1 Mechatronics Education

Job van Amerongen

† University of Twente

1.1 Introduction

A search at the internet for 'mechatronics education', yields many hits with information on many forms of academic mechatronic programs. They range from BSc to MSc programs as well as integrated four- or five-year programs. Sometimes there is a clear philosophy behind this choice, but often it is based on the local culture or possibilities. Several mechatronic programs seem to be based on just adding courses on electronics, PLC's and logic circuits to an existing ME curriculum. But mechatronics is more than just 'a controlled mechanical system'. Mechatronic design is 'the integrated and optimal design of a mechanical system and its embedded control system where solutions are sought that cross the borders of the different domains'. An integrated view on the system as a whole is needed in order to come to such a design. In addition to knowledge of the different components, a system overview offered by a proper interdisciplinary model of the system is essential. The curriculum should pay explicitly attention to this. Real mechatronic systems lead to out-of-the-box thinking and complete new products, which could not have been realized in a single domain. The optical disc, for instance, achieved its superior performance, among others, by replacing the need of accurate speed control, by an electronics-based clock. This was a revolutionary new approach which resulted in superior sounds. Without its embedded stabilizing controller a device like the Segway would be useless. But with this controller it is not only stable: a superior maneuverability is achieved in comparison to a mechanically stable device with more than two wheels. Any real mechatronics program should be based on a philosophy of obtaining synergy by an optimal combination of mechanics, electronics and information technology.

In this chapter we will discuss several forms of mechatronic programs in curricula of the University of Twente of the past 20 years. Many students have been educated in different forms of educational programs (van Amerongen, 2004). Changes in programs were often triggered by changes in the structure of university education, nation wide or even Europe wide. E.g. since a few years all universities in the EU are expected to offer academic education in the form of BSc and MSc programs.

1.2 Historical context

The University of Twente is explicitly active in the field of mechatronics since 1989. In 1989, after obtaining M€ 1.25 of extra funding from the Ministry of Education, five groups in the faculties of Electrical Engineering, Mechanical Engineering, Applied Mathematics and Computer Science started cooperation in the Mechatronics Research Centre Twente (MRCT). Cooperation between people from different disciplines is not always obvious but in the University of Twente it was relatively easy. The university started in 1964. In the beginning all departments shared a common first year that provided a broad program to all engineering students. Even after this common first year was abounded, it was good practice to have a representative of another department in the committee that guided and finally judged the thesis work of students. This close cooperation between staff members of the various faculties led to a good knowledge of each others activities and a lot of interaction. It has been the basis for many multi- and interdisciplinary research activities, now concentrated in a number of research institutes. In order to come to a real cooperation also good personal relations are crucial. In the early years of the MRCT the group leaders of the different participating groups visited Japan and the USA to see the state of the art of mechatronics in those countries. In addition to attending conferences, visits to mechatronic industries and universities were made. These visits not only gave us a good overview of the state of the art of mechatronic-like activities in Japan and the USA, but travelling as a group during four weeks in total, highly contributed to creating a team of the members of the different departments.

In order to learn what mechatronics was all about the MRCT used a major part of the extra funding to start a large research project (the MART project), involving four PhD students and many MSc projects in 1990. The idea was to build an advanced mobile robot that should be able to gather components from part-supply stations and assemble these components while driving around in a factory (Figure 1).

Figure 1 The MART robot

Apart from the aspect of being an attractive solution for flexibly building many variants of a product or a variety of products, the goal of this project was to learn and demonstrate a mechatronics approach in an interdisciplinary project. At about the same time a part-time professor in mechatronics was appointed for two days per week in the Faculties of Electrical as well as Mechanical Engineering. He had a lot of experience with mechatronic applications in industry, where he continued to be active the rest of his time. He acted as the project leader of the MART project. In a period of about 5 years, 4 PhD and approximately 50 MSc students did their thesis work in this project. Students from electrical engineering, mechanical engineering and computer science worked together in one project room. This alone has contributed to learning students with a basic education in their own field the language from other disciplines and to work together in a project with a clear systems approach. This means that not the best solution for an isolated problem could be sought, but that the consequences for other parts of the design and for the system as a whole had to be taken into account all the time. As a result, the mobile robot was completely realized (Schipper, 2001). It had many advanced features in the field of mechanical constructions and control such as an adaptive preload system to reduce friction and backlash (Kruijer, 1992), learning control (Starrenburg et. al., 1996), parallel computing, autonomous navigation (Oelen and Van Amerongen, 1994, De Graaf, 1994) etc. For many of the students working in this project it was the start of a career in mechatronics. More about this project can be found in Van Amerongen and Koster, 1997 and in a video, available at the web (See references: MART video). One of the PhD students started a successful mechatronic company and states that a large part of his network in the mechatronic community in the Netherlands consists of students and colleagues who were active in the MART-project.

Curriculum developments are often a result of changes in educational systems or funding sources. Since the start of the mechatronics activities in 1989, the University of Twente has offered mechatronics education in the MSc programs of EE and ME, for several years in the two-year post graduate 'Mechatronic Designer' program and again in the MSc programs of EE and ME. Since 2001 the University of Twente offers a two year international MSc program in Mechatronics. In the same year the university transformed its study programs to the new European BSc/MSc structure including an (English language) MSc in Mechatronics. In September 2004 the international MSc program merged with this MSc Mechatronics program.

The mechatronics activities of the University of Twente now range from education in the new BSc/MSc structure to research activities in PhD projects. In addition, there have been a number of projects that aim at supporting the industry in developing mechatronic skills or producing advanced mechatronic systems by means of knowledge transfer. One of these was the Mechatronics Innovation Center, subsidized by the Interreg III program of the EU and intended to transfer knowledge from the university and a Fachhochshule in Germany to small and medium sized enterprises in the border region (Euregio) of the Netherlands and Germany.

We believe that mechatronics, dealing with 'the integrated and optimal design of a mechanical system and its embedded control system' can only be performed well in an environment where mechanical and electrical engineering and information technology are combined in a synergistic cooperation. Section 2 goes further into detail on the educational activities.

2 Curriculum

There are several possibilities and examples of mechatronics programs. The simplest option is to add some elements of the other discipline into existing EE or ME programs. Often these elements are already there. But they can be made explicit by means of a project where some mechanical structure has to be built and controlled by a computer-based control system. A modern ME program simply needs to contain elements of electronics and computer-based control anyhow. Many universities have this type of projects and they are highly appreciated by the students because it is fun to work on such projects. Mechatronic projects can be well done in a BSc program. MSc programs in EE and ME which are flexible enough with respect to the elective courses that can be chosen by the students, allow for a lot of mechatronic content as well. But, unless there is some pre-structuring of these electives, there is no guarantee that a well balanced program is the result. Also the required basic knowledge, necessary for successfully following advanced courses may be missing. Therefore, a real mechatronics program is desirable.

The other obvious thing to do is PhD projects of a mechatronic nature. During a PhD project there is ample time to work on an interdisciplinary project. Finally specific BSc, MSc or combined BSc and MSc programs in Mechatronics can be designed.

It is hardly possible to say if there is a preference for a BSc, MSc or integrated BSc-MSc program in mechatronics. A choice is often influenced by local circumstances and regulations. It is a choice between a broad multidisciplinary basic education and specialization at the end or a more mono-disciplinary basic education followed by a broader scope at the end. One thing is clear however, a mechatronic designer should have a wider and consequently less deep scope of his knowledge than a specialist studying in a mono-discipline (Figure 2).

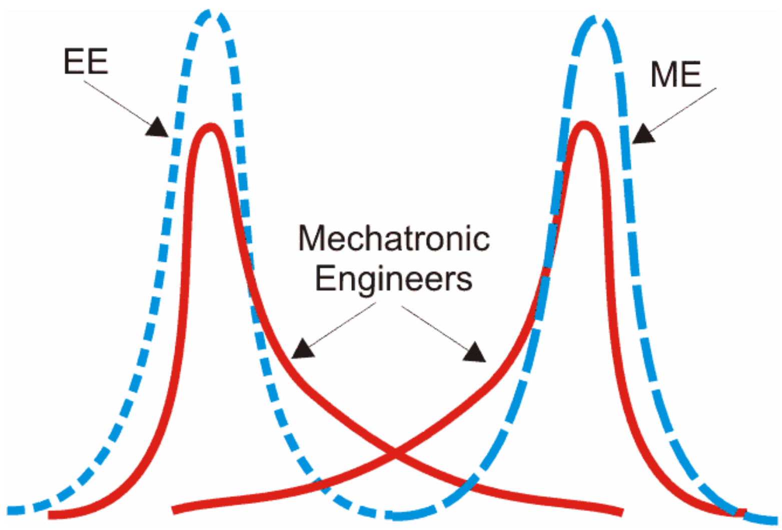


Figure 2 Mechatronic Engineers lack some depth in their 'original' discipline, but have broader knowledge of the other disciplines.

2.1 Mechatronic Designer program

During the 1980's the Dutch government decided that it should be possible to complete an MSc degree within four years (instead of five), also in the technical disciplines. This was intended to be a final degree for 60 percent of the students. The other 40 percent were supposed to continue their education in a four-year PhD-program or in a two-year Technical Designer program. A two-year ‘Mechatronic Designer’ program was started as a result of these developments. In this program the first year was filled with courses to obtain knowledge of the other discipline and deepen the theoretical knowledge while the second year was completely devoted to a design project in cooperation with industry. This program has produced several successful mechatronic designers and led to design results which were really implemented in industry. Some of these mechatronic designers successfully run a company now. Of course the four-plus-two curriculum allowed more time for mechatronic content than the typical three-plus-two BSc-MSc sequence. After a few years, because of a lot of pressure from the technical universities, the five year program came back again. For students the two extra years of the designer program lost a lot of their attractiveness. This was the end of the Mechatronic Designer program at the University of Twente, although it was continued at Eindhoven University of Technology for some time. Mechatronic education continued as a specialization in the MSc programs of the faculties of EE and ME.

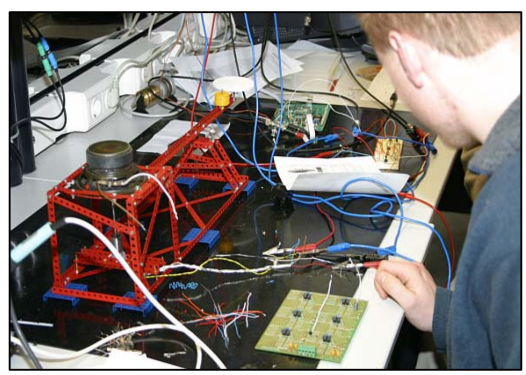
2.2 Bsc curriculum

A BSc curriculum either in EE or ME, offers ample opportunities to pay attention to the mechatronics design approach. Such an example of a system’s approach is attractive for all EE and ME students, even if they continue their study in other topics. The EE curriculum at the University of Twente offers a broad education in all aspects of electrical engineering and contains, among others, courses in mathematics, physics, electrical networks, electronics, electrical power engineering, linear systems, modeling and control. In each semester a number of closely related courses are offered. When electrical networks are taught, this goes in close relation with courses in mathematics needed to properly teach electrical networks. In a similar way courses on mechanics, transduction technology, measurements and instrumentation, linear systems, dynamical systems and control engineering are programmed closely together in the second half of the first semester and in the first half of the second semester in the second year. This series of courses is concluded with a two-week ‘mechatronics project’ that integrates the theoretical knowledge taught during the courses. The project is supervised by the lecturers of the different courses, aided by PhD-students and student assistants.

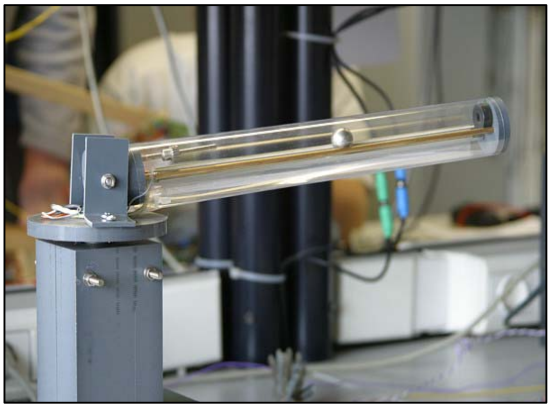
Before going into detail on the project itself, we will focus a bit on the contents of the courses dynamical systems and control engineering. In the course dynamical systems students learn to analyze and model physical systems in various domains. Emphasis is on electrical and mechanical systems. By using a port-based approach, modeling in various domains is relatively easy and the relation with the physical reality is maintained and not hidden by abstracting the models to block-diagram-based input-output models. This modeling approach is supported by the 20-sim software package (See section 3). This course builds on previous courses on linear systems, electrical networks, electromagnetism and mechanics. It forms a link between the more physical-oriented approach of the courses on electromagnetism and mechanics and the more mathematical and signal-oriented courses in electrical networks and linear systems. The course control engineering is given closely integrated with the modeling course and uses mechatronic systems as examples of the basic theory (stability, root loci, bode, nyquist, state space, non-linear systems and introductory digital control).

The planning of the mechatronics project is as follows. At day one of the project teams of four students get a transducer in the form of e.g. a motor, piezo element, loudspeaker, voice coil etc. Often these transducers can be used as an actuator and a sensor as well. During three days this transducer should be properly described by analyzing its operation principles and by measuring its relevant properties (integration of knowledge from the courses mechanics and transduction technique, measurement and instrumentation and dynamical systems). Because of its application later on in the project, the dynamics of the transducer should get special attention. A well-equipped lab is available to the students (Figure 3). Each team gets a lab space and a set of equipment consisting of a PC with software like Labview and 20-sim (see Section 3), function generators and power supplies, an oscilloscope, and so on. Instruction material about planning of the project, datasheets and diagrams for possibly needed electronic circuits, are made available at the project website. Based on the characterization of the transducer the team has to make a proposal for a mechatronic system, built around the transducer where in general a motion has to be controlled. The proposal should be based on an analysis of the dynamical properties of the total system and the possibilities to control its behavior.

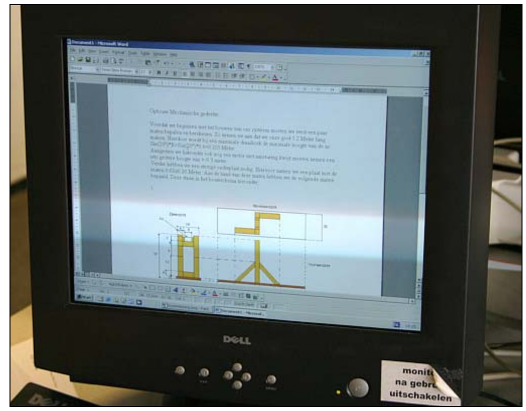
lab space



building a setup



finished design



draft report

checking of setup by supervisors

Figure 3
Impressions of the mechatronics project

After approval of the design and comments on the proposal by the supervisors the feasibility phase starts (three days). This includes making a dynamical model, design of one or more (digital) controllers and simulation of the controlled system. Nothing is really being built in this stage of the design, although it is encouraged to investigate the feasibility of the proposed solutions with test setups. During the feasibility study ideas can be discussed with the supervisors of the project. The feasibility phase ends with a written proposal that should clearly demonstrate and motivate why this design will lead to a working mechatronic system. This analysis should be confirmed by a computer simulation of the proposed design in 20-sim.

After approval of the feasibility study, the rest of the second week of the project is spent on building the system and finally giving a short presentation to all the supervisors. For the realization phase students have access to basic electronic components and mechanical construction material. In addition, they get a small budget of 50 euros to enable them to buy additional parts or materials for their setup. Care is taken that such parts do not have more than one day delivery. They may also use the mechanical workshop to construct certain mechanical parts they may need. For the realization phase empty printed circuit boards for making analog circuits with operational amplifiers are available as well as a DSP-board for realizing the digital controller (Figure 4).

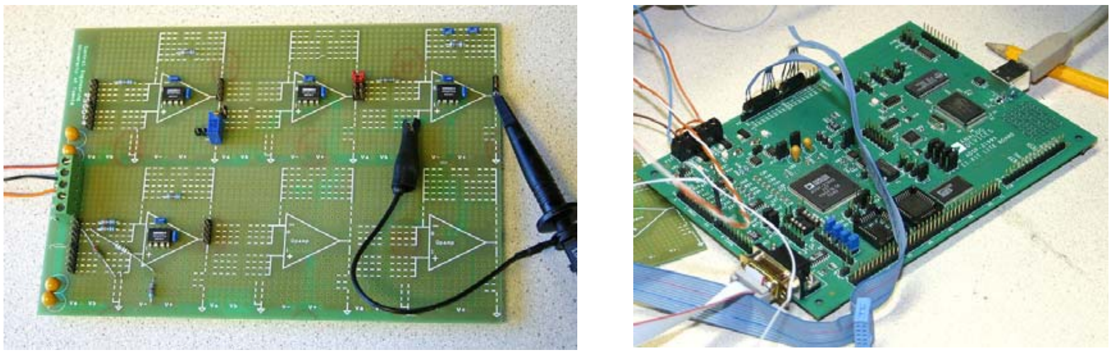


Figure 4 Analog board (left) and DSP board (right)

This DSP-board can be programmed by automatically generating code from the 20-sim simulation environment and downloading this code from the simulation PC to the processor board (Jovanovic et. al. 2003). The DSP boards are not hidden in a protective case. The first reason is that the case with connectors would be probably more expensive than a new board and the second is not to hide the technical content of the board in a 'black box'.

The project ends with a short presentation to all the supervisors on the last day of the project. At the same time a written report should be ready. All teams are judged based on the quality of the design as presented in the presentation and in the written report, on the quality of the presentation as such and the quality of the report. Figure 3 gives some impressions of the project. A video of some of the setups is available as well (Mechatronics project video).

During the years there have been various forms of the project. In the beginning students were completely free in the choice of transducers and type of setups. This led to a wide variety of setups. Later the transducers were provided and any setup could be proposed as long as the transducer was used. Recently all students were asked to construct a 'balancing stick' (say a Segway-type of setup). All these approaches have their advantages and disadvantages. Because there is only limited time for the project (two weeks full time) there is always a tendency to structure the project such that the learning goals: integration of the corresponding courses and coming to a working setup, are achieved. But more structuring does not stimulate creativity. There should always be space for creative proposals from students that do not strictly fit into the set boundary conditions.

In the third year of the BSc program of Mechanical Engineering there is also a mechatronics project. This project integrates a number of courses from the ME curriculum, such as Applied Electricity, Systems and Control, Measurements in ME and Dynamics. Focus is on the design and realization of a mechanism with structural flexibilities and computer-based control of this mechanism. Actuators, mechanisms, modal analysis, sensors and control systems are the keywords of this project.

During the workshop on Workshop on Higher Education in Mechatronics at the AIM conference in Zurich (2007) several universities presented other realizations of mechatronic projects (Braghin - Politecnico di Milano, Carryer - Stanford University, Forlani - University Of Bergamo, Mondada - EFPL Lausanne, Romano - U.S. Naval Postgraduate School, Siegwart - ETH Zurich, Nelson – ETH Zurich). Also the Mechatronics project at the University of Loughborough is well known (Parkin, 2002).

2.3 MSc curriculum

The MSc Mechatronics curriculum is a two year curriculum offered by the departments of EE and ME. It starts with a homologizing phase where students with an ME background get courses in electronics and signals and systems, and former EE students get courses in e.g. mechanical constructions and finite elements (See figure 5, left two tracks). In the next phase students follow compulsory courses on Construction Principles, Design of Mechatronic Motion Systems, Digital Control Systems and Measurement Systems for Mechatronics. The list of courses is completed by a number of elective courses. Students from Dutch universities have a compulsory internship in industry, preferably abroad. International students do some extra courses instead (See figure 5, right track). The study is completed by a 25 weeks MSc project. The program is open for students from Dutch universities with the appropriate BSc education and, after an admission procedure, to qualified students from abroad. If possible, the international students are given the chance to do their MSc project in cooperation with industrial partners or in industry. More information on this program can be found at the internet (see link Mechatronics education Twente).

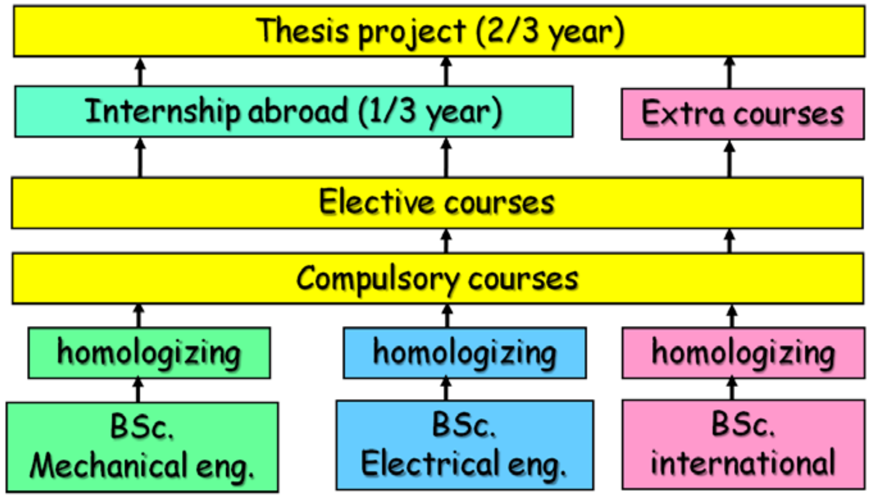


Figure 5 Structure of the Mechatronics MSc curriculum

3 Modeling of mechatronic systems

Modeling and simulation plays a crucial role in mechatronic design and should therefore get a good attention in the curriculum. The Control Engineering group of the University of Twente has been pioneering in modeling software and as a result of these activities the group developed already in the 1960's the simulation program THTSIM, that later got used all over the world as TUTSIM. A complete new program became available under the working name CAMAS (Broenink, 1990). It supported a port-based modeling approach (in the form of bond graphs), which is important for modeling physical systems that extent over various domains. It was successfully further developed into a powerful tool for modeling, analysis, simulation and design of mechatronic systems (Van Amerongen and Breedveld, 2002, 2003). Since 1995 the program is commercially available from the company Controllab Products under the new name 20-sim, pronounce: Twente-sim (See references 20-sim). It is now widely used in educational institutes and industry. Based on results of ongoing research projects, the program is continuously further improved and extended with better modeling and simulation algorithms and new functionalities.

Because a mechatronic system at least involves the mechanical and electrical domain, standard modeling packages that work in one domain only are not always useful for mechatronic design. Block-diagram-oriented packages like Matlab and most other simulation packages, lack the direct link with the physical reality. Parameters tend to be combinations of the physical parameters of the underlying model. In addition, models cannot easily be modified or extended. By connecting ideal physical models to each other through power ports, models can be built that are close to the physical world they should describe. This allows that instead of unilateral input-output relations, bilateral relations are described. The model equations are not given as assignment statements, but as real mathematical equations. In addition, a small modification or extension of the model does not require that all the equations that describe the model be derived again. The properties of a component may be changed, as long as the interface remains the same. This allows that sub models of different complexity be evaluated and tested (polymorphic modeling). A variety of presentations (multiple views) allows that an appropriate view can be generated for all partners in a mechatronics design team, whether this is an iconic diagram, bond graph, block diagram, control engineering representation, time response or 3D-animation.

An important feature of 20-sim is its ability to generate C-code from the models used in the simulator. It is, for instance, possible to generate code of a controller that has been tested in a simulation environment and download the code to some target hardware. By using templates for the specific hardware environment, a flexible solution is offered that enables code generation for a variety of target hardware. An example is the DSP board shown in Figure 4. More on the use of this port-based modeling approach for the design of mechatronics systems can be found in Van Amerongen (2002) and Van Amerongen and Breedveld (2003).

A motor selection wizard has been recently added. It couples a database of commercially available servo motors to the modeling and simulation environment of 20-sim. After specifying the demands with respect to the performance of the controlled system a motor is proposed to the user. This motor can be further examined with respect to its dynamic behavior, heat production and so on. An impression of the relevant screens is given in Figure 6 and Figure 7.

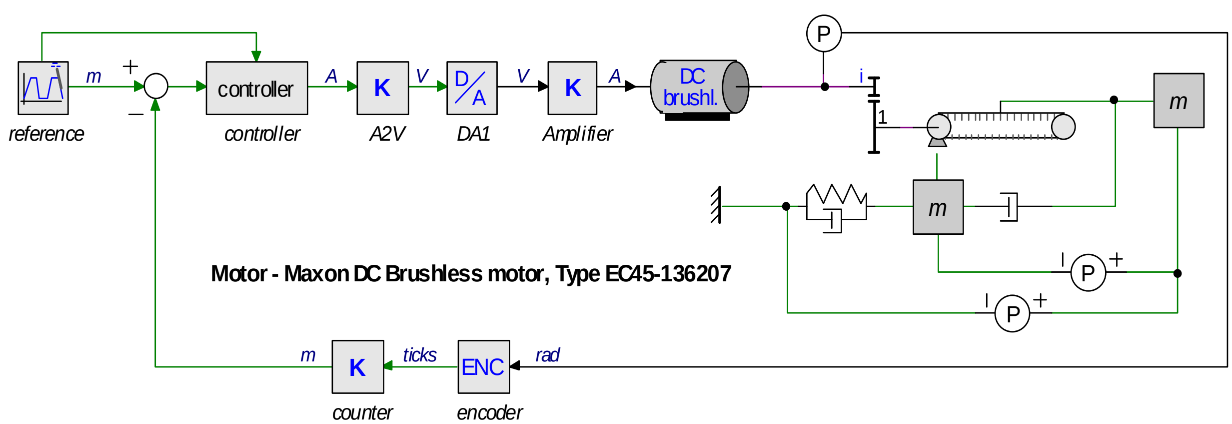


Figure 6 Model of the mechanical setup, actuator and controller used to examine the performance of the selected motor

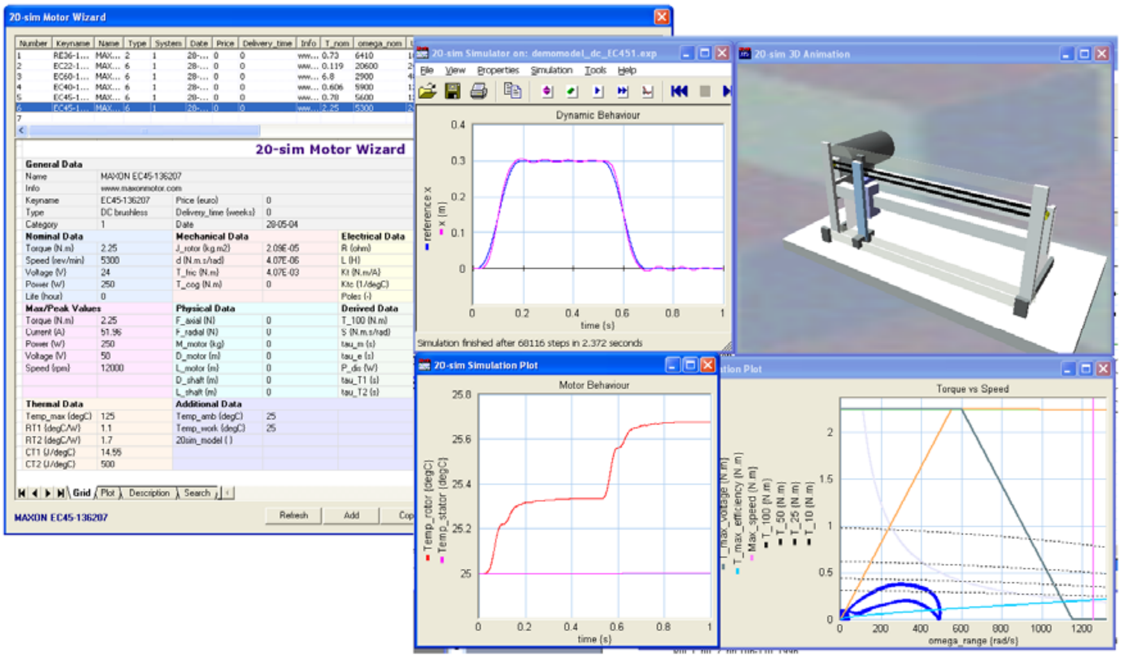


Figure 7 Screen dumps of the motor selection wizard and some screens, showing the behaviour of the controlled system, including the temperature change and a 3D animation

Besides from showing a useful tool for mechatronic design, this example demonstrates the multiple view feature of the software. Time responses, static diagrams, as well as 3D animations reveal different aspects of the system under investigation and may appeal to other members of the design team. Changes are reflected in all domains simultaneously. This contributes to real mechatronic design.

4 Conclusions

This chapter has given an overview of several forms of mechatronic programs. A general conclusion is that a good basic education in mechanical or electrical engineering followed by a mechatronics curriculum produces mechatronic engineers that have proven to be valuable in industry. Of course the need from industry depends on the type of industry. In the Netherlands there are few large players in the area of mechatronics. Companies like Philips (inventor of the CD player) or

ASML (world leader in wafer steppers) produce advanced mechatronic equipment. They need specialists and system integrators working in teams. Of course smaller companies that cannot afford such teams, require people with a broader education, able to deal with mechanical as well as electronic and IT issues.

In all cases a mechatronics curriculum should pay attention to teaching the languages of the different disciplines. Modeling and the possibility to present the ideas of the modeling process in multiple views is an essential part of this. Essential knowledge that every mechatronic engineer should have is in basic mechanical engineering topics such as:

- construction principles
- statics and dynamics
- design methods
- finite element modeling

in topics from electrical engineering like:

- electrical networks
- digital and analogue electronics
- signals and systems
- embedded signal processing
- sensors and actuators

and of course in topics like

- modeling of dynamical systems
- control engineering

In addition, courses which go more into depth in e.g. optimal or robust control or focus on applications such as e.g. biomechatronics as well as non-technical courses may be selected. An important element in mechatronics education should be to let the students work in multidisciplinary teams. This can be done as part of the compulsory courses, as in a ‘mechatronics project’, but should also be present in the individual projects such as a thesis project of sufficient length.

Mechatronics always involves input from disciplines like electrical and mechanical engineering. This appears not always to be easy. At workshops on mechatronic education, people complained about problems with departments that did not allow EE students to select ME courses or vice versa. Such problems can be solved by setting up a new mechatronics curriculum. But most important is the attitude of the people involved and the willingness to really cooperate.

Is there a need for ‘mechatronic engineers’? Yes there is. Higher precision, more flexibility and reduction of the cost of mechanical devices and new functionalities can only be achieved by integrating intelligent electronic control systems and embedded computers in the mechanical construction. People trained in systems thinking and able to find solutions that cross the borders of different domains are increasingly essential for making advanced, competitive products.

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