MODELLING OF DESIGN STRATEGIES FOR HYDRAULIC CONTROL SYSTEMS[1]

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Abstract

The control system design of hydraulic drives is demanding and time-consuming. An efficient support of the human engineer can be realized with software tools that automate several modelling and simulation jobs.

This paper contributes to this field within the following respect: It shows how a particular part of an engineer's design knowledge, namely modification (or repair) knowledge, can be classified, formalized, and operationalized on a computer.

Keywords: control system design, knowledge-based systems, modelling of design tasks, hydraulic drives

1 Control System Design

Figure 1 shows the major steps during the iterative process of control system design. Starting off with a system's preliminary design specified by an engineer, the system behavior is modelled and simulated within the analysis step. Within a subsequent evaluation step the analysis results are compared to the user demands. Unfulfilled demands are treated by modifying the system in the modification step.

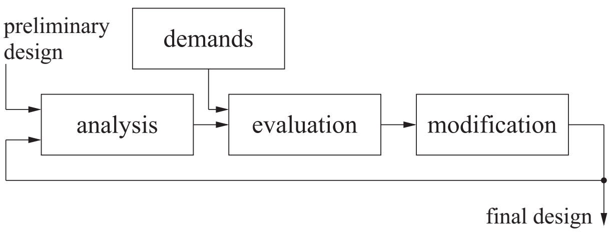

Figure 1: *Iterative process of control system design.*

Here, the analysis step is understood in a "conventional" sense; it means the computation of the system behavior by formulating and solving a set of nonlinear (differential) equations [4; 1]. However, demand representation, evaluation, and modification tasks ground on human criteria and strategies for decision-making and reasoning.

In the last couple of years we have been developing concepts to support the analysis of fluidic systems. A lot of these concepts have been realized within the system $^{\text{art}}$*deco*, which enables a user to formulate analysis problems by simply drawing hydraulic circuit diagrams [3; 5; 8; 6].

Moreover, our research does also concentrate on particular design aspects—the paper in hand contributes to this field: It shows how a particular part of an engineer's design knowledge, namely modification (or repair) knowledge, can be classified, formalized, and operationalized on a computer.

The paper is organized as follows. Section 2 elaborates on the role of modification knowledge in hydraulic circuit design. It associates design defects with repair measures and introduces a scheme to evaluate a measure within several respects. Section 3 shows in which way the design knowledge of section 2 can be formalized and processed. Section 4 works out an example to illustrate the presented concepts.

2 Modification of Hydraulic Systems

Modifying a given, preliminary design is the major engine when tailoring a hydraulic system to some customer's demands, or if a hydraulic system is to be improved within particular respects. However, two central points render the modification step difficult:

- Typically a variety of configurations is suited to fulfill the desired demands. Hence a solution has not only to meet the demands, but it has also to guarantee that the effort for reaching the goal is reasonable.
- Owing to the strong interdependences among the subsystems of a hydraulic drive, it must be considered that each modification may affect demands previously fulfilled.

By now there is no knowledge-base with well-organized modification measures available. Thus, within a first approach, we have extracted modification knowledge

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from specialized literature and analyzed foundations of hydraulic circuit and control system design. Additionally, hydraulic systems have been investigated respecting the influence of modifications on their static and dynamic behavior [2; 7].

Clearly, the success of the modification approach depends on the quality of the preliminary design: It is not intended to develop an optimum hydraulic system from any given raw design when considering hydraulic systems without restrictions regarding their topological set-up. Moreover, it can hardly be foreseen whether a particular measure always is a remedy for a malfunction; usually several measures have to be tested before an improvement is achieved.

Each hydraulic system is defined by a set of components along with a topology specifying relations between these components. Components in turn are described by both invariable characteristics and variable characteristics, so-called parameters. As a consequence, qualitatively different modification steps stand to reason:

- *Parameters* can be altered easily within their given ranges, e. g. opening of a throttle valve, controller gain.
- Changing *component characteristics* means the exchange of the component itself, for example a valve or a controller; this is a modification step that causes additional effort.
- *Topological modifications* change the arrangement of hydraulic components and their connections as well as the structure of the control system such as number of feedback channels, output feedback, state feedback etc. These have the most profound and far-reaching effects.

A modification becomes necessary, if a demand is "not fulfilled". For each detected malfunction a list of possible modifications can be set up. The modification jobs related to a certain demand A_k are subject to a local assessment (cf. figure 2). Currently, the following criteria are employed for evaluation and ranking:

- A modification's *effectiveness* is most important.
- The *repercussion* on the design of the hydraulic system describes undesired side effects, which must be expected.

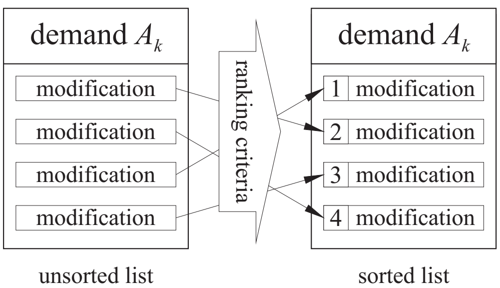

Figure 2: *Local assessment of modification jobs.*

- Another useful criterion is the *effort* required to carry out a modification. This is related directly to the differentiation in parameter, characteristics, and topological modifications.

To each modification job j assessment factors $V_{j,i} \in [0;1]$ are assigned. The influence of the i criteria—presently: effectiveness, repercussion and effort—on the *absolute confidence* $\mathcal{K}_j$ is weighted by the confidence factors $\kappa_{\text{ef}}, \kappa_{\text{re}}, \kappa_{\text{et}}$, where

$$\sum_i \kappa_i = 1 \qquad \text{with} \quad i = \text{ef}, \text{re}, \text{et} \quad . \tag{1}$$

The absolute confidence $\mathcal{K}_j$ of a modification job j can be calculated according to

$$\mathcal{K}_j = \sum_i \kappa_i \; V_{j,i} \tag{2}$$

with $\mathcal{K}_j \in [0;1]$ to obtain a ranking (figure 2). Applying modifications according to this ranking shall lead to an optimization of the design with respect to the chosen criteria and their weights. The number i of criteria can be extended, if necessary.

If more than one demand is not fulfilled, a global decision-making approach will be required to determine which modification step to apply first. Owing to the partially unpredictable interactions when modifying a hydraulic system, there is a convergence problem for the iterative design process. Here a flexible strategy is required that reacts to analyzed malfunctions and related modification measures.

Figure 3 depicts the process of designing hydraulic control systems when done by an engineer starting off from nothing but the given demands. Applying a modification measure to a given preliminary design is similar to a kind of backtracking and may cause a partial re-design of the hydraulic control system. To cut down the total number of iterations, the following rules should be obeyed:

(i) Reduce the complexity of the problem by considering its divide-and-conquer properties: Modifications with no side effects should be carried out first to fix the related malfunction.

(ii) Assess to which phase of the design process both a demand A_k and a modification job j is related to obtain a suitable sequence for processing modifications. It is not advisable, e. g., to optimize a controller while a working element does not provide the desired velocity.

(iii) Decrease priority of measures, which affect an early phase of the design process, in an advanced stage of re-design (increasing number of iterations).

3 Formalizing and Processing Modification Knowledge

The identification, validation, and classification of modification knowledge for hydraulic systems is a nontrivial engineering problem. However, getting this

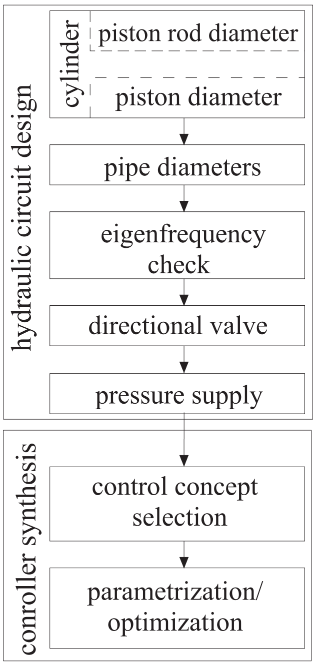

Figure 3: *Process of hydraulic control systems design.*

knowledge operationalized on a computer is even more complex. Some reasons for this are the following:

- *Expressiveness.* Design knowledge typically is very compact but of a high expressiveness; an example:

  `“An unsufficient damping can be improved by installing a by-pass throttle.”`

  This measure encodes a lot of implicit engineering know-how, among others the following: A by-pass throttle is connected in parallel, the component to which it is connected is a cylinder, if there are several cylinders in the system an engineer knows the best-suited one, a throttle is a valve, etc.
- *Flexibility.* Engineers use design knowledge in a flexible way; i. e., a particular piece of knowledge may be applied to a variety of hydraulic circuits.

Flexibility is a main reason which makes it difficult to encode the expressiveness of the above example on a computer. Consider we were confronted only with hydraulic systems of the same topological set-up, then measures like the above (`“Install a by-pass throttle.”`) could simply be hard-wired within a “design” algorithm.

One possibility to get the knack of the outlined formulation problem is to specify a lot of the implicit knowledge explicitly. For these purposes we have been developing a description language tailored to hydraulic circuit design. The language shall enable engineers to formulate modification measures, and it comes along with the following concepts:

- *Domain-adequateness.* Features for the formulation of topological relations in hydraulic circuits are provided; an example:

  ```
  select_component(in_series pump tank_2
                   after cylinder_2)
  ```
- *Extendibility and Abstraction.* Based on a set of core functions (`increase_parameter`, `select_component`, etc.) a user is allowed to define new and more complex modification routines.
- *Handling of Alternatives.* Related to an unfulfilled demand, alternative measures can be specified and tagged with a priority.

Modification measures are organized within knowledge classes, which in turn are collected in a knowledge base. A knowledge class always belongs to a particular component type; it defines the component’s structure, its parameters, possible symptoms indicating unfulfilled demands, and a list of related modification measures specified in our language. Subsequently an example of a knowledge class for a cylinder is given.

```
class Cylinder {
  connections{ Gate_A, Gate_B }
  parameters{ d_s, d_k, A_K, A_R, p_A, v }
  repair_rule(1){
   symptoms{ (v = 0) }
   modification{ increase((select_component
                  (type = pump)), p, 20%) }
   modification{ ...} }
  repair_rule(2){
   symptoms{ ...}
   modification{ ...} }
  ...}
```

Processing a knowledge base for a given circuit means: (*i*) to check the circuit for unfulfilled demands, (*ii*) to consult the knowledge base for a repair measure, and (*iii*) to apply the measure to the circuit by interpreting the language.

4 Example

In the following an example shall illustrate the application of the modification approach in combination with the description language. Given a hydraulic linear drive whose accuracy of positioning is analyzed via simulation and classified “unsatisfactory” within the evaluation step. The relevant subsystem “cylinder” can be modelled as an oscillatory 2nd order system; its damping factor $D = 0.08$ is judged to be too low so that modification measures should contribute to increase the system damping.

Table 1 comprises a selection of possible modifications each of which modifies the topology of either the hydraulic circuit or the structure of the control system.

The values for the absolute confidence $\mathcal{K}_j$ of a modification measure j result from the given $V_{j,i}$ and the chosen weights among the criteria. Here, the confidence factors are $\kappa_{\mathrm{ef}} = 0.5$, $\kappa_{\mathrm{re}} = 0.15$, $\kappa_{\mathrm{et}} = 0.35$. Consequently, installing a throttle in a by-pass to the cylinder (figure 4) is ranked first option.

Figure 5 depicts the effect of this modification on the system dynamics. The drain flow through the by-pass

Modification Measure	$V_{j,\mathrm{ef}}$	$V_{j,\mathrm{re}}$	$V_{j,\mathrm{et}}$	$\mathcal{K}_j$
throttle in mainstream	0.1	0.4	0.8	0.390
throttle in sidestream	0.4	0.4	0.5	0.435
throttle in by-pass	0.8	0.4	0.5	0.635
damping network	0.9	0.8	0.1	0.605
velocity feedback	0.6	0.8	0.3	0.525
acceleration feedback	0.8	0.8	0.3	0.625

Table 1: Modifications increasing the system damping.

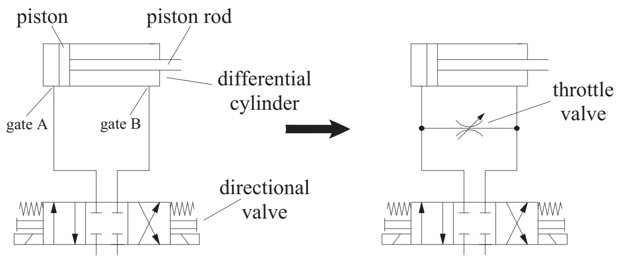

Figure 4: *Circuit set-up before and after modification.*

throttle moves the eigenvalues of the related transfer function to a higher damping (a). The step response emphasizes the high effectivenes of this measure (b).

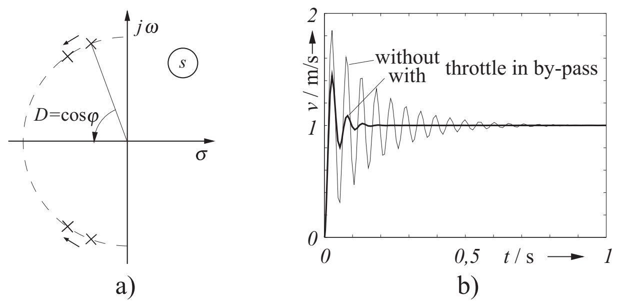

Figure 5: *Eigenvalues (a) and step response (b).*

Using our description language, the instruction for installing a by-pass throttle valve can be formulated as follows:

```
new component(comp-type=throttle_valve)
                              % Create a new component
                              % of type throttle valve
set(th_v1,op,0,03)
                              % Set parameter opening of
                              % component th_v1 (throttle
                              % valve 1) to the value 0,03
insert component between (this.A next-to)
      ...(this.B next-to) (th_v1)
                              % Insert component th_v1 bet-
                              % ween gates A and B of the
                              % regarded component (cylinder)
```

5 Conclusion and Outlook

Within the design cycle of hydraulic system, a lot of time is spent modifying a preliminary or intermediate design. Typical modification jobs strive for the elimination of unfulfilled demands or the improvement of a given system within different respects.

The paper in hand points out the prerequisites that are necessary to operationalize hydraulic modification knowledge on a computer. It is shown in which way the knowledge can be classified and evaluated regarding different aspects.

Clearly, modification knowledge must be processed in the cycle of analyzing, evaluating, and modifying a circuit. Thus, we have proposed (and prototypically implemented) a particular language to formulate modification knowledge. At present, this language is embedded within our drawing and simulation environment $^{\text{art}}$*deco*.

Future work is concerned with (i) the formulation of modification knowledge using our language, (ii) the evaluation of the proposed concepts using real-world examples, (iii) the development of strategies that cope with the large search space when processing the language.

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