Mechatronic design of a lens manipulator

CCM's specialization is the application of mechatronic methods for solving technical problems. An interdisciplinary team analyses a given problem into elements that are solved by the respective specialists. In this publication you will find an example of an accurate lens manipulator. An increasing number of customers of CCM come up with accuracy targets that go beyond straightforward solutions. In some cases this implies a costly motion controller, which threatens the target for low cost of goods demands in case of equipment for series production. You will find an example of using every available accuracy improving resource in a system, without losing individual operation of modules. The latter introduces short lead times in integration & test. A compact motion controller from Faulhaber, meant for point-to-point applications without accuracy demands during constant velocity, has been integrated in an accurate positioning system. Based on the known tracking relation between analogue set point (reference) position and the actual load position, an off-line adjustment of the set point results in improved accuracy. The complete system was developed by CCM.

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Introduction

During the development of an optical tracking system, CCM encountered the challenge to position a focus lens with the following system specifications:

- The focus point of the light beam had to be continuously adjusted with a velocity of 200 [μm/s]. An analogue value (±10V) represents the height variation within a ±150 [μm] position range.
- A maximum difference of 3 [μm] between reference and actual position was allowed.
- The lateral movement of the focus lens during focusing should be less than 10 [μm] and the reproducibility of the lateral position must be less than 0.1 [μm].
- The complete system should keep its performance within a lifetime of 100.000.000 cycles.
- The complete system must remain within accuracy specs for (external) disturbances of 0.15 m/s^2 @ 8-12 Hz

Mechanical design

The combination of accuracy and wear insensitivity, directed CCM towards using elastic hinges like described in reference 1. With the correct configuration of such a hinged guide (see figure 2) one can reliably predict the stiffness and its lateral accuracy. The double elastic hinged guide has an inner and an outer part to minimize lateral movement The inner part is forced to move half the distance of the outer part.

The actuation is performed by a motor with integrated gear box, which drives a cam disc. To avoid the need of a high performance gearbox, the cam disc is preloaded with a torsion spring to eliminate the play of the gearbox. There was calculated that mechanical imperfections, like hysteresis or backlash, imposes a position feedback of the lens position. In such a control strategy one should consider the dominant compliance between modal masses of motor and load. In reference 2 one can find that the 4^{th} order dynamic relation of such a kind seriously threatens the servo bandwidth.
In order to identify this most compliant mechanical part, the drive chain has been evaluated and the concerned parts are depicted in figure 1 It consists of a motorshaft with a diameter of 6 [mm]. From shaft bearing to cam disc there is a shaft length of 7.5 [mm]. The cam wheel has a bearing too and is connected to a hinge of the guide mechanism.

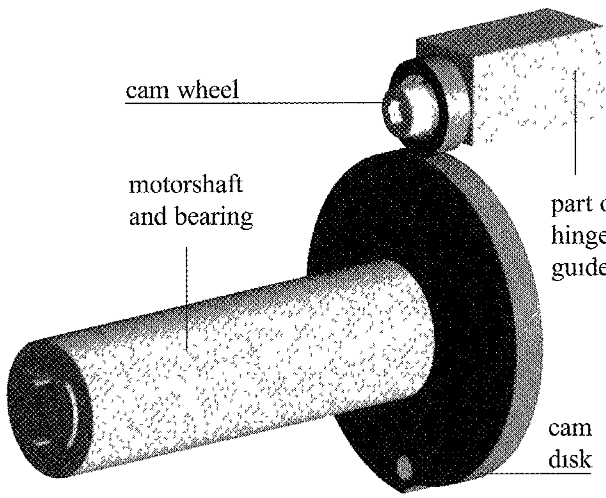

Figure 1 Transmission of drive system

In the drive system there are three relevant compliances:
C1.Motor shaft stiffness
C2.Motor bearing and cam wheel stiffness
C3.Contact stiffness between cam wheel and cam disc

$$C1\,[N/m] = \frac{F}{f} = \frac{3EI}{l^3} = \frac{3{*}2.1E11{*}\frac{\pi(6E\text{-}3)^4}{64}}{(7.5E\text{-}3)^3} = 1E8 \qquad [1]$$

$$C2\,[N/m] = 2.5E7 \qquad [2]$$

$$C3\,[N/m] = 5E7 \qquad [3]$$

Reducing these serial 'springs' into one spring results in the following:

$$C\,[N/m] = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} = 1.4E7 \qquad [4]$$

This value is referred to as the 'SD-Compliance' parameter in the simulation model of the system shown in figure 5

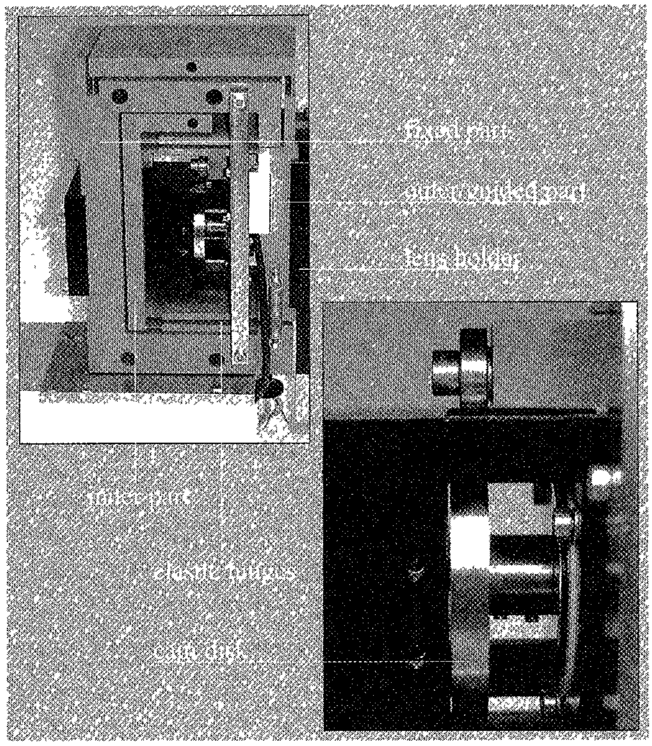

Figure 2 Manipulator overview

Controller choice

The manipulator is part of a machine that is built out of autonomous operating modules that are coupled to the central control unit. In these modules, servo systems were necessary for point-to-point motion. Tracking accuracy and settling time requirements are not demanding The physical area for the controller is restricted, and the interface medium had to be a serial port. We found out that the MCDC2805 motion controller from Faulhaber complied with the previously described requirements.

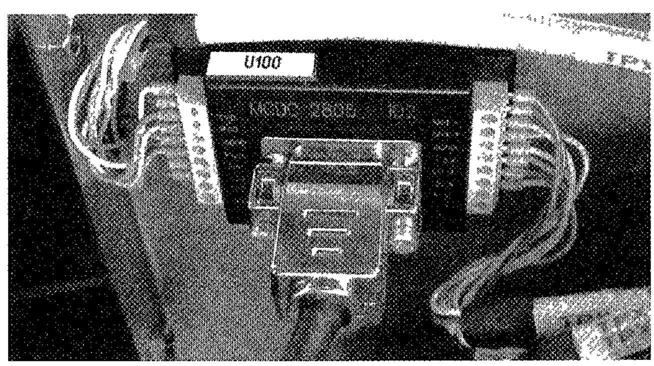

Figure 3 MCDC2805

The servo for the lens actuator, however, was different in terms of accuracy compared to the other modules It became doubtful whether the specs could be met. Hence a dynamic model of that particular servo was made.

Dynamic model

A 1D-model of the complete system has been realized using a simulation package called 20-SIM. The model concerns only the direction of movement of the system. Via this all parts that have a dynamic role between position set point and motion of the lens are described. The mechanical part is illustrated in figure 5 Illustrated here is a representation of the motor inertia (J-Motor) that is connected to a cam disc via an integral gearbox The curved disc introduces a conversion from the rotation to linear translation of the lens holder. One can find the position of the predefined compliance 'SD Compliance' just after the transmission of the cam disc.

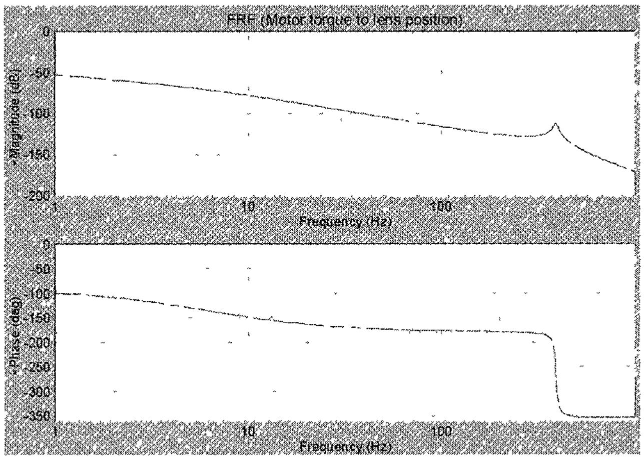

Figure 4 FRF of manipulator dynamics (only)

Simulation of the frequency response function (see figure 4) from motor force to lens position showed a resonance at 390 Hz, which appeared to be no thread for servo stability since the desired position bandwidth target is 30 Hz.

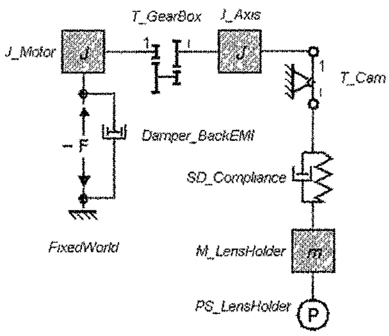

Figure 5. Mechanic model

The controller applies a velocity loop to realize artificial damping, which is necessary given the fact that the connected motor inertia is driven with a current controlled amplification stage. In figure 6 a block diagram of this control concept is shown. The gain of the position control loop is a fixed value while the velocity loop gain can be set via G-Kpv. An integral gain can be introduced via the adjustable parameter G-Kiv

When no I-action is chosen, one can represent the whole servo system as illustrated in figure 7, which shows a so called Ideal Physical Model (IPM). The 'spring' can be regarded as the P-action (G-Kpp) while the 'damper' results from the velocity loop.

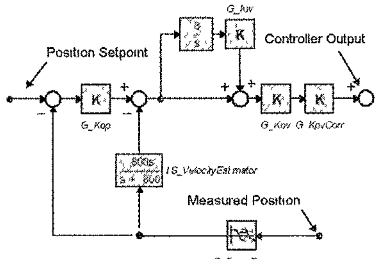

Figure 6. Controller model

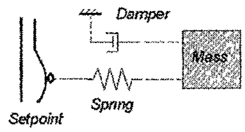

Figure 7. Basic IPM of servo

Simulation

With the current model CCM could derive that the tracking accuracy is strongly related to the gain between position and velocity reference. When we are running at constant speed, this gain factor will introduce a position (read tracking) error that is illustrated with the palest line in figure 8.

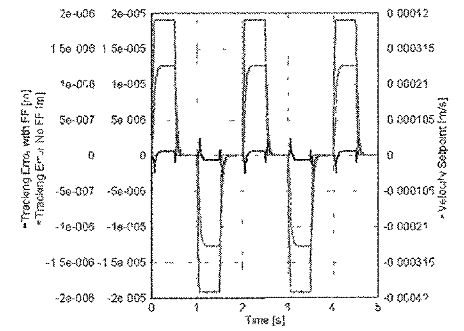

Figure 8. Tracking error

This behavior conflicts with our tracking error requirements. CCM came up with the following solution. The origin of the problem lies in the fact that we cannot add the desired velocity information into the summation point of the velocity loop. Such a read correction however is possible in the position reference too

The algorithm in figure 9 could be realized in the main control unit of the equipment. The result of this operation can

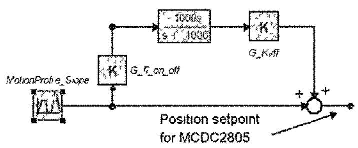

Figure 9 Feedforward correction

be found as the darkest line in figure 8. The tracking error is within budget now (mind the difference in y-axis scaling). Via this simulation CCM knew that improvement of the tracking accuracy is feasible. The impact of external disturbances, however, had to be identified via measurements using the prototype.

Verification

An experimental environment was set up to provide the required (analogue) set point and trace the motion simultaneously In practice there appears to be negligible disturbance in relation to the desired accuracy In figure 10 one can see that the tracking error stays well within a boundary of ±3 μm
The test setup has performed about 7.000.000 cycles without loosing performance. Nor any significant wear can be noticed.

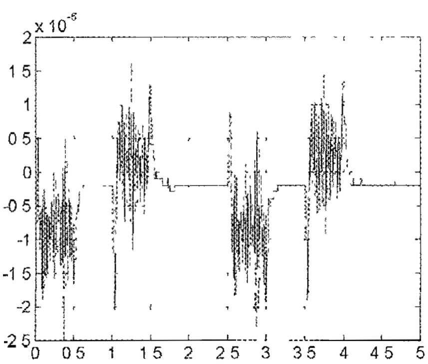

Figure 10 Tracking accuracy with FF

Conclusion

The implementation of a feed forward compensation technique together with a generic low cost motion controller has resulted in significant improvement of the tracking accuracy. The well-considered mechanical design has a significant contribution in the performance. Unpredictable disturbances, from various origins, might else have imposed violation of the desired accuracy boundaries. CCM has proven that an accurate positioning system can be developed without using too exotic components. A balanced use of know how from each discipline is the key for success.

References

Ref 1 'Constructieprincipes voor het nauwkeurig bewegen en positioneren', M P. Koster
Ref 2 Koster, M.P., W.T.C. van Luenen, T.J.A. de Vries (1998), 'Mechatronica', 7th edition, EL-RT, University of Twente, Enschede

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