Controlled hydraulics for a direct drive Brick Laying Robot

J. Heintze, P.C. Teerhuis and A.J.J. v.d. Weiden

Mechanical Engineering Systems and Control Group, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands. E-mail: heintze@tudw03.tudelft.nl

Abstract

Starting from a specific task requirement a Brick Laying Robot has been designed. The tight performance claims which have been imposed by the task specification, constitute the basis for the research on control of hydraulically driven manipulators. The main goal is to increase robot efficiency and task suitability by application of modern control techniques. The introduced cascade Δp inner loop for hydraulic actuators is presented as a solution for the posed control problem.

1. Introduction

At a temperature of 1700^o C raw iron is converted into steel in steel converters. A heat resistive inside wall is protecting the converter against melting during production. This wall (called a lining) consists of c.a. 12000 bricks, each weighting approximately 35 $[kg]$. After 2-3 weeks the bricks have been eroded seriously, and the converter has to be relined. The bricks have to be placed precise and careful, as no mortar is used and the life of the lining is directly influenced by the planeness of the interior. In order to automate the relining of steel converters a bricklaying system was developed in cooperation with industry[1].

Fig. 1: The Brick Laying Robot.

The brick laying system is placed on a lorry, such that it can be transported over road. The robot which is actually placing the bricks, operates from a platform on top of a telescopic mast which can vary in height from circa 2 up to 15 $[m]$. Besides the robot, other devices and an operator have to be upon the platform, which has a diameter of only 2.8 meter, see figure 3. These constraints impose severe limitations upon allowable size and weight of the manipulator. Therefore, a special direct drive robot has been designed, which is driven by industrial available hydraulic actuators. The first prototype of this Brick Laying Robot (BLR) is tested and still available at the laboratory of the authors, see figure 1. The total arm length of the BLR is 2.4 $[m]$, the maximum payload is 100 $[kg]$, and the requested positioning accuracy is within 2-3 $[mm]$. Figure 2 defines the four

[1]Eureka project EU 377 - FAMOS BRICK, Highly Flexible Automated and Integrated Brick Laying System. Project partners: Arbed S.A., Luxembourg; Paul Wurth S.A., Luxembourg; Scoril, France; Inria, France; Hydraudyne, the Netherlands, Delft University of Technology, the Netherlands. The latter two partners where responsible for the development and realization of the Brick Laying Robot.

Degrees Of Freedom (DOF): a planar movement in the (horizontal) $N_1 - N_3$ plane can be realized by the rotational DOF around axis I and II, the third DOF enables a height adjustment (via a parallelogram construction), a rotation of the gripper (which can hold a brick) is the final DOF.

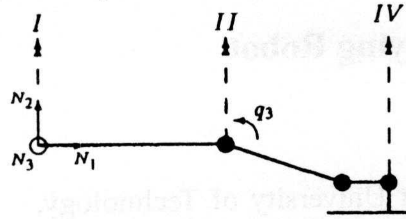

Fig. 2: Definition of the Degrees Of Freedom.

This paper will focus on the control of hydraulically driven mechanical systems, such as the BLR. Most research towards robot control is on electrical actuated manipulators, in which the actuators are regarded as static torque generators. This is completely different when hydraulic actuators are used, as will be clear in section 3.. Consequently, control methods known from the robotic community are not directly applicable to hydraulically driven manipulators. However, the standard control design methods for hydraulic systems do have some drawbacks, as pointed out in section 4.. A new and promising approach will be discussed in sections 5. and 6..

2. Problem formulation

One of the difficulties of the relining task is that beforehand only an estimate is known of the ultimate position of the bricks. The exact position follows from the following requirements: no clearance is allowed between the bricks, the interior side of the heat resistive wall should be as regular as possible, the lining of bricks should follow the average shape of the converter wall[2], and a clearance of circa 5 $[cm]$ is respected between converter wall and the bricks.

Specified was that a complete relining must be done within 50 hours. This means that the cycle time for placing a brick has to be less than 15 seconds. The placement of such a brick is functionally split into two parts for the initial industrial application. The robot is transporting the bricks from a fixed pick-up point to a safely estimated lay-down position (such that there is no risk of collision). A gripper with pneumatically actuated degrees of freedom (inducing limited contact forces) and a 'non-contact' distance sensor is performing the actual placement of the bricks. Between 9 and 10 seconds have been reserved for the actions of

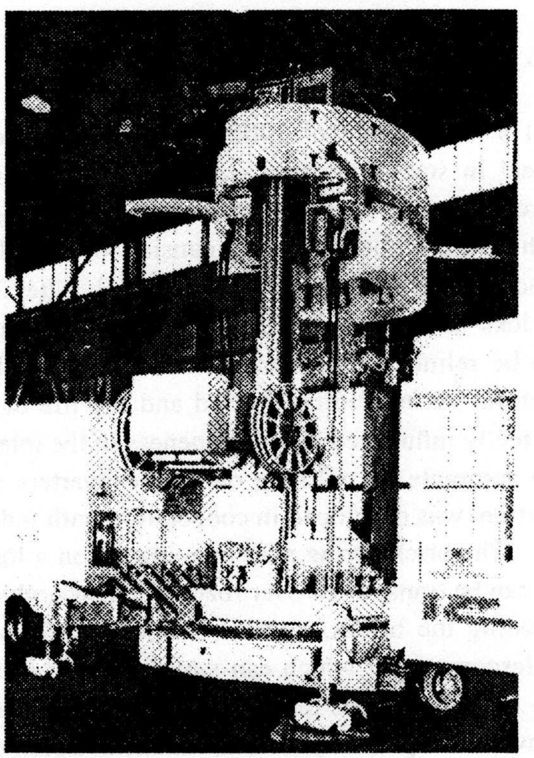

Fig. 3: Middle part of the lorry, with telescopic mast, platform, and on top a second prototype of the Brick Laying Robot.

[2] During the lifetime of a steel converter, the original (ideal) shape of the converter deforms due to the steel production process. Small deviations from the average shape should not be followed by the lining.

the gripper. i.e. picking up and placing the brick. The circa 5 seconds left for the robot to perform the transportation task is posing a challenge towards the control design.

From the above discussion, the following problem formulation is extracted:

- *Given the industrial configured Brick Laying Robot, enlarge the position tracking behaviour of the robot by means of control design.*
- *Given the original task specification (i.e. placing bricks at uncertain positions), enlarge the task suitability of the robot such that a functional integration of the task execution, without the additional degrees of freedom of the gripper, can be realized.*

3. A model of the Brick Laying Robot

A basic model for the BLR is composed of the dynamics due to the hydraulic part, and the dynamics due to the mechanical part. Examining only axis I and II, the following standard equation for a SCARA-type manipulator describes the mechanical part (the parameter values are for the case that $q_3 = 0$):

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} 686 + 348\cos q_2 & 161 + 174\cos q_2 \\ 161 + 174\cos q_2 & 161 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} -\dot{q}_2 174\sin q_2 & -(\dot{q}_1 + \dot{q}_2)174\sin q_2 \\ \dot{q}_1 174\sin q_2 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} \tag{1}$$

where τ_i are the torques in the joints in $[Nm]$, $\dot{q}_i$ and $\ddot{q}_i$ are the angular velocities and accelerations in $[rad/s]$ and $[rad/s^2]$ $(i = 1, 2)$.

In principle, a single hydraulic actuator consists of two oil compartments, separated by a movable part. In the case of a rotary actuator, this part is the vane, which is connected to the output shaft. The oil flows into and out of the compartments are provided by a servo valve, which is the regulating element. Servo valves are frequently used for position servo applications. A fixed input signal to such a servo valve will result in a constant oil flow (assuming a constant pressure drop over the valve), which will generate a rotation of constant speed. This explains the basic integrating (first order) behaviour of a hydraulic actuator. Because the oil in the two compartments is compressible, the two oil columns will act as two springs. A load attached to the shaft of the actuator is clamped between these 'springs', via the vane. This causes a second order behaviour, which is always found in series with the integrating character of a hydraulic actuator.

The nonlinear first order dynamics of the hydraulic part can be specified to be:

$$\frac{d}{dt}\Delta p + k_3 \Delta p = -k_1 \dot{q} + k_2 i_{sc} \sqrt{1 \pm \Delta p} \tag{2}$$

in which Δp is the pressure difference in the actuator, normalized with respect to the supply pressure given by the the pump, i_{sc} is the steering signal of the valve normalized with respect to the maximum valve steering. $k_1 = F\Psi(q)$, $k_2 = \dot{q}_{max} k_1$, $k_3 = LP_v k_2$ ($k_1, k_2 > 0$, $k_3 \geq 0$), where: F is a constant depending upon the oil compressibility and the pressure delivered by the pump, $\Psi(q)$ is a position dependent parameter, $\dot{q}_{max}$ is the maximum achievable velocity of the actuator (reflecting the valve dimension in relation to the dimension of the actuator), and LP_v is a parameter concerning leakage flow inside the actuator. The position dependent parameters $k_{1,2,3}$ are considered to be constants in one operational point. The term $\sqrt{1 \pm \Delta p}$ results from the pressure dependency of the valve and can be regarded as an input nonlinearity, the $(\pm)$ sign being opposite to the sign of i_{sc}.

The dynamics of the hydraulic part of an actuator (2) can be connected to a specific load as for example τ_1 in (1) via:

$$\tau = T_{mx}\Delta p - w\dot{q} + T_c + T_e \qquad (3)$$

where T_{mx} is the maximum torque to be generated by the actuator (reflecting the dimension of the actuator in combination with the oil supply pressure), w is the viscous friction coefficient, T_c is the Coulomb friction torque (opposing the direction of movement), and T_e accounts for an external torque acting on the actuator.

	$\hat{T}_{mx}$ $[Nm]$	$\hat{q}_{max}$ $[rad/s]$	$L\hat{P}_v$ $[-]$	$\hat{T}_c$ $[Nm]$	$\hat{k}_1$ $[1/rad]$
Axis I	6500	4.3	0.11	170	8 - 24
Axis II	1900	4.5	0.13	90	24 - 32

The estimated values for the two main actuators of the BLR are given in the table on the left hand side[3]. Because parameter $k_1 = F\Psi(q)$ is a function of the actuator position, it can take values within a certain region. However, specifically for the actuator of the first axis of the BLR, large differences where found between estimates of k_1 via different methods in identical actuator positions. This is a general problem with hydraulic actuators, parameter F is uncertain because the oil compressibility is very hard to estimate and the oil supply pressure can vary, depending upon sudden speed changes in the system. In a similar way is parameter $\Psi(q)$ also uncertain, on top of a known position dependency.

Summarizing: the combined dynamics of two hydraulic actuators connected to a mechanical system as (1), will be described by a combination of two coupled third order systems. In addition to the nonlinear and position dependent structure of equations (1)-(3), the uncertain parameter values within the hydraulic part do complicate the control design. Detailed information concerning the model structure, parameter identification and model validation can be found in [11, 4, 12].

4. Standard control design

The common way in industry to control hydraulically driven servo systems is an independent joint approach: for every actuator a pressure feedback and a position feedback loop is designed, not taking into account the couplings with the other actuators due to the mechanical system. With this controller structure, of which the gains could be tuned on the spot by an experienced person, one can partially influence the combined third order dynamics of a mechanical load actuated by a hydraulic actuator. In order to increase the position servo behaviour, the independent joint approach can be extended towards full state feedback, i.e. feedback of q, $\dot{q}$ and Δp, such that complete pole-placement for each actuator is possible (given a linearized model in a specific operating point, and omitting the multivariable character of the system). Note that this full state feedback controller design is based upon the availability of a mathematical model. For more information see e.g. [4, 9, 13, 10].

The two types of controllers have been applied to the BLR [2, 1]. An overall tracking performance improvement of a factor 2-3 has been achieved by the full state feedback controller.

[3]The viscous friction coefficient w is set to zero because estimated values where relatively small and varied much when using different estimation methods.

These standard control design methods do have two major difficulties. Firstly, full model knowledge is required, which could be a serious problem as explained with parameter k_1 in section 3.. Furthermore, when it is known from physical insight that a number of parameters are uncertain or do not have a constant value, it is not trivial how to translate this knowledge into limitations or deteriorations of the controlled behaviour.

Secondly, given a specific change in the task requirement of the robot, it is not clear how to change the designed controller other than starting all over with the model based control design. This is highly undesirable when a flexible use of the robot system is requested, with respect to task specification and on the spot adaptability of the controlled behaviour. Solutions for these problems are given in the next section.

5. Solving the difficulties of hydraulic actuators: - the cascade Δp inner loop -

The combined third order dynamics of an hydraulic actuator with load, see section 3., can be decoupled by a cascade Δp inner loop controller:

$$i_{sc} = \frac{1}{\sqrt{1 \pm \Delta p}} \{K_c(\Delta p_t - \Delta p) + K_{LP_v} \Delta p + K_{\dot{q}} \dot{q}_a\} \tag{4}$$

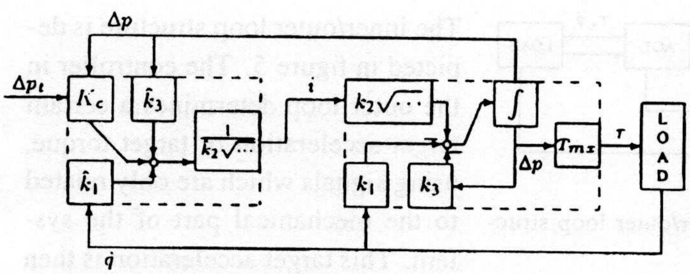

Fig. 4: Schematic representation of cascade Δp inner loop control (the default sign of a summation is +). The right dotted box is the actuator, the left dotted box is the controller.

This is a linearizing controller which transforms a hydraulic actuator with ordinary servo valve into a velocity independent and Δp independent torque generator, over a certain bandwidth. Δp_t is the reference input for this inner loop controller, resulting from a free to choose outer loop (see figure 5). Based upon the physical structure of the hydraulic part of the system, the controller consist of a velocity compensation $K_{\dot{q}} = \hat{\dot{q}}_{max}^{-1}$, a leakage compensation $K_{LP_v} = \hat{LP}_v$, and of course the Δp error feedback by K_c to enlarge the bandwidth. Furthermore there is a cancellation of the input nonlinearity due to the valve. This is schematically depicted in figure 4 (Note that $\hat{k}_1\hat{k}_2^{-1} = \hat{\dot{q}}_{max}^{-1}$ and that $\hat{k}_3\hat{k}_2^{-1} = \hat{LP}_v$: no explicit knowledge about k_1 is required). With the cascade Δp controller the bandwidth of the hydraulic subsystem (2) can be improved, such that the transfer $\frac{\Delta p}{\Delta p_t}$ resembles as much as possible a static unity gain.

The cascade Δp controller structure allows for a clear interpretation with respect to the deterioration or limitation of the controlled performance due to wrong estimated parameters ($\dot{q}_{max}$, LP_v) and neglected parasitic dynamics (valve dynamics, pipeline dynamics or a computational delay). In addition, no explicit knowledge about parameter k_1 is requested. However the consequences of the variation of k_1 due to the position dependency or other uncertainties are straight forward. The analysis of these subjects, validated by frequency domain and time domain experimental results are given in [5, 3].

Due to the cascade Δp inner loop for hydraulic actuators, the following results are established:
Result 1: Up to a certain frequency, a cascade Δp controlled actuator can be regarded as a torque generator (the pressure is equivalent to the torque, see (3)). As a consequence, the control design methods examined within the area of robot control (using electrical actuators) are now applicable to a hydraulically driven system.
Result 2: Recall from section 3. that ordinary servo valves have been used. These valves are well suited for position servo systems. However, when forces have to be controlled (e.g. contact situations between manipulator and environment) and standard control design techniques are used, then the less common (and more expensive) pressure controlled valves are in favour. But these pressure controlled valves are not well suited for a position servo system. A significant contribution of the cascade Δp inner loop is that, although using servo valves, the hydraulic system can be used either to follow a force trajectory or a position trajectory. The choice for a position servo system or a force servo system is made by the outer loop, while leaving the inner loop identical for both options. This will be shown in the next section.

6. Increasing task suitability by use of an impedance outer loop

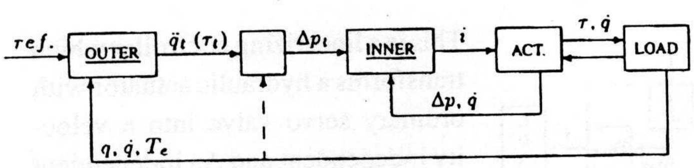

Fig. 5: Schematic representation of the inner/outer loop structure.

The inner/outer loop structure is depicted in figure 5. The controller in the outer loop determines a certain target acceleration or target torque, using signals which are only related to the mechanical part of the system. This target acceleration is then transformed into a target pressure. A compensation for friction effects could be made in this step, according to equation (3). The resulting Δp_t is the input for the inner loop, as described in section 5..

The outer loop is chosen to be an impedance controller [6, 8], such that stable interaction of the robot with an uncertain environment should be realizable. Similar to the independent joint approach in case of the state feedback controller, the chosen impedance controller consist of two independent simple linear second order target impedances of the following form:

$$\ddot{q}_t = K_t(q_0 - q) + B_t(\dot{q}_0 - \dot{q}) \tag{5}$$

where K_t in $[kg\, m^2/s^2]$ is the target stiffness, B_t in $[kg\, m^2/s]$ is the target damping, and $q_0, \dot{q}_0$ are the reference position and velocity in $[rad], [rad/s]$. Interaction forces with the environment are not accounted for in (5), because no force transducers are available on the BLR. On the spot tuning of the impedance outer loop is very well possible due to the clear physical interpretation of K_t and B_t[4]. For example, tuning K_t and B_t while feeding the system with some trajectory or a step input, one can easily realize a system with equally good position tracking behaviour as the full

[4]Of course, an infinite stiff behaviour can not be realized due to the physical limitations of the system.

state feedback controller (remember that on the spot design of this full state feedback controller was not possible). Reducing then K_t will give a system which is more compliant towards external forces. Reducing K_t to zero will even completely eliminate the influence of a position reference.

In view of the brick laying task the following very simple scheme is now possible: Generate a reference trajectory such that the to be placed brick would just collide with the already laid bricks, before the final requested position of the Tool Centre Point (TCP) has been reached. Start the movement with the outer loop adjusted such that a stiff position controlled system is realized. Then, a little before the collision will take place, reduce for both axis the K_t's to a low value and increase the B_t's, such that the speed in the system will be dissipated and the reference position trajectory is of minor importance. The final position of the TCP is now dictated by the already laid bricks, while the contact forces remain stable and limited.

The time instance just before collision could for example be detected with an standard ultrasonic 'non-contact' distance measurement device. Such a device is already experimentally tested upon the BLR, for the measurement of the shape of the converter wall relative to the task space of the robot, [7].

7. Conclusions

Motivated by the challenge of automatic steel converter relining, a Brick Laying Robot has been designed and realized as a part of a brick laying system. Because the hydraulic actuators of this BLR show nonlinear dynamical properties which cannot be neglected in the overall behaviour, attention is paid to the problem of control design for hydraulically driven mechanical systems.

Model based linear control design techniques have been used such that the tight position tracking performance specifications have been accomplished. The required full model knowledge and the inflexibility with respect to on the spot controller adjustment are drawbacks of these methods. A solution is given by the introduction of the cascade Δp inner loop for hydraulic actuators. The cascade Δp controller is simple to design, requires a minimal amount of model knowledge, delivers a high performance, and is robust with respect to parameter variations. In addition, limiting effects on the controlled performance due to neglected parasitic dynamics are clearly understood. With this cascade Δp inner loop, a hydraulic actuator can be controlled such that it can be regarded as a torque generator within a certain frequency band.

Due to the cascade Δp inner loop, known control methods from the robotic community can be used to contribute to the enlargement of the task suitability of the BLR. A plain version of impedance control is chosen as an outer loop, to show the possibility of flexible (task specific) controller adjustment and to show how a functional integration of the task execution can be achieved.

The dynamics of the cascade Δp controlled actuators, which are not included in the outer loop design, can be seen as neglected parasitic dynamics. Further more, as the mass properties of the manipulator are not exactly known, robustness with respect to parameter uncertainties is requested. Sliding mode control can explicitly account for parametric uncertainties and for neglected parasitic dynamics. Therefore, the application of a sliding mode control outer loop in combination with the cascade Δp inner loop is a current research topic. First results on a one degree of freedom setup are given in [3].

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