should immediately be reflected in other design parameters. If for example a smaller error is required for a mechatronic systems, than either a larger rise time of the reference function, or a higher natural frequency of the plant is needed.

Dependencies can be compared quite natural to constraints. Ullman [1992] describes a possible view upon the design process as: "when a new problem is begun, the design requirements effectively *constrain* the possible solutions to a subset of all possible product designs". The performance E_0 and reference path t_m (requirements) constrain the possible natural frequencies w_m (possible product designs). Besides requirements, laws of nature also constrain possible designs.

Implementation of the dependencies can actually be done by so-called constraints. In object-oriented programming *constraints* are considered to be functional relationships between entities of an object model [Rumbaugh *et al.*, 1991]. These relationships must be maintained during the design process, such that a change in one property results in a corresponding change in dependent properties of other objects. This process is called *propagation*. Technical details about these constraints and propagation are explained in De Vries *et al.* [1997].

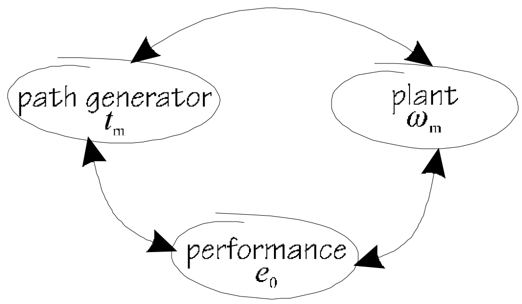

Figure 7: Dependencies within the Groenhuis design tool

As propagation will satisfy the dependencies shown in Figure 7 at any time, a proportional and derivative gain for the PD-controller can always be determined, under the condition that the mass ratio lies between its lower and upper bound. The exact values of the proportional and derivative gain depend on properties of the plant and on design parameter w_m. Relations between plant and controller can also be implemented by constraints, such that a valid controller and thus a controlled-system that fulfills all specifications always exists.

As the constraints can be solved in several direction, the causal relations between constraint variables are not fixed. To show a possible application of parts of the constraint system, unidirectional arrows between constraints and constraint variables are used here after. Constraints are represented by blocks that contain a number, which refers to the equation the constraint is based on. The following objects can be recognized in the design process of mechatronic systems that have properties that play a role in the constraint system:

– *Plant*

  Design parameters related to the plant are the natural frequency with blocked actuator w_m and the mass ratio a. These depend on the following physical parameters of the plant: the mass of the end-effector m_1, the mass of the motor m_2 and the dominant stiffness c. The five parameters mentioned above will all be implemented as constraint variables. The relations between these constraint variables have to be maintained during the design process and will therefore be implemented by constraints. If, for example, a higher end-effector mass occurs due to a change in the specifications, this will be propagated to a higher stiffness or a smaller natural frequency. In Figure 8 the latter of these two options is illustrated. The constraint is implemented using (2).

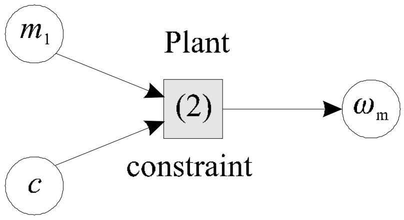

Figure 8 Constraint between end-effector mass, dominant stiffness and natural frequency

A similar figure can be drawn for the constraint between motor mass, end-effector mass and mass-ratio, using (1).

– *Specifications and performance*

As motion control of mechatronic systems is considered, the specification consists of the following parameters: the rise time t_m of the reference function and the amplitude h_m of the reference function. The absolute positional error u_0 and the bandwidth of the controlled system w_e can be considered as both a part of the specifications and of the performance, because they are predicted values. A constraint between the absolute error, the amplitude and the relative error can be written down, similar to Figure 8, using (3).

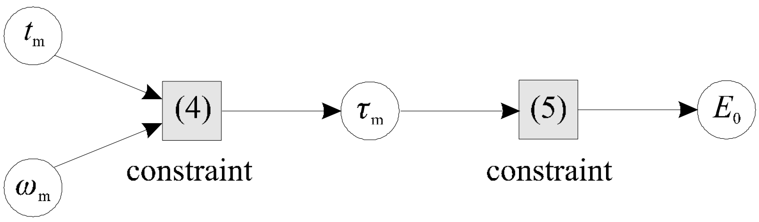

Figure 9 Main constraints in the Groenhuis design tool

The three dependencies shown in Figure 7 can be implemented by only two constraints, as shown above, as the third dependency is redundant. In Figure 10 the two main constraints between the three properties of Figure 6 and 7 are drawn. The constraint variable w_m is the same constraint variable as shown in Figure 9. The left constraint uses (4) and the right constraint uses (5).

- *Controller*

  The two parameters of the controller, the proportional action K_p and the derivative action K_d, can at any time be determined on basis of the dimensionless quantities and the parameters of the plant. Constraints can be made using equations (6) and (7). The dimensionless quantities have a fixed value for particular sensor settings and the other variables are already existing in the constraint system.

The use of constraints can be extended to representations of the subsystems of a mechatronic system, as indicated in De Vries *et. al* [1997]. The design tool will use iconic diagrams and Bode diagrams to describe both the open- and closed-loop system, as described in the next section.

5. Computer-based support

The mechatronic design environment 20-sim (Controllab Products inc.), that incorporates the software formerly known as MAX, the Modeling and Analysis eXpert [De Vries, 1994], supports conceptual mechatronic design from a modeling perspective. The Groenhuis design tool is implemented in the 20-sim environment, using a centralized propagation technique and the SkyBlue constraint solver as described in De Vries *et al.* [1997].

Model of the system under design

The underlying plant model of the design tool is a linear fourth-order state-space description with one input and one output. The elements of the matrices depend on physical parameters such as end-effector mass, motor mass and dominant stiffness. The constraint variables can be considered "pointers" to these parameters in the state-space description. If a constraint variable changes, the state-space description is automatically updated.

Also a model of the reference function and the PD-controller exist, that have a similar connection to the constraint variables describing these phenomena. At any stage in the design process the underlying models correspond to the situation in the constraint system, such that a valid mathematical description, of all subsystems of the design (Figure 1), exists.

Representation of design parameters

To provide better "look and feel", the design parameters are presented together with a corresponding representation. The physical parameters motor mass and end-effector mass and dominant stiffness are shown together with an iconic diagram of the fourth-order model, as shown in Figure 10.

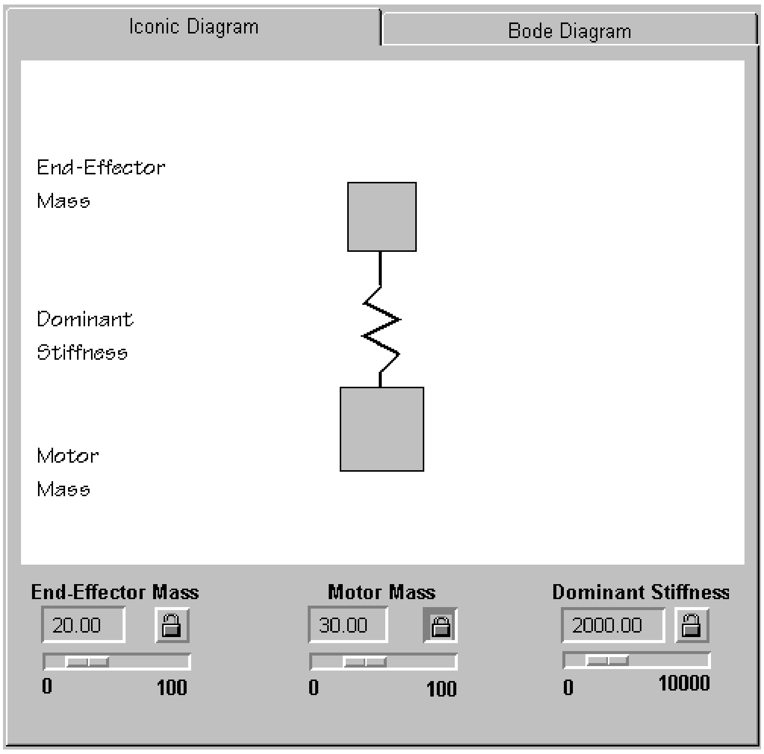

Figure 10 Iconic diagram with corresponding design parameters

A physical parameter is related to its representation by a constraint, such that a larger mass results in a larger mass icon. Similarly an increase in the dominant stiffness will result in a smaller stiffness icon. The iconic diagram will provide the designer with a feeling of the behavior of the system to be controlled. Looking at an iconic diagram with for example a large end-effector mass and a small stiffness intuitively shows that is difficult to control fast motions of the end-effector.

The natural frequency and the mass-ratio are shown in a Bode diagram of the open-loop system. The anti-resonance frequency in this diagram equals w_m and the distance between the resonance and anti-resonance frequency is related to the mass-ratio. Changing one of these design parameters will also change the Bode diagram.

The reference path and the input function are shown in Figure 11. The design parameters related to this diagram are the amplitude and rise time of the reference function. An indication of the closed-loop time response is also given in this diagram, to show the absolute positional error. Again the amplitude and rise time of the reference function in the diagram are related to the value of the design parameters by means of constraints.

The last diagram is Bode diagram of the feedback controlled system in which the attainable bandwidth is indicated.

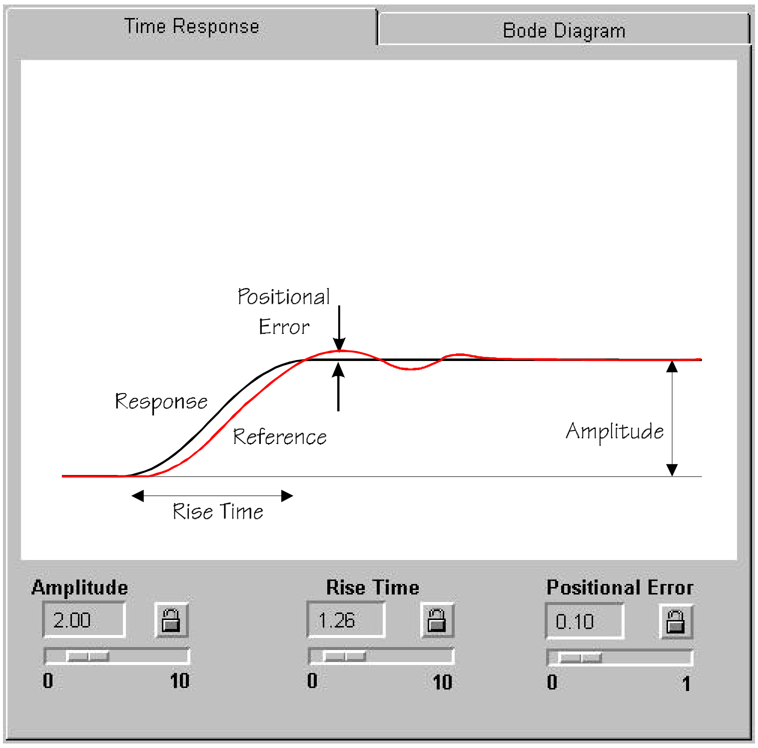

Figure 11 Time response with corresponding design parameters

Functionality

There exists a large number of dependencies in the system, that are all implemented by means of constraints. A change of one parameter can result in a change of many other parameters. Therefore the possibility to fix a design parameter is provided by a "lock" as indicated in Figures 10 and 11. Once a design parameter has a desired value it can be fixed, such that the constraint system cannot change it anymore.

Groenhuis indicates three feasible combinations of sensor locations, called concepts, that are indicated in table 2. By selecting a radio button a different concept can be chosen. Concept I, that uses measurement of the motor position and velocity, is chosen as default.

Results and verification

Results of application of the design tool are values for the proportional and derivative action of the PD-controller. These are used in the mathematical description of the controlled system, together with other parameter values. A DDE-connection to Matlab can be used to export the state-space description in order to verify the results in the Bode diagrams and the time response.

Evaluation of computer-based support

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 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, as sliders and locks can be used to (not) change the design parameters in the constraint system. If one parameter is changed, others will change automatically according the underlying constraints, so the designer can immediately evaluate the interaction between different subsystems.

A design goal can for example be the calculation the required stiffness of the system, given a reference function and an indication of the error. Therefore the masses, amplitude and rise time should be fixed. Changing the stiffness is reflected in a change in the error, such that the dependency is immediately clear. A change in design goal, for example the determination of the influence of mass changes of the end-effector, is easily made. The end-effector mass can be unlocked and the stiffness can be fixed on the useful value that was just determined. The dependency between positional error and end-effector mass can be made clear by using the sliders. This example shows that the design tool supports application of the Groenhuis design tool in an explorational design mode. Local design goals can easily be changed, while information after a change is preserved.

6. Conclusions

A limited use of constraints is useful to maintain parameter relations during the conceptual design process of mechatronic systems. Interactive computer-based support is developed, using these constraints, such that it:

- provides transparency in the relation between different design parameters;
- supports application of the mechatronic controller 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 efforts can be estimated at an early stage.

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