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FUNCTIONAL MODELING OF CONTROL SYSTEMS

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Abstract

Functional modeling represents a core area of research in the field of engineering design. Many researchers have proposed different design theories and methodologies each of which has been applied to a specific area in design. Most of these, however, pertain to open loop systems with very few control functions. A large proportion of the world we live in consists of feedback control systems that process a tremendous amount of information to achieve their desired function of monitoring and controlling an output variable. This research effort concentrates on the application of an existing functional modeling technique known as the functional basis to closed loop control systems. A systematic and formal methodology is developed to model closed loop systems. Generalized functional representations and examples are provided to aid easy understanding and repeatability of the methodology. The study reveals the existing functional modeling technique to be very robust and demonstrates its potential into being developed as a unified theory that subsumes other bodies of work in this area.

Keywords: Systematic Product Development, Empirical Study, Functional Basis, Design Methodology, Control System Modeling

1 Introduction

1.1 Scope

To enable functional decomposition, a standardized classification language to capture the entire range of product functions as well as a methodology to systematically model the devices is necessary. Several research communities have already developed various languages and methodologies to classify and represent functions occurring in various engineered products. Most of these products, however, are small to medium scale, open loop systems with significant power transmission and energy conversion [1]. In order to ensure the capability of the functional modeling scheme in representing the functionality of the whole gamut of products present, it is necessary to deal with systems that possess a considerable amount of signal processing as well. Thus new engineering domains need to be explored.

Control engineering, being a multi disciplinary field, provides a good starting point for this study involving the modeling of new products existing in various engineering domains such as electronics, electro-mechanical, pneumatic and hydraulic. Another important reason for conducting a study of systems in control engineering is that a large proportion of them being closed loop are inherently different from open loop systems that have been primarily used so far in functional modeling empirical studies. The inherent difference arises from the fact that closed loop systems possess self-correcting capabilities that are made possible by a significant amount of signal processing (information sharing) between the various sub-systems. This study aims at developing a functional modeling technique for control systems. The entire study is divided into two phases: building a classification scheme for modeling control systems and developing a methodology for modeling them in a formal and systematic manner. This paper presents the results of the second phase of the study.

The application and validation of the functional modeling technique to a new area (closed loop systems) serves three main purposes: (1) lends the advantages of function based methodologies to design control systems (2) improves the robustness of the functional modeling technique and (3) represents an important step towards realizing the final goal of developing a unified functional modeling technique based on the functional basis classification scheme.

1.2 Background

Many of the current function modeling methodologies follow a similar procedure [1, 2, 3, 4, 5, 6, 7]. They begin with the overall product function and decompose it into smaller easily solvable functions. For example, Pahl and Beitz [3] define a function to be an abstract formulation of the task, independent of any particular solution, that transforms input flows of energy, material and energy to output flows of the same type. One highlight of the Hundal and Byrne [7] work is that it appears to be the first instance where a basic closed loop system is represented functionally. Other researchers have tackled the common problem of an unambiguous representation of product function for a wide array of more specific design tasks [8, 9, 10, 11, 12, 13, 14, 15, 16]. In particular, and distinct from Pahl and Beitz inspired methodologies, Altshuller [9] formulated a design method called Theory of Inventive Problem Solving (TIPS) by analyzing over 2 million patents from around the world and identifies 30 functional descriptions for products.

Szykman et al. [17] propose a standardized representation of function for use by software vendors. Their intention is to develop a representation scheme that will facilitate easy exchange of design information and they link product function to form, limiting its use in conceptual design. Stone and Wood [2] propose a functional model derivation methodology to systematically model artifacts based on a function and flow classification scheme referred to as the *functional basis* and give clear definitions of the function and flow terms at various levels of abstraction. Initial validation trials indicate that the use of the functional basis does improve functional model repeatability [18]. The Szykman et al. and Stone and Wood works have been integrated in a more comprehensive function and flow vocabulary known as the *reconciled functional basis* [19].

During the first phase of this research project, an empirical study was performed using the *reconciled functional basis* to verify if the taxonomy could be applied to model control system components [20]. The study showed the existing basis functions to be robust for only 2 new functions at the tertiary level were added to the *reconciled functional basis*. This set of basis terms is used as the starting point for this work. The “Class” and “Secondary” level functions and flows are shown in Table 1 and Table 2.

2 Generalized Functional Representation of a Closed Loop System

Figure 1 shows a generalized functional representation of a feedback control system incorporating a single feedback loop. This along with the functional basis serves as the skeleton for the methodology to develop a form independent functional representation of the control system. Though the generalized representation of only a feed back loop is shown here, it should not be assumed that the methodology has been developed specifically for this type of closed loop system. Multiple input/multiple output (MIMO) control systems may be represented by placing multiple such representations in parallel. The dotted boundary line (A-A) in the generic representation (Fig. 1) represents the system boundary of the entire closed loop system. Material, energy and signal flows enter and leave the system boundary. The boxes within the system boundary represent the boundaries of the sub-systems that are present in a typical feedback loop.

Table 1: Primary and Secondary Level functions of the Basis (Adapted from [20])

Class (Primary)	**Secondary**	**Class (Primary)**	**Secondary**
Branch	Separate, Distribute	Convert	Convert
Channel	Import, Export, Transfer, Guide	Provision	Store, Supply
Connect	Couple, Mix	Signal	Sense, Indicate, Process
Control Magnitude	Actuate, Regulate, Change, Stop	Support	Stabilize, Secure, Position

Table 2: Primary and Secondary Level Flows of the Basis (Adapted from [19])

Class (Primary)	**Secondary**
Material	Human, Gas, Liquid, Solid, Mixture
Signal	Status, Control
Energy	Human, Acoustic, Biological, Chemical, Electrical Electromagnetic, Hydraulic, Magnetic, Mechanical Pneumatic, Radioactive, Thermal

In general, we observe that the flow(s) that enters the control surface as the input/set point is operated on by sub-functions within each of the sub-systems shown above and ultimately leaves the control surface as the controlled variable. This flow or set of flows shall be referred to as the *control flow*. Apart from the control flow, depending on the closed loop system, there may be other flows that are imported by some of the sub-systems, processed and exported.

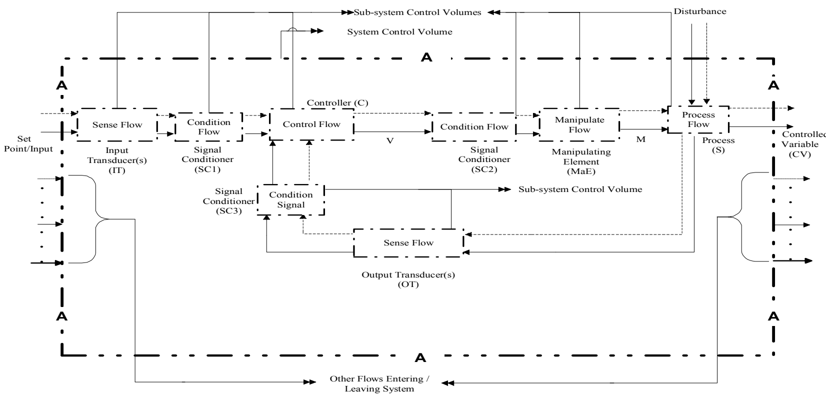

Figure 1: Generalized functional representation of a typical feedback loop in a control system

To improve clarity and provide a concise expression of the flows, a standard notation to represent each part of the control flow is presented in Table 3.

Table 3: List of various flows that form part of the Control Flow

Flow	Notation	Definition
Input/Set point	SP	Is that portion of the control flow that enters the control system and is imported by the Input Transducer (IT).
Input Transducer Output	ITO	Is that portion of the control flow that is exported by IT and imported by Signal Conditioner 1 (SC 1).
Controller Input	CI-1, CI-3	Consists of two flows. CI-1 is that portion of the control flow that is exported by SC 1 and imported by the Controller. The other is CI-3, the flow that enters the controller from SC 3.
Controller Output	V	Is that portion of the control flow that is exported by the controller and imported by Signal Conditioner 2 (SC 2).
Manipulating Element Input	MEI	Is that portion of the control flow that is exported by SC 2 and imported by the Manipulating Element (ME).
Manipulating Variable	M	Is that portion of the control flow that is exported by ME and imported by the Process (S).
Controlled Variable	CV	Is that portion of the control flow that is exported by Process (S). This is the output of the control system.
Output Transducer Input	OTI	Is the flow that is fed back and measured by the Output Transducer (OT).
Output Transducer Output	OTO	It is the flow that is exported by OT and enters SC 3.

The generalized functional representation, derived from the block diagram, presents the concept that closed loop systems comprise a group of modules that are connected in a specific manner. This in turn indicates that a functional model of an entire control system can be derived by developing sub-system functional models and then combining them to represent the whole system. This represents the central idea of the methodology to functionally model control systems. To aid in systematic and repeatable generation of sub-system functional models, the robust function and flow classification scheme shown in Table 1 and Table 2 along with a generic functional modeling methodology [18] are used.

3 Methodology

The process of creating the functional model of a closed loop system consists of four separate steps. These are shown schematically in Fig. 2. Each step is discussed in detail in the following sections.

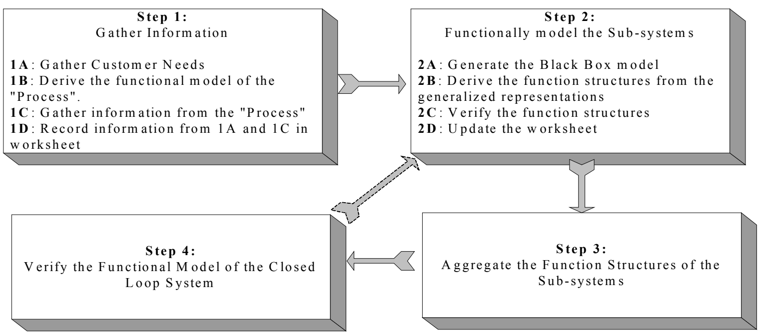

Figure 2: Steps to Functionally Model Closed Loop Systems

3.1 Step 1: Gather Information:

The first step deals with gathering information about the control system. This helps in establishing the system goals and specifications as well as thoroughly understanding the "Process" or "System" that is to be controlled. This step consists of the following sub-tasks:

- Sub-task 1A: Gather customer needs and requirements:

The first sub-task of the functional model derivation method is to gather customer needs for the control system (either existing or proposed) using established techniques [5, 21]. Apart from customer needs, information about the system may be obtained through general idea generation techniques and developing block diagrams. Table 4 lists the requirements for a feedback temperature control system that is described in Bateson [22]. Its block diagram is shown in Figure 3.

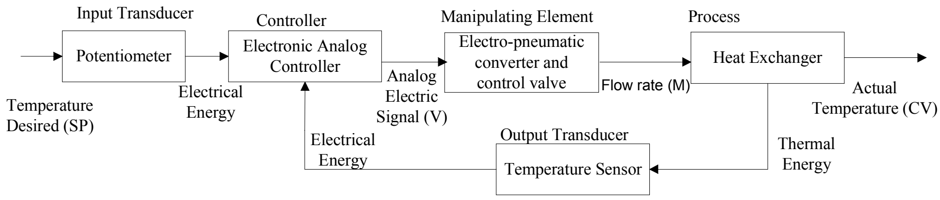

Figure 3: Block diagram of Temperature Control System

- Sub-task 1B: Derive the functional model of the "Process" block:

After gathering customer needs, the "Process" to be controlled is functionally modeled using the functional modeling derivation methodology [18]. The function structure of the "Process" module of the temperature control system is shown in Figure 4.

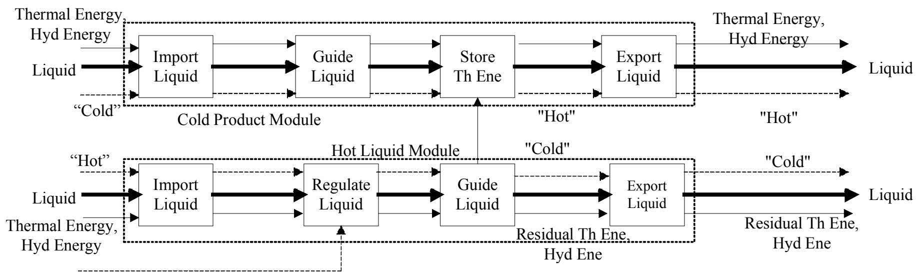

Figure 4: Function Structure of a Heat Exchanger

- Sub-task 1C: Gather information from the "Process" block:

The controlled variable is typically a parameter or property of a flow exiting the "Process" block. Flows interacting with the controlled variable usually represent possible choices of flows that can be regulated in the manipulating element. Thus, by inspection of the function structure, choices of manipulating variables can be identified. Modeling the disturbances that enter the system provides the designer with an idea on what type of closed loop control to employ. For example, in the temperature control system being discussed, the controlled variable is the temperature of the liquid and this is represented in Figure 4 as the thermal energy of the "Hot" Liquid leaving the system. Also, developing the function structure improves the understanding of the "Process" which is important to make proper choices of the sub-systems necessary for the control system.

- Sub-task 1D: Record the information:

All the information gathered from sub-tasks 1A and 1C is recorded. A worksheet similar to that shown in Table 4 can be used to record requirements of the control system, sub-systems needed and choice of control flows (Note that only the entries in the white cells are made at this point). It may be considered as a tabular form of the generalized function structure shown in Fig. 1.

All the customer needs gathered from various sources are listed in the left hand column of Table 4. These are then mapped to the various sub-systems listed in the next column. Information gathered from Sub-task 1C on possible choices of flows are listed in suitable boxes in the "Control Flow" column. It is preferable to use one worksheet for each controlled variable. The "Other Flows" column has been included to list the flows other than the Control Flow entering and leaving each sub-system. This serves as a quick reference for the designer while aggregating the function structures of the sub-systems.

3.2 Step 2: Derive the functional model of the sub-systems:

Once the requirements are gathered and choices of manipulating variables and variables to be measured are determined, the functional models of the other sub-systems listed in the worksheet are derived. The generalized function structures (Figures 8 – 12 in Section 5) may be used as templates to create the function structures directly from the black box model. This can be achieved by the following 3 step process illustrated by means of an example.

Table 4: Worksheet at the end of Step 1 for the Temperature Control System

Requirements	**Sub-systems**	**Control Flow(s)**		**Other Flows**		**Comments**
		Input	Output	Input	Output	
1. Accurate temperature control 2. Provide manual as well as automatic control 3. Should be easy to maintain 4. Should respond quickly to change in load 5. Should be easy operate. 6. Should be cheap and use easily available components 7. Should give feedback to the user on the current and actual temperature. 8. Should allow for various control modes	System	Liquid, Th. Ene, **Hyd. Ene.**	**Th. Energy**	"Hot", "Cold" "Flow rate"	Liquid, Hyd. Ene. "Hot", "Cold" "Flow rate"	
	Manipulating Element (ME-FB) 1, 2, 3, 4, 6	**Pn. Ene**	Liquid, **Hyd. Ene** Th. Energy	Air, Hand, Liquid, Th ene Hyd ene, HE "Flow rate"	Air, Hand, Pn. Ene, "Flow rate"	
	Output Transducer (OT-FB) 1, 3, 4, 6, 7	**Th. Energy**	**EE**	Liquid, "Ref. Voltage" "Temp."	Liquid, "Ref. Voltage" "Temp."	
	Input Transducer (IT-FB) 1,3,5,6,7	**Human Ene**	**EE**	Human, EE "Temp."	Human, HE "Voltage"	
	Controller (C-FB) 1, 2, 3, 4, 6, 7, 8	**EE**	**EE**	Human, HE, "Set point", "Actual temp"	Human, HE, "Controller Output", "deviation"	
	Signal Conditioner 1 (SC 1)	**EE**	**EE**			
	Signal Conditioner 2 (SC 2)	**EE**	**Pn. Ene**	Air, "Signal"	Air, "signal"	
	Signal Conditioner 3 (SC 3)	**EE**	**EE**			

- Sub-task 2A: Generate the black box model of the sub-system:

Once the requirements are ascertained, a black box model is created. The overall function is expressed in verb-object form, and then the flows associated with each requirement are identified and listed as input or output flows. The black box model of an input transducer module (a potentiometer) that allows the user (Human, Human energy (HE)) to set the temperature desired is shown in Fig. 5. Note that electrical energy (EE) is chosen as the external energy (which is a process choice).

- Sub-task 2B: Derive the function structure:

Next, the function structure is derived directly from the generalized function structures by plugging in the specific flows from the black box model and checking if the sequence of sub-functions in every sub-function chain transforms the input flow to the required output flow. This is best accomplished by 'becoming the flow' and imagining how you would be transformed as you travel through the device. Any modifications that need to be made to the sub-functions in the generalized function structure are implemented

Continuing with the input transducer example, from Fig. 5, we see that the transducer requires external energy and so the generalized representation of the active transducer (Figure 10) may be chosen as the template. The material entering the transducer in this case is the "Human" and the energy associated with it is "Human energy." The auxiliary or external energy is "Electrical Energy" and the signal carries information on the temperature desired. Thus these flows may be plugged into the template to generate the function structure of the input transducer.

Next, each flow is traced from its entry to exit to check if the sub-function chains are correct. First, the flow of the "Human" and "Human energy" are verified. The potentiometer imports the human hand and guides it to move in a particular manner. The human energy associated with the motion of the hand is converted to mechanical energy (by the knob). Then the hand leaves the system. Thus the third function in the sub-function chain of Fig. 10 ("Transfer Flow") is changed to "Guide Hand" and "Convert HE" is refined to "Convert HE to ME". Similarly, the flow of electrical energy ("EE") and "temperature" are verified. The modified function structure of the potentiometer is shown in Fig. 6.

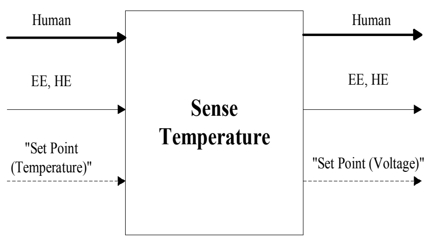

Figure 5: Black box model of a Potentiometer

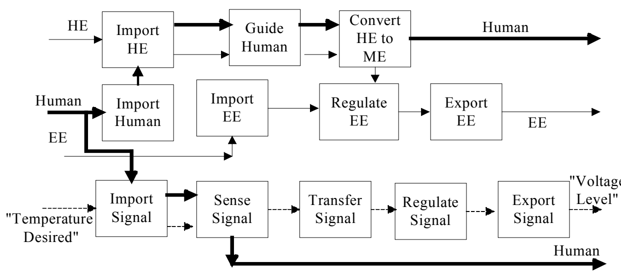

Figure 6: Function structure of a Potentiometer

- Sub-task 2C: Verify the function structure:

Finally, it is ensured that all the input flows identified in the black box model are mapped in the function structure. If there are any additional flows, then they are mapped and added to the generalized function structure.

Upon completing the derivation of the function structures of all the sub-systems, the worksheet is updated with the choices of flows for each sub-system. For example, with the temperature control system example, function structures of all the modules shown in the block diagram (Figure 3) are developed and the worksheet is updated (The green-shaded portions of Table 4).

3.3 Step 3: Aggregate the function structures

Now at the end of Step 2, the function structures of all the sub-systems comprising the control system are available. These need to be integrated to create the function structure of the whole closed loop system (similar to Fig. 1). This process is similar to the aggregation of function chains to create a functional model: the function chains being analogous to the function structures of the sub-system and the functional model referring to the function structure of the entire closed loop system. As with function chain aggregation, the aggregation of function structures involves addition of some sub-functions and removal/modification of some others. While combining the function structures of the modules, their control surfaces are collapsed. A typical integration process is depicted in Fig. 7.

3.4 Step 4: Verify the Functional Model with the customer needs or requirements

As a final check of the functional model, the next step involves ensuring that each customer need/requirement (which is not a constraint) is addressed by at least one sub-function. If any customer need is not represented, the tasks are iterated again starting Step 2. The verification process for the temperature control system is shown in Table 6.

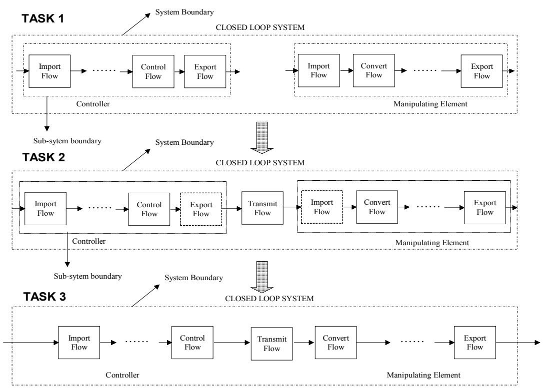

Figure 7: Illustration of the Aggregation process

Table 6: Customer Need Verification

Customer Needs/ Requirements	Related Flow(s)	Related Sub-functions
Provide accurate Temperature control	Th. Ene., Pn. Ene., HE, EE, “Temperature”, Human	Convert Th. Ene to EE, Sense signal, Change Signal, Integrate Signal, Differentiate Signal, Convert EE to Pn Ene, Convert Pn Ene to ME, Import HE, Convert HE to EE
Provide feedback on the current and actual temperature of the liquid	“Temperature”	Sense Signal, Display Signal
Provide manual as well as automatic control	Human, HE	Import Human, Import HE, Convert HE to ME, Actuate Signal
Should be able to respond quickly to changes in temperature setting	HE, Human, Pn Ene	Import Human, Import HE, Convert HE to EE, Import Signal, Add signal, Change Signal, Convert EE to Pn Ene, Regulate Flow
Should be easy to operate	Hand, HE	Import HE, Import Hand, Convert HE to EE,

		Convert HE to ME
Should provide a choice of control modes	Hand, HE	Import Human, Import HE, Convert HE to ME, Actuate Signal
Should be cheap and use easily available components	CONSTRAINT	
Should be easy to maintain	CONSTRAINT	

4 Conclusion

The methodology provides an innovative and new technique to systematically model closed loop systems by exploiting the modularity that exists in them. This approach makes it dynamic and flexible, i.e., the ordering of the sub-tasks can be changed to suit specific requirements.

Along with the methodology, guidelines for determining the input and output flows to sub-systems as well as generalized functional representations presented enhance the ease of deriving function structures. Since the functional basis and the functional modeling derivation methodology are used as the framework for developing the methodology, it is lends itself to developing repeatable functional models. Also, it represents a formal method as it is based on conventional principles of control theory. That is, it begins with the design of the process and then moves on to other sub-systems before finally integrating the modules.

The methodology breaks the overall problem into a number of small easily solvable steps that enable the designer to effectively solve the problem. It also preserves all the advantages of function based design methodologies. These include enabling better understanding of the problem, fostering generation of a number of solutions and providing a common language for product representation and information exchange.

Since the methodology was developed by applying the concepts of block diagram representation and control system theory to functional modeling, designers following conventional control system design techniques as well as those adopting a function based design approach can easily understand the underlying principles of this methodology. This makes the methodology user friendly and background independent.

The methodology lays the foundation for extending the benefits of functional modeling to control systems. In future, the function based design methodology could be introduced for designing and developing closed loop systems. This would augment the conventional design practices currently in place for designing control systems.

By using an existing technique as a foundation to develop a new systematic and formal methodology to model closed loop systems we have also demonstrated the functional modeling technique's flexibility. Thus this work represents an important step towards the final goal of developing a systematic, formal and unified functional modeling theory that can be used for several different applications.

5 Appendix

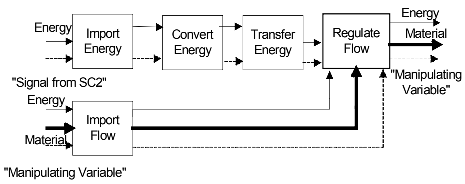

Figure 8: Generalized Function Structure of a Manipulating Element

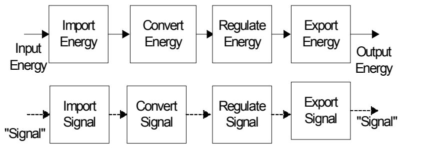

Figure 9: Generalized Function Structure of a Signal Conditioning Unit

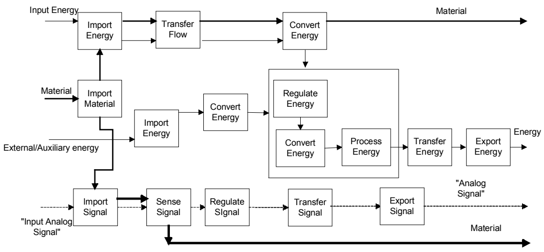

Figure 10: Generalized Function Structure of an Analog Active Transducer

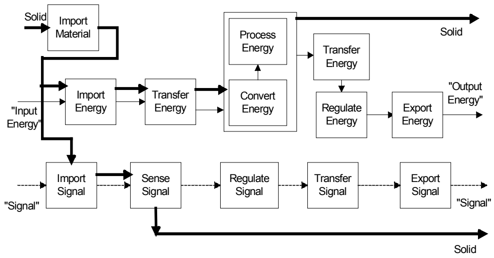

Figure 11: Generalized Function Structure of an Analog Passive Transducer

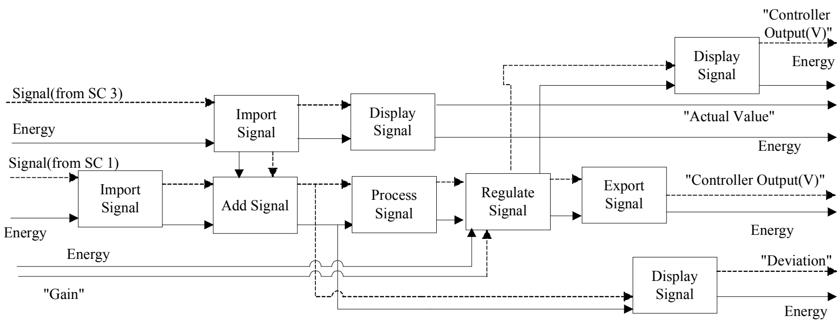

Figure 12: Generalized Function Structure of a Control System

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