An overview of Multilevel Flow Modeling

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Abstract: The paper presents an overview of the current status of Multilevel Flow Modeling (MFM). MFM is a methodology for functional modeling which is highly relevant for design of operator support systems and control systems. The paper presents the concepts of MFM and illustrates central aspects of MFM by an example. A brief discussion of main topics in ongoing developments of MFM is included.

Keyword: complexity; modeling; control; supervision; knowledge representation and reasoning

1 Introduction

The basic idea of Multilevel Flow Modeling (MFM) is to represent an industrial process or a technical infrastructure as an artifact *i.e*. as a system designed and operated according to given purposes. The MFM modeling paradigm has its foundations in the concepts of purpose, goal and function which are used extensively in both engineering design and operation of complex dynamic systems but without the scientific foundation provided by MFM. In the last decades concepts of goals and function have played a central role in the development of new advanced human machine interfaces for operation of industrial systems adapting the ideas of means-ends analysis of work domains[1]. Functional concepts have accordingly been proposed by industry to form the basis of an integrated approach to control room design in nuclear power plant[2]. The adoption of functional approaches to system design in industry is a very strong indicator of the engineering relevance of concepts of function and the means ends distinction.

The concepts of function play a key role in understanding the nature of the means-end relation and in the formation of a coherent modeling paradigm integrating means-end concepts with concepts of function. Due to the particular role of the concept of function for MFM it is a methodology for functional modeling (FM) of complex systems.

2 Uses of Functional Modeling

From an overall perspective, there are two main motivations for using FM:

- Concepts of functional modeling provide a systematic framework for formalizing inter subjective common sense knowledge which is shared among participants in design and operation of complex systems *i.e.* engineers and operators.

- Functional modeling is a systematic approach to applying different perspectives and degree of abstraction in the description of a system and to represent shifts in contexts of purpose. This aspect of FM is crucial for its use in handling complexity in systems design and operation.

These two basic features of FM make it a powerful tool for modeling complex automated systems. Further motivations for using FM in operator support systems and process and control system design are given below.

2.1 Operator support systems

Operators need information about plant states and means of action that fit with their current tasks in order to reduce the risks of decision error. FM can here be used as a systematic tool in HMI development to define the information content of displays and to design of decision support functions that can help an operator in problem reframing *i.e.* considering alternative representations of a situation. Problem reframing may be necessary in safety critical situations where a wrong decision can lead to damage of equipment, loss of production or undesirable consequences in the environment.

2.2 Process and control systems design

FM support integrated process and control system design by providing abstractions by which high level decision opportunities and constraints in process and control system design can be made explicit. FM can in this way also provide documentation of design rationale.
FM can be used to reason about control strategies, diagnosis and planning problems. FM can also be

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used to identify assumptions implicit in control systems designs based on differential equations.

Model based control based on FM can integrate diagnostic reasoning and reactive planning of counteractions and thereby respond intelligently to major plant upsets. Such FM based intelligent controls can also explain its purpose and functions and thereby make its behavior more transparent to an operator.

3 Multilevel Flow Modeling

In the following we will provide an overview of the current status of MFM. The concepts of MFM address modeling needs in a particular but large domain of industrial processes and technical infrastructures dealing with processing and distribution of energy and materials. MFM is accordingly able to represent a significant class of complex systems. It is not able to model everything because functions represent system purposes and are therefore specific to the needs served by the technology. Actually its specialization is one of its strengths. Representation of means-end relations and functions in complex systems require deep insight in the purposes and workings of the system and require a specialized language like MFM.

The overview of MFM presented below is necessarily incomplete and the reader is advised to consult recent MFM publications for more information.

MFM has been developed over more than two decades and a comprehensive literature is available presenting the concepts and application of MFM. The development of the conceptual foundations, the MFM modeling language, the tools and applications have been ongoing for more than two decades and are still in progress. The basic ideas of MFM were conceived by the author and developed over the years by his and other research groups in Japan, China and Sweden. The research originated in problems of representing complex systems in Human Machine Interfaces for supervisory control, but has developed into a broader research field dealing with modeling for design and operation of safety critical automated complex plants.

The basic MFM concepts are introduced in[3,4] and recent extensions with the role concept can be found in[5]. Comprehensive modeling examples are available from the nuclear domain[6,7] and from the oil gas domain[8]. The use of MFM for reasoning about failure causes and consequences is presented by Larsson[9], Petersen[10], Lind[11] and Zhang[12,13]. Heussen[14] presents the use of MFM for causal reasoning about control. Model examples from chemical industry and application of MFM for counteraction planning are presented by Gofuku [15,16]. Yang[17], Rossing[18] and Wu[8] present applications of MFM for reliability analysis and risk assessment. Lind[19] presents applications of MFM for modeling safety functions. MFM modeling methodology and tools are presented by Lind[6] and Heussen [20] .

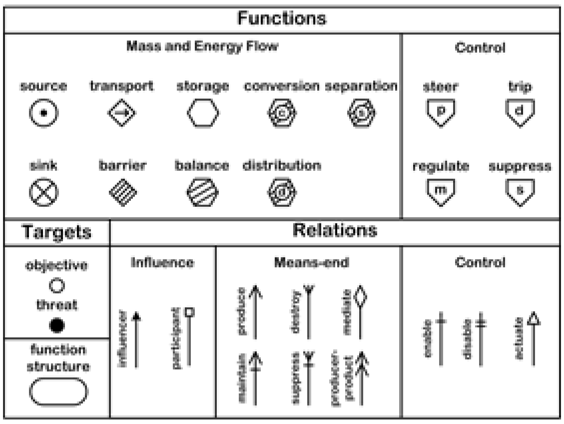

Fig.1. MFM concepts.

3.1 MFM Concepts

MFM represent goals and functions of process plants involving interactions between flows of material, energy and information. Functions are represented by elementary flow and control functions interconnected to form functional structures representing a particular goal oriented view of the system (Figure 1). An action theoretical foundation which is under development see MFM functions as instances of more generic action types (see *e.g.* Lind[4] where these types are used to define basic control functions). The views represented by the functional structures are related by means-end relations and comprise together a comprehensive model of the functional organization of the system.

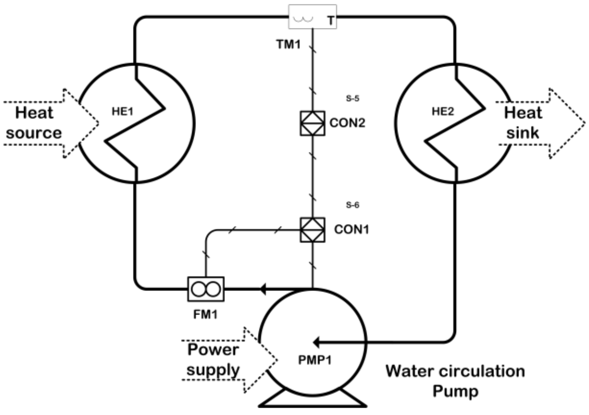

Fig. 2. The heat transfer loop.

3.2 A modeling example

The MFM concepts will be illustrated below by the heat transfer loop example shown in Figure 2. The example is taken from Lind[6] where the MFM model is used as a template for the development of an MFM for the MONJU nuclear power plant.

The heat transfer loop comprises two heat exchangers HE1 and HE2 connected by a circulation loop including a pump PMP1. The type of fluid used for heat transfer has no significance for the MFM model we are presenting but we will assume for convenience that it is water. We will also ignore physical details which are not relevant for the present purpose. This includes physical details of the power supply for the pump motor and of the systems serving as energy sources and sinks.

The water flow rate in the circulation loop is maintained by the controller CON1 on the basis of readings obtained from a flow measuring device (FM1). The purpose of the temperature controller CON2 is to regulate the temperature in heat exchanger HE1. This is done by compensating deviations in the temperature measured by the instrument TM1 by increasing or decreasing the set point for the flow of circulated water when the temperature increases or decreases.

We will present a model of the heat transfer loop without control systems and a model including the control systems. Later we will illustrate how to represent the safety functions of a shut-down system (not included in Figure 2).

3.2.1 MFM of the heat transfer loop without control

Figure 3 shows the MFM of the heat transfer loop without control system. It contains three functional levels comprising an energy flow structure efs1, a mass flow structure mfs1 and an energy flow structure efs2. These levels are nested into means-end structures.

Flow structure efs1 represents the functions involved in pumping of the water in the circulation loop when seen as an energy conversion process. The source sou1 represents the power supply, sto1 the accumulation of rotational and translational energy in the circuit and tra2 and tra3 represents conversion of the energy into kinetic energy of the water (tra2 and sin1) and friction losses in the circulation loop (tra3 and sin2).

Flow structure mfs1 represents the functions of the water circulation loop. The function tra4 represents the transportation of water resulting from the energy conversion in the pump represented by efs1. It is connected with efs1 by a producer-product relation pp1 which is a means-end relation. The relation pp1 is labeled with the name of the function in efs1 which is directly associated with tra4 namely tra2 (the so-called main function of the producer-product relation pp1). The recirculation of water in the heat transfer loop is represented by the combination of tra4 and tra5 and the balance functions bal1 and bal2. The balances are also connected with two barriers bar1 and bar2. They represent the prevention of material flows to enter (sou2 and bar1) or leave (bar2 and sin3) the circulation loop provided by the piping walls in the heat exchangers HE1 and HE2.

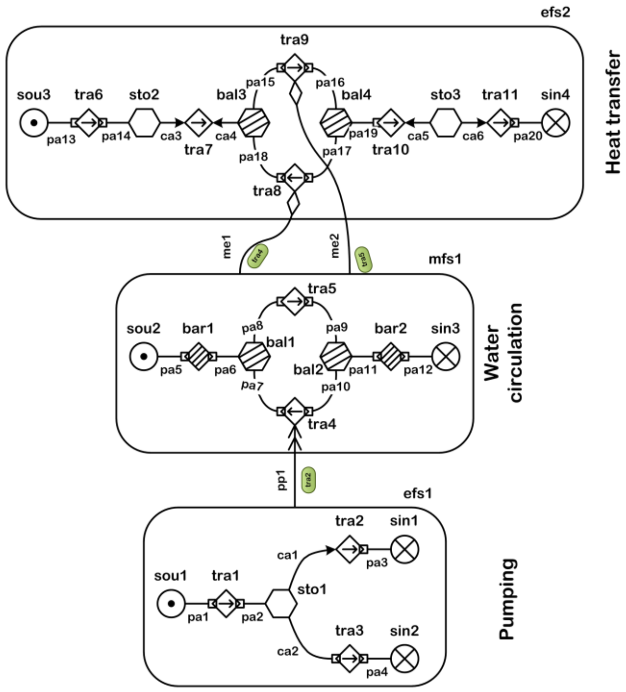

Fig.3. MFM of heat transfer loop without control.

Flow structure efs2 represents the heat transfer functions. The water circulation loop is here seen in the context of the systems serving as a heat source and a sink. The function of the loop is in this context to transport energy from the outlet of HE1 to the inlet of HE2 (tra9) and to transport from outlet of HE2 to the inlet of HE1 (tra8). Since the transportation of energy represented by tra8 and tra9 both are mediated by the circulating water, they are connected with mfs1 by two mediation relations me1 and me2. The mediation relations are both labeled by tra4 which is the main function in mfs1. The heat transfer from the source (sou3) to the primary side of HE1 is represented by tra6 and sto2. The transfer from the heat storage in the HE1 primary to the circulation loop is represented by tra7 and bal3 which is connected with the incoming and outgoing energy flows (tra8 and tra9). The heat transfer and storage in HE2 are represented in a similar way by functions bal4, tra10 and sto3. The heat transfer from the secondary side of HE2 to the sink is represented by tra11 and sin4.

3.2.2. MFM of the heat transfer loop with controls

The MFM model shown in Figure 4 includes the functions of the water flow controller and the temperature controller. The controller is here assumed to use the power supplied to the pump (tra1) to control the pump speed (sto1) so that the water flow rate (tra4) can be maintained at its desired value (obj1). The actuation relation act1 connects the control function con1 with the transport function tra1 as indicated by its label. Note that the MFM shown in Figure 4. is an example where a control function includes several functional levels (efs1 and mfs1). This means that the means-end relations can be included in the control function (pp1 and ma4 in Figure 4).

The functions of the temperature controller are represented by the function structure csf2 in Figure 4. The temperature is related to energy storage in HE1 (sto2) and is regulated by controlling the energy transferred to HE2. This energy transfer is represented by the transport functions tra8 and tra9 in the MFM model.

Note the control cascade pattern in Figure 4. Function con2 representing the function of the temperature regulator is connected by an actuation relation to cfs1 which represents the functions of the flow regulator. It is realized that in this case the control cascade includes three functional levels through the means-end relations pp1, ma1, ma2 and ma3.

3.3 Modeling safety functions

Objectives in MFM are states which should be achieved by the functions and are therefore promoted by the decisions of the process designer or the actions of a control agent. However designing or acting for reasons of safety deals with avoiding harmful situations. Such situations are obviously not promoted but opposed by proper design decisions or control actions. MFM therefore also consider functions which oppose states which imply a risk or are undesirable by being in conflict with the values of the designer or the control agent.

These situations or states are called threats and are represented by a black circle in MFM (Figure 1). Like an objective, a threat is referring to a situation or state.

But unlike an objective which refers to a desirable situation, a threat refers to something which is undesirable or a hazard. The distinction between objectives and threats express value related preferences of the process designer or the control agent. Objectives and threats share a common property of being situations which are the target of the designer's decisions and the agent action. Threats can be combined in MFM with destroy and suppress relations and the means or countermeasures used to oppose them. The use of threats to represent safety critical states ensures consistency of intentional structures in MFM. Intentions are considered consistent if they are rational in the sense that there is no conflict between the end and the means taken to achieve the ends. It would accordingly be inconsistent to connect a produce relation with a threat (unless the model represents the view of a saboteur)[19].

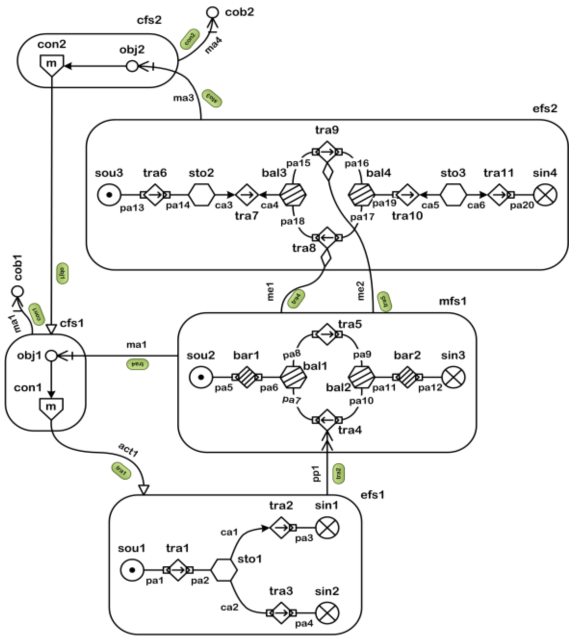

Fig.4 MFM of heat transfer loop with controls.

The use of MFM for modeling safety functions can be illustrated by the heat transfer loop example. We will assume that there is a risk of overheating of the fluid temperature on the secondary side of HE2. The temperature regulator shown in Figure 2 is therefore substituted by a protection system monitoring the temperature and responding with protective actions if the temperature gets too high. We will assume that the control system will change the set-point of the flow controller.

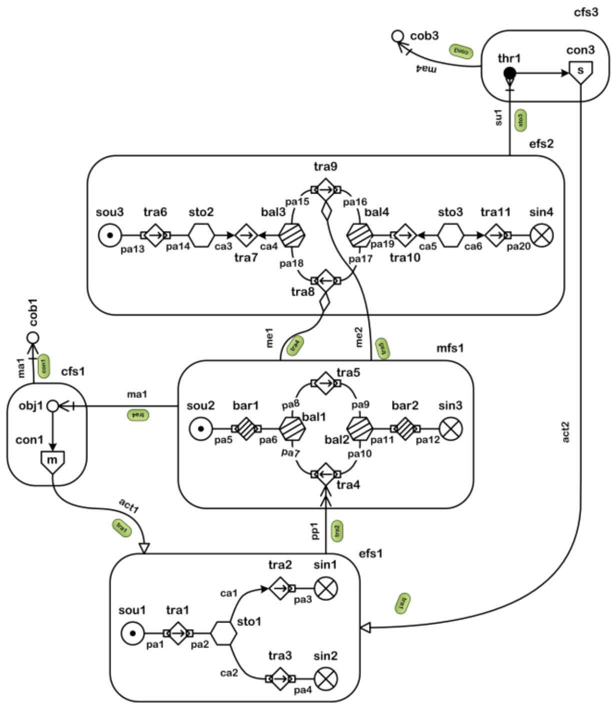

Fig.5 MFM model of heat transfer loop with a protection system suppressing high temperature in HE2.

Figure 5 shows the MFM model with the modifications required to represent the protection system. The modification comprise the control structure cfs3 modeling the function of the protection system including the threat thr1 which may be expressed by a temperature limit (related to the accumulation of heat in HE2 represented by the energy storage function sto3. The protection system is actuating (act2) the transfer of energy (tra1) inside the pump.

5 Discussions

MFM has achieved a high level of formalization but there is still room for improvements and consolidation of its foundations. One issue of particular importance is the necessity of ensuring completeness and consistency of the elementary flow functions. The present set of flow functions is the result of a long development focused on modeling power plants, but experiences from applying the flow ontology on other related process domains such as chemical engineering plants has indicated the need for extending the set of flow functions. The question is how these extensions should be done in a systematic way so that consistency and completeness is ensured of the set of elementary functions. Extensions should also try to keep the number of elementary functions as small as possible. Ongoing research is developing an action theoretical foundation for functional modeling (and thereby also for MFM) which promise to provide a systematic basis for constructing ontologies of domain functions.

Topics for ongoing research also include extensions of the principles for reasoning about dynamic situations, operation modes and control systems failure.

6 Conclusions

This paper has presented an overview of the current status of the functional modeling methodology MFM. An outline is given of the reasons why functional modeling is highly relevant for design of operator support systems and control systems. The paper presents the concepts of MFM and illustrates central aspects of MFM by an example. Ongoing developments of MFM are also discussed.

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