OFT—Objectives and Concepts

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Abstract

The research work carried out within the OFT-project shall provide insights, methods, and prototypic software to support the design of hydraulic closed loop control systems.

The paper in hand presents an overview of the research work, motivates the current objectives of the project, and provides useful background information. In particular we develop different views of the hydraulic design procedure, discuss related problems, show several fields where a computer-based support of the design procedure is promising, and focus on particular realization concepts.

Contents

1 Introduction

Hydraulic (closed loop control) systems establish an important driving concept for manufacturing processes and manipulation jobs in very different industries. Even for experienced engineers hydraulic control system design is a demanding and time-consuming task, and a support or a partial automation of this procedure would be very welcome. Loosely speaking, a support of the design procedure means the operationalization of a hydraulic engineer's design capabilities using computers.

The research work carried out within the OFT-project shall provide insights, methods, and prototypic software that lead to a simplification of this design procedure.

The paper in hand presents an overview of the research work; it motivates and classifies the actual research activities and provides useful background information. Section 2 develops two views regarding the design process of hydraulic control systems. Section 3 shows promising areas of support within the design procedure. Section 4 presents an approach to a topological analysis of hydraulic systems. Section 5 elaborates on the demand formulation problem and shows the steps that necessary to automatically balance the demands with the actual behavior of a hydraulic system.

2 Hydraulic Control System Design

Hydraulic control system design as performed by a human engineer usually happens within the following steps:

1. *Formulation and Analysis of the Demands.* The demands D at a hydraulic system may be given from a customer or developed in cooperation with the designer. D does completely specify the desired system. I. e., it defines the hydraulic operations to be performed, the courses of the forces at the cylinders, the switching diagrams, particular stationary and dynamic demands or restrictions, and other constraints. The analysis of D may give an experienced designer a first idea of the system's complexity, its power range, or eligible control concepts.

2. *Raw Design.* Guided by his experience the designer specifies his mental model of the system in the form of a plan that contains the main working, control, and supply elements. Within this creative synthesis step he states and solves model formulation problems at an abstract functional level. Usually the greater part of the related mental activities is performed automatically or subconsciously.

3. *Refined Design.* The stage of refined design is also a matter of synthesis. Within this stage the simplified plan of the system is completed towards a technical drawing, which specifies most of the components of the demanded hydraulic system.

   Depending on particular demands, the system's complexity, or the engineers experience, the design process either ends at this point, or it leads up to a detailed analysis stage.

4. *Detailed Analysis and Evaluation.* A detailed analysis and evaluation stage becomes necessary, if an answer to one or other of the following questions cannot be given easily: Does the switching logic realize the desired behavior? Will the piston velocities and forces be as prescribed? Which maximum pressure values will occur, and will these values be permissible? In which range is the closed loop deviation?

A detailed analysis of a hydraulic system is both a demanding and a time-consuming task. Firstly, it requires that a model of the system is formulated at an adequate level of precision; secondly, this model has to be simulated. Within the subsequent evaluation step the simulation results have to be interpreted respecting the demand set D.

Deviations found within this stage require a set back to one of the former two design stages.

Note that the design process is of a strongly iterative nature [3, 10]. Starting with the demands, a large number of iterations can be necessary to obtain a system that fulfills these demands (cf. figure 1). Variations of the four design steps apply to other technical domains as well. In the following we will further specialize these steps towards fluidic engineering.

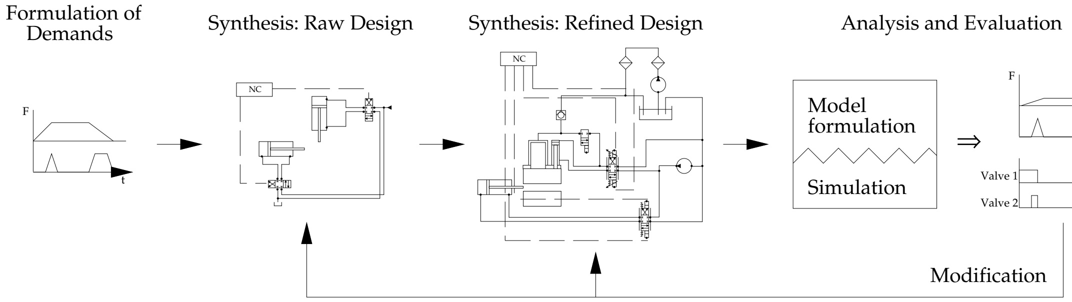

Figure 1: The iterative nature of hydraulic system design.

A closer analysis of the human design procedure does reveal additional design phases. These phases are often performed automatically or subconsciously by a human engineer—but with respect to a computer-aided support of the design process—they are of a high importance.

Preliminaries. Each hydraulic system shall serve a purpose; hence it fulfills some intended function F. In the very most cases F is composed from several subfunctions $f_i \subseteq F$. The hydraulic counterpart of such a subfunction is the concept of the *hydraulic axis*.
Of course the subfunctions f_i play together in some way in order to accomplish F. The hydraulic counterpart of this interplay is the concept of the *coupling of hydraulic axis*. In section 4 both terms are explained in greater detail.

Given these concepts, the human black box view of the raw-design-step can be replaced by a *phase view*. Such a view may be somewhat artificial, but it will exhibit additional design steps. Taking this phase view, the step two, "raw design", appears as follows:

2a. *Conceptual Design.*
  - *Functional Decomposition.* Detection of all subfunctions that are necessary to realize F. F is implicitly defined by D.
  - *Functional Composition.* Creation of a functional structure that models the interplay among the subfunctions.

2b. *Hydraulic Raw Design.*
  - *Hydraulic Mapping.* Mapping of the subfunctions onto suited hydraulic axes. This step rather establishes a classification step than a synthesis step.
  - *Hydraulic Coupling.* Coupling the hydraulic axis according to the functional structure.

Figure 2 contrasts both views graphically.

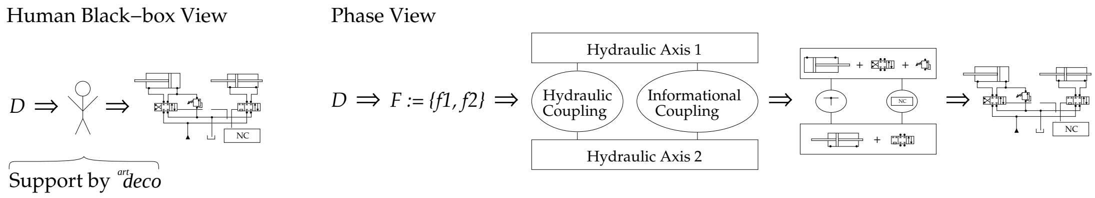

Figure 2: Two views to hydraulic circuit design.

I. e., the design of a hydraulic system can be explained in terms of the composition and modification of high-level building blocks, so-called hydraulic axes. Note that the idea of hydraulic axes can be applied to all stages of the design process. Also note that a human designer usually works at the component level, *implicitly* creating and combining hydraulic axes towards an entire hydraulic system. His ability to automatically derive function from structure (and vice versa) enables him to construct a hydraulic system without the hydraulic-axes-idea.

The remainder of this section shows the consequences that result from the two design views, the human black-box-view and the explicit-phase-view. Both views are useful and both views lead to important insights regarding the computer-based support of hydraulic control system design.

The ^{art}*deco* system[1] has been developed having the human black-box-view in mind. Its philosophy may be summarized by the following question: "Which are the strong points and which are the weak points of a human designer?"

Clearly, a designer's strong point is his creativity in the very first place; a weak point, for example, is his fault-proneness in connection with extensive numerical computations. Our observation was that even if we had a configuration system that could do the creative synthesis part of the hydraulic design process but left the time-consuming and fault-prone analysis part to the human expert, it would not be of much help.

So we developed ^{art}*deco* as a system which simplifies the formulation and the verification of an engineer's design ideas: ^{art}*deco* provides a tool box at the hydraulic component level and comes along with fluid-specific CAD capabilities. On the other hand, ^{art}*deco* is able to analyze a hydraulic plan up to a particular level. Both concepts lead to a decisive speed up of the entire design procedure.

^{art}*deco* automates large parts of the hydraulic model formulation and simulation problem; hence it is able to predict behavior or to check for parameter deviations. Nevertheless, ^{art}*deco*'s analysis capabilities are restricted to a particular level—examples: ^{art}*deco* cannot estimate the quality of the simulated behavior; although ^{art}*deco* is able to infer the cause of contradictory parameters, it cannot propose improvements for the construction. Especially with respect to the selection or configuration of hydraulic control concepts we see an interesting and useful potential for the operationalization of human design knowledge.

At this point the explicit-phase-view comes into play. This view reveals the *functional* structure of a hydraulic system, which constitutes an important type of hydraulic design

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[1] The ^{art}*deco* system originated in the DFG project no. Kl 529/3, where the Department of Measurement and Control, University of Duisburg, and the Department of Mathematics and Computer Sience/Knowledge-based Systems, University of Paderborn, were involved. More detailed information regarding this project can be found in [9, 6], and [7].

knowledge. Extracting and processing this knowledge will be essential to come up with a hydraulic system analysis that goes beyond the current capabilities of ${}^{\text{art}}$*deco*. Section 4 will further elaborate on functional structures in hydraulic systems.

3 Supporting the Design Procedure

Obviously, an engineer's highly developed design skill cannot be copied by one single design algorithm. Hence, a computer-based design support must be provided in several areas and at different levels of the entire design cycle. In many discussion with designers, manufactures of hydraulic components, and researchers we have examined the hydraulic design procedure. We wanted both to identify sub-jobs that can be automated and to find out how knowledge-based technologies can contribute to the automation. In the following a brief outline of this examination is given.

1. *Circuit Drawing, Superficial Drawing Analysis*[2]*, Behavior Envision.* A good deal of these jobs is realized by current ${}^{\text{art}}$*deco* concepts and will not be discussed here.

The five jobs below enclose core objectives to be achieved within the OFT project.

2. *Behavior Interpretation.* Given are a demand set D and a stationary or dynamic behavior description. Question is whether some portion of the behavior description violates a constraint stated by D.

3. *Detection of Crucial Components.* Given are a demand set D, a hydraulic system, and a dynamic behavior description. Task is the detection of components that could jeopardize the fulfillment of D.

4. *Parameterization of Crucial Components.* Task is the modification or, as the case may be, replacement of a crucial component in order to improve the systems dynamical stability.

5. *Selection of Closed Loop Control Concepts.* Given are a demand set D, a hydraulic system, and a dynamic behavior description. Task is the selection of a control concept such that D can be fulfilled by the system.

6. *Evaluation and Modification of Closed Loop Control Concepts.* Task is the evaluation and improvement of a hydraulic control system.

Note that these jobs base on each other: The detection of crucial components requires a smart behavior interpretation related to the demand set D; the selection of control concepts is closely connected to the behavior of crucial components; indeed, a skillful component parameterization may render control concepts superfluous.
Within all of these jobs the identification of a hydraulic system's functional structure plays a key role.

7. *Switching Logic and Driving Process Analysis.* This job has to do with demand analysis at a "macroscopic" level. Given are a hydraulic system along with a particular driving process; the question is whether or not the system is able to perform the demanded process.
   While a "microscopic" demand analysis concentrates on particular state values, a switching logic and driving process analysis looks at a hydraulic system as a whole.

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[2] Superficial drawing analysis relates mismatched connections, open pipes, and other syntactical faults.

8. *Diagnosis.* It is not useful to consider diagnosis as a single task here; particular diagnosis questions are hidden within nearly all of the mentioned fields—for example: "Which component is the most crucial one?" or "What makes a certain closed loop control concept behave so badly in a particular system?" In this connection the development of tailored diagnosis concepts may contribute to the solution of particular synthesis problems.

The outline shows several problems each containing potential for automation. The design knowledge necessary to solve these problems comprises hydraulic regularities, numerical algorithms, graph algorithms, rules, Fuzzy expressions, metaknowledge about the application of strategies, etc. This knowledge may be insecure, currently unknown, or vary in its usage.

Hence a long-term objective must provide concepts for an easy formulation, modification, or experimentation relating design knowledge in the form of a *design language*. Developments towards such a language thus are also a part of the OFT research.

The following sections describe the currently tackled research fields.

4 Topological Analysis of Hydraulic Systems

Key objective of the topological analysis of a hydraulic system is the identification of its underlying functional structure. The functional structure is reflected by the hydraulic axes along with the coupling of these axes. Vier defines the term "hydraulic axis" as follows.

> *"A hydraulic axis A both represents and fulfills a subfunction f of an entire hydraulic plant. A defines the connections and the interplay among those working, control, and supply elements that realize f."*
>
> Vier, [11]

Figure 3 gives a few examples for hydraulic axes.

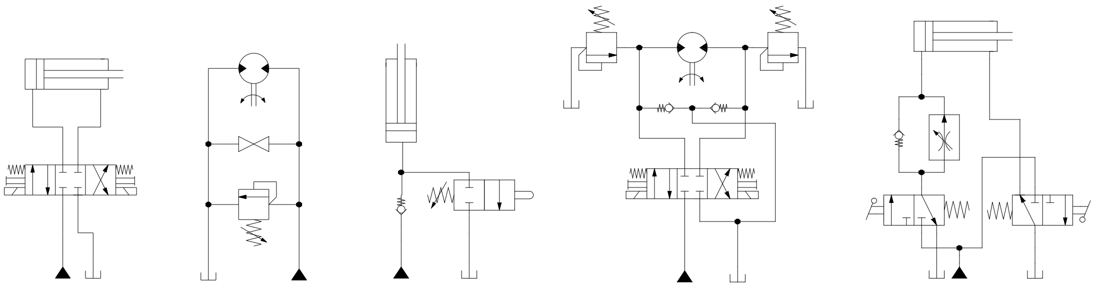

Figure 3: Examples for hydraulic axes.

To realize complex driving processes, several hydraulic axes must be coupled and play together. Figure 4 shows different kinds of couplings between hydraulic axes.

Determining a system's functional structure means to identify the hydraulic axes and their connections. Using hydraulic axes as building blocks, each hydraulic system has a structure as depicted in figure 5.

Note that the coupling between several hydraulic axes A_i is of a transitive nature. If A_1 and A_2 are coupled, and if A_2 and A_3 are coupled then A_1 and A_3 are coupled as well. The coupling level is prescribed by the weakest coupling (cf. subsection 4.3).

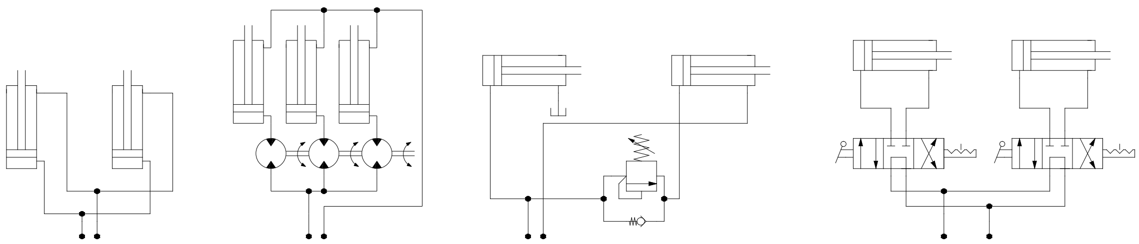

Figure 4: Different kinds of couplings between hydraulic axes.

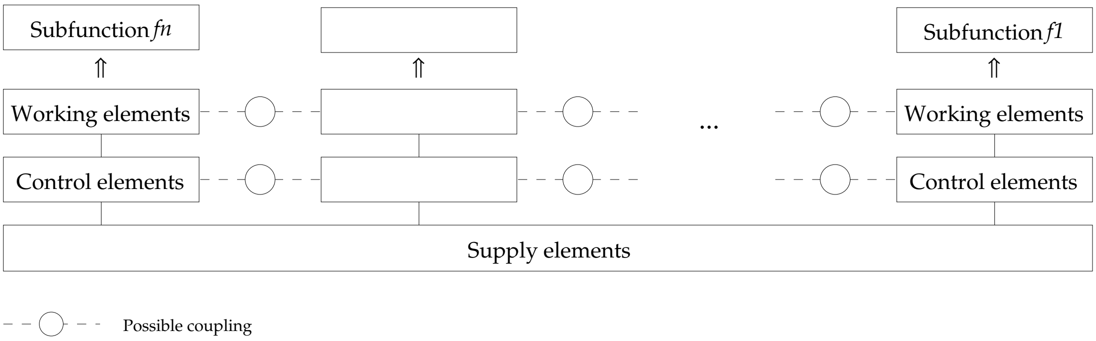

Figure 5: Abstracted structure of a hydraulic system.

4.1 The Rationale of a Topological Analysis

As motivated in section 2, the view of hydraulic axes reveals basic design decisions. With respect to a well-founded analysis of hydraulic systems, their identification and classification with regard to the coupling level plays a key role:

- *Structure Envision.* The identification of hydraulic axes within a complex circuit will help a designer to quicker get into the material. As a consequence, the modification, the extension, and the adaptation of existing hydraulic systems becomes simpler.

- *Complexity Classification.* The ability to reason about the complexity of the investigated system is a basic prerequisite to apply design knowledge at all.

- *Demand Interpretation.* The demand set D defines global as well as local demands. Local demands belong to particular subfunctions f_i realized by the hydraulic system. These demands can be assigned to single components only if the hydraulic axes are identified.

- *Smart Simulation.* Smart simulation is a human strategy when analyzing a complex system: Subsystems are identified, cut free, and simulated on their own. This strategy reduces the simulation complexity and simplifies the interpretation of simulation results. Hydraulic axes establish suited subsystems to be cut free since they perform an indivisible but complete subtask.

- *Parameter Variation.* Even a readily constructed hydraulic system has several parameters that can be varied in order to improve the system's behavior or to find an optimum setting respecting a certain other objective. Although the hydraulic axes of a system are coupled in some way, an isolated investigation may provide useful insights or optimization hints respecting a parameter setting. Note that an isolated investigation reduces the search space's dimension.

- ☐ *Detection of Crucial Components.* The term "crucial component" depends decisively on a component's usage respecting a particular position in a hydraulic system. Hydraulic axes define some kind of *equivalence classes for crucial behavior*. I. e., the investigation of a system regarding crucial behavior may be restricted to particular hydraulic axes.
- ☐ *Control Concept Selection.* Aside from the demands the selection of a control concept for a control quantity must additionally consider possible interactions of the controlled component with other components. The level of coupling of hydraulic axes provides an adequate measure for the magnitude of component interdependencies.
- ☐ *Control Concept Evaluation.* The evaluation of a control concept also founds on the relative importance and the coupling of hydraulic axes.
- ☐ *Diagnosis.* As shown in [8], the diagnosis of arbitrary hydraulic systems is a very difficult task, and, at the moment, it is not satisfactorily solved. In this connection the concept of hydraulic axes helps to break down a large system into entities that are tractable as well as sufficiently expressive from a diagnostic standpoint.

Note that within the normal design process, hydraulic axes are not used as explicit building blocks. The reasons for this are twofold: (*i*) It is not always possible to design a hydraulic system in a top-down manner, starting with hydraulic axes, which are refined within subsequent steps; (*ii*) both the experience and the ability of human designers to automatically derive function from structure enable them to construct a hydraulic system at the component level.

As an aside, the main working document for a designer is the technical drawing, and there is no tradition or standardized method to additionally specify the functional structure of a hydraulic system. This situation emphasizes the need for an *automatic identification* of the desired structural information.

4.2 Basics

From a structural viewpoint, the variety of hydraulic components can be reduced to a small number of classes. With the objective of a structural analysis in mind we introduce the following abstracted component classes:

a) *Working Elements.* All kinds of cylinders and motors contributing to the output power make up the class of working elements.

b) *Control Elements.* All directional valves that are used for the control of a working element make up the class of control elements.

c) *Supply Elements.* Pumps and tanks are the only elements of this class.

d) *Auxiliary Elements.* All elements which do not fall in one of the above classes make up the class of auxiliary elements.

Remarks. This division does not follow the engineering conventions in every respect: (*i*) Here, the classification of a component must consider its usage within a circuit. E. g. a directional valve that does not control a working element falls into class d, auxiliary elements. Stated another way, the membership within one of the classes a or b establishes only a *necessary* condition for being of the type "'working element"' and "'control element"' respectively. (*ii*) Among others, the class d, auxiliary elements, contains pipes, t-connections, pressure relief valves, and filters.

The identification of hydraulic axes as well as the couplings between these axes relies on graph theoretical considerations. In this connection we use the following definitions of graph theory in the standard way [1], [5]:

1. A *multigraph* G is a triple $\langle V, E, g\rangle$ where $V, E \neq \emptyset$ are finite sets, $V \cap E = \emptyset$, and $g : E \rightarrow 2^V$ is a mapping with $2^V = \{U \,|\, U \subseteq V,\ |U| = 2\}$. V is called the set of points, E is called the set of edges, and g is called the incidence map.[3]
2. A graph $H = \langle V_H, E_H, g_H\rangle$ will be called *subgraph* of $G = \langle V, E, g\rangle$, if $V_H \subseteq V$, $E_H \subseteq E$, and g_H is the restriction of g to E_H. A subgraph will be called an *induced subgraph* on V_H, if $E_H \subseteq E$ contains exactly those edges incident to the points in V_H. For $T \subset V$, $G \setminus T$ denotes the subgraph induced on $V \setminus T$.
3. A tuple $(e_1, \ldots, e_n)$ will be called a *walk* from v_0 to v_n, if $g(e_i) = \{v_{i-1}, v_i\}$, $v_i \in V$, $i = 1, \ldots, n$. A walk will be called a *path*, if the v_i are mutually distinct. Instead of using a tuple of edges, a walk may also be specified by a tuple of points, $(v_0, \ldots, v_n)$.
4. G will be called *connected*, if for each two points $v_i, v_j \in V$ there is a walk from v_i to v_j. If G is connected and $G \setminus v$ is not connected, v establishes an *articulation point*. The maximum connected subgraphs of G are called *connected components*.

Figure 6 illustrates the definitions.

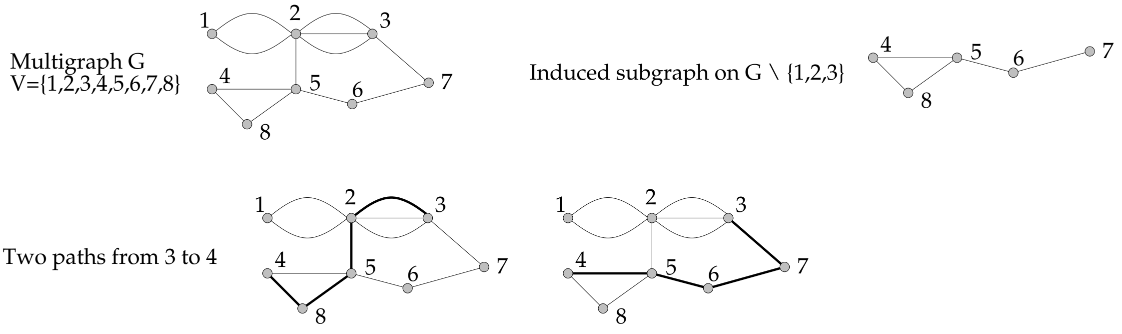

Figure 6: Illustrations of the graph definitions.

To work with a hydraulic circuit C as an ordinary multigraph $G(V, E, g)$ a mapping rule is required. Such a mapping defines for C the related hydraulic graph $G_h(C)$.

Definition 4.1 (Related Hydraulic Graph). Given is a hydraulic circuit C. Its related hydraulic graph $G_h(C) := \langle V_C, E_C, g_C\rangle$ is defined as follows. (*i*) V_C is a set; each non-pipe component of C is associated one-to-one with a $v \in V_C$, V_C does not contain other elements. (*ii*) E_C is a set; each pipe component of C is associated one-to-one with an $e \in E_C$, E_C does not contain other elements. (*iii*) $g : E_C \rightarrow 2^{V_C}$ is a function that maps e onto v_i, v_j, iff there is a pipe between the components associated with v_i, v_j, and if e is associated with this pipe.

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[3] We need multigraphs instead of graphs here since components of a hydraulic system may be connected in parallel. Also note that we restrict ourselves to finite graphs here.

Figure 7 contrasts a hydraulic circuit and its related hydraulic graph. The labels in the graph shall underline that there is a one-to-one mapping between the elements of the graph and the components of the hydraulic circuit.

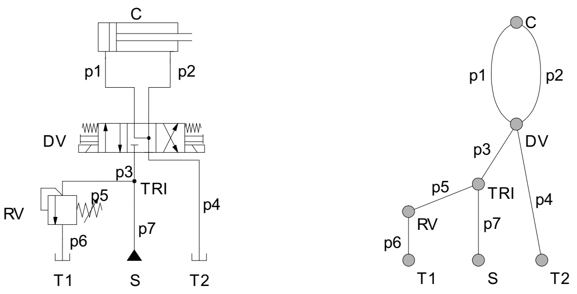

Figure 7: Sample circuit with its related graph.

Remarks. For each hydraulic circuit C there exists exactly one related graph $G_h(C)$. Note that g performs a topological simplification of C: (*i*) g_h comprises the substructures within (directional) valves down to one single point v, hence making all connected pipes incident to v. (*ii*) Variations of the topology coming along with valve switching are neglected. (*iii*) Directional information that results from the behavior of particular hydraulic components is dropped.
These simplifications have no effect on the classification of hydraulic axes couplings.

4.3 Hierarchy of Coupling Types

In order to determine those components of a hydraulic system that belong to a particular hydraulic axis A, couplings between A and other axes must be identified as such. A prerequisite for the identification step thus is a classification of possible coupling types. The following classification scheme provides a definition for these types; this scheme distinguishes between four coupling levels.

Definition* 4.2 *(Coupling Types). Given is a hydraulic circuit C containing two sub-circuits A, B, which realize two different hydraulic axes. Moreover let $G_h(C) := \langle V_C, E_C, g_C\rangle$, $G_h(A) := \langle V_A, E_A, g_A\rangle$, and $G_h(B) := \langle V_B, E_B, g_B\rangle$ denote the related hydraulic graphs of C, A, and B respectively.

- *Level 0 or No Coupling.* If $G_h(C)$ is not connected, and if $G_h(A)$ and $G_h(B)$ are subgraphs of different connected components in G_h, then the hydraulic axes A and B are not coupled.

- *Level 1 or Informational Coupling.* Let $\{e_1, \dots, e_n\}$ be in E and each e_i associated with a control line within C. If $G_{h'} := \langle V_C, E_C \setminus \{e_1, \dots, e_n\}, g_C\rangle$ is not connected, and if $G_h(A)$ and $G_h(B)$ are subgraphs of different connected components in $G_{h'}$, then the hydraulic axes A and B are informationally coupled (cf. figure 8).

  Note that control lines can be of hydraulic, pneumatic, or electrical type.

- *Level 2 or Parallel Coupling.* Let v_a, v_b be two points in V_A and V_B respectively. Furthermore let P_{v_a,v_b} comprise all power paths from v_a to v_b; i. e., each $p \in P_{v_a,v_b}$ is of the form $(v_{p_0}, \dots, v_{p_n})$, $v_{p_i} \in V_C$, $v_{p_0} = v_a$, $v_{p_n} = v_b$. The term "power path" shall express that no edge within a path $p \in P_{v_a,v_b}$ is associated with a control line. Then A and B are coupled in parallel if the following conditions hold:

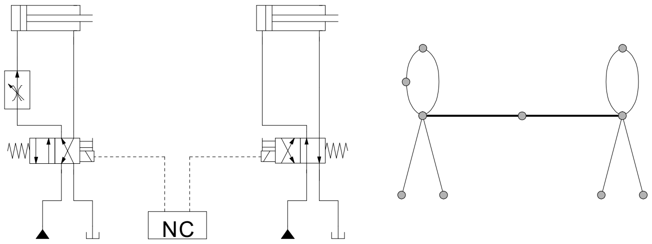

Figure 8: Circuit with informationally coupled hydraulic axes.

(*i*) $\forall p \in P_{v_a,v_b}\ \forall v \in p : v = v_a$ or $v = v_b$ or v is associated with an auxiliary element.

(*ii*) There exist two paths, $p_a = (v_a, \ldots, v)$, $p_b = (v_b, \ldots, v)$ where v is associated with a supply element and p_a (p_b) contains not v_b (v_a respectively).

Figure 9 gives an example.

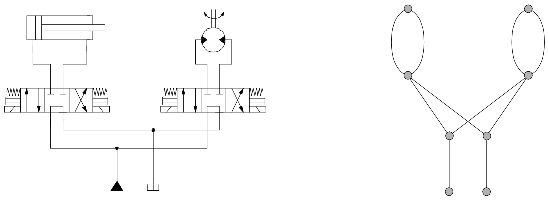

Figure 9: Circuit containing hydraulic axes coupled in parallel.

- *Level 3 or Series Coupling.* Let v_a, v_b be two points in V_A and V_B respectively. Furthermore let P_{v_a,v_b} comprise all power paths from v_a to v_b; i. e., each $p \in P_{v_a,v_b}$ is of the form $(v_{p_0}, \ldots, v_{p_n})$, $v_{p_i} \in V_C$, $v_{p_0} = v_a$, $v_{p_n} = v_b$. The term "power path" shall express that no edge within a path $p \in P_{v_a,v_b}$ is associated with a control line. Then A and B are coupled in series if the following conditions hold:

  (*i*) $\forall p \in P_{v_a,v_a}\ \forall v \in p : v = v_a$ or $v = v_b$ or v is associated with an auxiliary element.

  (*ii*) Let v be associated with a supply element. Then either each path $(v_a, \ldots, v)$ contains v_b or each path $(v_b, \ldots, v)$ contains v_a.

  Figure 10 gives an example.

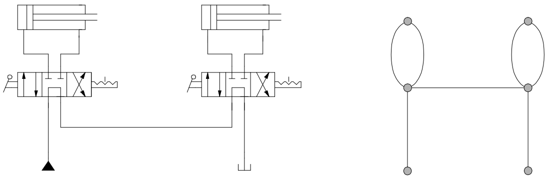

Figure 10: Circuit containing hydraulic axes coupled in series.

- *Level 4 or Sequential Coupling.* Let $V_{A \cap B} := V_A \cap V_B$. If $\exists v \in V_{A \cap B}$ that is associated with a control element, the hydraulic axes A and B are sequentially coupled. Figure 11 gives an example.

4.4 Discussion of the Coupling Types Definition

Parts of the coupling types definition seem not to be defined in a straightforward manner. In the following we discuss different aspects of the definition and motivate its rationale.

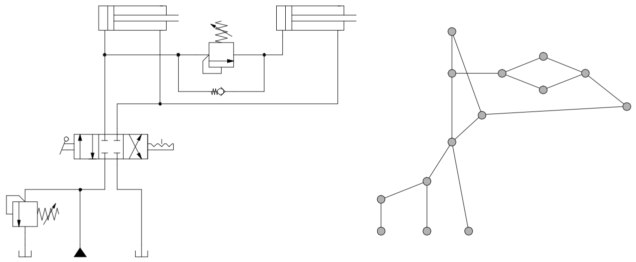

Figure 11: Circuit containing sequentially coupled hydraulic axes.

The definitions for parallel and series coupling rely on the graph theoretical definition of a *path* (and not on the definition for a walk). Consider the following figure 12: No path from point a to point b contains a control or a working element.

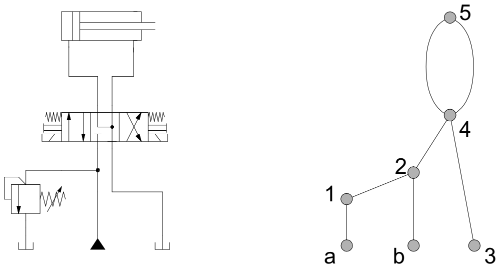

Figure 12: Paths and walks in a hydraulic graph.

A *walk* from point a to point b, on the other hand, is allowed to contain duplicate points. E. g. the node sequence $(a, 1, 2, 4, 2, b)$ both establishes a walk and contains a working element. However, $(a, 1, 2, 4, 2, b)$ violates the path definition.

Condition (*i*) of the definition for parallel and series coupling types ensures that v_a and v_b are not associated with an "′inner"′ component of a hydraulic axis: Each walk from such an inner component to another hydraulic axis contains at least one control element.

Condition (*ii*) of the parallel coupling definition ensures the parallel nature of the linkage: From v_a (v_b) a supply element can be reached independently of v_b (v_a), i. e., without crossing v_b (v_a).

By contrast, condition (*ii*) of the series coupling definition states that no two paths can be found, which are independent in this way.

There exist additional coupling types that are not covered by the definitions of the former subsection. The specific feature of these couplings is that they make the involved working elements behave identically. These working elements are therefore comprised into one single hydraulic axis. The following list itemizes those cases where several working elements are part of one single hydraulic axis.

- *Mechanical Couplings.* Mechanical couplings enforce a unique behavior over the connected components. Figure 13 gives two examples.

- *Identical Subcircuits.* Clearly, identical subcircuits that are controlled by a single control element also behave identically, and thus they are part of the same hydraulic axis. Figure 14 shows two circuits. The circuit on the left-hand side contains one hydraulic axis; the circuit on the right-hand side is slightly different but does contain two hydraulic axes.

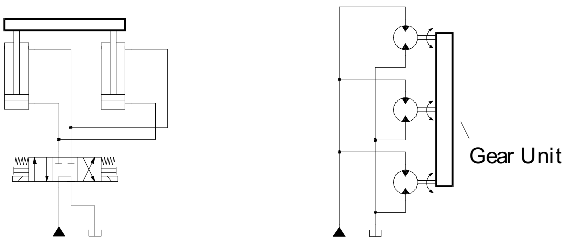

Figure 13: Examples for mechanically coupled working elements.

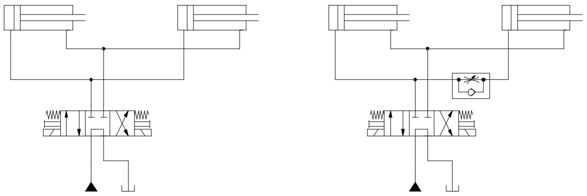

Figure 14: Two circuits with one and two hydraulic axes respectively.

The definitions and this discussion show that the identification of hydraulic axes is a sophisticated job, which cannot be tackled by simple ad-hoc approach. The next section presents the basic concepts of an identification approach.

4.5 Identifying Hydraulic Axes

Starting point is a hydraulic graph $G_h(C)$ of a circuit C. Our approach to the identification of hydraulic axes consists of three main steps:

1. *Graph Condensation.* Within the condensation step, a circuit's hydraulic graph G_h is reduced in order to simplify the accessibility analysis. Loosely speaking, G_h is "'stripped"' from components that do not form a hydraulic axis backbone. For the most part the stripped components belong to the class of auxiliary elements. Below this step is explained in greater detail.

2. *Accessibility Analysis.* Matter of the accessibility analysis is the application of the definitions to determine both the hydraulic axes and their couplings in the reduced graph.

3. *Graph Extension.* The graph extension step addresses the completion of a hydraulic axis in the reduced graph relating the original hydraulic graph.

Depending on the circuit in hand, the condensation step in turn may contain several sub-steps:

- ❑ *Condensation by Control Path Deletion.* Control paths establish no identification characteristic for hydraulic axes. They can be identified (and deleted) easily in G_h.

- ❑ *Condensation by Dead Branch Deletion.* In this connection a dead branch is a subgraph whose nodes are not associated with control or working elements and whose connectivity is 1. Figure 15 gives two examples.

- ❑ *Condensation by Particular Component Deletion.* In the former two condensation steps the delete operations are justified by the circuit context, which is either a control path or a dead branch. Outside these special subcircuits component deletion

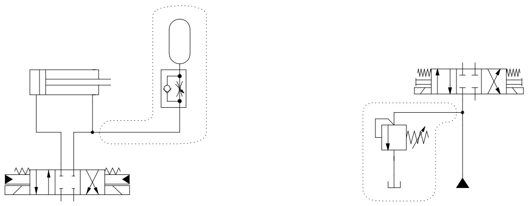

Figure 15: Two examples for a dead branch.

must happen carefully: Whether a valve constitutes a control element or an auxiliary element depends on its usage. Nevertheless there exist a few context-independent auxiliary components, whose corresponding nodes can be removed from G_h without a sophisticated investigation. The directional valve is an example for such a component.

- *Condensation by Loop Resolution.* A hydraulic circuit may contain cyclic structures and in-parallel-connected components. These structure are not necessary for identification purposes if they neither contain nor control a working element. Figure 16 gives a few examples.

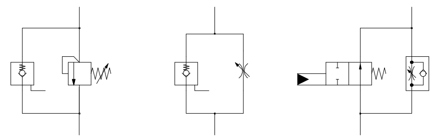

Figure 16: Examples for loops that can be cut.

Note that the directional valve in the rightmost circuit constitutes an auxiliary element; in its context of usage it cannot control a working element.

Let G'_h denote the condensation of G_h, achieved by the steps outlined above. The nodes in G'_h correspond to pipes, control elements, working elements, and supply elements. The accessibility is grounded on the definitions of subsection 4.3 and shall designate the hydraulic axes along with their coupling type. Note that a level 0 or a level 1 coupling can be detected easily before the condensation step, by simply applying the definitions.

For the coupling types 2, 3, and 4, the analysis is more sophisticated; it requires the following steps:

- Introduction of candidate axes for each control element.
- Determination of the candidate axes' working elements. Note that due to the contraction procedure the nodes associated to working and control elements of a hydraulic axis must be incident in G_h.
- Application of the definitions of subsection 4.3. In particular, two points v_a and v_b must be determined such that the conditions (*i*) and (*ii*) of the parallel (series) coupling definition hold. At the moment a direct specification of such points can not be given. A good heuristic is to start with the axes' control elements when searching suited points v_a, v_b.

Remarks. The reduced graph can also be exploited to investigate process-logical questions. For this G'_h must be expanded with respect to the internal structure of its working and control elements. Based on the resulting graph necessary conditions and heuristics relating the driving process can be derived.

5 On Demand Formulation and Behavior Interpretation

Formulating demands at a hydraulic system and comparing the simulated behavior with these demands can turn out to be a sophisticated job. Clearly, one reason for this lies in the complexity of the hydraulic domain. Another reason is that here the structure of a hydraulic system is a-priori unknown and thus no global scheme for demand formulation or behavior interpretation is at hand. E. g. the interpretation of parameter defaults and simulation results must consider a component's usage, global constraints, or the specification form of the demands (qualitative propositions, diagrams, etc.).

In fact, engineering know-how is essential in all phases that follow the raw design (synthesis) phase:

- *Demand Formulation.* Formulate the demands with respect to the actual system.
- *Component Instantiation.* Estimate parameters of components that are only partially specified.
- *Discrete-time Simulation.* Perform a simulation to the next steady-state.
- *Behavior Interpretation.* Interpret the simulated behavior.
- *System Modification.* Modify the hydraulic system, if necessary.

The sequence of these phases must be controlled by a global control instance. Figure 17 depicts these phases and illustrates their sequence.

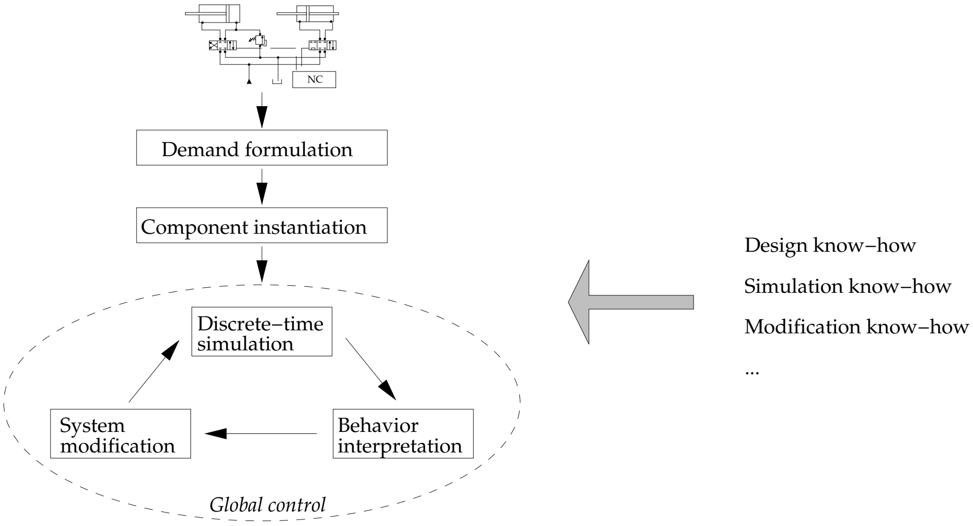

Figure 17: Phases within the process of behavior interpretation.

The next subsections focus on the phases depicted in figure 17. They outline concepts but also research work that still has been operationalized as part of the OFT-project.

5.1 Demand Formulation

This subsection classifies the different types of demands that can be stated at a hydraulic system; it also proposes techniques to realize their formulation within a knowledge-based system. Following types of demands are distinguished[4]:

- ❑ *Numerical Demands.* These type of demands comprises state values such as pressures and flows or components parameters. Their values can be adequately requested using dialog boxes.
- ❑ *Diagrams.* By means of diagrams particular relations between physical quantities are formulated. Normally such diagrams define a quantity over the course of time. Typical representatives are distance/time diagrams, force/time diagrams, but also velocity/distance diagrams.
- ❑ *Linguistic Demands.* Linguistic demands usually relate to particular state values; they are used if exact values can not be stated. Discussions with design engineers showed that Fuzzy-sets and Fuzzy-rules represent a suited formulation construct here.

A point that concerns all types of demands is the specification of tolerance and validity ranges. Aside from the numerical range specification, a linguistic specification is useful for numerical demands as well.

With respect to a hydraulic system's structure the demands can be divided into several classes; hydraulic axes play a special role in this connection. Three classes are distinguished here:

- ❑ *Global Demands.* Global demands must be valid for the entire system. In the stationary case they can relate to system pressures; with respect to dynamic behavior the fluid's density, temperature, or elasticy count to these demands.
- ❑ *Axis Demands.* Axis demands constrain the behavior of a single hydraulic axis. The definition of axis-specific constraints is a must for larger hydraulic systems that embody several subfunctions; they help to realize a smart behavior interpretation.
- ❑ *Component Demands.* The axis demands provide a guideline for the demands at the component level within a single axis. These demands encompass technical data of the working, control, and supply elements.

Obviously the plan of a hydraulic system forms an important basis for any kind of demand specification. A computer-based analysis tool hence should consider the information provided by the plan when requesting the stationary or dynamic demands.

5.2 Component Instantiation

A simulation for a given system needs an exact specification of all components. The greater part of this specification is made up by default values along with the component demands. Under-specified components define a component *profile* rather than a concrete component.

Aside from an evaluation of equations that encode physical dependencies, design know-how in the form of heuristics is necessary to fill such specification gaps.

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[4] The types listed here are based on [4]

5.3 Discrete-time Simulation

The discrete-time simulation predicts the behavior at the next steady state. Within a steady state, the time derivatives of the state values are zero.

In a first approach we used services of the $^{\text{art}}$*deco* system for both detecting the next steady state of a process and simulating the behavior. These basic services were completed by two modules that we have developed to tackle the oscillation problem and the stalled pressure problem:

- *Oscillation Problem.* Depending on a component's usage in a circuit, the component may oscillate, and thus a steady state is never reached. Within a discrete-time simulation such situations must be detected and resolved by truncation. In particular, truncation means that new behavior states are introduced for the oscillating component; the intrastate behavior (cf. [2]) for this component is truncated.

- *Stalled Pressure Problem.* In several situations a hydraulic circuit may contain subsections that are cut off from the rest of the system. The pressures in these subsection cannot be computed by the methods of a discrete-time simulation because the underlying equation system is under-specified.

  Our approach consists of the following steps: (*i*) determination of those sections that are cut off, and (*ii*) interval-based pressure propagation. In this place we roughly sketch out the basics of the approach.

  At first, unknown resistances are set to some value which not equals zero. Then the resulting nonlinear network is solved for some pressure potential. Those sections of the network whose flow does not equal zero are not cut off. For pipes in those sections that are cut off, the nominal pressures of incident pressure relief valves are used as a first pressure approximation. For pipes not incident with pressure relief valves, a history pressure value is used instead. Then, the pressure values are propagated *beyond closed* pressure relief valves. In particular, high pressure values are propagated down to lower values. Propagation comes to an end, if no new values can be inferred.

5.4 Behavior Interpretation

Behavior interpretation means to balance the simulated behavior of some circuit C with the demands that have been specified for C. Of course there is no global measure to perform a smart balance process; based on the global, the axis-specific, or the component-specific tolerance and validity ranges, the quality of the fulfillment of the demands can be checked. Depending on the representation of the range information, some kind of Fuzzy inference may become necessary here.

Note that behavior interpretation does not deal with single values only. If, for example, a particular cylinder course is to be driven, deviations detected at single points of the course must be integrated over a time interval.

Moreover, there is large bandwidth relating the level of demand violations. Usually it will be easier to increase the force at some cylinder than correcting a fault within the process-logical behavior of a circuit. Improving (within the meaning of repairing or diagnosing) a system that violates a demand is matter to the modification phase.

5.5 System Modification

The modification of a misbehaving hydraulic system shall be realized with modification rules. These rules talk about particular component classes and particular classes of circuit structures such as relief branches or hydraulic axes. I. e., these rules have to be instantiated with respect to an actual system before they can be fired and chained.

Two types of rules are distinguished:

1. *Component Rules.* Component rules modify single parameters of a component. They encode design heuristics that are coupled with physical connections. For example, if the system pressure exceeds the maximum value, the nominal pressure parameter of a relief valve can be corrected by a rule of this type.

2. *Structure Rules.* Structure rules modify a system's topology by inserting or deleting components. For example, the insertion of a bypass throttle in parallel to a cylinder can be formulated with the aid of structure rules.

Having instantiated and evaluated the modification rules, the actions formulated in the rules' consequences must be executed. At this point the $^{\text{art}}$*deco*-script-language comes into play. This language is currently developed and will provide commands that imitate a user's actions, such as parameter modification, circuit creation, starting the simulation, etc.

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