In the first generations we were confronted with systems lacking power to control a required position. The disturbing forces or motion of the targets were too large so that the required position could not always be achieved.
Therefore the first phase of our systems oriented approach was directed at achieving larger controlling power.
In the later phases we directed our attention to a more extensive analysis of the disturbances and to a more integral handling of the requirements.

The Power Design Approach

The power of a mechatronic system to maintain its required position is very much similar to the mechanical stiffness in passive systems. A disturbing force should not lead to a large position error. Therefore a design with a high stiffness is required. When dynamics are involved, the acceleration of masses will lead to disturbing forces. When these forces are small enough the position errors will also remain small. Combining the high stiffness and low mass leads to higher values for the natural frequencies of vibration.
For controlled systems the arguments are similar and we strive for high values of the bandwidth of the feedback controller. High loop gain through low masses and powerful feedback may lead to high bandwidths. Increasing this bandwidth however is limited due to contributions from all elements in the feedback chain.

From a mechanical design perspective, the presence of undesired vibrations provides a severe limitation. Our work on optical disc drives and wafer steppers has forced us to develop a profound understanding of these issues and to find effective methods to handle the vibrations.

In figure 2 the deformed shape of an actuator for an optical disc drive is shown. This actuator was in production for Audio CD application requiring a bandwidth of about 1000 Hz. The introduction of CD-ROM applications made it necessary to increase this bandwidth to about 3000 Hz. Due to a mechanical vibration at about 10 kHz this was not directly achievable. Conceptual changes were not acceptable because of short lead times for the product and the costs associated with that.
Based upon a thorough understanding of the dynamics involved, a solution was obtained where we reduced the mechanical stiffness and increased the moving mass of the actuator. With minor adjustments in the product we managed to build a successful generation of CD-ROM modules.

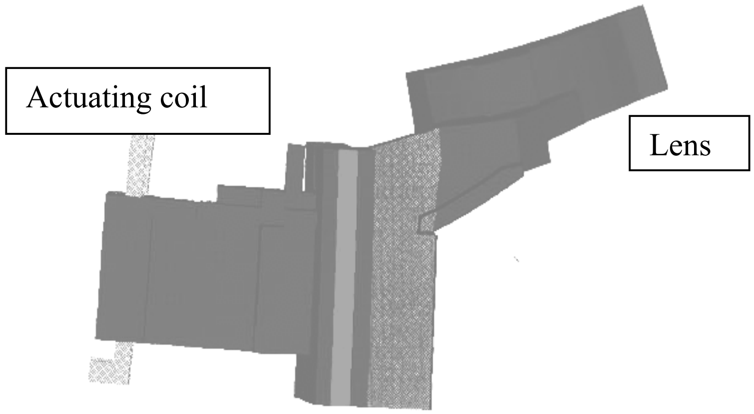

Figure 2. Deformed shape of the moving part of an optical disc lens actuator. Actual size is about 15 x 8 X 8 mm. while the moving mass is about 0.7 gr.

Eliminating Disturbances

Optimizing the design of the different elements in the feedback loop is limited and at a certain point in time it proved to be more economical to fight the disturbing sources and transmission paths. In figure 3 a simple lumped parameter presentation for a wafer stepper with a linear motor drive is shown. Floor vibrations form one of the disturbing effects. Such vibrations are transmitted through the machine base and lead to motion of the optical system. The controller must create forces to make the wafer follow these motions. Initially, the filtering frequency of the air mount suspension for the machine was about 3 Hz. Introduction of active vibration control technology in 1992 allowed for reduction of that frequency to about 1 Hz, yielding an improvement with a factor 10 for allowable levels of floor vibrations.

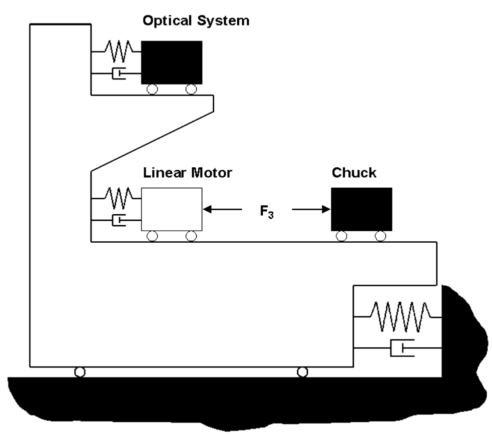

Figure 3. One DOF lumped parameter model for a wafer stepper. The chuck carries the wafer and must be positioned relative to the optical system. The linear motor drives the chuck.

In vibration isolation systems the reduction of the suspension frequency is beneficial for improving the isolation. Unfortunately low stiffness of the suspension makes it very sensitive to disturbing forces acting on the payload. To circumvent this effect we have developed a novel isolator system that combines high stability against disturbing forces with the extreme isolation performance of low stiffness suspensions.

One example of forces that are disturbing the payload is the reaction force from the linear motor. When high accelerations are needed for competitive performance, large driving forces are required. Such forces will excite the metrology structure and deteriorate the positioning accuracy. For the ASML lithography tools we introduced actuation concepts that avoid such excitation allowing for the combination of high speed and high accuracy. A similar solution is shown in figure 4 where two linear motor driven gantry stages work in one machine. When one stage accelerates at full power the other stage must maintain its positioning accuracy. A clever integration of two frames has allowed us to achieve this without requiring additional "power" of the feedback control.

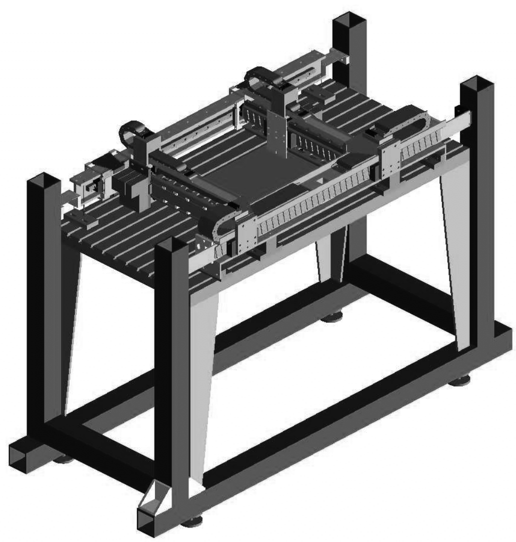

Figure 4. A functional model for a novel machine concept for SMD-placement where two frames are intertwined to separate driving forces from metrology components.

Managing the System Requirements

At the start of the development the requirements are determined. Initially the development teams take the specifications for granted and make designs based on the previous steps we described. Once the systems reach the limits in “power” and all disturbing effects have been optimally cancelled, insufficient performance (compared to the specifications) urges to look for new ways to satisfy the demands as set by the customer, or product management. It turns out that it is quite profitable to spend effort in setting up system error budgets. And make sure to include all parts of the system in this analysis. In many cases the customer, or product management, has done a top-level distribution of precision requirements. It pays of handsomely in many cases to reassess this distribution.

One example of such a system approach can be seen in he first generation wafersteppers from ASML. In these tools overlay accuracy of about 50 nm was achieved over a 6” wafer. Basically this requires a sensing system with accuracy of 0.3 part per million. This requirement is not easily or economically met in an industrial environment. Through a well-designed process of initializing the sensing system and imaging process a significant reduction of the requirements for the sensing system has been achieved.

Similar performance aspects can be found in the concept of the Ultra-Precision CMM developed by Theo Ruijl from Philips CFT. Rigorous application of Abbe’s rules, a description of a calibration strategy at the start of system development and extreme synchronization of data acquisition form the basis for high performance at an industrial cost level. This work forms the basis for the product developed by IBS and Philips CFT.

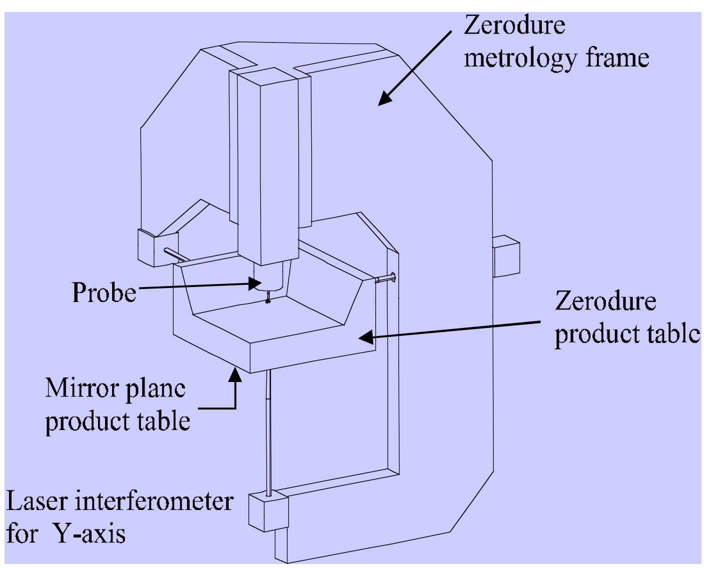

Figure 5. Schematic diagram of the metrology concept for the Utra-Precision Coordinate Measuring Machine.

Future Developments

The different development steps in our approach to System Engineering for High Precision systems will be followed by new advancements. In our environment we are now facing the challenge to improve the reliability of project planning for highly innovative projects. Continues learning in this respect has given us a good basis for this.

From a technology viewpoint we are closely following developments of adaptive and learning machines. These fields appear to be highly promising to shift the limits of performance ever further.
Application of our experience in he design of Micro Systems forms an additional field of activity. However the scale, manufacturing, test and packaging pose new challenges in addition to the current ones. Given the wealth of process improvements we think that the experience of good system design will be the basis for building the industrial success of these devices.