The Role of Control in Mechatronics

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Abstract This paper discusses some design issues of mechatronic systems. New tools for the design of controllers are needed in order to apply more advanced control algorithms in an industrial environment. In addition, modelling and simulation tools can play an important role to evaluate designs in an early stage and to support important design decisions. Reuse of models, and controller code can help to reduce the time to market of new mechatronic products. A number of examples illustrate the mechatronic design process.

1 Introduction

Mechatronics is attracting more and more attention. The term is used for a wide variety of applications. Sometimes it is even used for applications that, judged by a more narrow definition, hardly can be seen as a mechatronic system. The Industrial Research and Development Advisory Committee of the European Union, (IRDAC, 1986) has formulated a general accepted definition of mechatronics:

"*The term 'mechatronics' refers to a synergistic combination of precision engineering, electronic control and systems thinking in the design of products and manufacturing processes. It is an interdisciplinary subject that both draws on the constituent disciplines and includes subjects not normally associated with one of the above.*"

Essential in this definition is the 'systems approach'. This implies that the system is designed and optimised as a whole and not in sequential steps. However, not every design made by means of a systems approach is a mechatronic design. By concentrating on a limited application area, a mechatronic designer should have the domain-specific knowledge that enables him to realise really advanced products. Mechatronic design also implies teamwork. Specialists with a background in mechanical and electrical engineering, control and computer engineering should co-operate in a team, in all phases of the design, to come to a synergistic combination.

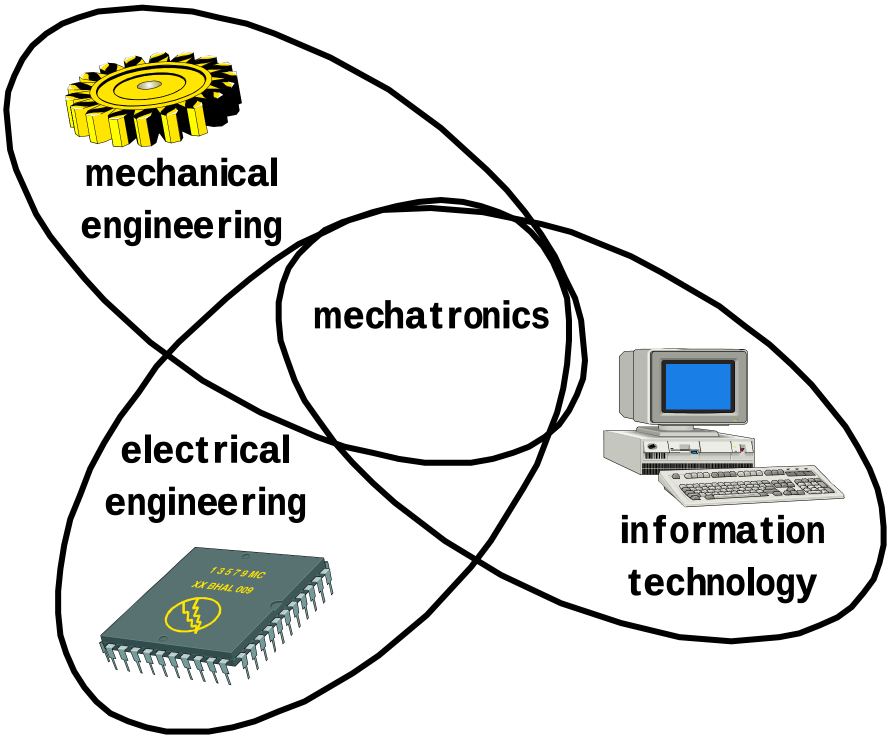

Figure 1 Mechatronics is a synergistic combination of mechanical and electrical engineering and information technology

Finally a good design philosophy is essential. Buur (1990) gives a more concise definition:

"*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*".

The aspect of spatial integration, in addition to functional integration, points to an interesting feature found in many mechatronic designs.
Although the word mechatronics is new, mechatronic products have been available for some time. In fact all electronically controlled mechanical systems are based on the idea of improving the product by adding features realised in another domain. Good mechatronic designs are based on a *real systems approach*. What has been lacking in the past, and is often still lacking today, is that systems are not designed as a whole. Mostly, control engineers are confronted with a design in which major parameters are already fixed, often based on static or economic considerations. This prohibits optimisation of the system as a whole, even when optimal control is applied. When tacho feedback is applied to an electrical motor, the mechanical time constant of the motor can be reduced at the expense of a better electric power amplifier. Old gramophones where equipped with heavy turntables in order to guarantee a constant number of revolutions. In the last days of vinyl disc players, more sophisticated designs used tacho feedback in combination with a light turntable to achieve the same. But a really new design was the compact disc player.

Instead of keeping the number of revolutions of the disc constant, it aims for a constant speed of the head along the tracks of the disc. This means that the disc rotates slower when tracks with a greater diameter are read. The bits read from the CD are buffered electronically in a buffer that sends its information to the DA-converter, controlled by a quartz crystal. This enables the realisation of a very constant bit rate and eliminates all audible speed fluctuations. Such a performance could never be obtained from a pure mechanical device only, even if it were equipped with a good speed control system. In fact the control loop for the disc speed does not need to have very strict specifications. It should only prevent overflow or underflow of the buffer. The high accuracy is obtained in an open loop mode, steered by a quartz crystal (Figure 2).

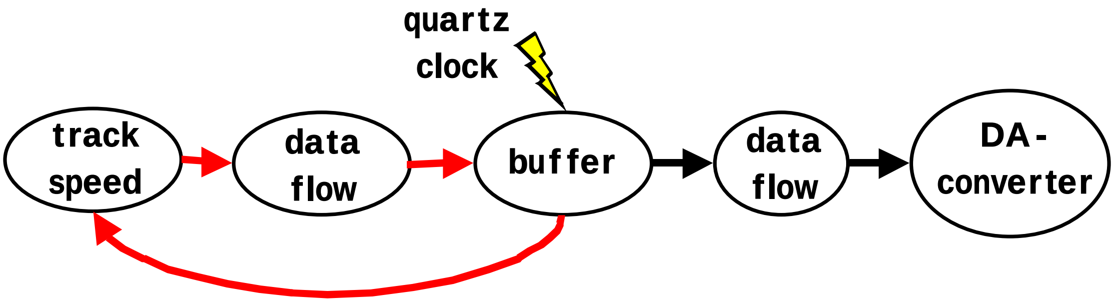

Figure 2. Combination of closed-loop and open-loop control in a CD-player

The flexibility introduced by the combination of precision mechanics and electronic control has allowed the development of CD-ROM players, running at speeds more than 30 times faster than the original audio CD's.

A new way of thinking was necessary to come to such a new solution. On the other hand, the CD player is still a sophisticated piece of precision mechanics. No electronic memory device can compete yet economically with the opto-mechanical storage capabilities of the CD and its successor the DVD. But this may change rapidly. Nowadays, electronic buffers with a memory capacity of up to 10 seconds, allow the use of these devices during outdoor exercises, such as jogging. The first devices that deliver CD-quality sound and use only solid state electronics in combination with powerful data compression techniques have become available already.

In the packing industry, many devices still rely on, for instance, gravity to get a certain behaviour of the product and the packing material. Such systems are sensitive to disturbances. In addition, a new packing requires a redesign or at least readjustment of the machine. By implementing active motion control, a more reliable, faster and more flexible device can be constructed.

If an aeroplane should have stable flight properties under pure manual control, the design possibilities are limited. When under all circumstances the presence of an automatic controller as a support system for the pilot is accepted, implying that it should be as reliable as the rest of the construction, aerodynamically more efficient designs become feasible.

Other good examples of mechatronic systems can be found in automotive applications such as ABS, electronic stabilisation systems and active suspension systems as well as automated highways.

In the Mini Symposium 'Mechatronics in Control System Design' at the Control '98 Conference in Swansea various applications and design issues were presented. Among these were papers on 'A knowledge-based mechatronics approach to controller design' (Bradshaw and Counsell, 1998). Papers on applications involved 'Vision-in-the-loop control applications in textile manufacture' (King, 1998), 'Development of a fuzzy behavioural controller for an autonomous vehicle' (Tubb and Roberts, 1998) and 'Development of adaptive cruise control systems for motor vehicles' (Richardson, Clarke and Barber, 1998).

The synergy of different disciplines allows the design of really advanced and simultaneously affordable products and production machines.

2 Mechatronic Design

Mechatronics is more a way of thinking than a completely new discipline. It still needs advanced knowledge of specialists from different disciplines who meet each other in a mechatronic design team. Mechatronics is a design philosophy. It has been mentioned in the introduction that it is important to make a design from a systems approach in order to get the best possible performance. But it is not realistic, nor needed to invent the wheel again and again, because time to market is an important issue. Mechatronic designs of production machines can help to react faster to market demands. A flexible production line that can be reconfigured by means of software is much easier to adapt than conventional lines that require that mechanical devices be manually reconfigured. But also in the design stage of products and production means, time to market is an important issue. By developing proper tools and knowledge bases, existing knowledge can be made available to less experienced designers. Such knowledge bases should not only be filled with standard solutions for mechanical components, but also with proper CAD tools and mathematical models of these components and with control structures suited for certain classes of problems. The knowledge base could also contain standard software modules that have been tested well; thus enabling the automatic generation of code for a computer based controller. One may doubt whether the design process could ever be done automatically. Although the power of computational intelligence is increasing rapidly, the human creativity can not yet be beaten by a computer. But providing the human designer with proper tools can considerably increase his productivity.

2.1 Tools for modelling, simulation and controller design

Simulation can play an important role in the process of designing mechatronic systems. With computer simulation alternative designs can be compared and evaluated without the cost involved with building real prototypes. Simulation tools used in control engineering are mostly based on a block diagram representation of the underlying mathematical model. These models have a direct connection with the transfer functions of the various components of the system. If necessary, they can be extended with non-linearities. For the design of mechatronic systems transfer functions and block diagrams are often not the most appropriate models. A basic assumption in a block diagram is that the different blocks do not influence each other's properties, or that any interaction between the blocks has been accounted for in the parameters. This implies that they cannot easily be replaced by other system components. Another problem is that the parameters of various physical components appear in various combinations and at various locations in the block diagram. Unless there is a supporting system available that automatically relates the different parameters of the mechanical system to the parameters of the block diagram, investigating the effects of parameter changes becomes a tedious job. Iconic diagrams like basic electrical network diagrams or mechanical diagrams do not have this problem. Energy based modelling approaches, e.g. the bond-graph approach, can form a link between iconic diagrams and mathematical equations. Such models can help to increase the insight in the design and may suggest alternative solutions (Figure 3).

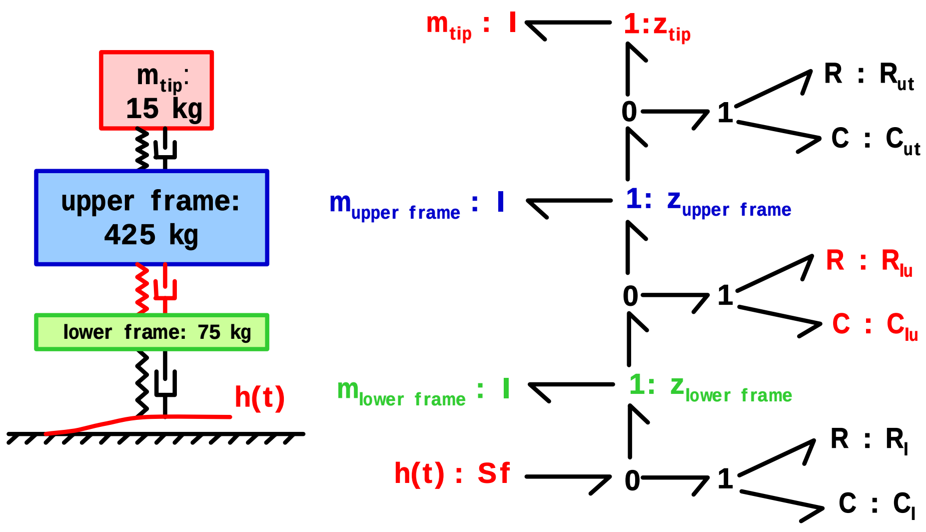

Figure 3. Iconic diagram and bondgraph of a mobile robot

In the Control Laboratory at the University of Twente a software package (20-sim) has been developed that supports the modelling and simulation with bond graphs, in addition to the use of equations and block diagrams. Versions 3 of this program also supports iconic diagrams and object orientation. The latter enables to start with a simple design, using only basic functions of the various components. When the design process proceeds, more complex representations of the component can be incorporated in the model, and their effect on the system behaviour can be examined. A model of a component is thus not fixed. It can have various shapes. The models are *polymorphic* i.e. they can have various levels of detail. Also viewing the system in various representations or in *multiple views* can help to get a good insight in the properties of the system (Figure 4). Among these various representations are: representations in the frequency domain, time domain, differential equations, bond graphs, iconic diagrams and block diagrams as well as more fancy representations like stereo views as found in virtual reality. 20-sim 3.0 can automatically generate (linear) state space descriptions from the simulation code. This allows the use of tools like Matlab for further analysis, control system design and generating other representations. Demo versions of 20-sim are available from the web.

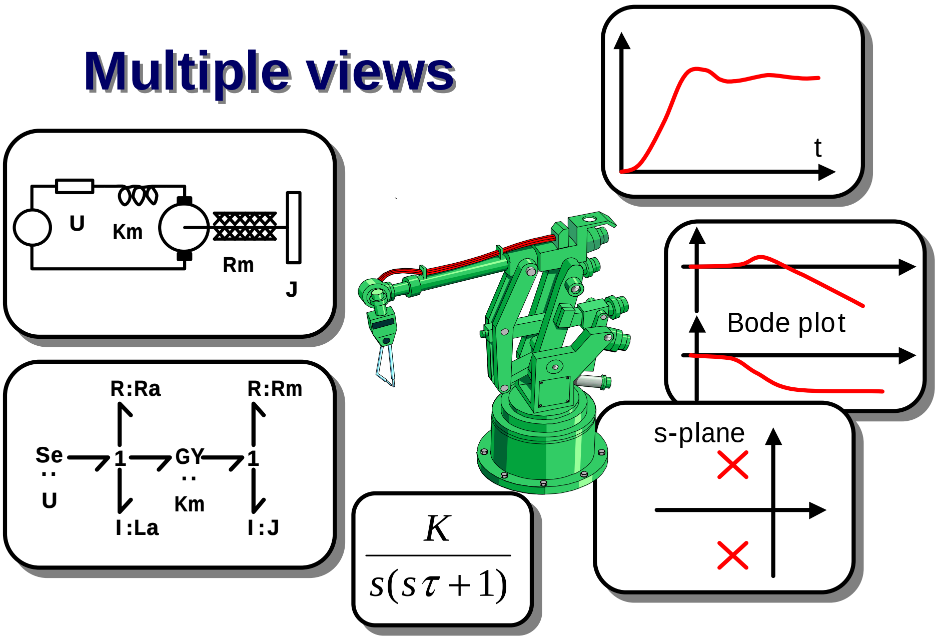

Figure 4. Multiple views of a servo system in open loop and closed loop

These concepts and their impact on mechatronic design have been described in the PhD thesis of De Vries (1994) and have been further worked out into a concept for a modelling and simulation language by Breunese (1996). Related work is done e.g. in the Schemebuilder project (Bradley, Bracewell and Chaplin, 1993). Proper software tools should support various representations and should allow converting one representation into another one.
In order to advance the applications of real mechatronic designs it is essential that design knowledge is formalised and brought together in a knowledge base. This will enable reuse of this knowledge. This knowledge base should contain reusable models, standard design approaches and support tools to retrieve the knowledge and to make a new design out of it.
A control engineering challenge is to introduce modern control methods into 'standard' mechatronic designs. In many cases, simple PID-type controllers are applied because of their ability to perform reasonably well without too many tuning and design efforts. It is a challenge to develop tools that allow the application of more advanced controller algorithms with the same or even less effort as required for tuning a PID-controller. By developing tools that support such a design for various classes of systems, this should be possible.

3 Examples

A few examples of mechatronic designs of projects that were recently carried out in the Control Laboratory of the Faculty of Electrical Engineering of the University of Twente will be shortly discussed here. All these projects were performed in the multidisciplinary environment of the Cornelis J. Drebbel Institute for Systems Engineering (formerly MRCT), a cooperation of the faculties of Electrical Engineering, Mechanical Engineering, Applied Mathematics and Computer Engineering. The projects indicate that good mechatronic designs require attention for the mechanical design, the choice of the sensors and of the control system and for the computer implementation.

3.1 Alasca project

In the Alasca project a device for placing IC's at a printed circuit board has been developed. It should replace older difficult to control pneumatic equipment by an electric servo system that should be able to rotate and translate simultaneously, with a high speed and accuracy. A design team of a mechanical and electrical engineer was formed to design the motor and its control (both students from the ‘Mechatronic Designer’ postgraduate course). An induction type of motor was developed with two sets of windings, one to realise the rotation and another one to realise the translation (Figure 5).

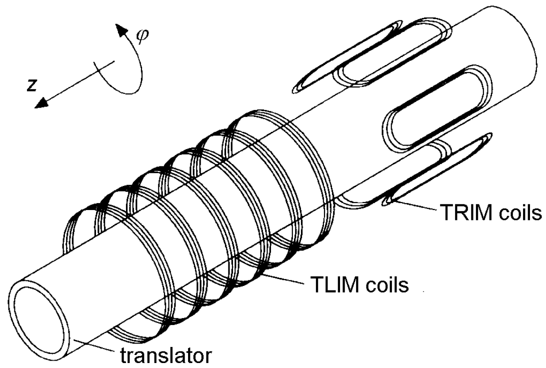

Figure 5. The windings for the Translational motor (TLIM coils) and for the Rotational Motor (TRIM coils)

To achieve the required accuracy, air bearings were used. This could only be done if contactless sensors were available to measure the two motions. The inductive sensor for measuring the translation was more or less a standard solution, although care had to be taken to use it in the presence of the magnetic fields of the motor. A contactless rotational sensor that should be able to accurately measure the rotation even when the actuator performs translational motions had to be developed. The sensor consists of a combination of three LED’s at the stator, a sheet of polarising material at the rotor/ translator and three photo diodes, covered with sheets of polarising material under angles of 120 degrees at the stator (Figure 6). The sensor signal is compatible with the signal of a synchro. A standard synchro-to-digital converter could thus be used as an interface between the sensor and the computer, yielding a resolution of 14 bits.

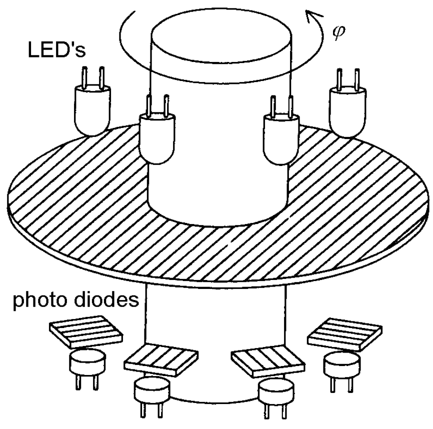

Figure 6. The rotational sensor

Because induction motors have a low efficiency, especially in low-power servo applications, especially attention was given to minimising the losses. This resulted in the ‘minimum dissipation control’ algorithm. By using proper computer support tools, the design could easily be adapted to changing requirements with respect to the dimensions of the actuator during the development process. Parallel to the motor design, a system was developed that could replace soldering of the leads of the IC, by laser welding. Besides attention for the process conditions of the laser welding, such as the required power, and the angle of attack of the laser beam, a fast and accurate servo system was developed, that finally enabled welding of 80 leads per second. More details of this project can be found in the paper of Van Amerongen and Koster (1997).

3.2 Learning Feed Forward Control

Another project carried out by a student of the 'Mechatronic Designer Course' was the development of a learning feedforward controller for an industrial linear permanent magnet motor used to build Cartesian robots. In a linear motor system, a linear relative movement exists between the translator and the stator. So the coils are moving along with the translator while the magnets are static. Due to the protrusions or poles on the translator, a force (in moving or opposite direction) is acting on the translator whenever the poles of the magnets and the poles on the translator are not aligned. So the translator has a number of preferred positions, independent of the fact whether a current is applied to the coils or not. The force experienced by the translator is approximately sinusoidal as a function of the position.

The force described here is formally called reluctance force. In most brushless permanent-magnet motors this force (torque in a rotating motor) is undesirable and is referred to as cogging force or detent force. Feedback control can only partly compensate for the disturbance forces caused by cogging. Feedforward control is only partly effective, because the force is only approximately sinusoidal, because the magnets and the distances between them are not exactly similar. The industrial motor and its controller could not achieve accuracy better than 100 μm, while 10 μm was desired. In order to achieve a better accuracy, more tight specifications of the magnets and their relative positions are a possible but expensive solution. The alternative is compensation tuned for each single motor. By applying a learning feedforward, realised with a neural network, accuracy better than 5 μm could be achieved (limited by the sensor accuracy). Learning takes approximately ten trial motions and is especially effective for repetitive motions, but because the inputs of the network are the desired position and velocity, rather than time, it performs well with non-repetitive motions too. In addition, the network will update itself when needed. The neural network uses the feedback signal as a training signal, based on the idea that with a proper feedforward the feedback signal should be zero, except for signals due to random disturbances (Figure 7). By selecting a proper learning speed, the latter will not be learned. Typical results are shown in Figure 8. This approach has also been applied to the path controller of the mobile robot described in the next section (Starrenburg, J.G., et.al., 1996) as well as to the control of a flexible beam (Velthuis, De Vries and Van Amerongen, 1996).

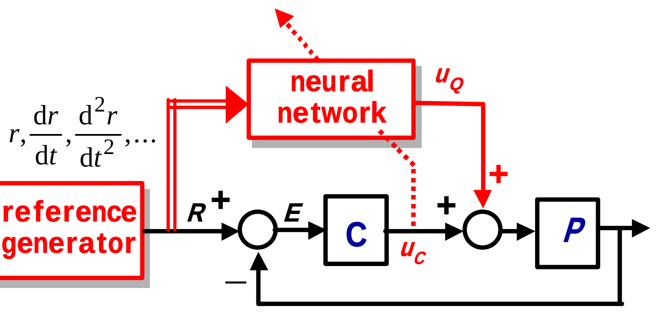

Figure 7. Learning feedforward control. The neural network is trained by the output of the feedback controller

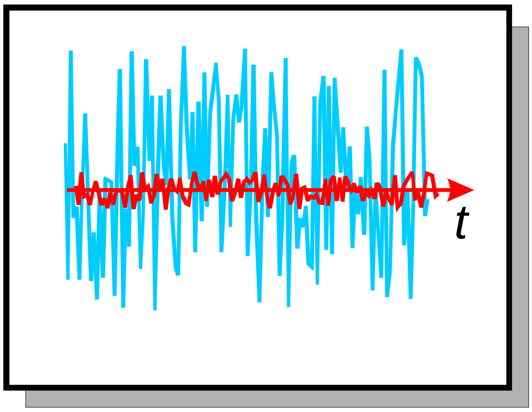

Figure 8. Error signal before training the network (about ±100μm) and after ten standard motion patterns (about ±5μm)

3.3 MART, a factory of the future

The Mobile Autonomous Robot Twente (MART) project aimed in the first place at investigating how different disciplines can cooperate in a mechatronic team. The objective of such a team should be the development of a technical system with solutions contributed from different disciplines. An automated assembly factory was adopted as a subject. It was a common effort of participants from mechanical engineering, control engineering and computer science. It resulted in an autonomously moving vehicle that, while riding a predestinated, product dependent route along a number of stocks, collects components and assembles them by a manipulator on board the vehicle. A vehicle, a manipulator, a gripper exchange system, a docking system, a navigation system together with all the hard– and software for task and path planning were developed, built together and tested. On board the vehicle, there is a 4-d.o.f. assembly robot (Figure 9).

Figure 9. MART robot

The robot takes components from a part supply system to the vehicle's deck and performs the assembly operations, even during riding. The design process started with the evaluation of basic concepts based on simple models. The outcomes of these evaluations directed the design of the different parts of the system. The more the designs grew, the more detailed the modeling became. It was interesting to see that deviations between the early predictions, the simulations in the final stage and the practical results, remained within 20%. Consequently, simple modeling was of much use in order to direct the project (Oelen, 1995).

3.4 Vehicle

One of the requirements the vehicle has to fulfil is offering the opportunity to the onboard manipulator to perform assembly while riding on an irregular floor. In the error budget of the tip (Figure 10) with respect to the vehicle deck, 0.1 mm is available for positional error due to passing a threshold of 2.5 mm. In order to achieve this, the frame was subdivided into a rigid lower frame with relatively rigid wheels, useful for odometry, and an upper frame, separated by relatively soft air springs. (Figure 10) .

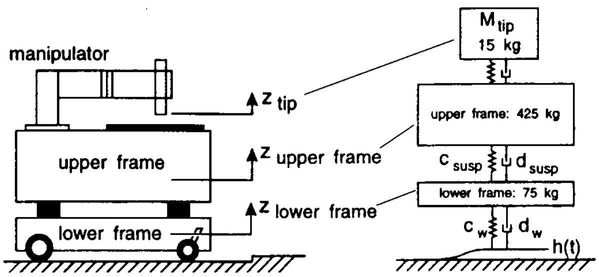

Figure 10. Model to determine the weight distribution over the upper and lower frame

The upper frame contains the majority of the mass, especially the batteries. The optimal distribution of the weights was determined with simulations.
Figure 11 shows the error ($z_{tip} - z_{vehicle}$) when passing the threshold at a speed of 1 m/s. The more mass is attributed to the upper frame the more it acts as a low pass filter. The upper frame will be the interface between the manipulator and the docking mechanism. The docking mechanism will ask for three points, rigidly connected to the manipulator base. Therefore, a tetrahedron-like upper frame was adopted . On the tip plane, the manipulator is carried. The lower frame is supported by a swivel wheel at the front and two servomotor–driven wheels at the rear. These drives contain encoders as a provision for odometry. Many more design aspects were involved (Van Amerongen and Koster (1997) and Koster (1997)).

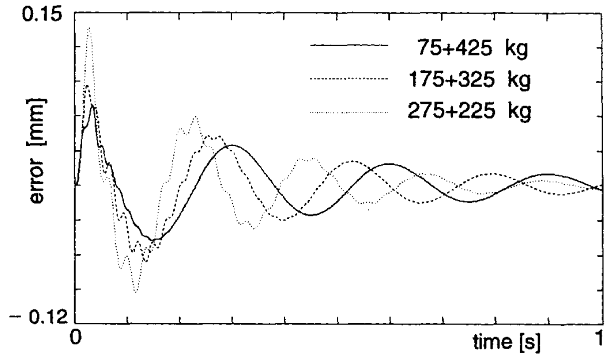

Figure 11 Simulations to determine the optimal weight distributions of the upper and lower frame

The earlier-mentioned learning feedforward controller was also used for the path following systems of the MART (Starrenburg, J.G., et.al., 1996). Starting with a rather elementary feedback controller, based on a simple model of the robot, the error over a typical path was as large as 12 cm. After 3 trials the error was already considerably smaller and after 15 trials the error was within the specifications (Figure 12). The learning feedforward controller even outperformed a feedback controller based on an extensive model of the robot (Figure 13)

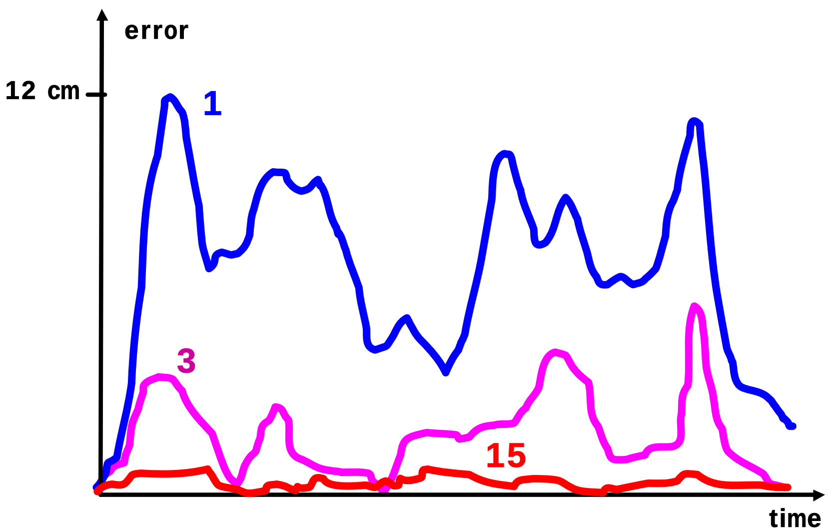

Figure 12. Learnig behaviour of the learning feedforward controller of the MART

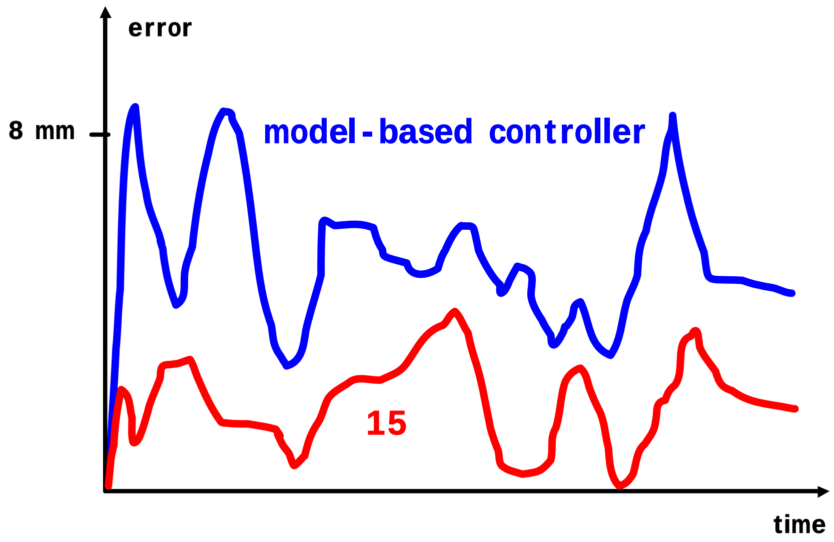

Figure 13. Comparison of a learning feedforward controller and a model based controller

3.5 Smart disc

A recently started project deals with the design of a device that combines a sensor, controller hardware and an actuator in one single small disc that can be placed in high-precision mechanical constructions to reduce deformation due to high-frequency vibrations. In the smart disc piezo material is used as sensor (to measure the deformation) as well as actuator (to reduce these deformations). All hardware necessary to compute the proper control actions will be integrated on the device itself (Figure 14). Preliminary experiments have indicated that small, but high frequency, vibrations in the construction can effectively be reduced. This is an another example of a device with functional and spatial integration. More information is available on the web-site of the control laboratory http://www.rt.el.utwente.nl/mechatronics).

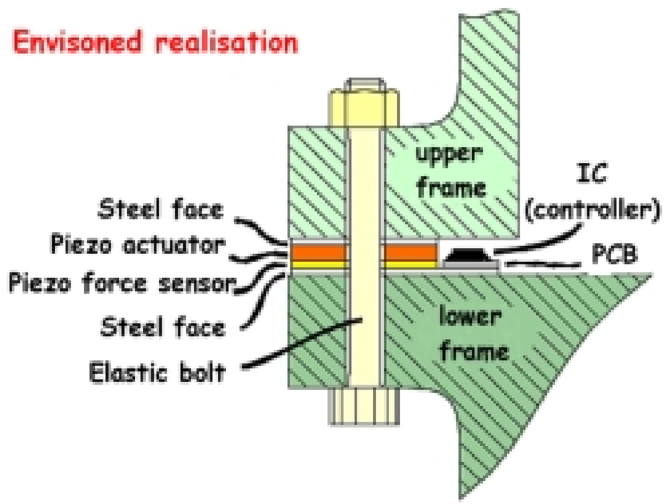

Figure 14. Smart Disc

4 Conclusions

In this paper it has been stated that mechatronics is a design philosophy for the design of electro-mechanical systems, based on a systems approach. A successful introduction in industry requires that proper support tools be available. Some of these tools have been discussed: modelling and simulation tools, based on reusable models. The concept of polymorphic modelling that enables a design model to become gradually more complex and realistic, was discussed shortly. It was also concluded that tools for easy design of complex controllers for mechatronic systems are needed. A few examples demonstrated some aspects of mechatronic design.

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