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STRUCTURAL ANALYSIS OF HYBRID ELECTRO-HYDRAULIC POWER STEERING SYSTEM - A BOND GRAPH APPROACH

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KEYWORDS

Structural analysis, inverse model, bond graph.

ABSTRACT

In this paper, the design of an hybrid electro-hydraulic steering system is addressed from a structural view-point. The aim is twofold. First, the model structural invertibility is studied and the admissible inputs/outputs are derived. Second, the differentiability of the specified output functions (required for numerical simulation purposes) is deduced from essentiality orders. This analysis is conducted on the bond graph model of the system.

INTRODUCTION

The design and sizing of steering systems for heavy vehicles, such as trucks, have become critical areas in the continuous evolution of the automotive industry towards more efficient and sustainable solutions. The pursuit of enhanced performance, improved fuel economy, and reduced emissions has prompted the automotive industry to explore novel solutions.

Traditionally, hydraulic power steering (HPS) systems dominated the landscape (Claeys et al., 1999). However, the growing demand to reduce emissions and improve overall performance has led to a significant transformation in this sector (Zhao et al., 2019). Electrification has introduced new solutions, such as electro-hydraulic power steering (EHPS) systems (Morton et al., 2014), where the hydraulic power source can be electrical, typically a controllable electric pump. Another solution uses an electric actuator (EPS) in parallel with the hydraulic part, referred to as hybrid system (Wiesel et al., 2009). More recently, the hybrid EHPS system, combines both EPS and EHPS systems (Park et al., 2019).

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This paper deals with the sizing of an hybrid EHPS system, based on a structural analysis (depending on the types of physical phenomena involved in the system and on the way they are energetically connected one to another) of the system. Structural analysis refers to generic properties of a model that are true for almost all parameter values (Dion et al., 2003). This analysis is part of an overall design and sizing methodological framework, based on model inversion concepts (Ngwompo and Scavarda, 1999). The methodology aims to assist engineers in designing mechatronic systems based on dynamic and energy criteria. This analysis is performed using the bond graph formalism (Karnopp et al., 2012), well suited to the multiphysical, energetic and structural context of the study.

Besides the bond graph model of the hybrid EHPS system, the objective of this document is twofold and corresponds to the first two steps of the methodology. First, the structural invertibility of the model is studied and the admissible inputs/outputs combinations are derived. Second, for each admissible combination, the differentiability of the specified output functions is deduced from the essentiality orders. This provides a necessary and sufficient condition for the mathematical expression of the specifications. The analysis results are then interpreted, offering some sizing guidelines.

In a first section, we introduce the hybrid EHPS system as well as its bond graph model. The second section states the design and sizing aspects of the system, specifying the inputs (to be sized) and the outputs (specified) considered in the study. In the third section, the design and sizing methodology based on the inverse model and the bond graph language is introduced. Then, a structural analysis of the bond graph hybrid EHPS model, fundamental point of the methodology, is presented. The conclusion is given in the last section.

MODELLING OF THE HYBRID EHPS SYSTEM

System description of the Hybrid EHPS system

The hybrid electro-hydraulic power steering (EHPS) system is shown in the schematic diagram in Figure 1. The hybrid EHPS system includes a mechanical passive steering system, an EHPS system with a recirculating ball mechanism and an electric power steering (EPS) system, directly mounted on the top of the hydraulic ball screw gearbox. A steering system typically serves two primary functions: the kinematic function and the power assistance function.

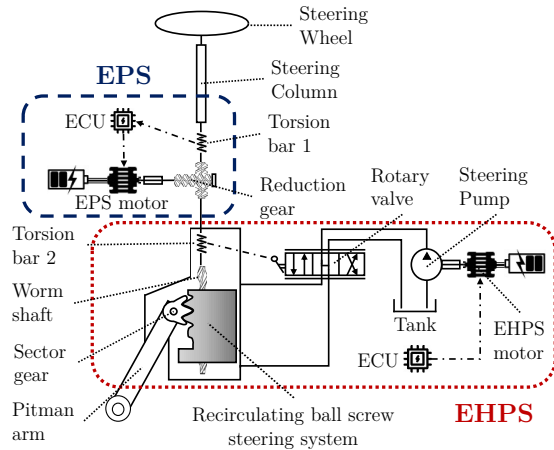


Figure 1: Simplified model of the Hybrid EHPS system.

The Hybrid EHPS system works as follows. When the driver turns the steering wheel, the steering column moves accordingly and the torsion bar 1 is twisted. From this torsional angle, a torque angle sensor can measure the steering torque and the angle of the driver input. Then the electronic control unit (ECU) of the EPS system, with other measurements from the vehicle, determines the amount of assistance torque on the steering column.

Torsion bar 2 is also twisted, leading to the opening and closing of specific ports in the rotary valve. This action generates the assistance force on the ball-nut cylinder through the differential pressure between the left and right chambers. The hydraulic section incorporates a pump, which is powered by a controlled electric motor. The primary purpose of this motor is to deliver the necessary torque for the pump, ensuring it meets the hydraulic system's requirements.

Bond graph modelling of the Hybrid EHPS system

Figure 2 shows the bond graph representation for the hybrid EHPS system. This bond graph model clearly shows three actuating lines acting in parallel on the pitman arm at the output of the steering box, and consequently on the wheels. The main actuating line corresponds to the passive mechanical part of

the steering system and is controlled by the driver (top left). The other two secondary actuating lines are linked to EPS and EHPS systems. The action of these different actuating lines is superposed, with the secondary ones assisting the main one.

The driver is assumed to generate the motion of the steering wheel, which is represented by a modulated flow source MSf . The rotational kinetic phenomena of the steering wheel and column are combined in an I element. The energy storage linked to the torsion bar is depicted by a C element. A sensor is installed to measure the corresponding torque. The rotational kinetic phenomena of the column reduction gear are represented by an I element in relation to the principal actuating line model. Viscous friction in the column as well as the reduction gear is taken into account by dissipation elements R .

The part in the dashed box corresponds to the EPS system, and comprises a DC motor powered by a voltage obtained from the assistance law. The voltage supplied is represented by a modulated power source MSe . The motor's electrical component is represented by a pair of I and R elements, while electromechanical coupling is represented by a gyrator element GY . The I and R elements represent kinetic phenomena associated with rotor inertia rotation and friction. A reduction gear couples the DC motor to the principal actuating line at the column pinion level, represented by a TF element.

The part in the dotted box corresponds to the EHPS system, and includes a DC motor modelled similarly as for the electric assistance. However, in this case, the motor drives a pump. Compliance and resistance of the pressure hose are modelled by a pair of C and R elements. The rotary valve comprises four resistances modelled by four MR elements that correspond to the right and left, in and out orifices of the valve. Each resistance pair is accompanied by a compliance element (C elements) representing hydraulic chamber compressibility. The ports of the rotary valve open based on the torque of the torsion bar 2, which is modelled by a C element. The transformer TF represents the area A_p of the hydraulic piston section in the rack component, which converts hydraulic pressure into longitudinal force.

The remainder of the EHPS system bond graph model comprises mechanical transmission to the pitman arm. A pair of I and R elements represents kinetic phenomena associated with the rack in translation and rack friction. Then a transformer represents the sector gear, which converts rack velocity to pitman arm angular velocity. A pair of I and R elements represents kinetic and friction phenomena of the pitman arm. A modulated effort source MSe is used to model the effort feedback to the steering system, due in particular to the road interactions and the kinematic of the front axle.

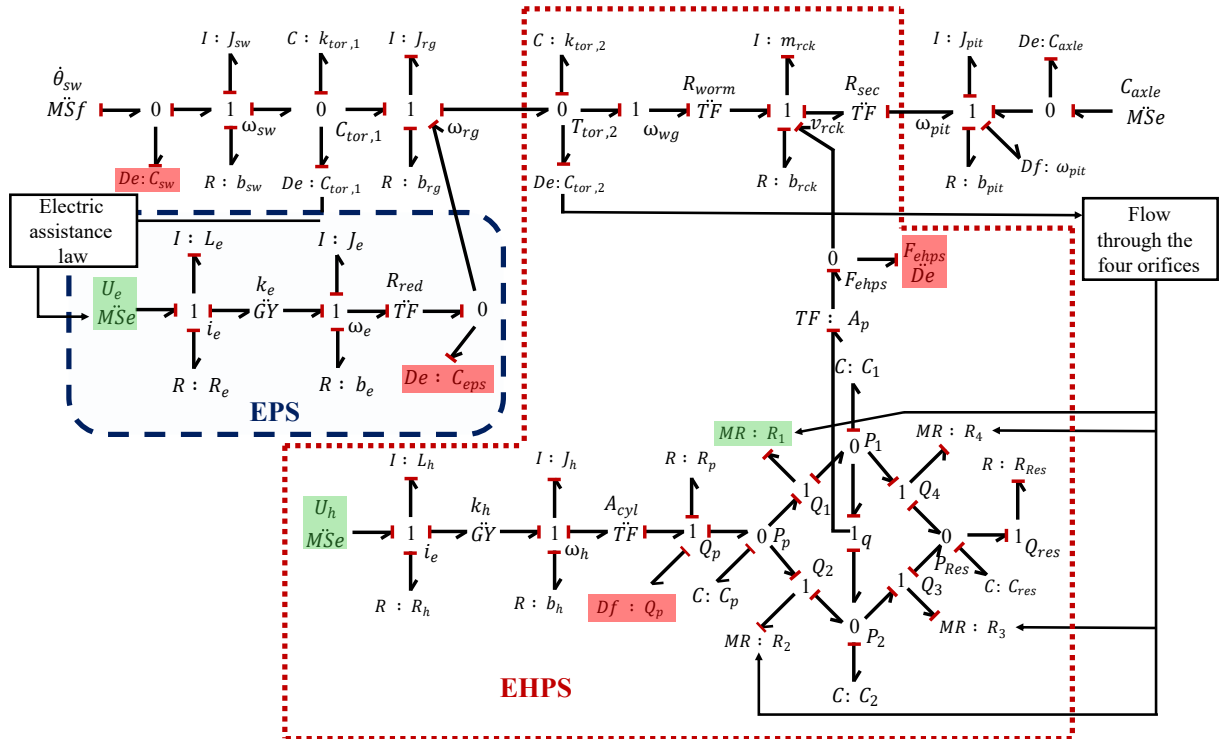


Figure 2: Bond graph model of the hybrid EHPS system.

DESIGN ASPECT AND SIZING OF THE HYBRID EHPS SYSTEM

The existing method relies predominantly on established solutions that have demonstrated their effectiveness and are frequently replicated in successive studies. Some specifications emphasize the passive mechanical component, while others give more attention to the assistance aspect. In our case study, the focus of the discussion is mainly on the assistance part.

Inputs to be determined

When addressing the sizing of assistance, various components come into consideration. The dimensions of some elements, like the pump or piston area, are pre-determined and restricted by spatial constraints and other factors. Nonetheless, the following elements are considered adjustable:

- *Rotary Valve (R_1)*: affects hydraulic pressure and, consequently, the force produced by the EHPS system. The sizing concerns the orifice areas of the rotary valve A_1 and A_2 , which appear in the MR elements that describe the fluid dynamics through the orifices. In the sequel, for conciseness in the notation, R_1 is treated as the input to be determined;
- *EHPS DC motor (U_h voltage)*: modulates the pump's flow rate, which impacts hydraulic force;
- *EPS DC motor (U_e voltage)*: modulates the electric assistance torque.

Specified outputs

Outputs are defined according to sizing criteria. Truck manufacturers employ various criteria and tests to validate their steering system design decisions. These outputs enable the evaluation of diverse scenarios in which the vehicle will operate, resulting in a specific characterization of the steering system, especially in terms of its power assistance. Naturally, the "parking" tests make it possible to check whether the level of assistance remains within a given range of values when manoeuvres are carried out at various low speeds and whether the torque felt by the driver is acceptable or not.

The criteria that must be satisfied for sizing can be articulated as follows:

- *Steering torque (C_{sw})*: condition on the steering torque to lighten the load on the driver but also to guarantee the feel of the vehicle's handling. The constraint on steering torque depends on vehicle speed and effort feedback;
- *power-assisted efforts (F_{ehps} and C_{eps} , whether hydraulic or electric)*: variations in these efforts can be restricted in different ways;
- *pump flow (Q_p)*: for the energy contribution used to vary hydraulic assistance.

The specified outputs depend primarily on the front axle weight of the vehicle. We will see in the next sections how these specified outputs are defined.

Figure 3 summarises the input variables to be determined and the output variables specified for the steering system (elements also highlighted in red and green in Figure 2, respectively).

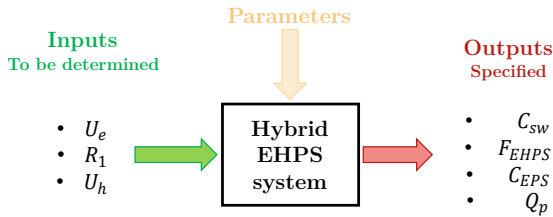


Figure 3: EHPS system inputs and outputs.

DESIGN AND SIZING METHODOLOGY

The problem of system design and sizing is usually addressed through the iterative process of simulation and model adaptation, the so called “trial - error - correction” method. In a sizing context, the outputs are specified (known) and the inputs are to be determined (unknown). The inverse model approach therefore seems a more suitable solution to the sizing problem. This approach significantly reduces the number of iterations that the “trial - error - correction” process imposes in a direct model approach.

Inverse based bond graph approach

A detailed presentation of the methodology can be found in references (Jardin et al., 2008). The sizing methodology using inverse bond graph models takes place in three steps. In the context of structural analysis, we only focus here on the first two steps:

- **1st step: structural invertibility:** This step is based on an acausal analysis (which consists of inspecting the power bonds on the bond graph model without causal assignment and the relationship between these bonds), and followed by a causal analysis to verify that the model is structurally invertible. The designer checks that the specifications can actually be achieved by the chosen model structure. Remind that structural invertibility means that the system is invertible for almost all parameter values;
- **2nd step: time differentiability:** Assuming that the model is structurally invertible, this step consists of graphically establishing the inverse model corresponding to the given sizing problem. Then, based on the inverse model, the differentiability of the specified output functions is deduced. The designer checks that the specifications are well formulated. This dynamical conditions are required for numerical simulation purposes.

The last step of the methodology concerns the selection of the technological components to be chosen as well as the validation of the design. This last step is no

longer limited to a structural analysis, but requires a level of numerical analysis, and will not be addressed in this paper.

Hybrid EHPS system case - multi-acting structure

Formulating the design problem in the form of an inverse problem implies reformulating the specifications in terms of temporal functions, which can be tricky or even irrelevant in terms of technical specifications. To address this issue, several approaches can be exploited, such as expressing the specifications as a function of the system’s power variables (Mechin, 2003) or coupling them with an optimisation problem (Mouhib et al., 2009).

The bond graph structure of the hybrid EHPS system comprises a primary base and two auxiliary assistance systems. The three drive chains converge at a singular load entry point, namely the steering box. This represents a multi-acting structure, wherein the specifications pertain to the subsystems rather than the load itself. When applying the methodology to the existing steering system, defining a time trajectory becomes challenging. Due to the assistance-type structure, a connection is established between a load variable (or an actuation chain variable) and the specified outputs, as depicted in Figure 4, referred to as constraint functions. Figure 4 shows the overall structure of the inverse bond graph model of the hybrid EHPS system. In this figure encircled dots summarize some parts of the figure 2 bond graph. The “J” elements stand for either 1 or 0 junction. The elements SeSf (resp. DeDf) serve to impose (resp. compute) the specified outputs (resp. inputs).

For illustrative purposes, the specifications associated with two outputs, one on the main drive train and another one on an assistance chain. These specifications are articulated through the constraint functions $f(\cdot)$ and $g(\cdot)$, which depend on system variables.

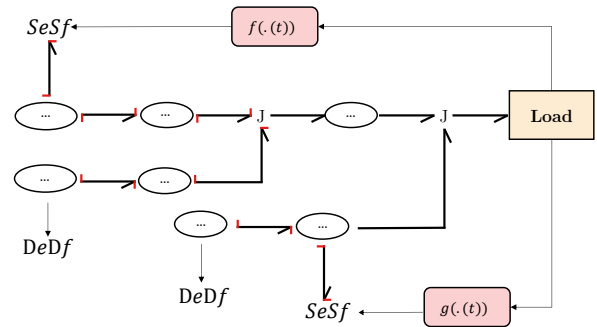


Figure 4: Inverse word bond graph with constraint.

This solution has the advantage of eliminating the need to create an output trajectory explicitly as a function of time. It also provides a better translation of the specifications, which are often formulated in terms of maximum and minimum values, as well as some tendency to be respected.

STRUCTURAL ANALYSIS OF THE HYBRID EHPS BOND GRAPH MODEL

Step 1 : Structural invertibility

Based on the system inputs and outputs (Figure 3), an acausal analysis of the model indicates that there are three possible choices for a square system of size three (among 24 possibilities) with disjoint I/O power lines (an alternating sequence of power bonds and multi-ports elements), shown in figure 5. The acausal analysis validates the model's first invertibility condition for the relevant combinations. For the first combination, figure 6a shows the set of disjoint power lines.

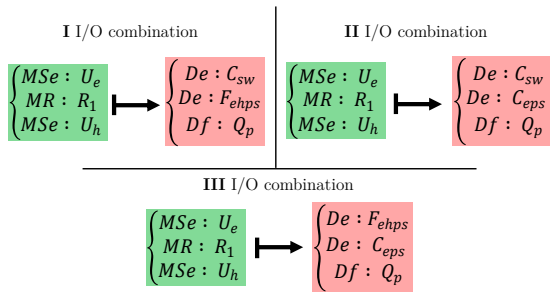


Figure 5: EHPS square I/O combinations with disjoint power lines.

Note that since the remaining sets of I/O combination do not fulfil the acausal analysis, there is no need to go further in the analysis. This is most likely due to the fact that there are not enough “energy routing channels” to drive all available degrees of freedom on the system.

The causal analysis of the model allows us first to verify the second criterion for the model invertibility. The second necessary condition consists of the existence of a set of disjoint I/O causal paths (a causal path between two variables of the bond graph is an ordered sequence of variables related to each other by the equations of the causally oriented elements without any of these variables appearing more than once in the sequence). For the three I/O combinations of figure 5, the inspection of the causal bond graph shows that there is at least one set of three disjoint causal paths, so the criterion is valid. Figure 6a shows an example of a set of disjoint paths (of minimal order), associated with the first I/O combination. From a mathematical point of view, if there are no sets of disjoint I/O causal paths, this means that the inputs could not be simultaneously expressed in terms of the outputs and thus that the model is not invertible. The two conditions validated for the moment are only necessary conditions for the structural invertibility of the model, but not sufficient.

To determine if the model is structurally invertible, we must also examine the solvability of the junction structure of the bicausal bond graph. The bicausal

bond graph is derived from the acausal model using sequential causality assignment procedure for inversion, “SCAPI”. This model extends to calculation schemes that no longer coincide with the “natural” observed evolution of physical phenomena, in the sense of physical causality (Gawthrop, 1994). For the three I/O combinations, the bicausal model is constructed without encountering any causal unsolvability, confirming the structural invertibility of the model. Figure 6b depicts the bicausal assignment for the first I/O combination.

Here it is worth noting that the output Q_p is mandatory in the inversion process. If Q_p is not considered in the inverse model, there is no disjoint set of I/O power lines. Consequently, the model will be structurally non-invertible. For non-square systems in general, with more outputs than inputs, this analysis can be helpful in identifying the outputs that must be considered in a sizing problem. Further, it remains to pick two outputs over the three remaining ones C_{sw} , F_{ehps} , C_{eps} (Q_p being necessary for invertibility as mentioned above). One of the outputs will therefore not be imposed in the inverse model. The behaviour of the discard output (the one not imposed to the inverse model) will be validated (or not) only after numerical simulation results.

Step 2 : Time differentiability

The next step of the methodology concerns the specifications, and more specifically their mathematical expression. The specification expression must respect a certain class of differentiability. This information can be found structurally using the order of a causal path, based on the concept of essentiality order (Commault et al., 1986). These essentiality order corresponds to the maximum time derivative order involved in the expression of the inputs in the inverse model. Therefore the higher the essentiality order, the higher the output time differentiability shall be in the specifications. It is obtained on the bond graph representation assigned with the bicausality (El Feki et al., 2012). On the bond graph representation in bicausality, the order of essentiality of an output is determined by the absolute value of the minimal order that a causal path can have between this output and any input. The set of I/O causal paths, used to establish the essentiality orders of the outputs for the initial I/O combination, is depicted in Figure 6b. Table 1 summarises the outputs for each invertible square I/O system, along with the evaluated essentiality orders.

These results can be interpreted as follows:

- **I I/O combination:** the two constraint functions f and g that define the output trajectory $C_{sw} = f(C_{axle})$ and $F_{ehps} = g(C_{axle}, C_{eps})$ must be at least three times and one time differentiable, respectively;
- **II I/O combination:** the two constraint functions

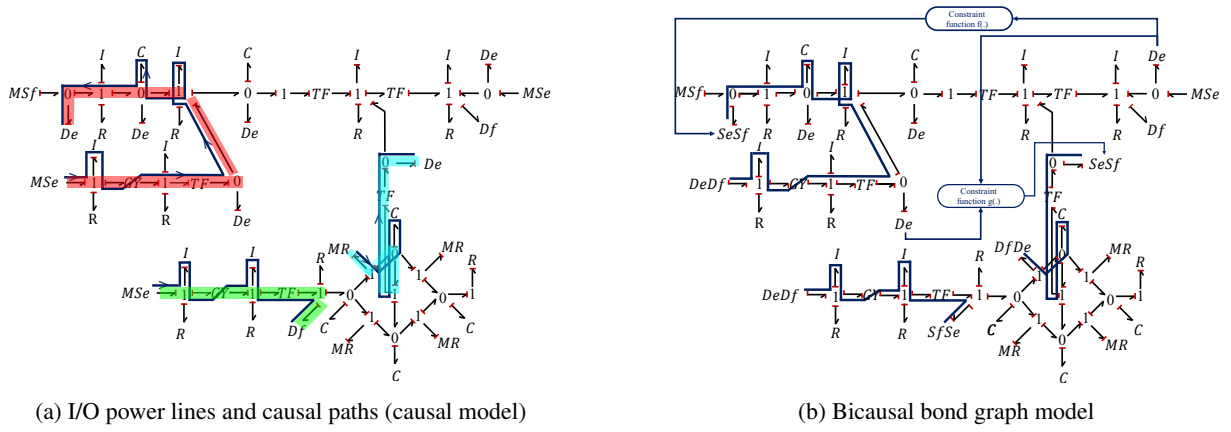


Figure 6: Causal and bicausal bond graph model for the first I/O combination

I/O combination	Output	Essentiality order
I	C_{sw}	3
	F_{ehps}	1
	Q_p	2
II	C_{eps}	1
	C_{sw}	5
	Q_p	2
III	C_{eps}	1
	F_{ehps}	1
	Q_p	2

Table 1: Essentiality order

g and f that define the output trajectory $C_{eps} = g(C_{axle}, F_{ehps})$ and $C_{sw} = f(C_{axle})$ must be at least one time and five times differentiable, respectively;

- **III I/O combination:** the two constraint functions f and g that define the output trajectory $F_{ehps} = g(C_{axle})$ and $C_{eps} = g(C_{axle})$ must be at least one time differentiable.

As already mentioned, Q_p is necessarily considered within the set of outputs. Note that in all combinations, there are exactly two derivatives with respect to time in the input expression for the output Q_p . It should be noted that the lower the essentiality order, the fewer the constraints there are on the output curve shape. In our case, the third I/O combination has fewer constraints when it comes to write specifications. On the other hand, the second I/O combination must have a mathematical form of the output C_{sw} that is at least five times differentiable.

PERSPECTIVES AND CONCLUSION

This article focuses on the structural aspects of sizing an hybrid EHPS system. In order to analyse the system structure, its bond graph model was exploited. A design and sizing methodology using the inverse approach was applied, with a focus on the two first steps. First, the structural invertibility of the model is

studied and the admissible inputs/outputs are derived. Then, the differentiability of the specified output functions is deduced from the essentiality orders. The first step allows the engineer to determine if the sizing problem is well-posed without inspecting the model equations or running any simulations. This represents a significant time-saving as it allows an early detection of ill-posed sizing problems in the design process. The concept of essential order assist the engineer in writing specifications.

The perspectives for this work would concern the final step of the sizing methodology, more specifically the selection and validation phase. With the specifications given and the inverse model, a simulation is needed to bring the requirements as close as possible to the technical components to be determined. The methodology based on model inversion is not limited solely to the context of architecture synthesis and sizing. In fact, it can be applied for several engineering problems such as parametric synthesis, steady state research or determination of the open loop control. Another perspective regards the sizing of non-square systems with more outputs than inputs. In this case, one or several specified outputs are not imposed in the inverse model (the case of the EHPS system). At the simulation step, if one of the non-imposed specified outputs is not respected, the I/O combination has to be reviewed. In this case, it may be necessary to consider an invertible I/O combination with this output.

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