

The Virtual Disk Drive - Mixed-Domain Support for Disk Electronics over the Complete Life-Cycle

Dr. Georg Pelz

c/o Infineon Technologies, Network and Computer Storage

P.O.Box 800949, D-81609 Munich, Germany,

Phone: +49-89-234-83171, Fax: ...-717431, E-Mail: Georg.Pelz@infineon.com

Abstract

This paper is about high-level, mixed-domain modeling to support a product through its complete life-cycle, from concept phase over circuit design and testing to application engineering in field. This is illustrated through an example, which is the electronics for a disk drive system comprising digital and analog/power electronics, mechanics and the respective firmware.

1 Introduction

Most previous work on modeling for mixed-domain systems has been devoted to just one aspect of a product's life-cycle. Nonetheless, this kind of models in general and especially in the mixed-domain area is useful all over a product's life cycle:

- In the concept phase, high-level models form an executable specification which can be validated by simulation. This model also serves as a framework for design space exploration and in certain cases may even allow early firmware development.
- In the design phase, the virtual prototype forms a general testbench. In this high-level system model, one may 'zoom' into the components under design, replacing high-level component models by their implementation. This may be done for any part of the system, while the system modeling has to be carried out just once. Moreover, this reveals information on the real-life system behavior rather than more or less synthetic data on signals at some component's interface. For a disk drive the focus may be for instance on spin-up, track-following or seeking.
- Also for virtual testing, it is indispensable to devise some high-level system model.

Combined with a model of the testing equipment, the test program development may be carried out much earlier.

- Finally, when the product is at the customer, i.e. some disk drive company, or even in field, the analysis of spurious behavior on the system model is much easier for application engineers, since every signal or quantity is visible. Unfortunately, this does not cover all possible faults of a device, since 2nd and 3rd order effects are not taken into account in system modeling. On the other hand, it should be easy, to prove or disprove any hypothesis, the application engineers may have on the root cause of system failures.

In the following, this will be illustrated through the example of a disk drive system.

2 The Disk Drive

This section details some typical configuration of a disk drive and discusses how this translates to requirements for the respective modeling, see also Fig. 1. The common drive contains one up to five rotating disks. This disk (stack of disks) is driven by the spindle motor which is a brushless DC motor. The rotational

velocity varies between 4200 and 15000 revolutions per minute¹.

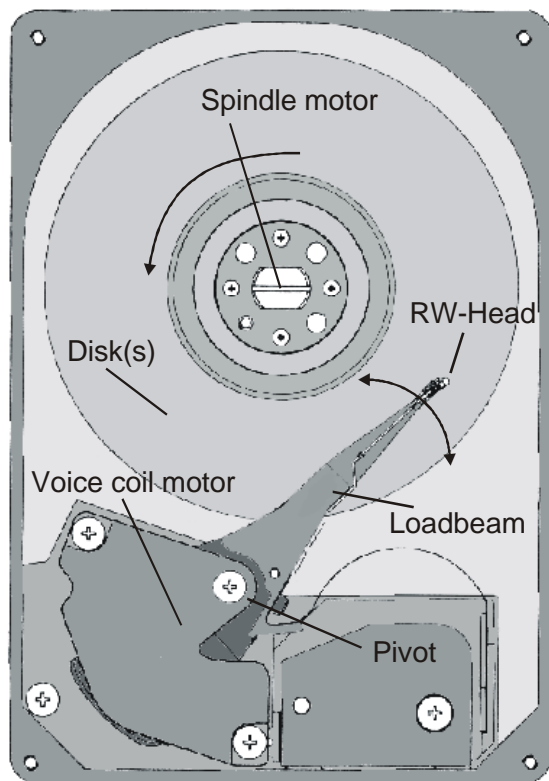


Fig. 1: Hard disk drive overview.

The RW-head is flying on an air cushion at a distance of 10 to 50 nm over the disk surface. It is supported by the loadbeam which can be moved about its pivot by the so-called voice coil motor. This consists of a coil which lies in a fixed magnetic field provided by permanent magnets, see Fig. 2. Any current through the coil results in a torque on the loadbeam and thus in a circular motion of the RW-head.

The data on the platter is organized in circular tracks. The outmost track may be located at a radius of 1.8 inch for a typical

3.5 inch form factor drive². With that, the maximum length of a track is 11.3 inches which for a 10000 rev/min drive leads to a linear speed of about 1880 inch/sec. Together with a bit density within a track of e.g. 400 Kbit/inch in turn leads to a peak data rate of 750 Mbit/sec. Interestingly enough, 1880 inch/sec – in terms of the velocity of a car – is far beyond any speed limit while bits of the length of about 60 nm are dependably read.

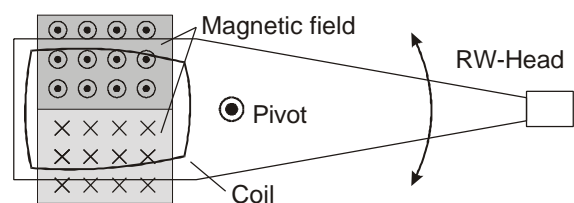


Fig. 2: Voice coil motor.

The track density of drives currently under design is in the range of 30000-100000 tracks per inch. Together with bit densities of 300 to 500 Kbit/inch this leads to areal densities of 9 to 50 Gbit/inch². Given the current track densities, the track pitch is in the range of 250 nm (100000 tracks/inch) to 850 nm (30000 tracks/inch). Controlling the head position to 10% to make sure that most of the track width adds to the signal and to keep noise at bay, results in a required precision of 25 nm to 85 nm when controlling the track following.

3 System Modeling

The disk drive comprises digital and analog/power electronics, firmware and mechanics which results in three major interfaces: hardware-software, analog-digital and electronics-mechanics. These interfaces have to be handled at the same time, which

¹ Higher as well as lower rotational velocities are chosen at times, e.g. to cope with low latency or low noise requirements.

² Note that no dimension of a 3.5 inch drive really is 3.5 inch. The disk's form factor is just the same as for a 3.5 inch floppy drive.

does not necessarily mean that the complete drive has to be present in any system simulation, but for instance when assessing the servo loop for controlling the track seeking or track following, all interfaces are present, see Fig. 1. Without loss of generality, we restrict ourselves to the servo loop in the following.

The model comprises the seeking and track following controller which is formulated in C and in the real system is implemented in firmware. Its inputs are the current track and the required track. Its output is some digital value for the required current to drive the actuator. According to this value, the current is regulated by an analog/power circuit which is called motion-control. The voice coil motor transforms the current into motion of the head assembly which may or may not contain resonances. The mechanical motion results in a track position which is fed into the firmware controller. The track content including track-id – as well as the logic to detect it – is reduced to a more or less trivial digital model, since it does not add to the overall function of the servo loop.

The simulation of the servo loop is performed on the basis of the mixed-mode simulator Saber. The analog part of the system – motion-control and mechanics – are modeled in the analog hardware description language MAST. Some basic digital modeling including the synchronization between the regulator C-routine and the rest of the system is carried out with the digital capabilities of MAST.

4 Simulation and Results

The high-level model of the servo loop as described in the previous section can be used for concept engineering. E.g. it is trivial to change the number of servo fields in a track which at a fixed rotational speed determines the frequency of position measurements and thus the frequency of the digital controller. In the same manner, most of the other variables determining function and performance of a drive may be varied. This can even be carried out systematically, e.g. through a parameter

sweep or – if more than one parameter is involved – on a Monte-Carlo basis. All these variations can be simulated efficiently. For instance, the simulation of a long seek over 20,000 tracks takes about 80 CPU seconds for 20ms real-time on a SUN Ultra 60 workstation, see Fig. 2. One can easily spot the 'bang-bang' strategy of maximum acceleration, constant speed at the speed-limit and maximum deceleration to lock into the new track position.

In the next step, the motion-control part of the servo loop top model was replaced by its implementation, represented by about 300 CMOS transistors and some DMOS power transistors. With that, real-life circuitry has been verified in a virtual disk drive which is by far more meaningful than the results of classical analog testbenches. With the same configuration as compared to the previous long-seek analysis, the simulation takes about 9 CPU hours which is not far from the simulation time for the transistor circuit alone. Note that most seeks are performed much quicker and that track-following can be reasonably assessed in an even shorter period. Apart from the standard tasks of seeking and track following, it is now easily possible to review the implementation of special features, e.g. a request to park the heads in the landing zone.

Currently under evaluation is the virtual test, for which it is absolutely indispensable to devise some high-level system model. This will be combined with a model of the tester equipment, which allows to start test program development long before silicon is available.

The support of application engineering is mostly about analyzing the system to explain spurious behavior which in turn allows to devise fixes and to implement them. This includes fault modeling for components of any domain. One might easily include for instance:

- Head assembly resonances of certain frequencies (mechanics)

- On-resistances of power transistors higher than specified (analog electronics)
- Timing problems in the serial communication between motion-control and disk controller (digital electronics)
- many more

This allows to assess the influence of the respective fault on the system behavior which in turn can be compared to the behavior observed in field.

5 Conclusion

The paper shows how system modeling and simulation can support a product over its complete life-cycle. In that vein, the multi-domain nature of the system increases both the need for a systematic solution and the problems in modeling and simulation at the same time.

6 Acknowledgement

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7 Literature

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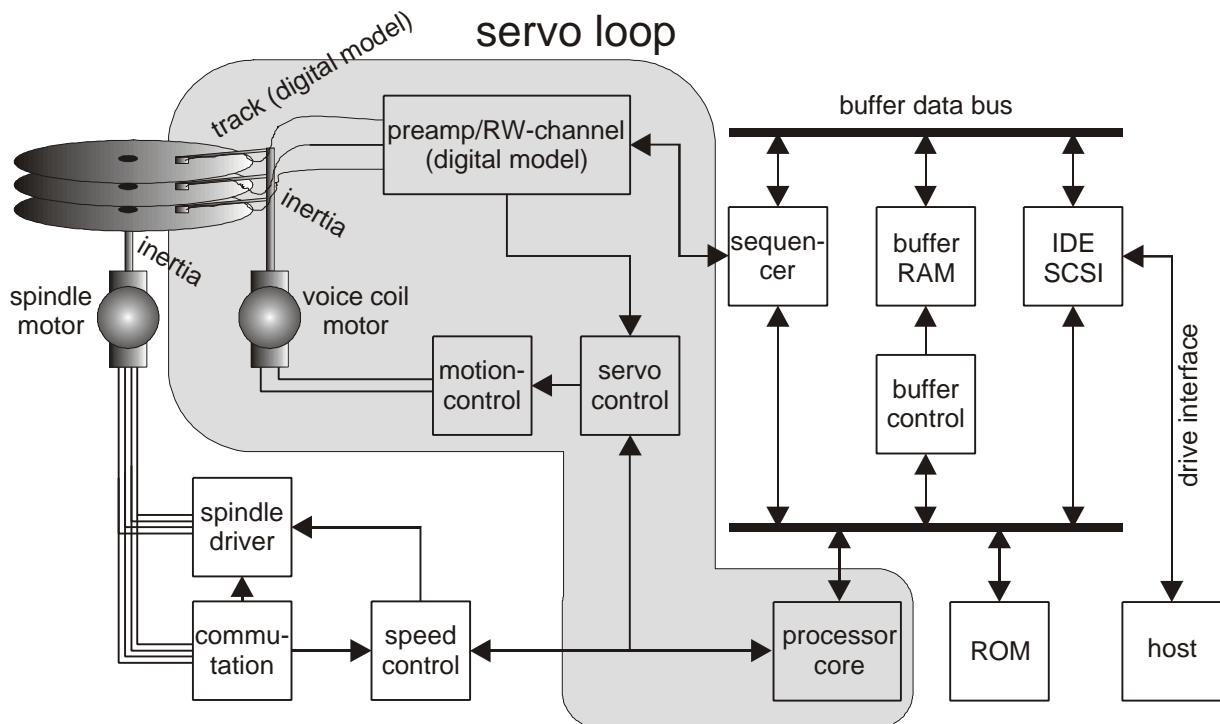


Fig. 3: Disk drive schematic with servo loop.

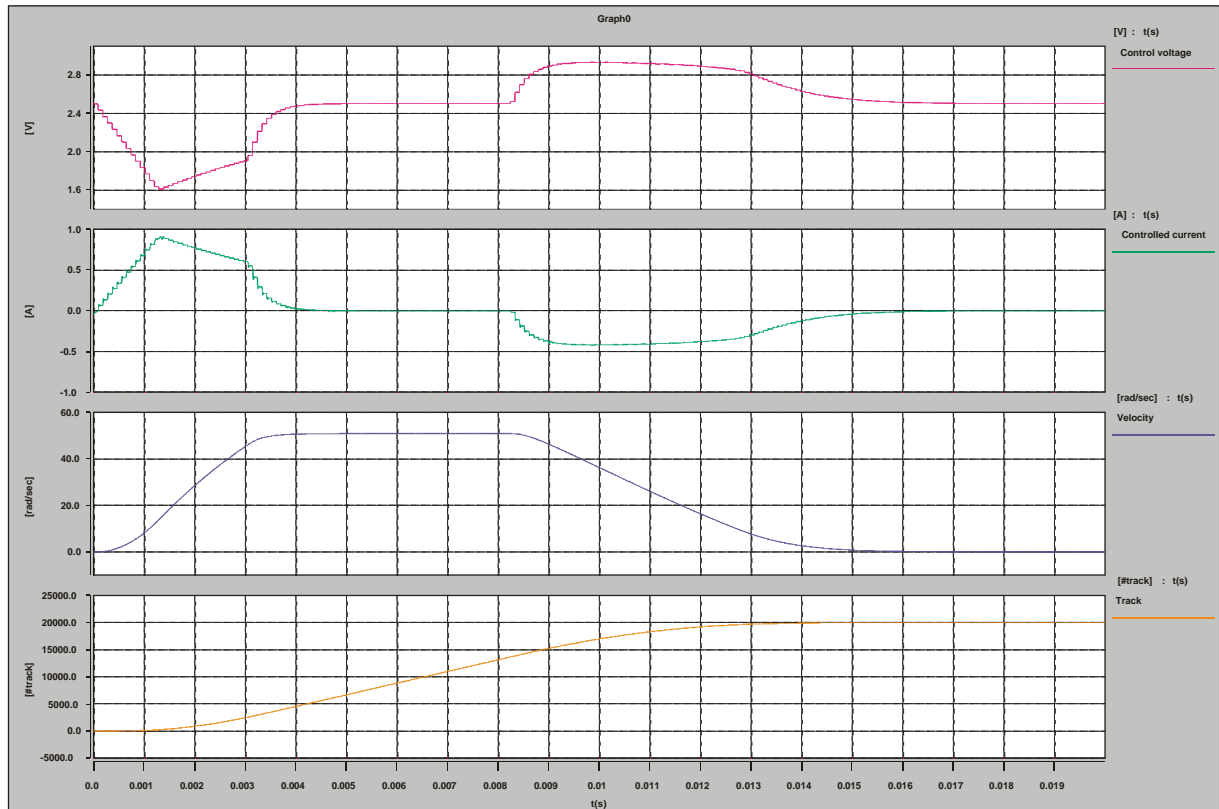


Fig. 4: Simulation results for long seek over 20.000 tracks. From top to bottom: digital output of firmware controller , controlled current, velocity of rotational actuator and track-number.