

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany

**1 Introduction**

In the last several years, the use of digital technology has significantly improved the performance of hydraulic drives. These improvements are not limited to the dynamic and static characteristics of the axes, but affect to an even greater degree characteristics like remote diagnosis, parameterability, and reproducibility. The first-generation hydraulic digital components usually contained only a field bus interface for parametering and set point specification. In the case of pumps and valves, these set points were usually associated with hydraulic variables, pressure, and volume flow. The second step of development added additional control functions into the devices, such as position, speed, or force control. Parallel to these device-internal developments, freely-programmable external control units with expanded sensor interfaces became more commonplace. This report will describe a toolbox concept that consists of both internal and external control modules.

**2 Overview of the M3000 concept and its products**

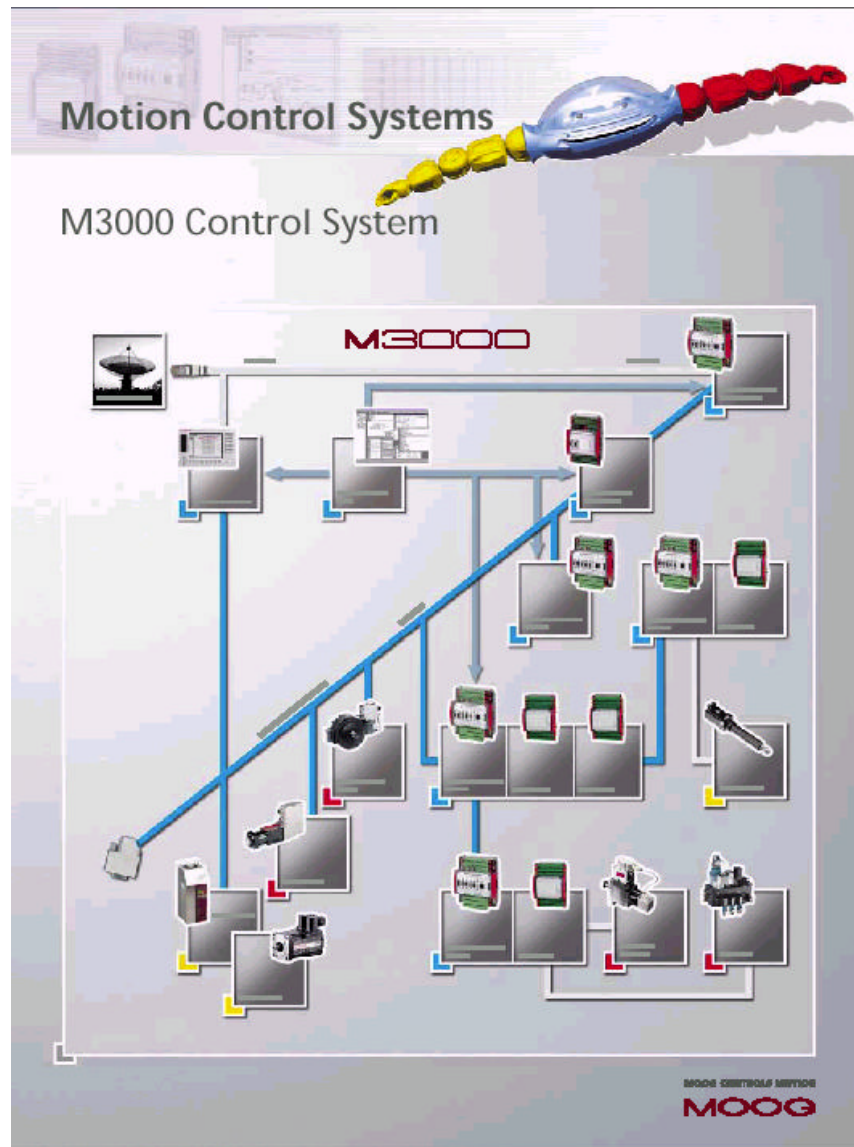
The M3000 system is a system that is optimally configured for automation tasks in hydraulic and electrical drive engineering. To achieve the highest possible performance, optimized control concepts are required at every level.

If the controller is located directly in a hydraulic valve (hydraulic pump or electric motor) that can be optimized during production, the requirements will differ from those for controlled systems implemented by the end customer on the machine controller.

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen

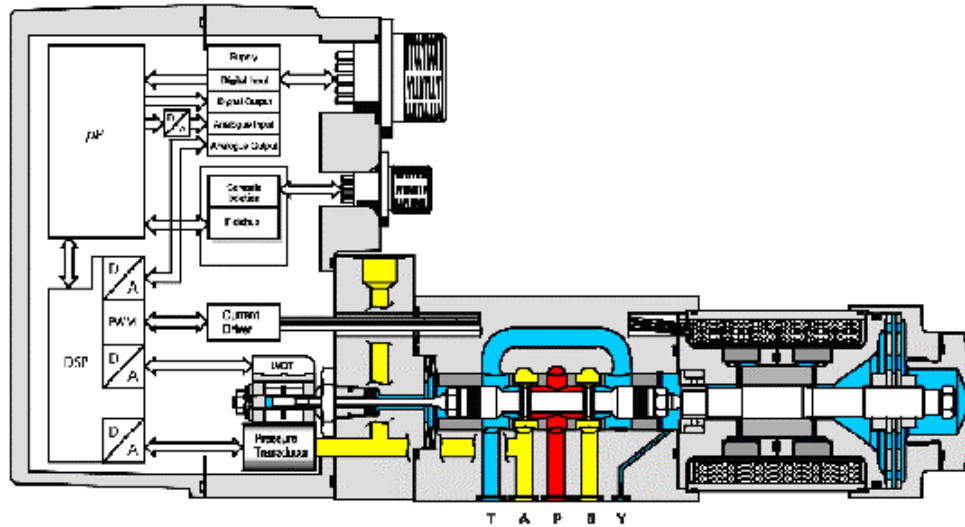
Moog GmbH, Böblingen, Germany

**Figure 1:** Overview of the M3000 system**3 Hydraulic axis-control valves and pumps**

A number of developments in hydraulics during the last few years have been characterized by the use of digital control electronics combined with field bus interfaces. At Moog as well, an initial step involved the development of digital servo and proportional valves. The second generation of these devices offers complete axis controllers, thereby representing another step in the direction of decentralized controller intelligence.

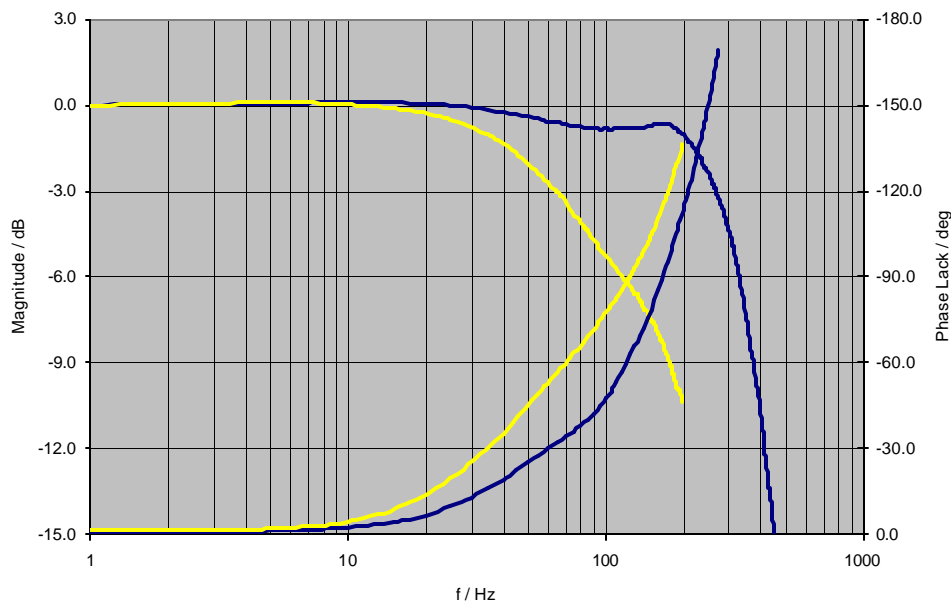
M3000 – A Motion-Control Toolbox for Hydraulic Axes

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
 Moog GmbH, Böblingen, Germany



**Figure 2:** Axis-control valve

The axis-control valve shown in **Figure 2** is based on a two-processor design. The main processor performs superordinate control tasks as well as all of the field bus communication. A digital signal processor is a subordinate unit that executes all input and output operations, the coil-current control, and the actuation and evaluation of the LVDT. This arrangement enables universal implementation of a 100- $\mu$ s cycle time for all control circuits in the system.



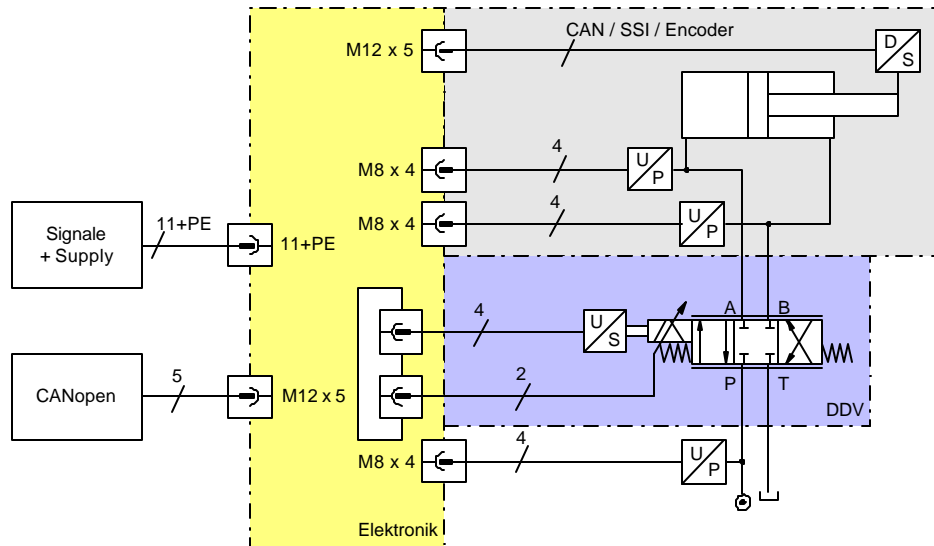
**Figure 3:** Comparison of frequency responses of analog and digital valves

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
 Moog GmbH, Böblingen, Germany

When compared to analog control systems, the implementation of nonlinear control structures is relatively easy in digital systems. **Figure 3** contrasts the frequency responses of control valves with analog and digital electronics.

**3.1 Hardware & software structure**



**Figure 4:** Axis-control valve

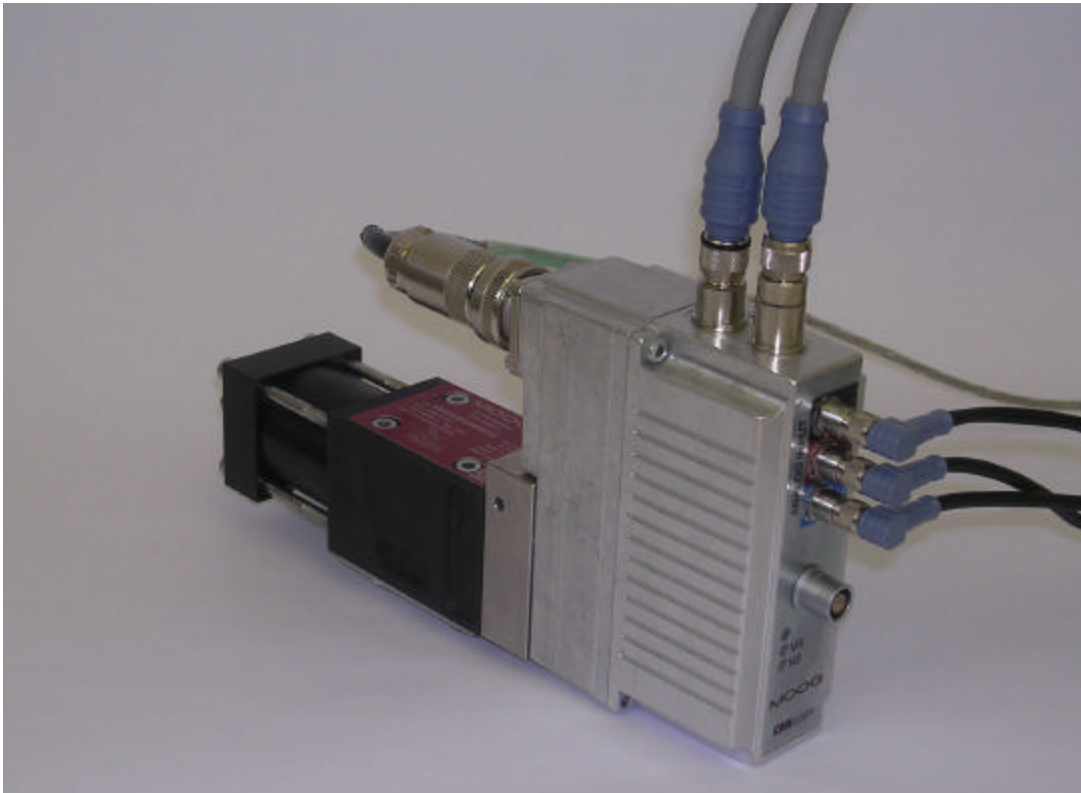
The axis-control valve's interfaces were configured in such a way that all major axis-control functions familiar from servohydraulics can be realized. As shown in **Figure 4**, the hydraulic axis can read-in the position and pressure signals of the cylinder chambers as well as the valve's supply pressure.

The depiction of the axis-control valve in **Figure 5** demonstrates that additional interfaces would lead to cabling requirements that are no longer manageable under practical conditions. The axis's position signal can be read-in over a second CAN interface, an SSI interface, or an encoder interface. With this arrangement, the following control circuits are easy to establish:

- Position
- Speed
- Pressure
- Differential pressure / force
- Parallel

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany



**Figure 5:** Practical execution of the axis-control valve

These control circuits are already implemented as fixed structures within the axis-control valve and can be selected and parameterized externally. A so-called event handler fulfills the requirement for actuating controllers (such as a position or velocity control that is then triggered by a pressure control closed loop). This event handler enables an event-controlled changeover from one controller mode to another.

### 3.2 Controller structures

The implemented controller structures were carefully chosen so that most applications that appear under practical conditions can be covered. During selection, the focus was on finding the most generally-applicable structures and achieving simple parameterability. The next two examples will demonstrate how these requirements were fulfilled.

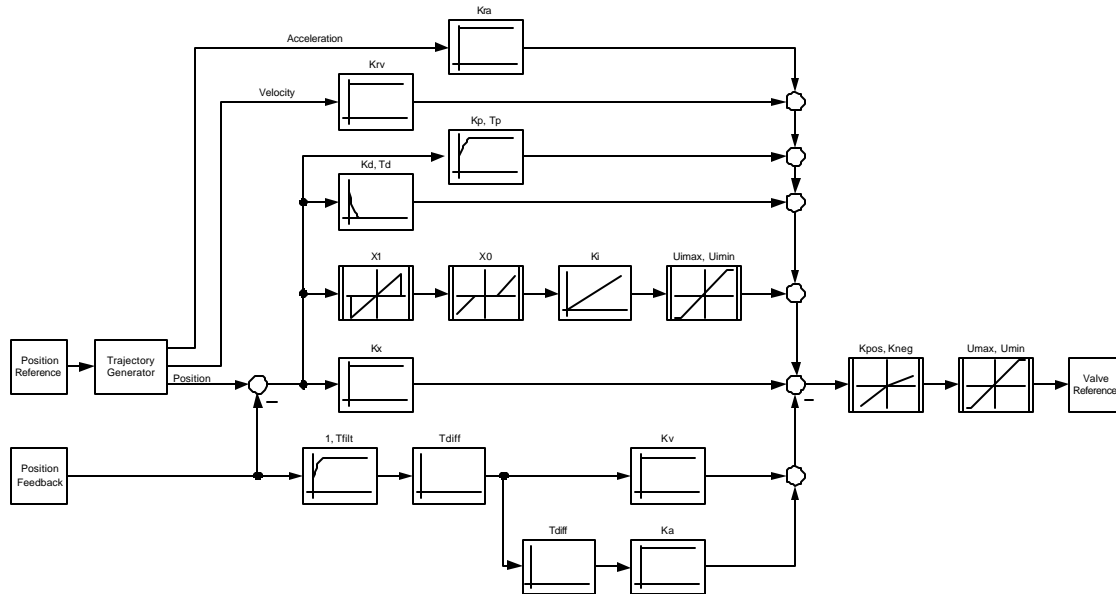
#### 3.2.1 Example "Position-control closed loop"

The position controller was configured so that it can be used with both high-frequency and low-frequency drives. **Figure 6** shows a classic PID core that was expanded for low-frequency drives by adding feedback of the state variables "speed" and

### M3000 – A Motion-Control Toolbox for Hydraulic Axes

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany

"acceleration". The integrated feedback is activated only under certain conditions that the user must parameterize. It is possible to parameterize yielding and a delaying feedback of the controller fault for high-frequency drives.



**Figure 6:** Structure of the implemented position controller

A major component of the position controller is the trajectory generator. This block conditions the incoming position set points in such a way that a smooth path with limited speed and acceleration values will be specified.

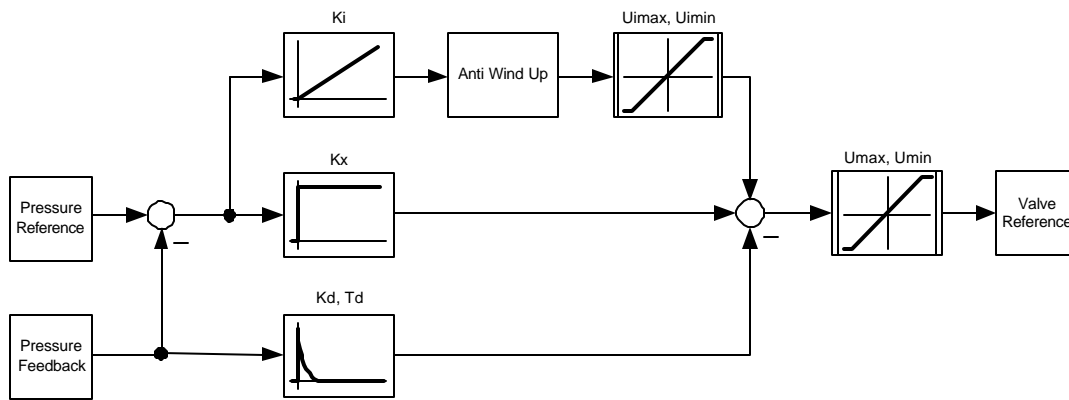
#### 3.2.2 Example "Pressure-control closed loop"

As shown in **Figure 7**, the pressure controller exhibits the structure  $1//2/$ , as known from common sources. The controller consists of a PI core with a nonlinear anti-wind-up function and yielding feedback of the actual pressure value.

Although the controller structure shown here may appear to be very simple, in practical situations there are often difficulties achieving the optimal setting of the  $K_i$ ,  $K_d$  and  $T_d$  controller parameters.

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany



**Figure 7:** Structure of the pressure controller

However, truly simple formulas for calculating these parameters can be derived from the transfer functions for disturbance and command behavior:

$$K_x = \frac{C_H \cdot D_v \cdot \omega_v \cdot (\sqrt{2} - 1)}{V_{QU}} \quad (1)$$

$$K_I = \frac{C_H \cdot \omega_v^2 \cdot (2 \cdot \sqrt{2} - 3)}{4 \cdot V_{QU}} \quad (2)$$

$$K_D = \frac{C_H \cdot (2 + \sqrt{2} \cdot (2 \cdot D_v^2 - 1) - 2 \cdot D_v^2)}{V_{QU}} \quad (3)$$

The equations (1) through (3) contain only valve variables and the hydraulic capacity

$$C_H = \frac{V}{E_{\dot{O}l}} \quad (4)$$

The computing rules (1) through (3) are recalculated in the valve, so that the user must optimize only one parameter.

## 4 Flexible controller structures in machines and systems

### 4.1 Digital control for machines that are used daily

Digital control technology has been used successfully for several years to optimize the control of all types of machines and systems. It is precisely these new technologies that have enabled German mechanical engineering companies to achieve the competitive edge they need to be successful in the global marketplace.

The most important advantages of digital over traditional analog solutions are: the ability of digital control loops to flexibly adapt to specific applications, the ability to optimize the

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany

control directly at the machine ("online"), and even the ability to implement self-optimizing solutions. Engineers can realize very complex control structures that enable them to extract the greatest possible benefit from the application. But, under normal everyday conditions, this blessing often turns out to be a curse.

Engineers with the required knowledge are rare. To produce an optimized solution, an engineer must have both an excellent knowledge of control technologies and far-reaching process know-how in addition to being well-versed in software and information technology. The users must not only lay out the perfect controller structure and optimize it for long-term stability, they must also implement this structure in software in the most optimal manner.

Especially smaller and medium-sized companies are not able to keep up with the necessary pace of finding and retaining the right people to perform these tasks. Although the process know-how may be available, implementation of the controller structures in the machine controller software is lagging. As a result, this part of a project is often delegated to outside experts. This type of dependency often lasts many years and can result in not insignificant costs.

#### **4.2 A wish list for an optimized machine controller**

In the search for a resolution to this dilemma, engineers are looking for an easily programmable machine controller with which even more complex control loops can be created without requiring a degree in information science. The ideal solution would be a flexible system whereby both controller functions and program control are covered in one device. With all these requirements, the device should also remain affordable.

Accordingly, the following items are on the "wish list" for a machine or system that is capable of highly dynamic applications (control cycle of 1 msec and faster):

##### **Software:**

- The ability to have flexible controller structures
  - Controller structure can be adapted to the application
  - Implementation like that learned academically, with individual controller blocks
  - Adoption of simulation results into the program
- "Online" optimization
  - Ability to display all state variables during ongoing operation



**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany

- Oscilloscope function with integrated graphical evaluation
- Integrated visualization
- Simple programming
  - IEC61131 (no exotic programming languages)
  - Programs that are easily understood (graphical)
  - Integrated documentation
  - Low requirements for training and adjustment
  - Can be executed even without a degree in software
  - Can be transferred to future systems
- Simple but flexible interfaces for
  - "Up"  
Connected with control station; office; remote service  
(such as ethernet / TCP/IP connection)
  - "Lateral"  
To other software packages for data collection / evaluation / visualization / statistics programs, etc.  
(such as over OPC and DDE)
  - "Down"  
To sensors, actuators, decentralized modules, other controllers;  
input and output devices, etc.  
(such as over field buses like CANopen; Profibus over SSI, etc.)
  - Flexible parameterizing of the entire system with all applied elements,  
over a central interface from a programming environment

**Hardware**

- A device that is suitable for rapid control loops as well as for program controllers (PLC)
- Modular design
  - Can be flexibly adapted to the application
  - Scalable according to need
  - Small number of standard modules for all types of machines
- Control loops
  - High resolution analog inputs/outputs
  - Fast & flexible digital inputs/outputs
  - Connection of high resolution digital sensors
  - Sufficient processor power to facilitate fast control loops
- PLC
  - Scaleable / expandable

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany

- Modular design
- But still centralized configuration
- Modular design
  - Can be flexibly adapted to the application
  - Scalable according to need
  - Small number of standard modules for all types of machines
- Justifiable costs

**4.3 The M3000 automation system**

Considering the large number of industrial applications, it would hardly be possible to develop a system that is ideal for every application. The system introduced below meets the requirements of a range of clearly defined applications while still optimally fulfilling all of the requirements in the list above.

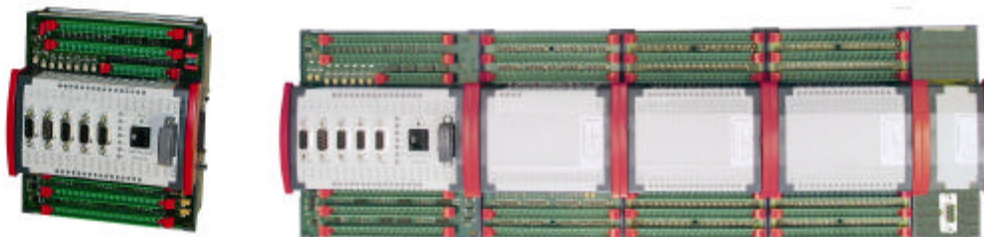
The target groups are:

- Small to medium sized mechanical and systems engineering companies that produce machines and systems in small to medium quantities and whose portfolio includes several machines in similar yet different versions.
- Series of small to medium quantities
- At least one axis requires a highly dynamic control loop

The introduced M3000 system is a modularly constructed automation system that permits execution of virtually every component of a machine from one system.

**4.3.1 Hardware structure**

The central component of the M3000 automation system is the Moog Servo Controller (MSC). A large number of extension modules that can be "snapped" onto the main module provide a flexible means of expansion.



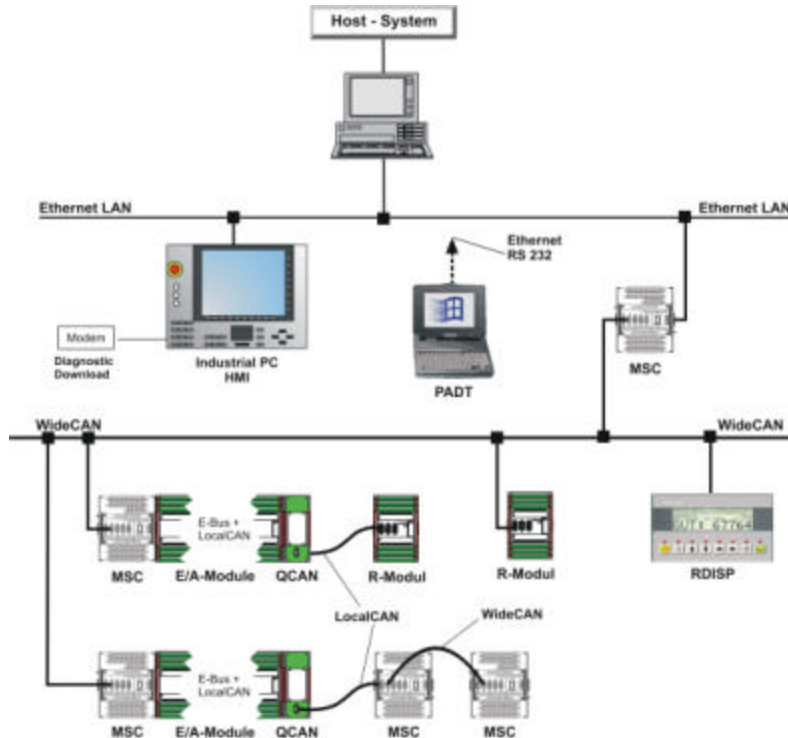
**Figure 8:** MSC

Extension modules are "snapped" laterally into place

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
 Moog GmbH, Böblingen, Germany

Other modular (even decentralized) extensions are possible with E/A modules, terminals, temperature controllers, sensor connections, field bus interfaces, etc. or directly with the connection of valves, hydraulic pumps, motor controllers, and all types of sensors.

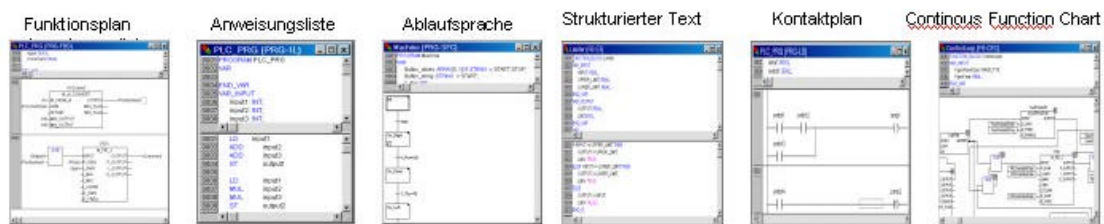


**Figure 9:** System overview of centralized and decentralized components

**4.4 Simple programming in a concrete example**

**4.4.1 Implemented programming languages according to IEC61131**

A total of six programming languages are integrated in the MACS software and can be used individually or together, depending on the current requirements or the programmer's personal preferences.



**Figure 10:** MACS programming languages

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany

**4.4.2 Graphical control-loop structures in the continuous function chart**

The "continuous function chart" makes control-loop structures especially clear and easy to program.

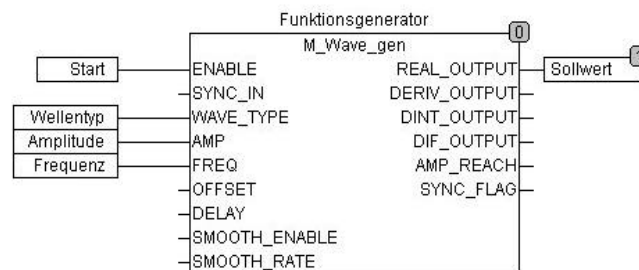
In these cases, existing control blocks are easily put in place graphically and their inputs and outputs are also connected to each other graphically. A background syntax check and automatic dialogs that ask the programmer to enter things like the desired level of accuracy or data format permit less experienced programmers to generate a program in a short period of time.

**4.5 Detailed examples****4.5.1 A simple example of a test machine**

This example will demonstrate the realization of a hydraulic vibrator for a test machine used in vibratory and shaking tests. The components used will be a hydraulic cylinder with a path-measuring system, a hydraulic servo valve, and an MSC for the control loop. The realization of the software in MACS is shown here in four simple steps:

**Step 1: Set point signal for the vibratory motion**

The function block of an adjustable frequency generator is used.



**Figure 11:** Function generator for the set point position

The user must be able later to adjust on a screen or terminal the inputs start, wave type, amplitude, and frequency. Therefore, these are defined as input variables. The system automatically queries the appropriate data types; default values can be entered directly. The block's output signal serves as the set point position for the cylinder. Here as well, a variable is provided so that it can be easily shown graphically at a later time (for example on the integrated oscilloscope for the optimization of the controller parameters).

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen

Moog GmbH, Böblingen, Germany

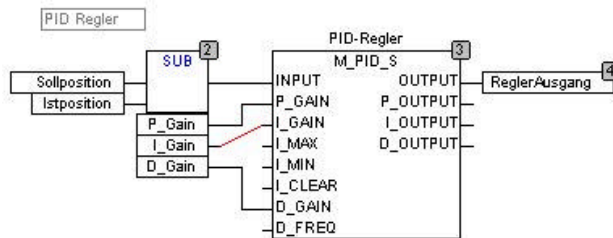
```

VAR
  Funktionsgenerator: M_WAVE_GEN;
  Sart: BOOL;
  Wellentyp: INT;
  Amplitude: REAL:=5;
  Frequenz: REAL:=1;
  Sollposition: REAL;
  
```

**Figure 12:** Variable definitions were automatically set in the user dialog.

**Step 2:** PID controller for the hydraulic axis

The control difference of the set point position and the actual position is forwarded to a PID control block with adjustable P, I, and D factors.

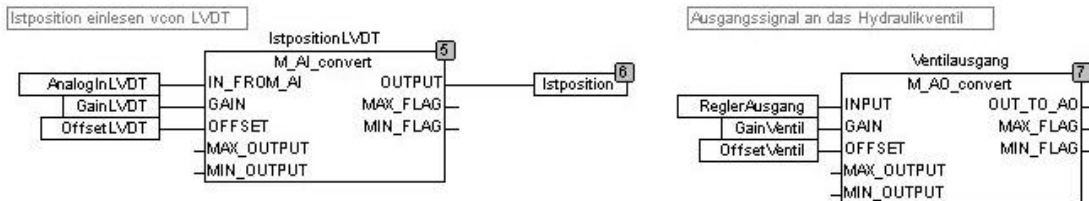


**Figure 13:** The structure of a PID controller

**Step 3:** Read in and read out the interfaces

The path-measuring signal of an LVDT should be used as the input. This will be scaled immediately in the read-in block to physical units (such as mm).

A valve will be actuated directly at the output; here as well, appropriate scaling will be done in the block. The subsequent choice of interface (4..20mA or +/- 10V) can be defined in the hardware configuration and has no influence on the programming.



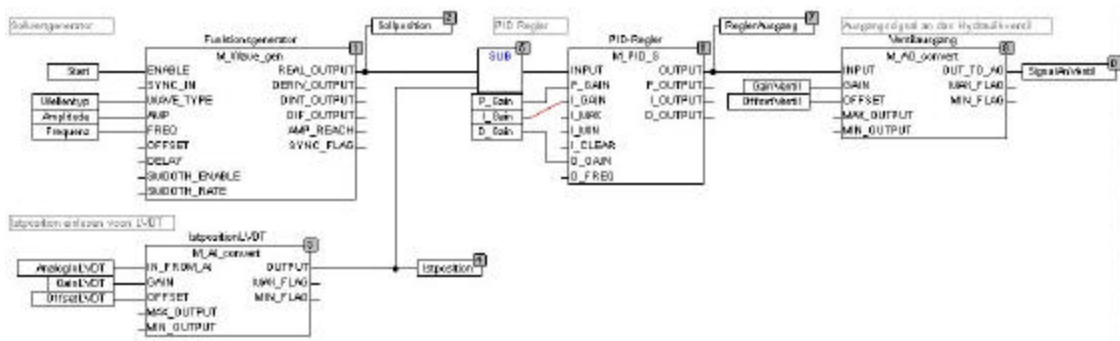
**Figure 14:** Detecting the actual position and outputting the signal to the hydraulic valve.

**Step 4:** Connecting the blocks from steps 1 through 3

It is now time to connect the blocks from steps 1 through 3. Compile the program, check, load onto the machine controller, and finished.

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

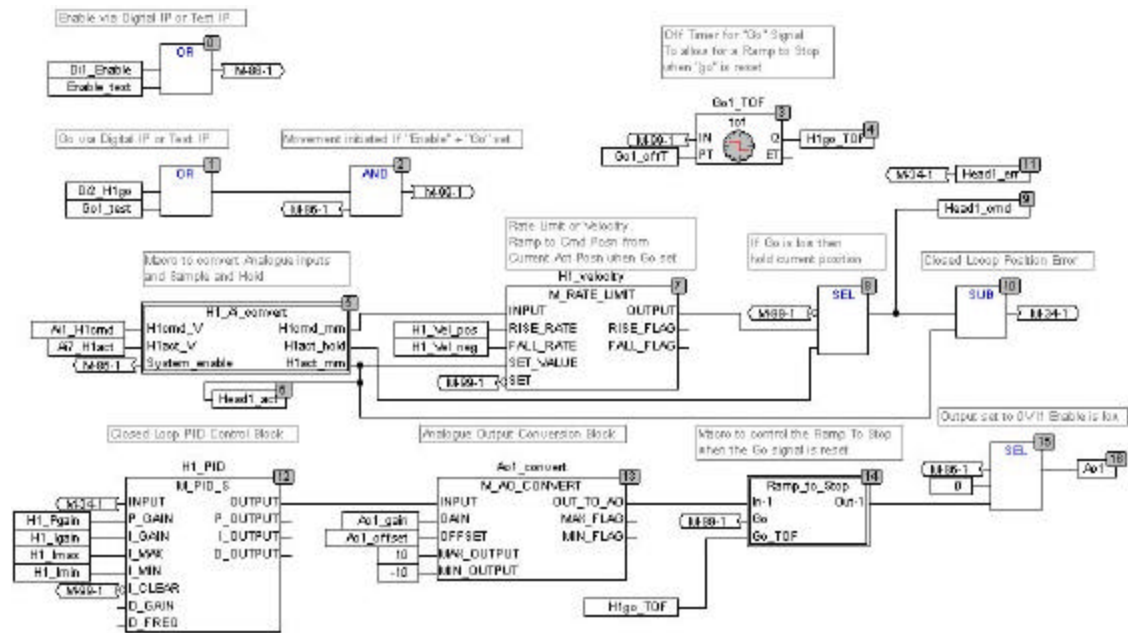
By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany



**Figure 15:** Controller and set point generator for the vibrator of a test machine

**4.5.2 A more complex example of a test machine**

The following example demonstrates in concrete terms the realization of a somewhat more complex control of a machine axis in a test machine. In addition to a large number of conditions and elements related to program control, other elements are also transformed. For example: selectable ramps, set point jumps, limiters, timers, safety switches, interface monitoring, etc.

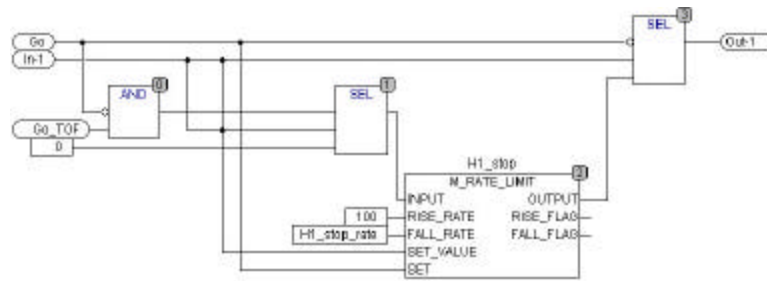


**Figure 16:** Test machine with controller and program control

The overall machine controller still remains too complex. Macros were used for individual functions. Additional functionality is found behind the macros, but, for the sake of clarity, these were shown simply as blocks with a double border and the associated inputs and outputs. For instance, the following functionality is hidden behind the Ramp\_to\_Stop macro block:

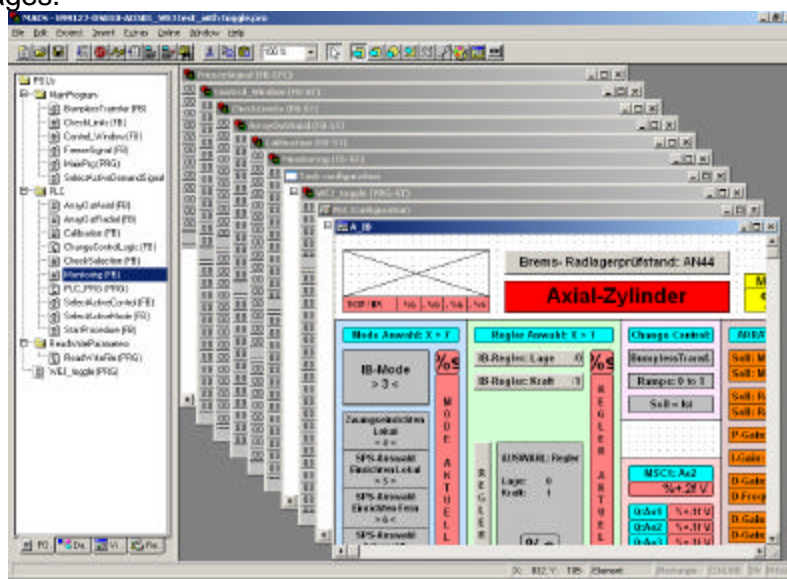
**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany



**Figure 17:** xxx

A machine usually has several axes for the control loop and several functions for program control. It is possible (but not necessary) to distribute these to various program modules, which can also be generated in several different programming languages and still interact with each other. If the programmer then employs a visualization tool (the hardware configuration, etc.) then he will quickly have several windows, as shown in the following images.



**Figure 18:** Individual program parts are shown in their own windows

**5 Summary and outlook**

The toolbox shown here shows how effective control loops that are adapted to the peculiarities of hydraulic drives can be implemented with relatively little difficulty. The major control functions for hydraulic axes are already implemented within the hydraulic components. If these are not sufficient or if several axes must be linked, the MSC/MACS system introduced here is a good choice.

**M3000 – A Motion-Control Toolbox for Hydraulic Axes**

By Dr.-Ing. C. Boes and Dipl.-Ing. J. Weiblen  
Moog GmbH, Böblingen, Germany

**6 Literature**

- /1/ Boes, C. / Müller, J. / Lenz, W.  
Digital Servo Valves with Fieldbus Interface in closed Loop Applications,  
The Eight Scandinavian International Conference on Fluid Power, May 7-9,  
Tampere, Finland
- /2/ Murrenhoff, H.  
Servohydraulik, Umdruck zur Vorlesung, RWTH Aachen, Shaker publishing

**7 Symbols**

|                |  |             |
|----------------|--|-------------|
| $C_H$          | Hydraulic capacity                       | $m^3/Pa$    |
| $D_V$          | Servo valve damping                      | -           |
| $\omega_V$     | Servo valve eigen angular frequency      | rad/s       |
| $V_{\alpha U}$ | Servo valve volume flow amplification    | ltr/min / V |
| $E_{\alpha}$   | Reserve compression module               | MPa         |
| $K_x$          | Proportional controller amplification    | V/MPa       |
| $K_I$          | Integrating controller amplification     | V/Mpa s     |
| $K_D$          | Differentiating controller amplification | V/Mpa/s     |

German language version also available, visit <http://www.moog.com/techpapers/>.