15 YEARS OF EXPERIENCE WITH MECHATRONICS RESEARCH AND EDUCATION

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Abstract

This paper describes the experiences with mechatronic research projects and several educational structures in the University of Twente since 1989. Education took place in a two-year Mechatronic Designer programme, in specialisations in Electrical and Mechanical Engineering and in an (international) MSc programme. There are two-week mechatronic projects in the BSc curricula of EE and ME. Many of the PhD and MSc projects were done in projects sponsored by the industry or by application-oriented research programs. Research topics included modelling and simulation (learning) control, embedded systems and mechatronic design.

1 Introduction

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 general first year was abounded, it was common 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 departments 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. Besides attending a conference, visits to mechatronics industries and groups in universities were made. In Japan we observed an awareness of the mechatronic design philosophy, although not always fully practiced. In the USA we had to explain several times what we understood under ‘mechatronics’. “You mean motion control”, was a common reaction. These visits not only gave us a good overview of the state of the art of mechatronic-like activities in the USA and Japan, but travelling as a group during four weeks in total highly contributed to creating a team of the members of the different departments.

2 Historical developments

In order to learn what mechatronics was all about the MRCT used a major part of the extra funding to start in 1990 a large research project (the MART project), involving four PhD students and many MSc projects. 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. 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 prof. Koster was appointed part-time professor in Mechatronics for two days per week in the Faculties of Electrical as well as Mechanical Engineering. He had a lot of industrial experience in Philips Centre for Industrial Technology, 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 systems as a whole had to be taken into account all the time. As a result the mobile robot was completely realised (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 (Kuijer, 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 the technical details of this project can be found in Van Amerongen and Koster, 1997 and in a video, available at the web (MART video).

Developments are often a result of changes in educational systems or funding sources. During the 1980's the Dutch government decided that it should be possible to complete an MSc degree within four years, 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-programme or in a two year Technical Designer programme. Although these numbers were never realised, the Mechatronic Designer programme that was started as a result of these developments was very successful. (See section 3.2). At the time, entering a two year designer programme enabled a student to escape from the military service. When the compulsory military service disappeared, and the government finally realised that a technical study could not be completed in four years, the five year programme came back again and two extra years in the university lost a lot of its attractiveness. This was the end of the Mechatronic Designer programme 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 programmes of the faculties of EE and ME. Since 2001 the University of Twente offers a two year international MSc programme in Mechatronics. In the same year the university transformed its study programmes to the new European BSc/MSc structure including an (English language) MSc in Mechatronics. In September 2004 the present international MSc programme will merge with this new MSc Mechatronics programme.

In the 1990's there was a strong tendency in the University of Twente to organise the research in interdisciplinary research institutes. As a result in 1998 the MRCT got a more formal status in the form of the Drebbel Research Institute for Mechatronics. The research mainly takes place in PhD projects. Several of these projects are carried out in an interdisciplinary context. BSc and MSc students are also involved in this research when doing small or larger individual projects. Now, more than five years later, research is even more concentrated in a small number of large institutes. The multidisciplinary character of mechatronics involves that there are links with almost all of these institutes. They range from applications of information technology in pure mechanical systems to applications in biomedical systems and to applications in micro-systems technology. Therefore it is expected that in the near future the Drebbel institute will be converted back to a more informal cooperation like the MRCT, but with new participants from different institutes that have in one way or another a link to the growing application area of the mechatronic design philosophy

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 are a number of projects that aim at supporting the industry in developing mechatronic skills or producing advanced mechatronic systems. 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 3 goes further into detail on the educational activities and Section 4 on some of the research projects. Section 5 describes the links with the industry.

3 MECHATRONIC EDUCATION

There are several mechatronic programmes offered at universities worldwide. These programmes range from complete programmes to shorter programmes, following a BSc or even an MSc programme. Also mechatronic components have been introduced in Electrical and Mechanical Engineering programmes. Mechatronic projects are in general considered as motivating elements of a study programme, also for students who are more interested in other topics. Here we will shortly discuss the various mechatronic programmes that run or have run in the University of Twente.

3.1 Projects in the BSc curriculum

Mechatronic projects are stimulating for students in electrical as well as in mechanical engineering. As an example, a description will be given of the mechatronics project of the BSc programme in Electrical Engineering. The second trimester of the second year is filled with courses like linear systems mechanics and transduction technology, measurements, modelling and simulation of dynamical systems and control engineering. In order to integrate the knowledge taught in these courses there is a two-week project at the end of the trimester. Students work in teams of four. Each team is provided with 'a transducer' and is asked to build a mechatronic system with this transducer. In many cases the transducers can be used both as a sensor or actuator. They may use all kinds of other construction material available (e.g. Lego or meccano) as well as other sensors and actuators. They get a budget of 50 Euro to buy not standard available components. For each team standard measurement equipment such as a multi-meter, oscilloscope and signal generator are available as well as a PC with Labview. On the PC they can run the modelling and simulation package 20-sim (see Section 4 for a short description of this package) as well as word-processing software for reporting. 20-sim can be used for analysis of the system design, for controller design as well as for automatic generation of C code for the digital controller that may be necessary in the systems. The controller code can be downloaded into a DSP board that is available for each team to test the digital controller (Figure 1) (Jovanovic et.al., 2003). An (empty) printed circuit board is provided for easy interfacing the DSP with the rest of the system by means of analogue circuits with operational amplifiers.

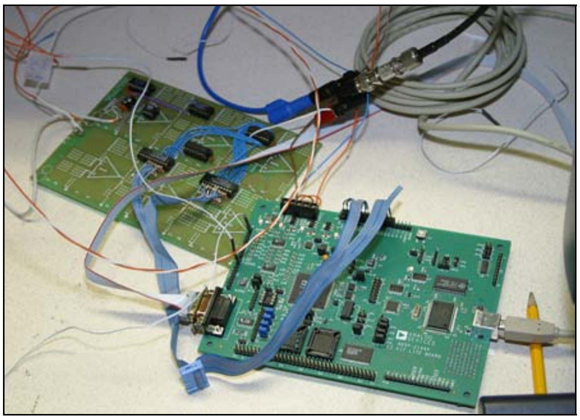

Figure 1

Op-amp board and DSP board. The DSP board can be loaded with C-code, automatically generated by 20-sim

The project starts with half a day introduction and last two full two weeks. After two days a plan has to be delivered that is judged by the supervisors (teaching assistants and staff from the various groups involved in the project). After approval of the plan a more detailed plan, including simulations and detailed characterization of the components in the setup to be build has to be completed. At the end of the first week this plan is judged again by the supervisors and only after approval of this plan the construction of the various parts of the system may start.
Students like the project and sometimes impressive setups are being realized. An impression is given in Figure 2. Also in ME a mechatronics project is carried out as part of the BSc programme embedded in a problem guided learning structure.

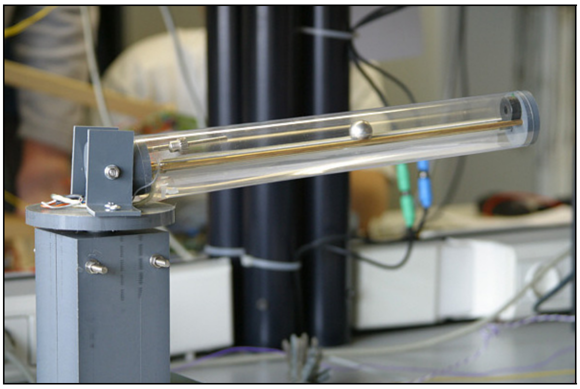

Figure 2

One of the setups realized in a recent mechatronics project

3.2 Mechatronic Designer programme

Traditionally the academic engineering education in the Netherlands consisted of a five-year programme leading to an MSc degree. During a number of years a four-year programme was offered. 40% of the students were supposed to follow an additional two-year designer programme or a four-year PhD programme. During this period the University of Twente offered a two-year Mechatronic Designer programme, later followed by the other two Dutch technical universities. The first year was filled with courses intended to teach graduates from mechanical engineering some essential topics from EE and electrical engineering graduates, some essentials from ME. A number of advanced courses deepened the knowledge in topics relevant for mechatronics, including some non-technical courses. The second year was completely filled with a design project, preferably with an industrial partner. Many interesting projects were carried out in this period. The projects with industry clearly demonstrated that the graduates of this programme were indeed able to get impressive results with sometimes complex mechatronic projects:

- in a project with Philips two students developed a small AC servo motor that could simultaneously rotate and translate. It was intended to place SMD's on a printed circuit board. A third student developed a laser welding system that could weld the leads of the SMD as a replacement for the, from an environmental perspective less attractive, conventional soldering (a video of this ALASCA project is available).
- with Unilever Research in Vlaardingen several projects were carried out for designing advanced handling and packing devices for the food industry.
- building on the experience of the project with Philips, an aseptic pump for the food industry was developed. It consisted of a cylinder with a piston for pumping the fluids. The AC-motor was completely integrated with the piston. A control system was developed and implemented that could accurately dose the amounts of fluid.

All these projects were carried out in a competitive environment. Industrial teams worked on similar projects and not always with better results.

The Mechatronic Designer programme stopped when the educational system changed from a four-year programme to a five-year programme again. Mechatronic thesis projects continued, especially for the EE and ME students as specializations in the programmes of ME and EE. Because less time was available the mechatronics content of these specializations was considerably lower than in the Mechatronic Designer programme.

3.3 MSc Mechatronics

The new European BSc/MSc structure offers new possibilities for a proper Mechatronics programme. Since 2001 the University of Twente offers an (international) MSc programme Mechatronics taught in English. Candidates are admitted after a rigorous selection. From September 2004 on the international programme will be incorporated in the new two-year MSc programme Mechatronics. The programme will be tailored for each individual student and will consist of the following elements:

- removing deficiencies
- homologizing phase
- courses to deepen the knowledge
- elective courses
- thesis project.

The first year starts with the homologizing phase (1 trimester) where deficiencies for the Mechatronics programme are being removed. Students with a BSc in EE will follow ME courses and students with a BSc in ME will follow EE courses. For graduates from polytechnics an extra trimester is compulsory, mainly filled with mathematics courses. The second trimester is filled with compulsory courses such as:

- digital control
- introduction to system identification
- measurement systems for mechatronics
- mechatronics
- advanced motion control
- embedded control systems

The last trimester of the first year is filled with elective courses. For students with an undergraduate education of a Dutch university, the second year starts with one trimester of industrial training, preferably abroad. The others can follow additional courses to remove any deficiencies in their knowledge or choose from the electives. The last two trimesters are filled with a thesis project in one of the ongoing mechatronic research projects in the participating groups. Reactions from international MSc students on this programme have been enthusiastic so far. More information on this programme can be found at http://www.ce.utwente.nl/MSc_mechatronics/

One could argue whether it would be better to complete a basic education in ME or EE, followed by additional mechatronics education, or that a coherent mechatronics programme is desirable. The philosophy at the University of Twente has always been that a good basis in one of the basic disciplines is desirable. Providing the missing information in a second phase will help to bring the student at the level of a valuable partner in a mechatronic design team. In other words, the specialised mono-disciplinary education in traditional EE or ME curricula has to be widened and some basic knowledge of the other discipline should be taught to mechatronic engineers. Without extending the programme, this goes at the expense of a little bit less deep knowledge of the own discipline. This is indicated in Figure 3. The originally, more narrow, EE and ME programmes are made broader, leading to a mechatronic engineer, who still has clearly distinguishable roots in either EE or ME.

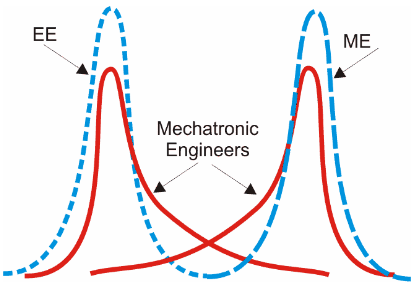

Figure 3

Mechatronic engineers versus conventional mono-disciplinary EE's and ME's

4. RESEARCH PROJECTS

In the Drebbel Institute groups from various departments of the University of Twente work together on mechatronic research projects. These projects range from more theoretical projects in applied mathematics to projects that deal with mechatronic design in cooperation with industrial partners. Applications in the group Mechanical Automation in ME often deal with laser welding and material treatment with the aid of robots. In EE the emphasis is on mechatronic measuring systems, modelling and simulation, control engineering and embedded control systems. A few representative projects in the last three areas will be further described in this paper.

4.1 Modelling and simulation

Modelling and simulation plays an important role in mechatronic design and is traditionally a major research activity in the Control Engineering group. As a result of these activities the group developed already in the 1960's the simulation programme THTSIM, that later got used all over the world as TUTSIM. A complete new programme became available under the working name CAMAS (Broenink, 1990). It supported a port-based modelling approach (in the form of bond graphs), which is important for modelling physical systems that extent over various domains. It was successfully further developed to a powerful tool for modelling, analysis, simulation and design of mechatronic systems (Van Amerongen and Breedveld, 2002, 2003). Since 1995 the programme is commercially available from the company Controllab Products under the

new name 20-sim (Twente-sim). It is now widely used in educational institutes and industry. Based on results of ongoing research projects, the programme is continuously further improved and extended with better modelling and simulation algorithms and new functionalities.
Because a mechatronic system at least involves the mechanical and electrical domain, standard modelling packages that work only in one domain 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 are derived again. A variety of presentations 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 (Figure 4). As a result of recent research more efficient simulation code could be generated, e.g. by symbolic manipulation of models that would otherwise require less efficient, implicit simulation algorithms (Golo, 2002). In a new research project it will be investigated how this approach can be linked to finite element type of modelling.

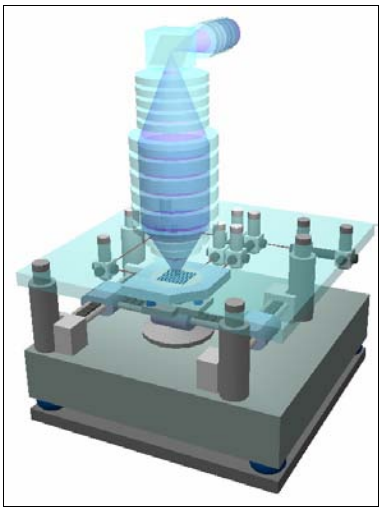

Figure 4

3D model of a wafer stepper, generated with 20-sim

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 1. More on the use of this port-based modelling approach for the design of mechatronics systems can be found in Van Amerongen (2002) and Van Amerongen and Breedveld (2002, 2003).
In an ongoing project a motor selection wizard is being developed. The basic idea is to create a database of commercially available servo motors and to couple it to the modelling 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 behaviour, heat production and so on. An impression of the relevant screens is given in Figure 5 and Figure 6.

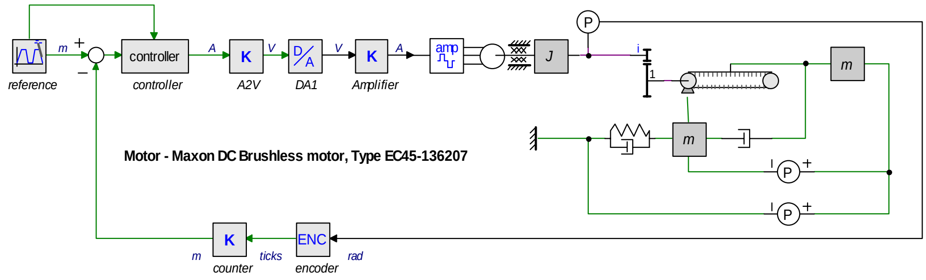

Figure 5 Model of the mechanical setup, actuator and controller used to examine the performance of the selected motor.

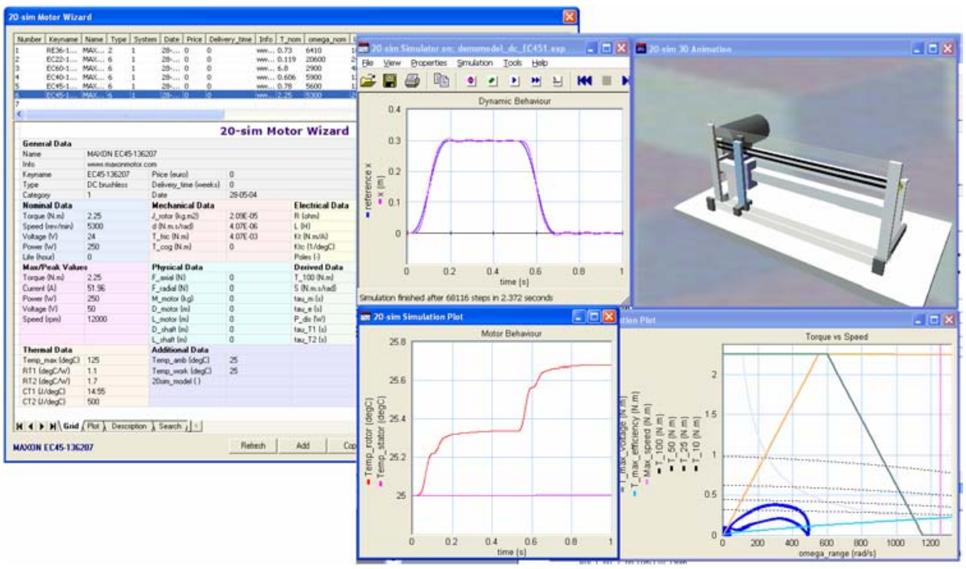

Figure 6 Screen dumps of the motor selection wizard and some screens, showing the behaviour of the controlled system, including the temperature change and a 3D animation

4.2 Learning feed-forward control

Feed forward is a powerful tool to give a control system a desired behaviour. However, it requires good knowledge of the process to be controlled. Such knowledge is in most cases not available, especially when the process is highly non-linear and time varying. This implies that this knowledge has to be gathered by some learning mechanism. "Standard" neural networks are able to approximate complex non-linear functions but they are not always suited for on-line control purposes either, because of the low learning rate and high memory demands for complex functions. In (learning) feed-forward control we consider the basic structure of Figure 7. A standard feedback controller structure deals with unknown and unpredictable disturbances. The feed forward improves the performance for setpoint changes and predictable disturbances.

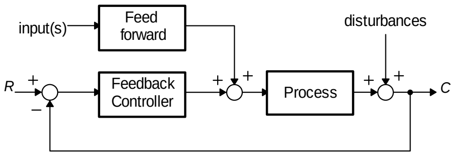

Figure 7

Feed-forward control structure

For periodic motions the required feed-forward signal is also periodic. If the feed-forward element were able to reproduce the steering signal of the last motion, after a few iterations steering could be based on feed forward only. The feed-forward element is then basically a time delay of one motion period. Although this requires a memory to store all the samples of the steering signal of a complete period of the repetitive motion, the memory requirements are still moderate. Such a structure is called iterative learning control (ILC). In ILC learning is mostly based on the error signal as indicated in Figure 8. Iterative learning control is applicable to repetitive motions, e.g. to compensate for the eccentricity in a CD or DVD (Steinbuch and Van de Molengraft, 2000).

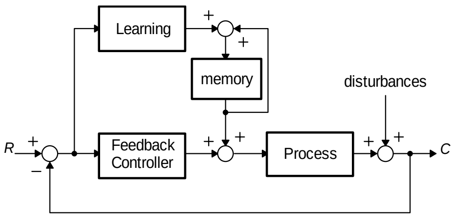

Figure 8 Iterative Learning Control

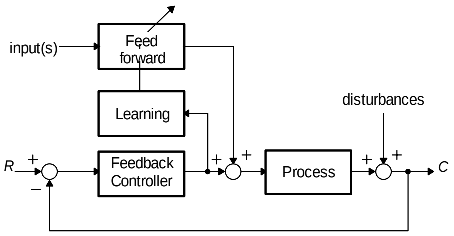

Figure 9 Learning feed-forward control

An alternative structure called Learning Feed-Forward Control (LFFC) is given in Figure 9. The idea is as follows. Assume there are no unpredictable disturbances. For repetitive motions the input of the feed-forward network can be time. If the feed forward worked perfectly for repetitive motions the output of the feedback controller would be zero. Thus the output of the feedback controller is a measure for the correctness of the feed-forward controller. This output can be used to train the feed-forward network by means of a learning algorithm. An LFFC structure that generates the feed-forward signal as a function of time is called time-index LFFC. It can only be used for repetitive motions. The structure can be used for non-repetitive motions when instead of time, the (desired) position, velocity or acceleration are used as network inputs. This is called path-indexed LFFC. In early work a B-spline network was used in the feed-forward block (Velthuis, 2000). It learns relatively fast and the memory requirements are moderate, making it suitable for on-line control. When more than one input is used special training procedures are necessary to limit the memory requirements of such a more-dimensional network.

This idea was successfully applied in several mechatronic setups. One of these was based on a request from industry to improve the accuracy of a linear motor. This type of direct-drive motors has the advantage that no transmission is needed between the actuator and the end effector. A disadvantage is that non-linear effects of the motor itself directly affect the end effector. Two of these effects are cogging and friction. Cogging is the phenomenon caused by the magnetic forces between the permanent magnets in the stator and the iron in the translator. These magnets are clearly visible in Figure 10. It has been demonstrated in this practical setup that by applying learning feed-forward control the accuracy could easily be improved with a factor 10 (from 80 μm to 8 μm) and for repetitive motions even with a factor 25 (Otten et.al., 1997). Also the friction or a variable mass can be learned and compensated for. The results of this research were also successfully applied in a project to improve robot tracking control for laser welding (Schrijver, 2002).

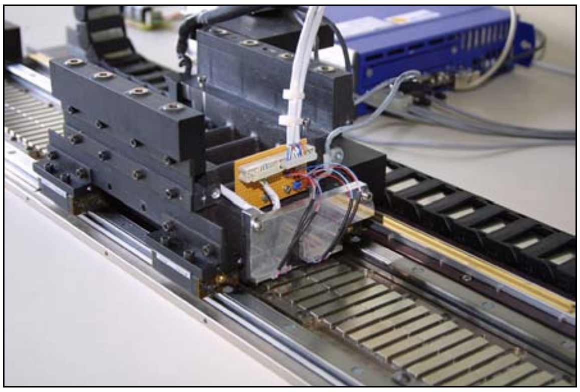

Figure 10

Linear motor with permanent magnets

A similar approach to achieve good accuracy with a cheaper built motor. By paying less attention to placing the magnets with small tolerance and by using cheaper magnets the motor can become less expensive. But without compensating for these imperfections with better control, the position accuracy will be worse. Experiments showed that it is possible to use feed-forward control to compensate for tracking errors that are introduced by such a low-cost construction. For all configurations that were considered the performance of systems controlled by LFFC was better than the configuration with well-placed magnets and PD control only. (De Kruif and De Vries, 2002-1).

When the feed-forward network has many inputs the dimension of the B-spline network suffers from the curse of dimensionality, unless a special training strategy is used that allows the use of a number of one-dimensional networks instead of one higher-dimensional network. The purpose of the recently completed PhD-project of the Kruif (2004) was to find a function approximator that could be used as part of the Learning Feed Forward Controller, and that was not as prone to the curse of dimensionality as the B-spline network. In this work new function approximators were developed that can be used in an off-line and on-line setting.
The *off-line function approximator*, called Key Sample Machine (KSM), represents the data by a subset of the data. This approach is similar to the approach of the Support Vector Machine (SVM) (De Kruif and De Vries, 2002-2). Because the prediction is made based on similarities with training samples, the input space is not necessarily divided into regions, as done by e.g. B-splines and the Radial Base Functions Network (RBFN). KSM uses a subset selection scheme to find key samples that summarise the data set. In this procedure, all the training data is used to train the parameters accompanying each key sample. Because the subset selection is an explicit step in the approximation scheme, a selection scheme that is appropriate for the problem on hand can be used. The scheme includes one key sample a time, until a good enough approximation is found. The calculation time required remains small when the number of key samples remains small. The variance of the Gaussian noise that corrupts the targets is used to test whether the inclusion of an extra key sample is statistically relevant. This variance is often unknown but can also be interpreted as a design parameter to trade off few key samples and an accurate prediction. Evaluation shows that KSM can handle high-dimensional input spaces and that only a limited number of key samples are needed for a prediction. In comparison with other support vector based methods, it is rather fast and gives a smaller prediction error for noisy data.

A recursive version of KSM has been developed for *on-line learning control*. This recursive function approximator is called Recursive Key Sample Machine (RKSM) and is capable of updating its parameters as well as adapting its structure. Evaluation of RKSM showed that it is capable of selecting a good set of key samples from the continuous data stream. The mean squared error (MSE) of the on-line version was nearly equal to the MSE of the offline version. This has been realised by including an omission scheme that omits samples that have become superfluous. As the behaviour of the on- and off-line approximators is nearly the same, the handling of high-dimensional input spaces is also nearly equal. The on-line approximator can handle high-dimensional input spaces just as well as the off-line approximator. Similar to KSM, the approximation is dependent on the quality of the data. When a forgetting mechanism is incorporated time-variant functions do not pose a problem for RKSM.

The new approximators have been used in a learning feed-forward controller for the 'Tripod setup'. This is a mechanical setup consisting of three coupled linear motors. The phase-corrected learning feed-forward control scheme was used. This variant corrects the phase lag present in traditional LFFC. The KSM was capable of learning the state dependent effects out of the data, by which the tracking error decreased significantly. The effects the KSM compensated for depended on three variables. The recursive version of KSM, updated its approximation at each training sample that became available, i.e. each millisecond an update was calculated. The RKSM in the learning feed-forward controller was tested for 3, 4, 5, 6 and even 9 inputs, and realised a significant error reduction. However, several inputs had little predictive power. Including them unnecessarily complicated the approximation, resulting in a larger tracking error than was obtained with a smaller number of inputs.

Figure 11

Setup to test Learning Feed-forward controllers in a multivariable environment

The use of the noise estimate to tune the accuracy of the function approximator was found to be intuitive. Only one parameter with a clear physical interpretation has to be tuned. Convergence of the learning controller was fast. After 25 seconds of learning, the tracking error did not decrease significantly anymore. In the experiment, the limitations of the learning control scheme were found to be due to the limited mechanical stiffness.

These dynamic effects could not be compensated for by the current setup and will be subject of further investigation.

A study has been performed to proof the stability learning controllers. As a start the stability of ILC was investigated. Recently Verwoerd, Meinsma and De Vries (2003) have demonstrated that an ILC controller can also be implemented as a normal feedback controller and that iteration ('learning') is not necessary. A connection has been established between the standard ILC problem and a stabilization problem in controller design. Goldsmith (2001, 2002) had already shown that to every converging sequence there corresponds an equivalent stabilizing controller. The results of Verwoerd however show that the converse is also true, which shows that both problems are truly equivalent. This makes all the analysis tools that are available for standard feedback control also available for the analysis of Iterative Learning Controllers. Stability of LFFC it is still an open research topic.

4.3 Active vibration control

In high precision machines the reduction of vibrations is important. When passive means are not sufficient, active vibration control is an option. In 1997 a project was started with the idea to make a construction element that could compensate for deformations in a mechanical construction. This construction element, consisting of piezo elements as sensors and actuators was called SMART DISC. The original idea was to make an element with negative compliance that could compensate for the undesired compliance of a mechanical setup. It was also intended to integrate sensor and actuator together with the control electronics in one single small element, the SMART DISC. This element should be used off the shelf and be used without a lot of design efforts to tune the controller. However, Holterman (2002) showed that compensation of compliance is not the way to go. Instead, he demonstrated that a robust, passivity based controller could be constructed that is able to considerably increase the damping. This idea was tested and applied to an experimental wafer stepper of one of the leading wafer stepper manufacturers (Holterman and De Vries, 2004). Three SMART DISCS, each with two degrees of freedom (Figure 12) were part of the lens support of a wafer stepper, a device similar to the one in Figure 4.

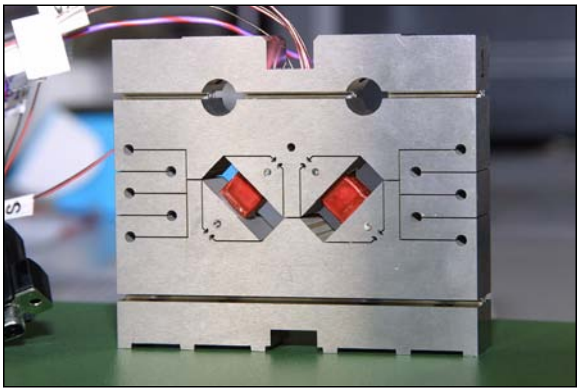

Figure 12

SMART DISC element

Even the smallest vibration of the lens causes unsharpness of the images that are projected on the wafers and thus reduces the minimum line width that can be achieved. Such vibrations can be the result of acoustic disturbances caused by the air flow that is necessary in a clean room environment. With the SMART DISC the damping of these vibrations could be significantly reduced.

The SMART DISC, being a robust passivity based controller, requires a minimum of knowledge about the properties of the process. Figure 13 gives a simplified model of the SMART DISC. The elementary SMART DISC is modeled as a spring k in series with a position actuator (a piezo-element). The position actuator is controlled by the controller $C(s)$. The force acting on the SMART DISC is measured by a force sensor (another piezo-element).

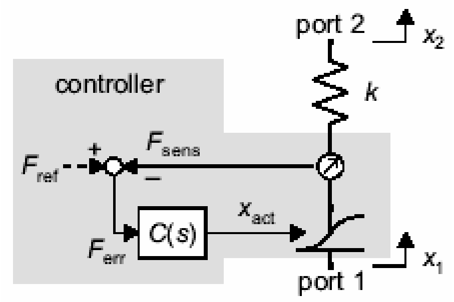

Figure 13

Model of the SMART DISC

When used as a construction element, the model has to be slightly extended (Holterman, 2002).

Because the sensor and actuator are collocated, an inherently passive controller is realized as long as the controller itself can be modelled as a passive element. An integral action or a low-pass filter as controllers, have shown to yield good results. The possibilities to improve the damping in a system with two vibration modes modelled, in combination with an integral controller is shown in the root locus of Figure 14. Because a pure integral controller worsens the performance for low frequencies, a leaking integrator (low pass filter) can be used. Figure 15 shows that this goes at the expense of less damping for the lowest vibration modes.

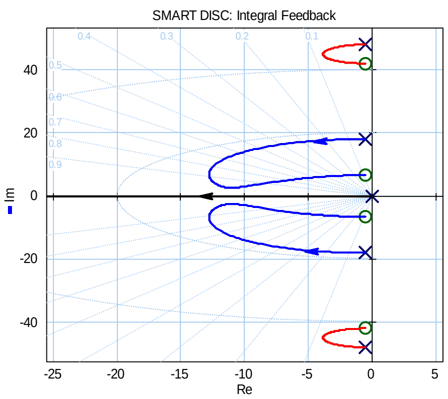

Figure 14 Possibilities to increase the damping with integral feedback

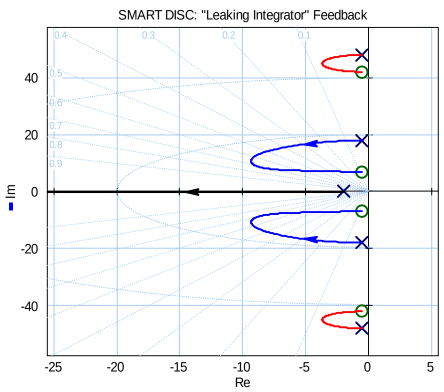

Figure 15 Root locus for 'leaking integrator' feedback

The higher modes are hardly affected. The location of the pole is thus a compromise between the desired extra damping for the lowest vibration mode and a good performance for lower frequencies. Note that because of the collocation all other higher vibration modes will show a similar behaviour. The root locus branch moves through the left half plane from the complex pole to the complex zero. This is true as long as the zeros that accompany the complex poles are closer to the origin than the poles. With these pole-zero configurations an inherently stable control system is realized.
Recently it has been shown that the original idea of a simple element consisting of sensor, actuator and controller is really feasible. The controller and all necessary

electronics can be realised in a single operational amplifier (Holterman and Van Amerongen, 2004).

4.4 µSPAM

In cooperation with the Systems and Materials for Information Storage (SMI) and the Transducers Science and Technology (TST) groups of the Department of EE the µSPAM is carried out. In this project we seek to design and build a high capacity, low volume micro Scanning Probe Array Memory for application in embedded systems. This new type of memory combines the low volume and power consumption of the Flash RAM with the high capacity of the hard disk. As the conventional magnetic storage media like hard disks and tape streamers become more compact and store more and more information on unit space, there is an increasing concern about effects that influence storage processes for example thermal instability, data-rate, access time, etc. Therefore, it is foreseen that major problems will appear within the next few years, when trying to increase data density and miniaturize the actual hard disk technology even more. Hard disk technology uses a certain fixed number of heads for reading/writing, while µSPAM will be able to connect/disconnect some of the many thousands of read/write units, according to user demand: if a lot of processing of data fetch/write is needed, then a lot, maybe all of the probes will work in parallel. However, while the processing unit is idle or only uses a constant, low-level bandwidth, only a few probes will remain operative, while others will be parked in order to reduce power consumption.
So far the Control Group has mainly investigated the coarse *xy*-positioning device of the µSPAM, the µWalker, a micromechanical device which is still under development. A dynamical model of the present prototype of the µWalker has been implemented in 20-sim. Simulations and animations have been made. The continuous dynamics of the µWalker have been studied. Hybrid dynamics will be taken into account. 3 PhD students with a background in control engineering, micro mechanics and magnetic storage are active in the µSPAM project.

4.5 Micro manipulator

Recently a project has started that is intended to develop a micromanipulator – a multi-axis micro stage with sub-nanometer resolution. This manipulator should be able to handle very small samples, cut off a silicon wafer during the production stage. This project involves 3 PhD students with a primary background in control engineering, mechanical engineering and micro mechanics.

4.6 Embedded Control Systems

The controller part of a mechatronic system is mostly realized in software as an embedded control system. Embedded control systems are hard real time systems and the reliable operation of such systems is crucial for reliable operation of the system as a whole. In the embedded control systems project, tools and strategies are developed to realize embedded controllers for mechatronic systems. Following a similar philosophy as in the modelling project, more abstract and basic designs are gradually refined to embedded controllers that can be mapped on real hardware (Broenink and Hilderink, 2001). Ten years ago, when transputers were popular, research of parallel processing was a major topic (Wijbrans, 1993). Although transputers became obsolete, mechatronic control systems are often inherently parallel in nature. Thanks to continuing research in this area, the ideas of OCCAM and CSP can now be mapped on other heterogeneous hardware as well. Controllers that have been tested in a simulation environment that is close to reality, can be translated into code for the embedded controller without the need for manual recoding (Jovanovic, Orlic and Broenink, 2003).

The realisation of embedded control systems for large mechatronic systems is not trivial. The Boderc project, a cooperation between various universities in the Netherlands and industrial partners such as the copier manufacturer Océ, focuses on distributed embedded real-time controllers for complex mechatronic devices such as modern copiers. We cooperate in this 70 men-year project with one PhD student.

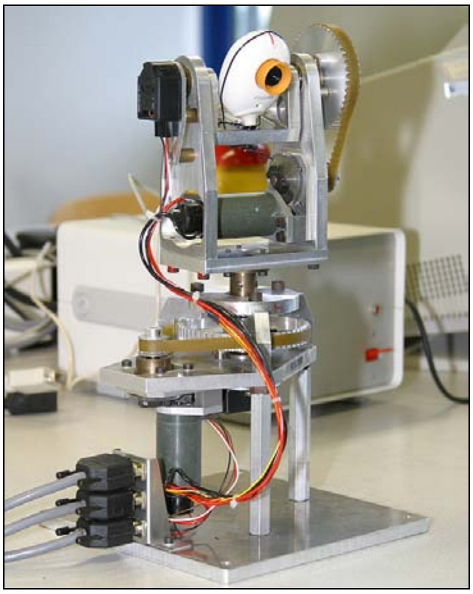

Figure 16

Test setup for testing embedded control systems

5 COOPERATION WITH INDUSTRY

The majority of the research projects are carried out with external funding from European and national funding agencies. Main sources are the Technology Foundation STW and Innovative Research Programmes like the programmes Precision Technology and Embedded Systems. In all these projects partners from industry participate in user committees and give their input about what in their opinions are the most relevant research topics. These larger projects attract mainly the larger companies like Philips (consumer electronics and production machines), ASML (Wafer steppers) and Océ (copiers). These companies are major players in mechatronics themselves.

In 2002 an EU sponsored project was started together with the Fachhochschule Gelsenkirchen (Bocholt, Germany) intended to transfer knowledge to small and medium sized companies (SME's) in the 'Euregio', the boundary region of the Netherlands and Germany. Due to the cooperation with a Fachhochschule (a polytechnic institute) both research *and* development projects can be dealt with in the 'Mechatronics Innovation Centre' on a size suitable for SME's. Training on advanced mechatronic topics is one of the goals of the Mechatronics Innovation Centre. The project on learning feed-forward control is carried out in the Mechatronic Innovation Centre, together with the mechatronic engineering company Imotec (a spin-off company of the University of Twente). There is also a good cooperation with a number of other companies near the University of Twente. These companies have organized themselves in 'Mechatronics Valley Twente'. One of the goals of this foundation is to stimulate the research and education in mechatronics at the University of Twente, because they urgently need well educated mechatronic engineers. One of the first activities of Mechatronics Valley Twente was the financing of a part-time professor in Mechatronic Design in the University of Twente. The company that took the initiative for the founding of

Mechatronics Valley Twente, Demcon, itself is a successful spin-off company of the University of Twente. The majority of the staff has an MSc, PhD or Mechatronic Designers degree from the University of Twente.

6 CONCLUSIONS

In the last fifteen years mechatronics has become a major field of research worldwide. Possibilities offered by modern analogue and digital electronics and software enable that mechanical systems get more functionality, better accuracy and flexibility and can be produced cheaper while keeping the performance at the same level. In order to come to a good mechatronic design, a true systems approach is needed. This implies that students should be taught how to integrate these elements from mechanical and electrical engineering, as well as computer science. Basic knowledge in the area of mechanical constructions, electronics, modelling and simulation, sensors and (embedded) control systems is essential for all members of a mechatronic design team.

Fifteen years ago it was still a question whether mechatronics was just a buzzword or something that would sustain. Since then the popularity of mechatronics has only grown. This is clear from the growing number of educational programmes world wide, as well as from the (too large) number of mechatronics (related) conferences. Its importance will not be less in the future, because advanced mechanical products can only be constructed with a proper integration of mechanical and information technological components.

This paper described a number of research activities in mechatronics at the University of Twente, carried out in the Mechatronics Research Centre Twente and the Drebbel Research Institute for Mechatronics. Groups from Mechanical Engineering, Electrical Engineering and Applied Mathematics work together in this institute and cover together the whole range from Systems and Control Theory, Measurement and Instrumentation, Control Engineering, Embedded Control System until mechanical constructions and industrial applications. Interdisciplinary cooperation is not always easy. This is true in companies as well as in universities. Good personal relations are important and structural reorganisations in an organisation makes life not always easy. It is likely that the cooperation in the University of Twente will be continued in a form similar to the Mechatronics Research Centre Twente. It is expected that more design-oriented groups from ME as well as from EE will be attracted to this cooperation. Because of the increasing need of small and high precision designs a stronger link to groups working on micro systems is to be expected.

Most of the research projects are application oriented. Cooperation with industry gets specific attention in the context of Mechatronics Valley Twente and the Mechatronics Innovation Centre, sponsored by the EU.

The partners in the Drebbel Institute for Mechatronics have 15 years of experience in mechatronics education in various forms. 15 years ago we started with mechatronic education in the mechatronics designer programme. Many graduates of this two-year programme are now making a successful career in mechatronics. The new MSc programme ‘Mechatronics’ offers new possibilities to educate the mechatronic engineers who are urgently needed by the industry.

More information of the research projects can be found at the web pages of the Control Engineering group, including copies of many of the references, and the Drebbel Institute for Mechatronics. The web pages of the Mechatronic Innovation Centre are only available in Dutch and German. More information on the educational programme can be found at http://www.ce.utwente.nl/MSc_mechatronics/.

References

Amerongen J. van, M.P. Koster (1997), "Mechatronics at the University of Twente" in *Proceedings American Control Conference (AAC)*, Albuquerque, New Mexico, U.S.A, pp 2972-2976, ISBN 0-7803-3832-4

Amerongen J. van, P.C. Breedveld (2002), Modelling of Physical Systems for the Design and Control of Mechatronics Systems, *IFAC Professional Briefs*, (http://www.ifac-control.org/publications/pbrieflst.htm), Laxenburg, Austria, pp 1-56

Amerongen, J. van and P.C. Breedveld (2003), Modelling of physical systems for the design and control of mechatronic systems (IFAC Professional Brief), *Annual Reviews in Control* 27, Elsevier Ltd., pp 87–117, ISBN S1367-5788

Amerongen J. van, The Role of Controls in Mechatronics, in *The Mechatronics Handbook*, CRC Press, Boca Raton (FA), USA, Robert H. Bishop, ed., pp 21.1-21.17, ISBN 08 493 00665, 2002

Broenink J.F. (1990), Computer-aided physical-*systems modeling and simulation: a bond-graph approach*, PhD thesis, University of Twente, Enschede, Netherlands, p 207, ISBN 90-9003298-3

Broenink, J.F. and G.H. Hilderink (2001), A Structured Approach to Embedded Control implementation, in: *2001 IEEE International Conference on Control Applications, September 5-7, 2001, Mexico City, Mexico, pp 761-766, ISBN 0-7803-6735-9*

Graaf, A.J. de (1994), *On-line measuring systems for a mobile vehicle and a manipulator gripper*, PhD thesis, University of Twente, Enschede. The Netherlands

Goldsmith, Peter B. (2001). The fallacy of iterative learning control. In *Proceedings of the 40th Conference on Decision and Control*, pages 4475–4480, Orlando, Florida, USA

Goldsmith, Peter B. (2002). On the equivalence of causal LTI iterative learning control and feedback control. *Automatica*, 38(4):703–708

Golo G. (2002), *Interconnection structures in port-based modelling: tools for analysis and simulation*, PhD thesis, University of Twente, Enschede, Netherlands

Holterman J. (2002), *Vibration Control of High-Precision Machines with Active Strutural Elements*, Ph.D. thesis, Twente University Press, University of Twente, Enschede, The Netherlands, pp iii-284, ISBN 90 365 17931

Holterman J. and T.J.A. de Vries (2004), Active Damping within an advanced microlithography system using piezoelectric Smart Disc, Journal of Mechatronics, 14, Elsevier Ltd., pp 15-34

Holterman J. and J. van Amerongen (2004), Analog controller design for an active damping element, to be published in the Proceedings of the 3rd IFAC Symposium on Mechatronic Systems, September 6-8, Manly Beach, Sydney, Australia

Jovanovic, D. S., B. Orlic, J. Broenink, J. van Amerongen (2004), “Inexpensive Prototyping Environment for Mechatronic Systems”, in: *Proceedings WESIC 2003*, Miskolc, HUNGARY May 28-30

Jovanovic D, B. Orlic and J.F. Broenink (2003), An automated transformation trajectory from a model of a controlling system to the control code, in *Proceedings XLVII Conference ETRAN, XLVII Conference ETRAN*, Herceg Novi, Serbia and Montenegro, Jun 8-13

Kruif B.J. de, T.J.A. de Vries (2002-1), Improving Price/Performance ratio of a linear motor by means of learning control, in Proceedings 2nd. IFAC Conference on Mechatronic Systems, Berkeley, California, USA

Kruif B.J. de, T.J.A. de Vries (2002-2), Support-Vector-based Least Squares for learning non-linear dynamics, in Proceedings 41st IEEE Conference on Decision and Control, Las Vegas, USA, Dec 10-13

B.J. de Kruif (2004), *Function Approximation for Learning Control a key sample based approach*, PhD thesis, University of Twente, Enschede, Netherlands, pp. xiv - 189, 90-365-2050-9,

Kruijer, C.W (1992)., Geregeld voorspannen van tandwielen, MSc thesis, University of Twente, Enschede. The Netherlands (in Dutch)

Oelen W. (1995), *Modelling as a tool for design of mechatronic systems*, PhD thesis, University of Twente

Oelen, W. and J. van Amerongen (1994), Robust Tracking Control of Two Degrees of Freedom Mobile Robots, *Control Engineering Practice*, Vol. 2, No. 2, pp. 333–340

Otten G., T.J.A. de Vries, J. van Amerongen, A.M. Rankers and E.W. Gaal (1997), Linear Motor Motion Control Using a Learning Feedforward Controller, IEEE/ASME Trans. Mechatronics, Vol. 2, no. 3, pp 179-187.

Schipper, D.A. (2001), *Mobile Autonomous Robot Twente - a mechatronics design approach*, PhD thesis, University of Twente, pp. 155, ISBN 9036516862

Schrijver, E. (2002), *Improved robot tracking control for laser welding – Disturbance estimation and compensation*, Ph.D. thesis, University of Twente, Enschede, The Netherlands ISBN 90 365 1730 3

Starrenburg, J.G., W.T.C. van Luenen, W. Oelen and J. Van Amerongen (1996), Learning Feed forward Controller for a Mobile Robot Vehicle, Control Engineering Practice, Vol. 4, No. 9, pp. 1221-1230

Steinbuch, M. and M.J.G. van de Molengraft (2000), Iterative Learning Control of Industrial Motion Systems, in Proceedings of the 1st IFAC conference on Mechatronic Systems, Darmstadt, Germany

Wijbrans K.C.J. (1993), *Twente Hierarchical Embedded Systems Implementation by Simulation a structured method for controller realization*, PhD thesis, University of Twente, Enschede, Netherlands, p 123, ISBN 90-9005933-4

Verwoerd M.H.A., G. Meinsma and T.J.A. de Vries (2003), "On equivalence classes in Iterative Learning Control", in: *Proceedings of the American Control Conference*, Denver, Colorado June 4-6, pp 3632-3637, ISBN 0-7803-7897-0

20-sim (mechatronic design software): http://www.20sim.com

ALSACA project video: mms://video.utwente.nl/Control_Engineering/ALASCA.wmv

Control Engineering: http://www.ce.utwente.nl

Drebbel Institute for Mechatronics: http://www.drebbel.utwente.nl

MART video: mms://video.utwente.nl/Control_Engineering/MART.wmv

Mechatronics Innovation Centre: http://www.mic.utwente.nl/

MSc Mechatronics in Twente: http://www.ce.utwente.nl/MSc_mechatronics/

µSPAM project: http://www.el.utwente.nl/~ptcu/microSPAM/