Multi-variable Control Concepts for a differential cylinder with an independent metering valve configuration

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Abstract

In this article a novel idea how to realize energy efficient multi-variable control concepts for a differential cylinder with an independent metering valve system for industrial applications is presented. The Extension of the operating area of such a system by using energy regeneration and pressurization control is also discussed. The proposed control concepts for the system are a LQR configured multivariable state-feedback controller with an integral extension and a decentralized decoupled controller. It is shown that the degrees of freedom in this new control approach can be used to control the position and the rod side pressure level and therefore the pressurization level of the cylinder drive at the same time. The main focus in this paper is the decentralized control compared to the already presented LQR MIMO controller in /5/ and /6/. In addition, the principal structure of the logic control system that recognizes the possibility of a regenerative mode and then switches to the most energy efficient valve configuration is revised briefly. The functionality and the performance of both controlled systems are compared by simulation results of a differential cylinder drive.

KEYWORDS: fluid power, independent metering, LQR, multivariable control, energy efficiency, decentralized control

1. Introduction

Today directional four-way control valves are the most frequently used valves for motion and/or force control in industrial hydraulic applications. These valves allow for the simple realization of robust motion or force controlled electro-hydraulic systems with high control performance and simple single input single output system structures. A disadvantage, however, are the high power losses due to throttling of the fluid flow when used in constant pressure systems /8/.

One well known possible way to increase the energy efficiency of a valve controlled hydraulic system using a differential cylinder is to use regeneration flow. Regeneration flow can be defined as pumping fluid from one cylinder chamber to the other by using no or minimum flow from the pump while external forces F are small during extension of the rod or act in direction of the motion using no or less volume flow from the pump /2/, /10/ and /12/.

A known topology to realize regeneration is an independent metering valve configuration. A system that uses independent metering is more flexible than a conventional system since there are more degrees of freedom and thereby more outputs to control /2/, /3/. With the loss of the mechanical dependency of the metering edges one of the main questions is how to use this new degree of freedom. Previous investigations in mobile hydraulics already proved the increase of energy efficiency by using such systems for energy regeneration /12/. In Addition to energy regeneration the degrees of freedom in this new control approach can be used to control the position x and for example the rod side pressure and therefore the pressurization level of the cylinder drive at the same time. Exploiting this, it is possible to increase the stiffness of the cylinder drive and thereby its natural frequency which finally leads to a better tracking behaviour. Similar systems utilizing individual metering with four independent valves are discussed in /2/, /3/ and /12/. Further the functionality of special designed control valve pistons can be created by adjusting the control software. The main disadvantage of independent metering control is the increased control and sensor effort.

The requirements for a control approach of such an independent metering system in industrial hydraulics are different to mobile applications. For industrial hydraulics a fully automated motion and/or force control for cyclical nominal values with minor expense of commissioning is needed /9/. Furthermore a high level of energy efficiency and specified system dynamics and precision are often desired.

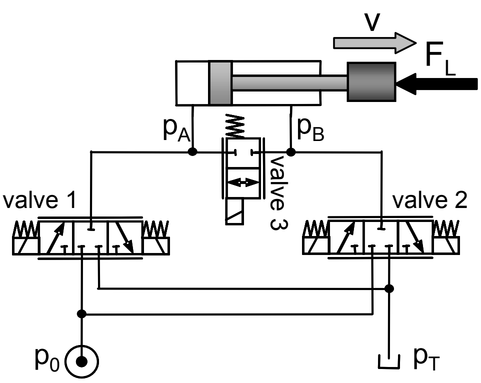

Figure 1: Independent metering valve with a differential cylinder

In this paper a novel idea how to realize two different multivariable control concepts for a differential cylinder with an independent metering valve system as shown in Figure 1. is presented. The system consists of two 3/3 directional control valves which connect each cylinder chamber to the pump or tank. Additionally one 2/2 control valve connects both cylinder sides directly. This third valve is used for energy regeneration. The proposed multivariable control concepts are a LQR configured state-feedback controller with an integral extension and a decentralized control. A similar LQR control concept was also proposed in /3/ to control a swing arm function using two 2/2 pressure compensated "valvistor" type valves.

The main focus in this paper is the decentralized control compared to the already presented LQR MIMO controller /5/. In addition, the principal structure of the logic control system that recognizes the possibility of a regenerative mode and then switches to the most energy efficient valve configuration is revised briefly /6/. The functionality and the performance of both controlled systems are compared by simulation results of a differential cylinder drive.The energy regeneration works only in specified operating areas. These operating areas of the independent metering device are discussed in the next chapter.

2. Four quadrant operation using energy regeneration

In order to save energy during extension or retraction of the cylinder drive regeneration flow is used /2/, /10/, /12/. By using regeneration flow the working areas of the cylinder drive are extended as shown in Figure 2. In principal three different modes can be used with this valve configuration. During all regeneration modes the rod-side chamber pressure is controlled as well. The "normal mode" shows the independent metering mode with p_B control using the two 3/3 valves as already shown in Figure 1.

The "powered extension regeneration mode" of the cylinder drive is normally used in order to control the cylinder in the first quadrant /2/, /12/. By the control of p_B through the third valve the drive can handle positive and also negative forces (second quadrant) as well. This is an advantage that can be achieved by the multi-variable control of the independent metering valves compared to systems like the proposed A-hybrid circuit valve in /10/. During this mode the required volume flow from the pump is reduced to $Q_{0reg}=Q_0(1-1/\alpha)$. The maximum positive force during extension, however, is reduced as well to $F/F_{max}=1-1/\alpha$. The maximum achievable velocity could be increased at the same time depending on the valves and cylinder characteristics. In order to compare the working areas to "normal mode" all the valves have the same edge characteristics.

During the "extension regeneration mode" no volume flow from the pump is needed at all /2/, /12/. The maximum achievable velocity depends on the preload pressure of the tank (in this case 10% of p_0). For practical use this mode is very difficult to control because the rod-side pressure p_B is very low and p_A needs to be even lower ($p_B>p_A$). Therefore cavitation in one of the cylinder chambers is very likely to occur /2/, /12/.

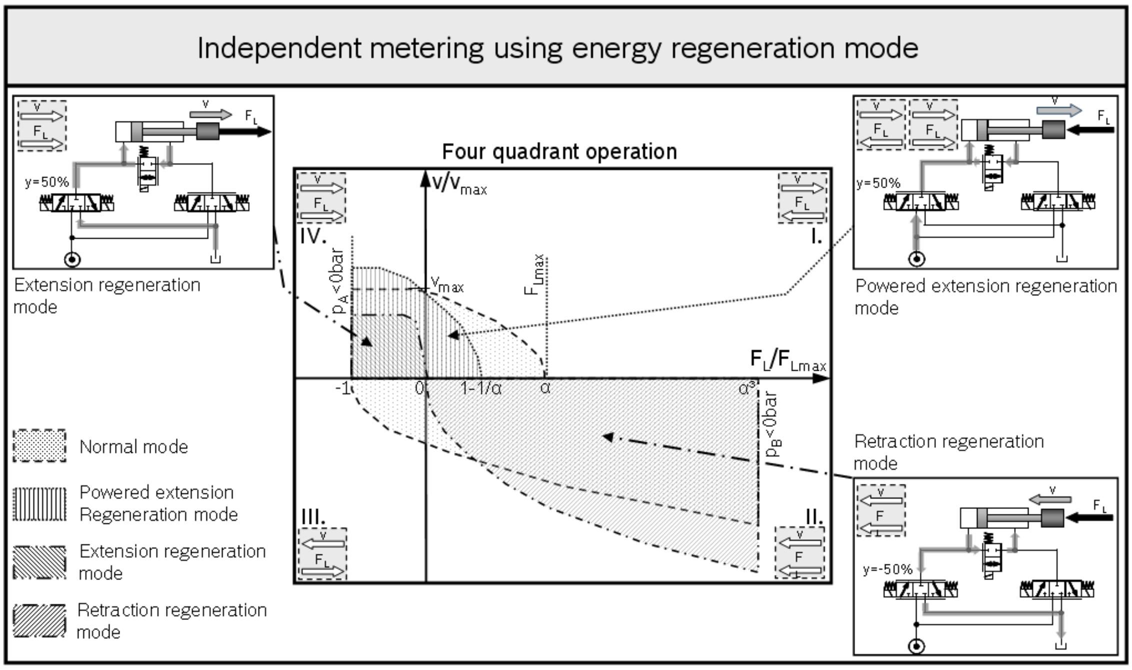

Figure 2: Four quadrant operation using energy regeneration

Working in the "retraction regeneration mode" the cylinder drive could also be positioned without the need of volume flow from the pump /2/, /12/. As it is shown the maximum achievable velocity during this mode is theoretically higher than in normal mode. The rod-side pressure p_B however must be lower than the piston side pressure

p_A. It has already been proven that by use of regeneration flow the needed volume flow is reduced /2/, /12/, /5/.

The challenges for this independent metering valve system are how to control such a system in the different modes and how to generate nominal pressure values for the different modes with one multi-variable control system. Further a logic control which recognizes the possibility for energy regeneration is needed that switches between the different modes in order to save energy. In order to prove the functionality of the control system a simulation model of the drive is needed.

3. Control Structures

3.1. Structure of the LQR multivariable control

This approach uses a multivariable state-feedback controller to gain the desired damping of the cylinder drive /5/. In order to guarantee the stationary accuracy of the control variables an integral extension is implemented /4/, /10/, /13/. It also includes an optional feed-forward control. The complete system is shown in Figure 3.

The state controller matrix is called K_x and the integral extension control matrix is called K_e /11/. The controller matrices K_x and K_e are optimized to work in normal mode and regeneration mode so there is no need to switch between different controller structures in the system. This is one of the main advantages of this control approach. The switching between the modes is realized by activation and deactivation of the valve inputs (vector u) only. The complete derivation and optimization of this control approach is described in /5/.

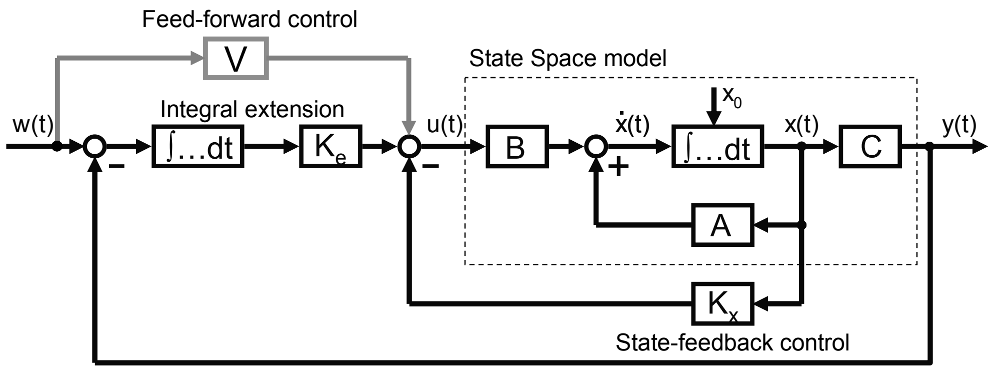

Figure 3: Structure of the multi-variable control

3.2. Structure of the decentralized control

The decentralized control is based on the system matrices shown in /5/. In contrast to the multivariable LQR control two SISO control structures are needed. One for the normal mode as described in Chapter 2 and one for the regeneration mode. At first we look at the normal control mode where the systems position is controlled by valve number one and the pressure on the rod-side of the cylinder is controlled by valve number 2 (Figure 1). The third valve is neglected in the system matrices /5/.

The resultant multivariable system can be remodelled easily as a P-structure system as shown in Figure 4. The interconnections in the System G_{12} and G_{21} /1/,/4/ can be obtained by /4/

$$\mathrm{G(s)} = C(sI - A)^{-1} B + D \quad (1)$$

In a decentralized System each control variable is controlled by a Single-Loop controller as shown in Figure 4 /1/, /4/. In order to improve the control performance it is possible to decouple the Systems interconnections in the linear model /1/.

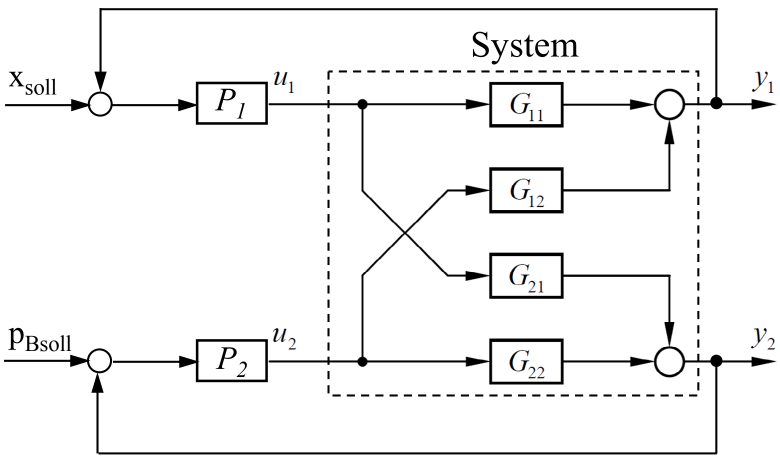

Figure 4: Controlled decentralized system in P-Structure /1/

In the P-Structure the coupling of the system structure can not be derived directly from the system by G_{12} and G_{21} //. Therefore the System is transformed into the V-Structure as shown in Figure 5. The System is derived by /1/, /4/

$$Y(s) = diagF_{ii}(s)\big(U(s) + V(s)Y(s)\big). \quad (2)$$

This linearized System can be easily decoupled through V_{12} and V_{21} /1/ as shown in Figure 5.

In Figure 6 the controlled system is shown. For position control a State Controller, for the pressure control a PID-Controller and a switching integral extension for stationary accuracy is used. The controller parameterization is realized by an optimization through trial and error /1/. In the future the system will be also numerically optimized.

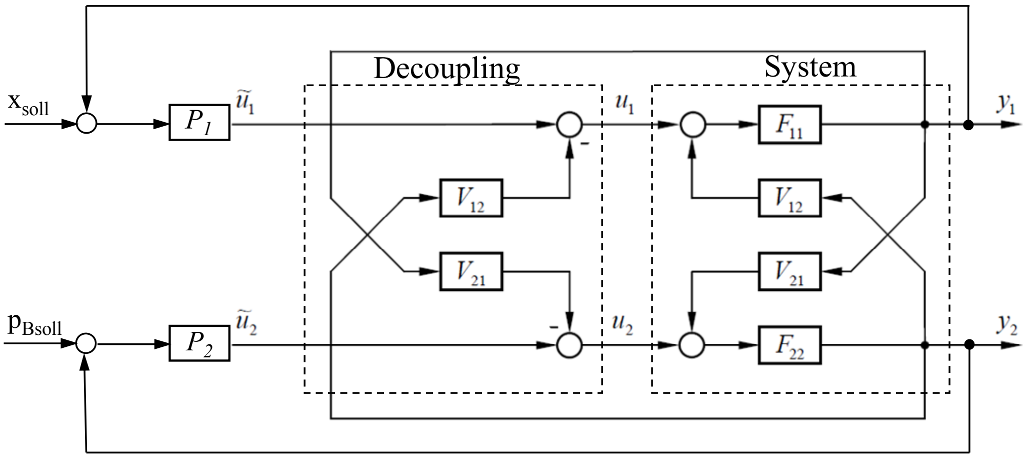

Figure 5: Decentralized system controller with V-Structure and decoupling /1/

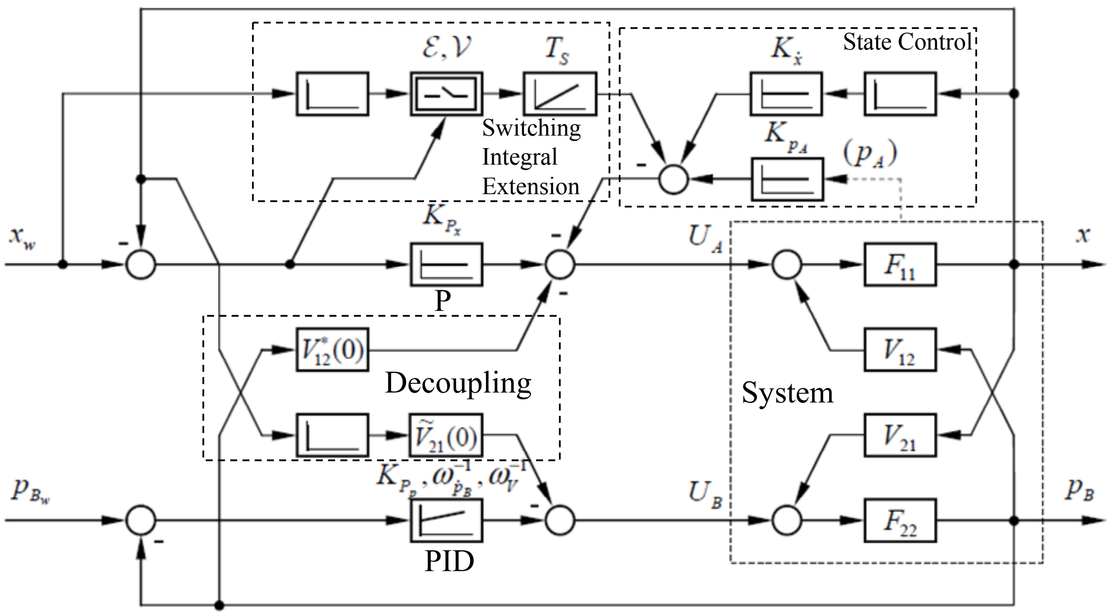

Figure 6: Decentralized system controller with V-Structure, decoupling, position state control and PID pressure control /1/

4. Logic Control

In order to save energy using the different modes a logic control that recognizes the possibility for energy regeneration, switches to the optimal control mode and sets the appropriate command values that are needed. The principal structure of the complete system is shown in Figure 7.

The nominal value of p_B is determined on the basis of the in Figure 2 shown operating areas of the different control modes. The actual value of p_B is created by the logic control presented in /6/. The recognition of the possibility for energy regeneration will be part of future work.

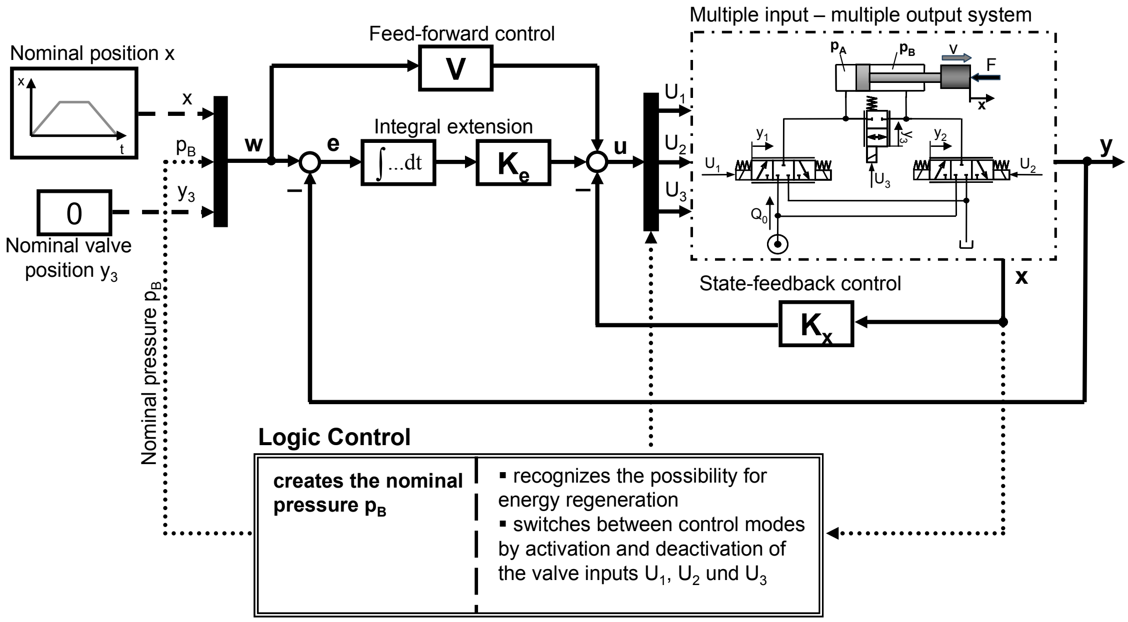

Figure 7: Proposed LQR control concept /5/, /6/

5. Simulation Results

For both control concepts three simulations on the nonlinear model // are performed. At first we look at the step response of both control concepts. At t=0s a position step from x_{soll}=0,1m to 0,2m is performed. The decentralized step response of the system is a little bit faster than the LQR MIMO controller due to a higher amplification. The controlled pressure p_B on the other hand is much better using the LQR MIMO controller since you have nearly no pressure error because of the better compensation and damping of the interconnections through the state-feedback controller. The pressure error for the decentralized controller instead is so high that during t=0,25 s the pressure is negative therefore cavitation would occur.

At t=1s a pressure step is performed. Both control concepts have a good step response but the decentralized controller is a little bit slower in order to minimize its oscillation.

At t=1,3s another position step is performed using the regeneration mode. The step response of the decentralized control concept is again a little better than the MIMO controller, but the control of the pressure is better in LQR MIMO controlled mode. The pressure in both chambers at t=1,5s is 0bar because the controller tries to reduce the positive position error. Therefore the regeneration mode can only be used during a constant movement of the cylinder, for breaking the normal mode should be used.

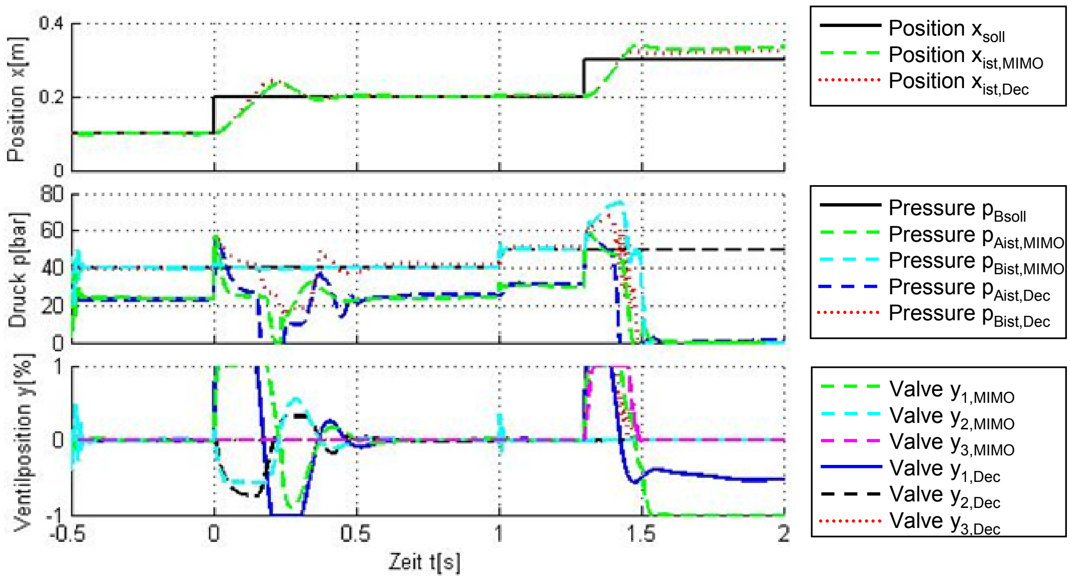

Figure 8: Step Response to both control concepts

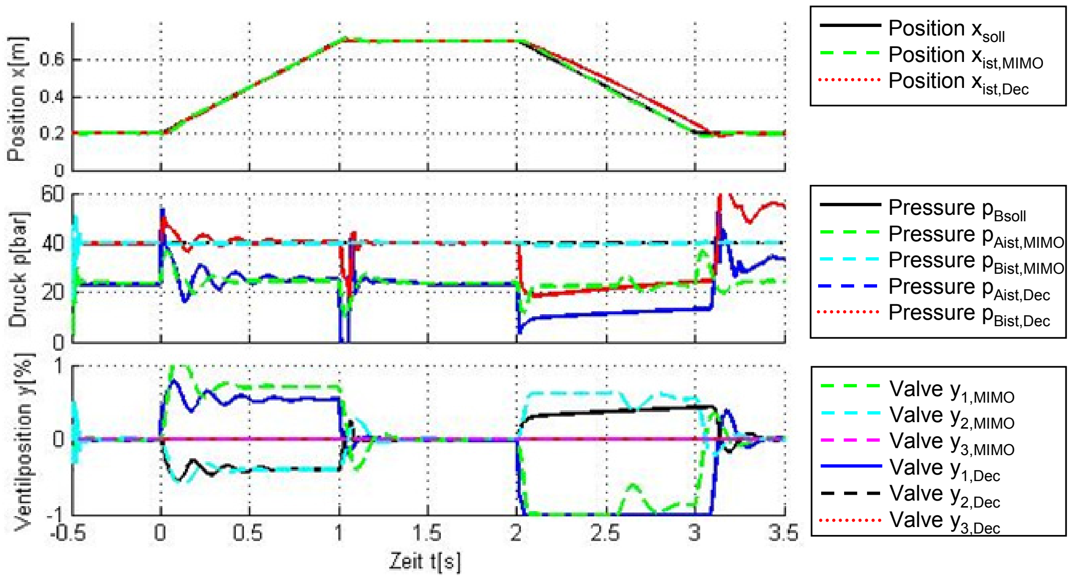

Figure 9: Response to constant velocitys to both control concepts

Next the response to constant velocity v=±0,5 m/s during normal mode as shown in Figure 9 is examined. Again the controlled pressure p_B is much more accurate when using the MIMO controller. The PID controlled pressure oscillates during the extension movement. During the retraction of the cylinder the decentralized PID controller is not able to hold the pressure at 40bar because it is to slow, therefore the retraction has a lag against the position of the MIMO controller.

In Figure 10 the step response in regeneration mode is shown. During t=0,1s to t=0,9s the regeneration mode is active. For starting and the breaking the normal mode is used. As you can see, both control concepts realize a good behaviour of the pressure

p_B during regeneration. The decentralized control however is oscillating as you can see at the behaviour of valve y_{3Dec}. On the other side the switching at t=0,1s is smoother using the decentralized control.

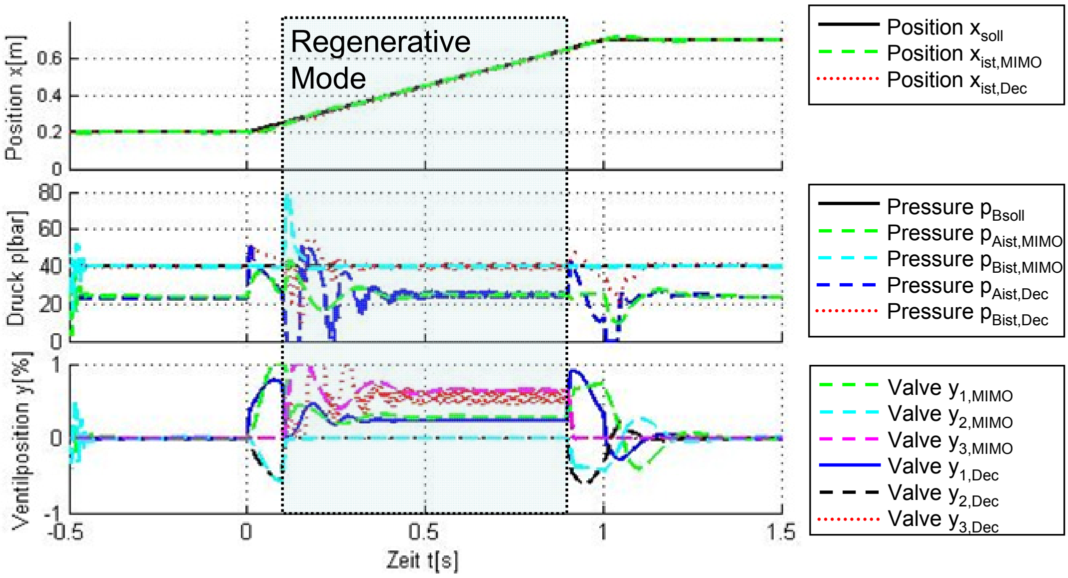

Figure 10: Response to constant velocity using regeneration mode

Nevertheless the simulation results of both concepts have positive and negative aspects. But the parameterization of the decentralized control is much easier than the numerical optimization of the LQR MIMO control. The overall control performance however is better for the LQR MIMO control concept, because the pressurization level is always accurate during every control mode.

6. Conclusion

In this paper an independent metering valve system with a LQR configured multi-variable state-feedback controller /5/ is compared to a system with a decoupled decentralized controller. The functionality and the performance of the control system are shown on simulated application results. The simulations show that through the usage of these control concepts the pressurization level and the position of the cylinder can be controlled at the same time. The overall control performance however is better for the MIMO control concept, because the pressurization level is always accurate during every control mode the control effort on the other side is much higher. Nevertheless the smoothness of a 4/3 proportional valve controlled cylinder drive could not be matched with this independent metering concept. The robustness of the control concept on a test bench has not yet been proven and will be part of future investigations just as the further development of the logic control and the optimization of the MIMO control concept on the nonlinear model.

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8. Nomenclature

α	surface ratio of the cylinder	
$G(s)$	transfer function matrix	
K_e , K_i	controller gain (matrix)	
F_L	loading force	N
p	pressure	bar
t, T	time, time constant	s
v	velocity	m/s
V	pilot control matrix	
x	position	m
y	valve opening	