DESIGN SUPPORT FOR MOTION CONTROL SYSTEMS

— A MECHATRONIC APPROACH —

PROEFSCHRIFT

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Summary

This thesis discusses the development of design support for motion control systems, using a mechatronic design approach. The placement module of the Philips Fast Component Mounter (FCM), an industrial pick-and-place machine, is used as a running example.

To fully exploit the advantages of mechatronic design, tuning a ready-for-use controller is not sufficient. Rather, an elaborate and complex trajectory for the design of a control system has to be followed to obtain a deep understanding of the design problem. By providing high-quality design support the amount of knowledge about the design problem early in the design process will increase. This is important, as at these moments there is still considerable design freedom. Consequently, better founded design decisions can be made and the development time decreases.

Two distinct stages of mechatronic control system design are addressed: conceptual design and detailed design.

For conceptual design an assessment method is formulated that supports the design of a feasible reference path generator, control system and electromechanical plant with appropriate sensor locations, in an integrated way. This method is based on a classification of standard transfer functions, plant models and closed-loop systems. The assessment method can be applied in several ways, depending on the available knowledge about the design problem. Together with dedicated computer support, the assessment method quickly provides insight in the design problem and feasible goals and required design efforts can be estimated at an early stage.

For detailed design, a transparent and structured design method is proposed, in order to meet the more or less conflicting requirements for a controlled system, in terms of performance, stability, disturbance attenuation and robustness. A standard control configuration is used that involves a feedback component, a disturbance observer, a feedforward component and a reference path generator. Starting from a successful conceptual design, the structured design method supports the (evolutionary) design of motion control systems, by providing relevant design procedures and computer support. It enables the design of control systems, which are successful in practice, with fairly simple means, in relatively short time and simultaneously with the design of the plant.

In a mechatronic design process, physically motivated plant models are generally used to describe the dynamic behavior of the electromechanical plant. The physical parameter values in such a model are often only known within bounds. Computer support, based on Quantitative Feedback Theory (QFT), has been developed for the design of control systems which assure that the motion specifications are met, despite this uncertainty. A review on dealing with physical parameters in QFT is presented, as well as a procedure that converts point-to-point motion specifications into appropriate frequency-domain specifications. The resulting design support gives a clear view upon the influence of physical parameter uncertainty on the design of the closed-loop system.

By means of practical application to the placement module of the FCM, we illustrate the design support presented in this thesis. We mainly focus on evaluation of the design enhancement and not on maximization of the performance of the controlled system.

The design support presented in this thesis helps the designer to more easily gain insight in the design problem, without requiring advanced control engineering skills, while indicating whether performance and robustness demands of the final design are being satisfied. An important consequence is that the required overall development time decreases.

Samenvatting

Dit proefschrift behandelt de ontwikkeling van ontwerpgereedschappen voor bewegingsregelingen voor elektromechanische systemen, waarbij gebruik wordt gemaakt van een mechatronische ontwerpaanpak. De plaatsingsmodule van de Philips Fast Component Mounter (FCM), een industriële *pick-and-place* machine, wordt als lopend voorbeeld gebruikt.

Om de voordelen van de mechatronische ontwerpaanpak volledig te benutten, kan niet volstaan worden met het inregelen van een bestaand regelsysteem, maar moet een uitgebreid traject voor het ontwerpen van een regelsysteem worden gevolgd om een diep inzicht in het ontwerpprobleem te verkrijgen. Door het aanbieden van goede ontwerpondersteuning, kan de kennis van het ontwerpprobleem vroeg in the ontwerp proces, vergroot worden. Dit is belangrijk want op dat moment is er nog aanzienlijke ontwerpvrijheid. Het gevolg is dat beter gefundeerde ontwerpkeuzes gemaakt kunnen worden en dat de ontwikkeltijd af neemt.

Twee verschillende ontwerpstadia worden besproken: het conceptuele en het gedetailleerde ontwerpstadium.

Voor het conceptueel ontwerp is een methode geformuleerd die het geïntegreerd ontwerpen van de referentiepadgenerator, het regelsysteem en het elektromechanische proces inclusief sensor locatie, ondersteund. Deze methode is gebaseerd op een classificatie van standaard overdrachtsfuncties, proces modellen en gesloten-lus systemen. De methode kan op verschillende manieren worden toegepast, afhankelijk van de beschikbare kennis over het ontwerpprobleem. In combinatie met de specifieke computerondersteuning verschaft de methode inzicht in het ontwerpprobleem en kunnen realistische doelen en de benodigde inspanning vroeg in het ontwerpproces ingeschat worden.

Voor het gedetailleerde ontwerp wordt een transparante en gestructureerde ontwerp methode voorgesteld, om de min of meer tegenstrijdige eisen van een geregeld systeem te behalen. Deze eisen zijn gesteld in termen van prestatie, stabiliteit, verstoringsonderdrukking en robuustheid. Een standaard regelaarconfiguratie wordt gebruikt, die bestaat uit een terugkoppeling, een vooruitkoppeling, een verstoringschatter en een referentiepadgenerator. Uitgaande van een succesvol conceptueel ontwerp ondersteunt de gestructureerde ontwerpmethode het

(evolutionair) ontwerpen van bewegingsregelingen, door het aanbieden van relevante frequentiedomein georiënteerde ontwerpprocedures en computerondersteuning. Het maakt het ontwerpen van regelsystemen mogelijk, die succesvol zijn in de praktijk, met tamelijk eenvoudige middelen, in een relatief korte tijd en simultaan met het procesontwerp.

In een mechatronisch ontwerpproces worden in het algemeen fysisch gemotiveerde modellen gebruikt om het dynamische gedrag van het elektromechanische proces te beschrijven. De waarden van de fysische parameters in deze modellen zijn vaak alleen bekend binnen bepaalde grenzen. Computerondersteuning, gebaseerd op Quantitative Feedback Theory (QFT), is ontwikkeld voor het ontwerpen van regelsystemen die er voor zogren dat de bewegingsspecificatie gehaald wordt ondanks deze onzekerheid. Een overzicht van het gebruik van fysische parameters in QFT wordt gepresenteerd, evenals een procedure die bewegingsspecificaties omzet in geschikte frequentiedomein eisen. De resulterende ontwerpondersteuning geeft een helder beeld van de invloed van fysische parameter onzekerheid op het ontwerp van het gesloten-lus systeem.

Door middel van een praktische toepassing op de plaatsingsmodule van de FCM, illustreren we de ontwerpondersteuning uit dit proefschrift. We richten ons met name op de evaluatie van de ondersteuning en niet op het maximaliseren van de prestatie van het geregelde systeem.

De ontwerpondersteuning uit dit proefschrift helpt de ontwerper om op eenvoudige wijze inzicht in het ontwerpprobleem te verkrijgen, zonder vergaande regeltechnische vaardigheden te verlangen, terwijl wordt aangegeven of de prestatie- en robuustheideisen van het uiteindelijke ontwerp gehaald kunnen worden. Een belangrijke gevolg is dat de vereiste ontwikkelingstijd korter zal zijn.

List of symbols and abbreviations

Symbol	Meaning	Unit
c	stiffness (translation)	$[\mathrm{N \cdot m^{-1}}]$
d	damping (translation)	$[\mathrm{N \cdot s \cdot m^{-1}}]$
e_0	maximum positional error	$[\mathrm{m}]$
g	stability margin in s-plane	
h_m	motion distance	$[\mathrm{m}]$
i	transformation ratio	
j	$\sqrt{-1}$	
k	stiffness (rotation)	$[\mathrm{N \cdot m \cdot rad^{-1}}]$
k_d	gain in velocity loop	$[\mathrm{N \cdot m^{-1} \cdot s}]$
k_m	motor constant	$[\mathrm{N \cdot m \cdot A^{-1}}]$
k_p	gain in position loop	$[\mathrm{N \cdot m^{-1}}]$
m	mass	$[\mathrm{kg}]$
$n(t)$	measurement noise	
$p\,(s, q\,)$	polynomial with physical parameters	
q	(vector of) physical parameter(s)	
$r(t)$	reference path	$[\mathrm{m}]$
s	Laplace operator	
s_l	low-frequency disturbance suppression	
t	time	$[\mathrm{s}]$
t_m	motion time	$[\mathrm{s}]$
$u(t)$	control signal, *i.e.* plant input	
$u_\mathrm{c}(t)$	control signal from $\mathcal{C}$	
$u_\mathrm{f}(t)$	forcing function or control signal from $\mathcal{F}$	
$v(t)$	measured velocity	$[\mathrm{m \cdot s^{-1}}]$
$w(t)$	disturbance signal	
$\hat{w}(t)$	estimated disturbance signal	
$x(t)$	state (vector)	
$\hat{x}(t)$	estimated state (vector)	

$x_\mathrm{o}(t)$	observer state (vector)	
$x_w(t)$	state (vector) of disturbance model	
x_0	initial state	
$y(t)$	measured (position) output	[m]
$z(t)$	output (position) to be controlled	[m]
A	system matrix	
A_w	system matrix of disturbance model	
B	input matrix	
C	output matrix	
C_w	output matrix of disturbance model	
$C(s)$	feedback compensator transfer function	
D	throughput matrix	
E	observer transfer matrix	
E_0	relative maximum positional error	
F	(input) force	[N]
$F(s)$	prefilter transfer function	
G	relative stability margin in s-plane	
$H(s)$	command response or closed-loop transfer function	
I	unit matrix	
J	inertia	$[\mathrm{kg} \cdot \mathrm{m}^2]$
K	proportional gain	
L	observer gain matrix	
L_D	observer gain matrix for disturbance model	
L_P	observer gain matrix for plant model	
$L(s)$	loop transfer function	
$L_0(s)$	nominal loop transfer function	
M_S	peak of the sensitivity function	
$P(s)$	plant transfer function	
$P(s,q)$	plant transfer function with physical parameter uncertainty	
$P_0(s)$	nominal plant transfer function	
Q	Q-box	
$S(s)$	sensitivity function	
$S_\mathrm{o}(s)$	observer sensitivity function	
$S_\mathrm{u}(s)$	input sensitivity function	
T	torque	$[\mathrm{N} \cdot \mathrm{m}]$
$T(s)$	complementary sensitivity function	
$T_\mathrm{o}(s)$	observer complementary sensitivity function	

$\mathcal{C}$	control system or feedback component
$\mathcal{D}\left(j\omega_i, Q\right)$	denominator template
$\mathcal{F}$	feedforward component or prefilter
$\mathcal{F}_{\mathbb{C}}\left(j\omega_i, Q\right)$	value set
$\mathcal{F}_{\mathrm{N}}\left(j\omega_i, Q\right)$	template
$\mathcal{H}_{\mathrm{spec}}$	frequency tolerance band
$\mathcal{N}\left(j\omega_i, Q\right)$	numerator template
$\mathcal{O}$	disturbance observer
$\mathcal{P}$	physical (electromechanical) plant
$\mathcal{P}_{\mathrm{m}}\left(s, Q\right)$	mixed uncertainty model
$\mathcal{P}_{\mathrm{p}}\left(s, Q\right)$	parametric plant family
$\mathcal{R}$	reference path generator
$\mathcal{T}_{\mathrm{spec}}$	thumbprint specification
$\mathcal{W}$	set of waveform structured signals

α	absolute damping	
$\alpha(\omega)$	lower-bound on frequency tolerance band	
β	tameness factor	
$\beta(\omega)$	upper-bound on frequency tolerance band	
ε	performance constant for second-degree reference path	
γ	performance constant for third-degree reference path	
ϕ_{m}	phase margin	
φ	motor angle	[rad]
ρ	frequency ratio	
τ	periodic ratio	
τ_{d}	derivative time constant	
τ_{h}	high-frequency roll-off time constant	
τ_{i}	integral time constant	
$\upsilon_i(t)$	i-th elementary waveform function	
ω	frequency	$[\mathrm{rad}\cdot\mathrm{s}^{-1}]$
ω_{ar}	anti-resonance frequency	$[\mathrm{rad}\cdot\mathrm{s}^{-1}]$
ω_{b}	bandwidth	$[\mathrm{rad}\cdot\mathrm{s}^{-1}]$
ω_{c}	gain cross-over frequency	$[\mathrm{rad}\cdot\mathrm{s}^{-1}]$
ω_{d}	velocity loop quantity	
ω_{l}	upper limit of low-frequency disturbance	$[\mathrm{rad}\cdot\mathrm{s}^{-1}]$
ω_{peak}	frequency of the peak of the sensitivity function	$[\mathrm{rad}\cdot\mathrm{s}^{-1}]$
ω_{p}	position loop quantity	
ω_{r}	resonance frequency	$[\mathrm{rad}\cdot\mathrm{s}^{-1}]$

ω_σ	frequency for observer poles	$[\mathrm{rad} \cdot \mathrm{s}^{-1}]$
ζ	relative damping	
Δ	unstructured uncertainty	
$\Upsilon_i(s)$	Laplace transform of i-th elementary waveform function	
Ω	frequency space	
Ω_p	optimal dimensionless controller settings for position loop	
Ω_d	optimal dimensionless controller settings for velocity loop	
$\mathbb{C}$	complex plane	
$\Im$	imaginary part	
$\Re$	real part	
AR	anti-resonance - resonance	
COM	center of mass	
D	double integrator	
FCM	Fast Component Mounter	
N	non-minimum phase	
PCB	Printed Circuit Board	
PM	Placement Module	
QFT	Quantitative Feedback Theory	
R	resonance	
RA	resonance - anti-resonance	

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1 Introduction

1.1 Products involving motion control

In modern society, an increasing number of products is in operation that relies on automatic control of motion. This motion may be the primary function of the product, such as in cruise control of cars, but more often it is a precondition for the functionality of a product. This can be seen in consumer products such as compact-disc players, videocassette recorders and cameras, as well as in professional products such as assembly machines. These products all have moving parts that require high-performance automatic control; see *e.g.* (Steinbuch and Norg, 1998). When the functionality of a product relies on accurate motions, then motion control is a crucial issue in the design of that product.

Global market developments show a continuous demand for new, cost-effective, high-quality products. Simultaneously, the market fosters the need to develop these products at a very rapid and accelerating pace. These trends have consequences for the design of both products and production machines, because there is less time to design and manufacture higher-quality products, at lower costs. Technological advances *and* enhancement of the design process are required to fulfill these needs.

As an illustration we consider current developments in electronics. Technological advances lead to larger variations in the size of electronic components and to components with more pins. As a consequence, the requirements for assembly machines for printed circuit boards (PCB's) are changing. Assembly operations must be performed more flexibly, faster and with higher accuracy. An example of the current state of the art is the Fast Component Mounter (FCM) of Philips (Philips, 2000). Flexibility is obtained by enabling in-flight component centering and fault detection by means of a laser alignment system. This machine is capable of placing 60,000 components per hour, under nominal conditions. The FCM comprises a series of up to 16 servo-controlled pick-and-place robots, the so-called Placement Modules or PM modules. In figure 1.1 a schematic diagram of the motion in y-direction of the PM module is shown. A more elaborate description of the FCM is given in appendix A.

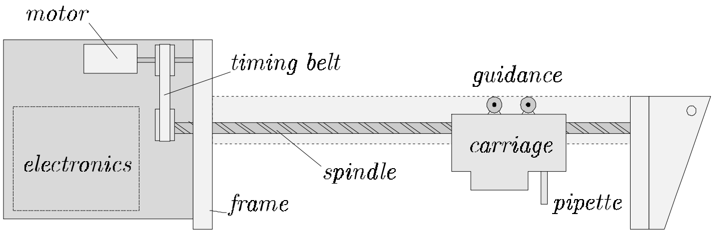

FIGURE 1.1 *Schematic diagram of a placement module of the FCM*

Control aspects within the integrated design of this type of electromechanical motion systems are subject of this thesis. While focusing on the role these aspects play or should play in the design process, support is developed to enhance the design.

Section 1.2 describes the scope of research; topics that are discussed are control engineering, mechatronic design, motion control in the mechatronic design process and the use of design tools. In section 1.3 the aim of research is defined and section 1.4 finally gives an outline of the contents of this thesis.

1.2 Scope of research

1.2.1 Control engineering

From the desired functionality of a product, several tasks can be deduced for the design of a technical (sub) system. The objective of *control engineering* is to obtain a certain dynamic behavior that allows the system to actually perform these tasks in an optimal way. In case of the PM module of an FCM, the functionality is to mount electronic components on a PCB. The main task of this module can be characterized as moving the pipette along the spindle from one position to another, within a certain time and with certain accuracy (figure 1.1), *i.e.* to perform a point-to-point motion.

Controlled systems are generally represented by a block diagram as in figure 1.2, where the following elements can be distinguished:

- The *plant* $\mathcal{P}$ is the system to be controlled. It has inputs u, outputs z that have to be controlled and measured outputs y.
- The *reference path generator* $\mathcal{R}$ produces a reference signal r that indicates the desired behavior for the output z of $\mathcal{P}$.

- The *control system* $\mathcal{C}$ uses the reference signal r of $\mathcal{R}$ and measurement y of $\mathcal{P}$ to generate a control signal u to manipulate the output z of $\mathcal{P}$.

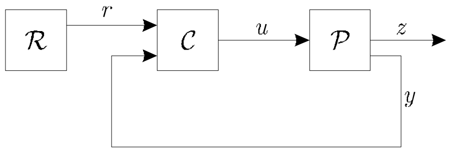

FIGURE 1.2 *Block diagram of a controlled system*

Once the task has been determined and some knowledge about $\mathcal{P}$ is available, one can start with the design of the control system. In case the designer lacks thorough knowledge and experience of specific problems in this problem domain, two possible design trajectories exist:

1. *Short trajectory.* A ready-for-use controller is applied, which is tuned for the particular problem; see *e.g.* (Åström and Hägglund, 1995).
2. *Elaborate trajectory.* A custom-made controller is obtained through an iterative design process that involves problem specification, modeling, identification, linearization, controller design, simulation, evaluation and implementation.

The controller obtained by the short trajectory generally gives worse performance, but the development time is relatively short. The elaborate trajectory can lead to far better solutions, but only if the designer has the skills to gain a *deep understanding of the problem.* The consequence for the design process is that the elaborate design trajectory causes a longer development time. Not all designers will have sufficient skills, therefore Graebe stated an open challenge in the field of high-performance robust control, *i.e.* "*decreasing the control engineering skills required of a designer*" (Graebe, 1999). From this perspective, we will take a closer look at each of the individual steps in the elaborate trajectory:

Problem specification. The task for the (control) system often has to be transformed into specifications that can be handled by available design methods. Tasks are often indicated in space and time, *e.g.* the point-to-point motion for the PM module of the FCM. A design method such as optimal control requires specifications to be expressed in terms of an appropriate cost criterion. It is not straightforward to find a criterion that will indeed be adequate for the task.

Modeling the plant. Controllers are generally designed on basis of a dynamic model of the plant. Different analytical modeling techniques can be used for obtaining a plant model, depending on the design stage, the design knowledge, the desired model or the type of plant. Examples of techniques that are used for modeling mechanical plants are finite element methods (Zienkiewicz, 1971; Cook, 1974) and multi-body systems (Wittenburg, 1977; Kane and Levinson, 1985; Jonker, 1988). Bond graphs (Paynter, 1975; Cellier, 1991) are both a modeling technique as well as a representation that is suited well for systems involving different physical domains. Other useful representations are equations, block diagrams and iconic diagrams.

Identification. In addition to analytical modeling, an analytical plant model can be obtained or verified by experimental modeling. In this case a finite number of data is extracted from the physical plant. Consecutively, several techniques are available, in both time and frequency domain, to identify models from these data. Identification techniques can also be used to estimate parameter values of the analytical model on the basis of measured data (Söderström and Stoica, 1989; Ljung, 1999).

Linearization and *reduction.* The resulting plant model often is too complex, *i.e.*, it may contain nonlinearities and higher-order terms that initially do not have to be considered for control system design. To obtain a suitable plant model, linearization (Kailath, 1980) can be applied and consecutively the resulting linear model can be reduced to an appropriate order (Decoster and van Cauwenberghe, 1976a; Decoster and van Cauwenberghe, 1976b; Wortelboer, 1994). This allows the application of analytical design methods for linear systems.

Controller design. Once specifications and a suitable plant model are obtained, the actual design of the control system can start. There are many methods for control system design (Levine, 1996). Which of the methods is preferable depends on the specifications, the plant model and the knowledge and experience of the designer.

Simulation and *evaluation.* To predict the behavior of the controlled system, simulations are performed with both the linear reduced-order model and with the full-order, nonlinear model. Using simulation results, frequency responses and other tools, the design of the controller is evaluated. Depending on the outcome, iterations will take place or the controller will be implemented.

Implementation. Once the design of the controller has been evaluated successfully, the control system can be implemented. In mechatronic systems the control system is generally implemented as a computer algorithm.

Remark 1.1

> *The implementation of the controller in a computer results in the interconnection of a continuous-time system with a discrete-time system. Due to sampling and quantization, this may have consequences for the dynamic behavior of the total system (Åström and Wittenmark, 1997). However, in this thesis we will only consider continuous-time controllers, which is justified when the discrete-time controller is implemented appropriately.*

1.2.2 Mechatronic design

Before a new system is ready for production, decisions have been made on how the system will function, what its components are, how its components will be produced and assembled, and many more. These decisions are part of the design process (Ullman, 1997). In the design process we distinguish the following steps:

1. *User specifications.* Give a rough description of the functions and properties of the product.
2. *Technical specifications.* Translate the user specifications into quantified technical terms and split up the overall functionality in subfunctions.
3. *Conceptual design.* Generate concepts that are to perform the different subfunctions and make a selection based on rough evaluations.
4. *Detailed design.* Generate physical embodiments of the selected concepts and make a rough selection, based on ample evaluation.
5. *Evaluation.* Perform thorough analysis of the selected concepts and designs and make a definitive solution.
6. *Documentation.* Make the complete documentation needed for the manufacturer of the prototype.
7. *α-test.* Manufacture and test each subsystem.
8. *β-test.* Assemble and test the complete system.

De Vries (1994) proposed a *model of designing*, in order to explain the applicability of design support on the basis of characteristic features of the design process and to predict what kind of support would increase chances for successful completion of the design process. Three characteristics of design were identified as crucial (De Vries, 1994):

- design is context dependent.
- design problems are ill-structured and incomplete.
- design involves a time-constrained initiation of change.

Therefore, we will view design as a *contextually situated evolutionary process*. This concerns the product being designed as well as the knowledge about the design problem.

The design and development activities in the design process are related to the field of *systems engineering*. This is not an engineering discipline in the same context as for example electrical and mechanical engineering, but it can be considered as “a process employed in the evolution from the point when a need is identified through the production and/or construction and ultimate deployment of that system for consumer use” (Blanchard and Fabrycky, 1990). This was recognized as essential in product or system design, because the engineering specialists in the underlying disciplines were not capable of considering the system as a whole. An important characteristic of systems engineering is that an *integrated approach* is employed to the design of the system as a whole. The purpose is to achieve a design that optimally uses the design freedom in all underlying disciplines. A desired functionality can be implemented in one or another physical domain or an imperfection in one part of the system can be compensated for by another part.

Generally, complex design problems are solved by separation into partial subproblems. Hence, one uses the fact that complex problems, like designing, are "ill-structured in the large, but well structured in the small" (Simon, 1973). Complex ill-structured design problems are split into small well-structured problems, to which local problems solvers are applied. However, the application of an integrated design approach complicates the design process, as domain specific subproblems should be solved by taking into account the consequences of a solution in other domains or by finding alternative solutions in other domains (figure 1.3). As these choices may have major consequences for the design, it is wise to make these choices early in the design process. Therefore, "the conceptual design task is of crucial importance when using an integrated problem solving approach" (De Vries, 1994).

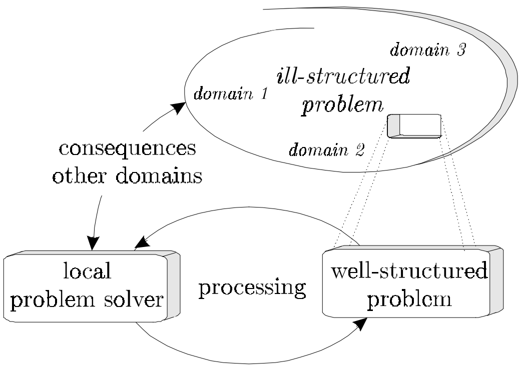

FIGURE 1.3 *Schematic structure of solving ill-structured problems (adapted from (Simon, 1973))*

In this thesis, the design of controlled electromechanical systems is considered. The application of an integrated approach to this multidisciplinary field is referred to as mechatronics. Mechatronics is defined in various ways; two useful definitions are:

Definition 1.1a Mechatronics

> *Mechatronics is 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).*

Definition 1.1b Mechatronics

> *Mechatronics is a synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes (IRDAC, 1986).*

The first definition stresses the fact that mechatronics considers functional interaction and spatial integration of subsystems. The second definition indicates that mechatronics is not a conventional engineering discipline or a technology, but a design approach. A more restrictive description, which is however suitable for our present concerns, is that "mechatronics encompasses the knowledge base and the technologies required for the flexible generation of controlled motion" (Van Brussel, 1996).

Mechatronics considers the design of controlled electromechanical systems as a whole, instead of a subsequent design of domain specific subsystems. Classical design patterns started with the design of the mechanical subsystem, followed by the design of electronics and finally the design of the controller. In order to obtain functional interaction and spatial integration, subsystem designs need to overlap, and hence simultaneous involvement of several disciplines needs to be realized in a coordinated way. Or, as Isermann (1996) states: "simultaneous engineering has to take place". The design process of controlled electromechanical systems with a mechatronic design approach is therefore generally more complex, but leads to systems with a superior price-performance ratio. Other credits that are claimed by mechatronic design are that it leads to more flexibility, higher performance, higher reliability and that it often opens up a new dimension to the product's operation (Hewit and Bouazza-Marouf, 1996). The application of mechatronics can even lead to the design of products that would have been impossible without this interdisciplinary and synergistic approach (Van Amerongen, 1998).

The complexity of today's products is often such that generally a team of people from diverse areas of expertise is required to transform an idea into a product (Ullman, 1997). Mechatronic design is teamwork; the specialists from the underlying disciplines that work in this design team must have the ability to look beyond the design problem within their own field, in order to profit from the advantages of mechatronics design.

1.2.3 Motion control in the mechatronic design process

This research is focused on a particular class of mechatronic systems:

Definition 1.2 Electromechanical motion system

> *An electromechanical motion system is an electrically actuated mechanical plant that requires the control of the position of the end-effector (figure 1.4).*

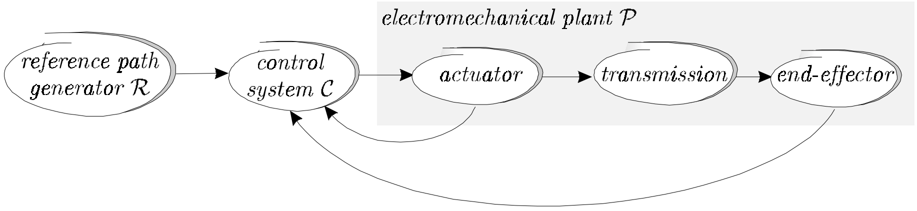

FIGURE 1.4 *Electromechanical motion system*

Characteristics of this class are that a path generator indicates a reference path for the end-effector. The actuator drives the end-effector through a transmission. The controller processes information from the (position) sensors that are generally located at the actuator and/or the end-effector, such that the desired behavior of the position of the end-effector is obtained.

Within this restricted class of electromechanical motion systems, we define motion control in a mechatronics sense:

Definition 1.3 Motion Control

> *Motion control is that part of the mechatronic design process that is concerned with the design and implementation of the control system $\mathcal{C}$ and the reference path generator $\mathcal{R}$ for the position of the end-effector of electromechanical motion systems.*

Control engineering, as one of the underlying disciplines of mechatronics, is concerned with the improvement of the dynamic behavior of complex technical systems conform the requirements. It is directed towards synthesis, using methods, techniques and tools from systems engineering and several other disciplines. Control theory is concerned with obtaining fundamental knowledge, by taking an abstract perspective, such that it provides a profound mathematical basis for practical application.

McClamroch (1998) assessed the conflict between the abstract perspective of control theory and the application perspective of control engineering: “The former views a control system in terms of abstract input-output equations or state equations and poses control questions in abstract terms. The latter takes a more concrete view and attempts to make use of the special physical features of such systems, both in forming control problems and in designing controllers. The control design approach associated with the former view attempts to formulate a standard mathematical problem that captures the important control design objectives. The latter view makes use of prior knowledge and experience with similar operational control systems together with extensive trail and error; moreover it often views control design as only a part of the larger issue of system design." The last statement corresponds with our view of mechatronic control system design.

In (Åström and Wittenmark, 1997) this conflict is described as "reconcile the large-scale, fuzzy, real problem with the simple well-defined problems that control theory can handle". This problem can be found in many engineering disciplines, but "control engineering is a field where a comparatively sophisticated theory is needed to understand problems" (Åström and Wittenmark, 1997).

The best approach is an integration of both perspectives. The abstract perspective of control theory offers many formalisms, methods and techniques for solving general (complex) control problems, while the physics-based application perspective of control engineering can exploit the context of the total system. McClamroch (1998) asserts that more attention needs to be given to achieving true integration of both perspectives.

When we want to achieve this integration of perspectives, a deep understanding of the practical design problem is required, in order to formulate the problem in abstract terms that control theory can handle. This deep understanding is also required to fully exploit the advantages of mechatronic design. Therefore, the elaborate trajectory for control system design has to be followed (section 1.2.1). Ideally, this is done during the design of the overall system, *i.e.* during mechatronic design. However, this trajectory can also be followed to improve the performance and robustness properties of an existing electromechanical system.

1.2.4 Design tools

The rapid technological developments and the continuing need for reduced time-to-market of new products demand more and more advanced design tools. Design tools are instruments that support parts of the design process and may exist in the form of methods, techniques and software. Successful application of mechatronic control system design requires proper design tools to handle complexity and to support the elaborate design trajectory.

Control theory provides a wide variety of methods for the design of controllers. Most of these methods are developed from a mathematical perspective and consider the plant as unalterable. Examples of these design methods are optimal control (Anderson and Moore, 1971; Kwakernaak and Sivan, 1972), Quantitative Feedback Theory (Horowitz, 1982; D'Azzo and Houpis, 1995; Houpis and Rasmussen, 1999) and H_∞ control theory (Doyle *et al.*, 1989; Kwakernaak, 1993; Zhou *et al.*, 1996).

There are only a few methods for the design of controllers for electromechanical motion systems that do look upon the design problem from a mechatronic perspective. These methods simultaneously consider the design of the controller and the plant. Examples can be found in (Groenhuis, 1991; Rankers, 1997; Koster *et al.*, 1999). However, these methods do not consider all aspects of control system design and are generally not sufficient on their own to obtain high performance.

For the design of modern control systems, the use of computer tools is indispensable. Such tools facilitate (automated) manipulations of the proposed design, allow to record and browse through relevant knowledge and experience, and document the process (Van Amerongen *et al.*, 2000). In the control community, Matlab and Simulink (MathWorks, 2000) are widespread tools for modeling, controller design, identification and controller realization. These tools do not provide specific support for problems of mechatronic control system design. “Because mechatronic design is a relatively young area, the level of support is below that of the individual domains that can be found in mechatronic systems” (Breunese, 1996).

It is our belief that design tools that are currently available can be enhanced to better support mechatronic design of control systems for electromechanical motion systems.

1.3 Problem statement and approach

Section 1.1 signaled an increasing need for electromechanical motion systems with higher performance and good reliability that are developed within shorter time. These demands can be partially met by the application of a mechatronic design approach, but at the cost of a more complex design process (section 1.2.2). Within this design process more attention needs to be given to achieving true integration of the abstract perspective of control theory and the physics-based application perspective of control engineering; moreover, the design of the control system should be considered as a part of the design of the system as a whole (section 1.2.3). To fully exploit the advantages of mechatronic design and of integration of perspectives, an elaborate and complex trajectory for the design of a control system has to be followed to obtain a deep understanding of the design problem (section 1.2.1 and 1.2.3). These requirements confirm the need for enhancement of existing design tools, in order to better support the design of control systems for electromechanical motion systems (section 1.2.4).

By contemplating the issues mentioned above, we define the aim of this research as:

Aim of Research

> *Enhance (mechatronic) design of control systems for electromechanical motion systems, such that insight in the design problem is obtained more easily, the control engineering skills required of the designer decrease and performance and robustness properties of the final design improve. As a result, the required development time should decrease.*

Figure 1.5 reflects the design paradox of Ullman (1997) and visualizes our aim of research. Design enhancement should increase the amount of knowledge about the design problem early in the design process, when there is still considerable design freedom. Consequently, better founded design decisions can be made and the development time decreases.

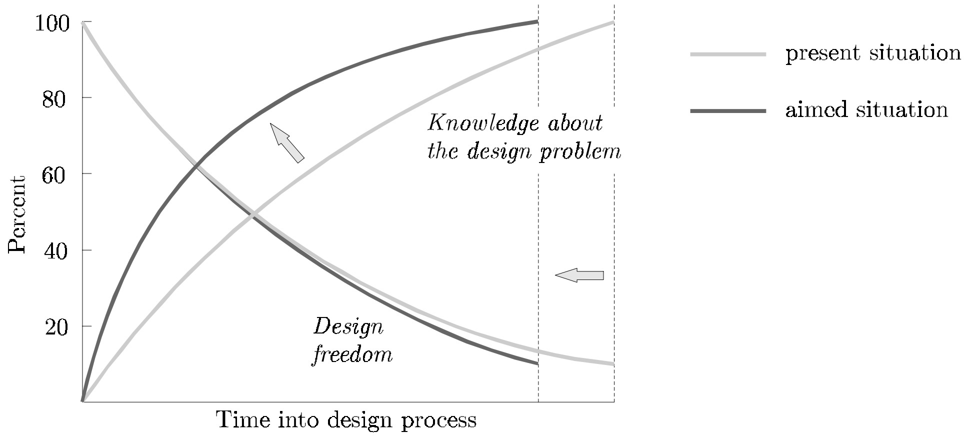

FIGURE 1.5 *Objectives of design enhancement*

From the model of designing De Vries (1994) identified three ways to enhance designing:

1. formalize design knowledge.
2. automate activities on the basis of formalized design knowledge.
3. incorporate formalized knowledge and automated activities in computer-based systems that are helpful in design practice.

We will use this approach in order to reach our aim of research. We will address two distinct stages in the design process, *i.e.* conceptual design and detailed design, as these stages concern design problems with different characteristics, designers work in different ways and different kinds of design support are required. In order to evaluate the (automated) design enhancement, we will consider the design of a control system for the PM module of the FCM as a practical application.

1.4 Outline of thesis

In chapter 2 we will address *conceptual design*. First, we shortly describe the specific problems in this design stage. Standard situations will be classified in different forms. An existing design method, appropriate for a restricted class of systems, is modified such that it is applicable to other classes as well. Finally, the modified design method is used to develop computer-based support, which includes design automatons for model simplification and model reduction.

In chapter 3 a framework for the *detailed design* of motion controllers is proposed. This framework will guide the designer from the conceptual design towards a final design in a structured way. Gradually, more disturbances, uncertainties and nonlinearities are incorporated in the plant model while the control system is extended with appropriate functionality. For the control system we use a standard configuration that contains a reference path generator, a feedback component, a feedforward component and a disturbance observer. Computer support for detailed design is provided as a 20-sim library (Controllab Products, 2000) containing standard templates and components for control system design.

During detailed design, one may have to deal with physically motivated plant models that contain *uncertain physical parameters*. In chapter 4 we argue that Quantitative Feedback Theory (Horowitz, 1982) is an appropriate controller design method in these situations. However, before being able to apply QFT, the designer has to construct uncertainty regions in the Nichols chart (templates) and has to convert time-domain specifications into the frequency domain. These are not straightforward tasks. In chapter 4 we will review several template construction methods and we will formulate a procedure to convert the specifications. The result will be an automated design tool, which uses 20-sim (Controllab Products, 2000) and the Matlab QFT toolbox (Borghesani *et al.*, 1994), that supports the design of a control system, given time-domain performance specifications and a plant model with uncertain physical parameters.

Chapter 5 discusses the practical *application* of the proposed design enhancement. We present a design of the control system of the PM module of the FCM, which has been introduced in this chapter.

In chapter 6 the design enhancement and experimental results are discussed. Finally the conclusions are drawn.