REPRESENTATION AND USE OF TELEOLOGICAL KNOWLEDGE IN THE MULTI-MODELING APPROACH

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1. INTRODUCTION

Artifacts are intentionally designed to serve some purpose. These purposes provide important information for understanding and reasoning about their behavior. The teleological analysis of an artifact is aimed at identifying the purposes associated to it by the designer and at explicitly representing their organization. Although teleological knowledge plays a fundamental role in understanding and reasoning about physical systems, the problem of how to represent and use it for activities such as diagnosis, design, simulation, etc. has been faced so far only in a partial and inadequate way. Past work on Qualitative Physics has mostly focused on how the behavior of a system can be derived from its structure using first principles (Bobrow, 1984); therefore, it does not deal with teleology. An exception is represented by the teleological analysis proposed by De Kleer (1984) within the electrical domain. More recently, Downing (1990) has investigated the role of teleological knowledge for the evaluation and explanation of physiological systems in satisfying purposes such as oxygen transport, carbon-dioxide dissipation, and heat conservation in diverse environments. Finally, some attention has been devoted to teleology by researchers focusing on functional representations. Sembugamoorthy and Chandrasekaran (1986), for example, propose a functional representation which is based on the assumption that understanding how a device works can be achieved by showing how an intended function is accomplished through a series of behavioral states. Keuneke (1989) enhances this functional representation including the specification of a taxonomy of function types, or purposes, such as: achieving a state, maintaining a state, preventing an undesirable state, and controlling state change.

Current work on modeling teleological knowledge presents several problems. First, in the literature there is often ambiguity between the terms function and purpose, and some authors do not even distinguish between them. Secondly, the concept of purpose is difficult to formalize in objective terms: it often seems to depend on the observer viewpoint and on the context rather than on well defined features of the physical system at hand. Moreover, usually several different goals are attached to an artifact and their mutual relationships may be very intricate. Finally, it is necessary to explicitly represent the relationships existing between teleology and other types of knowledge which characterize the representation of an artifact, such as function, behavior, and structure.

The research reported in this paper is aimed at exploring the issue of representation and use of teleological knowledge within the frame of the multi-modeling approach proposed in recent years by the authors (Chittaro et al., 1989; Brajnik et al., 1989). The ideas presented in this paper have been tested in DYNAMIS, a research prototype, developed in Quintus Prolog on a SUN 3, dealing with the diagnosis of a thermostat-controlled home heating system.

The paper is organized as follows. After a brief survey of the multi-modeling approach in section 2, we illustrate our concept of function as a bridge between behavior and teleology in section 3. In section 4 we define and discuss in detail the main elements of our teleological model, namely the concepts of goal type, primitive and composite goal types, and the instances of goal types i.e. goals. The issue of goal decomposition and the relationship between goals and phenomena in the functional model are investigated in that section as well. Finally, in section 5 we focus on the contribution of teleological knowledge to diagnosis, i.e. to exclude unproper use of a system as the cause of an unexpected behavior (operator diagnosis) and to focus the diagnostic activity towards missing phenomena and abnormal variables. A summary of the results achieved and an outline of research perspectives conclude the paper.

2. THE MULTI-MODELING APPROACH: A SURVEY

Our multi-modeling approach is based on a systematic and simultaneous exploitation of several types of knowledge. Representation of a physical system is obtained by means of several different models, each one containing only a specific kind of knowledge and organized into a set of (sub)models corresponding to different levels of detail of the representation and to different phenomenological perspectives (Chittaro et al., 1989; Brajnik et al., 1989).
More precisely, in multi-modeling, knowledge relevant to the representation of physical systems is classified according to three criteria, namely: epistemological type, aggregation level, and physical view. These are briefly illustrated below.

By *epistemological type* of a model we mean the class of epistemological features the model represents about the system at hand. More precisely, in our approach we identify five epistemological types:

- *structural knowledge*, i.e. knowledge about system topology. This type of knowledge describes which components constitute the system and how they are connected to each other;
- *behavioral knowledge*, i.e. knowledge about potential behaviors of components. This type of knowledge describes how components can work and interact in terms of the physical quantities that characterize their state (variables and parameters) and the laws that rule their operation;
- *functional knowledge*, i.e. knowledge about the roles components play in the physical processes in which they take part. This type of knowledge relates the behavior of the system to its goals, and deals with functional roles and processes;
- *teleological knowledge*, i.e. knowledge about the goals of the system and the operational conditions which allow their achievement through a correct use. More specifically, this type of knowledge encodes the reasons and intentions of the system designer, that influenced his/her conceivement of system structure and components.
- *empirical knowledge*, i.e. knowledge concerning shallow associations between system properties. This type of knowledge concerns, in particular, compiled knowledge, competence, and subjective experience that usually human experts acquire through direct operation of the system.

The *aggregation level* of a model of a given epistemological type refers to the degree of granularity of the represented knowledge. For example, a structural model of a plant may be detailed to the level of major subsystems or may be further refined to that of elementary components. Of course, given a physical system and focusing on a specific epistemological type, several models featuring different levels of aggregation may generally be considered.

Finally, *physical view* represents a feature of knowledge organization which allows a dynamic control of the focus of attention, in such a way as to take into account at each step of the reasoning process only those parts of a set of models which are relevant to a physical aspect of interest, such as, for example, mechanical, electrical, geometrical, thermal, etc. Views are not new models, but ways of looking at existing ones from a given perspective using an appropriate filter. Of course, views can cross through several models of different epistemological type and aggregation level. The availability of views allows the reasoning process to consider only those parts of the models which are relevant to the task at hand, discarding other details which turn out to be useless or immaterial for the solution of the current subproblem.

Reasoning on a system represented according to the multi-modeling approach is based on two fundamental activities:
- *reasoning inside a model*, which exploits knowledge available within a single model by using specific problem-solving mechanisms;
- *reasoning through models*, which supports opportunistic navigation among models in order to allow each individual step of the overall problem-solving activity to take place in the most appropriate model; of course, this requires an explicit representation of strategies for (i) evaluating the appropriateness of a model with respect to a given task, and (ii) appropriately switching from one model to another, exporting partial results so far obtained.

In the next section we will concentrate on the main features of our functional model in order to illustrate its relationships to the teleological model.

3. FUNCTION AS A BRIDGE BETWEEN BEHAVIOR AND TELEOLOGY

In literature there is often ambiguity between the terms teleology (i.e. intended use or purpose) and function. This section makes explicit the role functional knowledge plays in multi-modeling and gives the reader the necessary background to follow our discussion about teleology.

In our approach we call *function* of a system the relationship between its behavior and the goals assigned to it by the designer. The concept of function is therefore understood as a bridge between behavioral and teleological knowledge. Accordingly, the *functional model* of a system is a conceptualization aimed at describing how the behaviors of individual components cooperate in achieving the behavior of the system as a whole and, ultimately, the designer's goals. The mapping between behavior and teleology has been explicitly represented as follows.

First of all, physical variables in the behavioral model are classified on the basis of the role they play in physical phenomena interpreted as flow-structures. From this perspective, it is possible to identify two types of *generalized variables* common to different physical domains:
- *Generalized substance*, i.e. the abstract entity which flows through a system. The concept of generalized substance can be further decomposed into two subtypes: *generalized displacement* (e.g. electrical charge, heat, volume, position, etc.) and *generalized impulse* (e.g. flux linkage, momentum, etc.).
- *Generalized current*, i.e. the amount of generalized substance which flows through a unitary surface in a time unit. Therefore, according to the type of generalized substance which is flowing, we distinguish between *generalized flow*, i.e. flow of displacement (e.g. electrical current, heat flow, velocity, etc.) and *generalized effort*, i.e. flow of impulse (e.g. voltage, temperature, pressure, force, etc.).

Generalized variables are, of course, independent of any specific physical domain. When they are instantiated in a specific physical domain we obtain the usual physical variables.
This conceptualization can then be interpreted from the perspective of the Tetrahedron of State (Paynter, 1961): an abstract framework common to different physical domains, which describes domain-independent relationships, called *generalized equations*, between generalized variables. The Tetrahedron of State is used to identify a set of *functional roles* which are considered sufficient to interpret the behavior of any component of practical interest. A component role is thus identified by the type of relationship (i.e. the generalized equation) the component behavior satisfies. These roles are: the conduit, the purely conductive conduit, the barrier, the reservoir and the generator. The correspondence thus defined between generalized equations and functional roles constitutes the first pier of the bridge between behavior and teleology which functional knowledge is expected to constitute; more precisely, it represents a first link between behavior (generalized equations) and function (functional roles).
Using functional roles, a set of *generic processes* can be defined, which represent the elementary building blocks necessary to define physical phenomena. For the large class of physical phenomena whose behavioral model can be interpreted in terms of the Tetrahedron of State, we have identified the following generic processes: transporting, reservoir charging, and

reservoir discharging. For example, the heating of the water contained in a bowl is an instance of a charging process in the thermal domain, the transmission of rotation from the barrel to the escapement of a mechanical timepiece is an instance of a transporting process (of angular velocity) in the mechanical domain, etc.

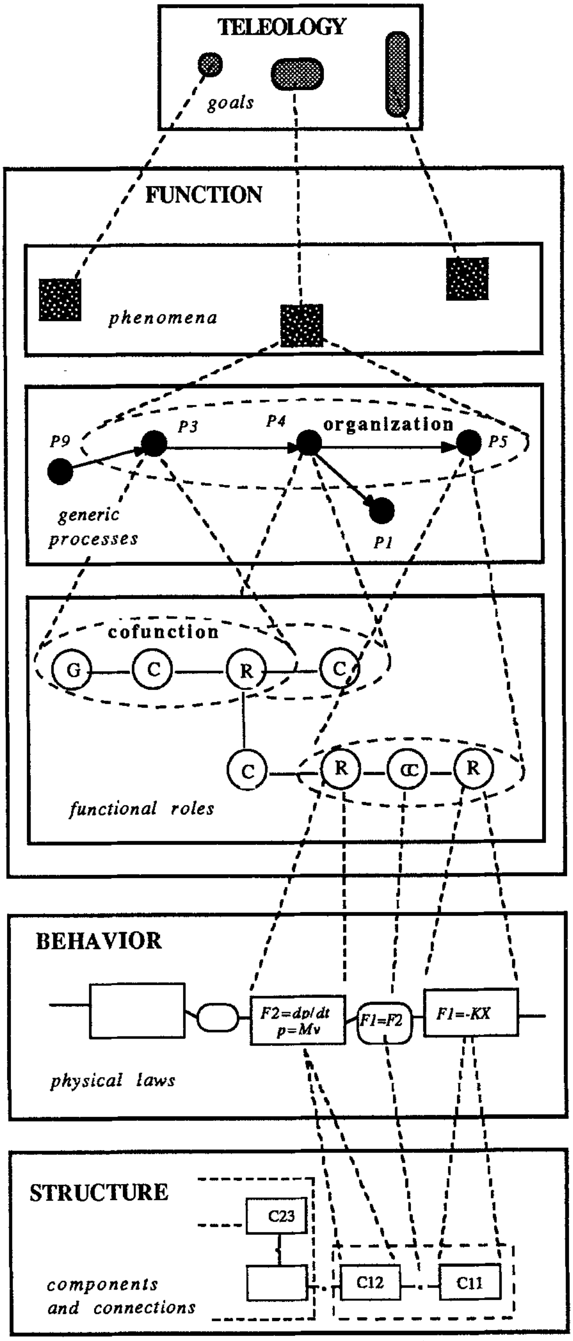

Fig. 1: A schematic diagram of our approach to modeling of physical systems with a detailed insight of the functional model.

The specification of which functional roles are needed to support a generic process and the way they must be related together is called *cofunction*. Cofunction takes part in the definition of generic processes, which also includes their *preconditions*, *effects*, and *posteffects*, expressed in terms of behavioral knowledge. So, generic processes represent a further link between behavior (preconditions, effects, and posteffects) and function (cofunction).
Finally, the concept of *phenomenon* is introduced. A phenomenon is characterized by an *organization* i.e. a network of interrelated generic processes defining i) which generic processes are needed and ii) how they must be related together in order to enable the occurrence of the phenomenon. For example, the organization of the phenomenon of oscillation is represented by four generic processes: the processes of discharging of displacement and charging with impulse and the processes of discharging of impulse and charging with displacement.

The link between the functional and the teleological model is obtained by a correspondence between goal types i.e. classes of goals (as it will be discussed in the following section) and phenomena: in this way the second pier of the bridge between behavior and teleology which functional knowledge is expected to constitute is established. Figure 1 illustrates the above concepts in a schematic diagram. For more details see (Brajnik et al., 1990).

4. THE TELEOLOGICAL MODEL

The *teleological model* of an artifact describes the goals associated to it by the designer. We assume that every artifact is committed to achieve a given set of goals: the teleological model describes these goals (i.e., the intentions of the designer in terms of effects or results obtained by operating the artifact) and their organization.
The fundamental concept of the teleological model is that of goal type. A *goal type* represents a class of goals that share a common generic purpose. Consider, for example, a ram, a pump, and a single phase alternator; all these devices may be considered as power transducers, since they convert power from one physical domain to another. However, the ram specifically converts power from the hydraulic to the mechanical domain, the alternator from the electrical to the mechanical domain, etc. "To transduce power from one domain to another" is, thus, the generic purpose, i.e. the common type, of their goals.
A goal type is characterized by a *name*, which intuitively describes the goal type (e.g., TO_TRANSDUCE), a *purpose*, and a set of *operational conditions*.

The *purpose* specifies the behavioral effects that are expected from the system when the goal has been achieved, i.e. it provides the semantics of the goal type in terms of the intended correct behavior of the system. The term "correct" means here "matching the intentions of the designer". The purpose is represented by specifying: (i) the system variables which are considered relevant to the goal type, (ii) the functional relationships that are expected among the values of these variables and parameters, (iii) a set of constraints on admissible values for the relevant variables (e.g., maximum and/or minimum value, tolerances, etc.).
For example, the purpose associated to the goal type TO_KEEP which intuitively means "to keep a variable at a given reference value" is that a generalized variable VAR achieves and maintains a value that lies within the interval: $X \pm \Delta$, where X represents a parameter (reference value) specified in the operational conditions (see below), and Δ is a tolerance described in the constraints.

The *operational conditions* specify what is necessary for the achievement of the purpose. More specifically, the operational conditions are expressed in terms of:
- *Inputs* which specify what should be provided as input to the system in order to enable it to achieve its purpose. Inputs are expressed in terms of admissible values (or ranges of values) for exogenous variables, i.e. system variables whose values are fixed by the user or by phenomena that are outside the particular system under consideration.
- *settings* which specify how to adjust system parameters in order to enable it to achieve its purpose. Settings refers, for example, to the controls (e.g. knobs, switches, buttons, levers,

etc.) the operator may use to determine the desired behavior. Settings include the specification of:
- ° *modes*, i.e. qualitative states dividing system behavior into different regions of operation. Each region is specified in terms of inequalities among some relevant system parameters;
- ° *reference values*, i.e. parameters values which can be set by the operator to calibrate system behavior;

- *Environment* which specifies the admissible values for environmental variables (e.g. force, pressure, temperature, humidity, etc.) outside which the achievement of the goal is no longer guaranteed.

Goal types may be primitive or composite. *Primitive goal types* are goal types whose purposes can be directly achieved by a single generic process. Examples of primitive goal types are:
- TO_TRANSFER: this type represents the class of goals whose purpose is to move a generalized substance from a point to another of a system. Examples of goals of this type are "TO_TRANSFER HEAT FROM THE BOILER TO THE RADIATOR" associated to a heating system, "TO_TRANSFER ELECTRICITY FROM THE BATTERY TO THE LIGHT" associated to an electrical circuit, etc. The purpose can be achieved by a transporting process;
- TO_ACCUMULATE: this type represents the class of goals whose purpose is to increase the amount of a generalized substance inside a system. Examples of goals of this type are "TO_ACCUMULATE HEAT" associated to a boiler, "TO_ACCUMULATE ELECTRICITY" associated to an electrical capacitor, etc. The purpose can be achieved by a reservoir charging process;
- TO_CONSUME: this type represents the class of goals whose purpose is to decrease the amount of a previously accumulated generalized substance inside a system. Examples of goal of this type are "TO_CONSUME WATER" associated to a discharging container, "TO_CONSUME HEAT" associated to a cooling fin, etc. The purpose can be achieved by a reservoir discharging process.

The link between primitive goal types and generic processes in the functional model is represented by the mapping between the arguments of a goal type and the generalized variables associated to the functional roles belonging to the cofunction of the generic process that achieves that goal. This mapping is domain-independent. Figure 2 describes this mapping for the goal type TO_TRANSFER.

Composite goal types represent purposes that can be achieved by phenomena whose organization is usually represented by more than a single generic process. Examples of possible composite goal type are:
- TO_TRANSDUCE: this type represents the class of goals whose purpose is to convert an effort or a flow from a physical domain to another. Examples of goals of this type are "TO_TRANSDUCE FORCE INTO PRESSURE" associated to an hydraulic ram, "TO_TRANSDUCE TORQUE INTO CURRENT" associated to a single phase alternator, etc. The purpose can be achieved, for example, in magnetic or electrostatic actuators by two coupled storage processes (two reservoir charging processes) of electrical and mechanical energy.
- TO_CONTROL: this type represents the class of goals whose generic purpose is to regulate a current flowing out of a system by some substance accumulated inside the system. Examples of goals of this type are "TO_CONTROL ELECTRICAL_CURRENT BY SWITCH_POSITION" associated to an electrical switch, "TO_CONTROL WATER_FLOW BY THE ANGULAR_DISPLACEMENT OF A TAP" associated to a valve, etc. The purpose can be achieved, for example, by a phenomenon whose organization is composed by a reservoir charging process that regulates a transporting process.
- TO_KEEP: this type represents the class of goals whose generic purpose is to maintain a specific partial state in time. This state is described in terms of the values which some relevant physical variable describing the purpose of the system must hold. Examples of goals of this type are "TO_KEEP ROOM_TEMPERATURE AT 18 C°" associated to a

thermostat-controlled home heating system, "TO_KEEP ANGULAR_VELOCITY OF THE PLATTER AT 45 RPM" associated to the control system of a turntable, etc. The purpose can be achieved by a phenomenon whose organization is represented by a complex network of interrelated generic processes.

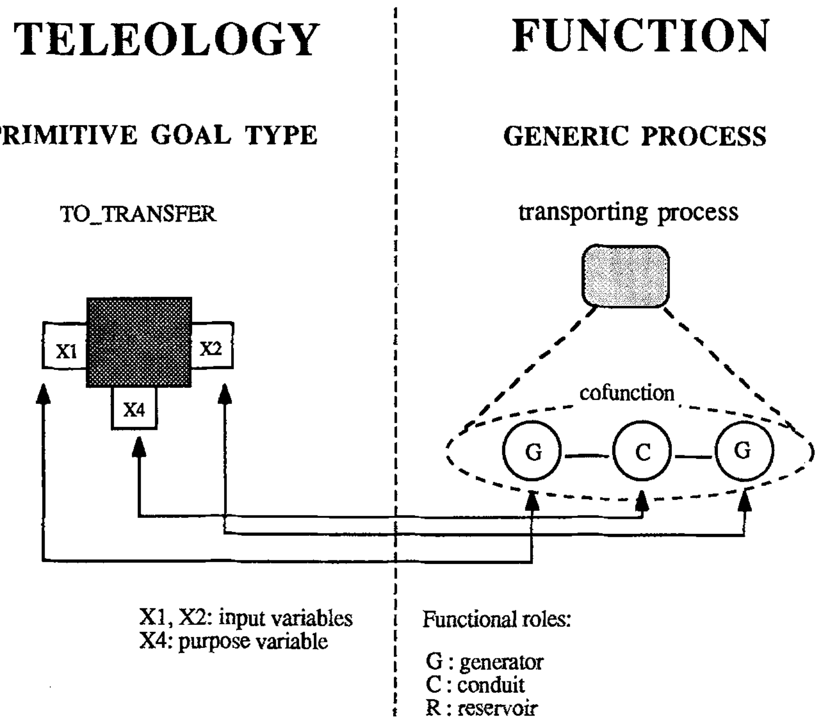

Fig. 2: Relationship between the primitive goal type TO_TRANSFER and the generic transporting process in the functional model.

Composite goal types can be defined by composing together primitive (or composite) goal types. Therefore, a composite goal type may be described through its *decomposition*, i.e. by explicitly specifying the primitive and/or composite types (called subtypes) upon which it is based and the relationships existing among them. Usually, a composite goal type can be decomposed in several different ways. Therefore, a composite goal type may be described, in general, by specifying the set of *alternative decompositions* of the composite type into subtypes. Allowing multiple decompositions for a given goal type is motivated by the fact that, when designing artifacts, in general, several alternatives exist to implement a single purpose. Each of these alternatives can potentially be associated to different decompositions of the goal type, and all the decompositions obtained constitute a library of templates that can be used, for example, in design activities.

Composite goal types are associated to phenomena in the functional model. Since there may exist alternative decompositions of a single composite goal type in subtypes the mapping between goal types and phenomena is, in general, many to many: a goal type can be mapped into a set of alternative phenomena that can achieve that goal. On the other hand, the same phenomenon can participate to more than one goal type decomposition. Each decomposition of a composite goal type leads to a set of interrelated primitive goal types that constitute the leaves of a decomposition tree. Primitive goal types correspond directly to generic processes in the functional model and the relationships existing among the arguments of the primitive goal types are mapped into phenomenological relationships between their corresponding processes. In this way the phenomenon associated to the composite goal type is characterized by an organization that is the network of the generic processes associated to the primitive goal types that constitute the leaves of its decomposition.

Goals are instances of goal types. A goal type is instantiated when its arguments refer to a specific physical situation i.e., when the generalized variables occurring in the purpose and operational conditions of the goal type are associated to specific physical variables of the model of a given physical system, their values (or admissible ranges of values) and the parameters values are specified, and the relationships between variables and parameters are explicitly stated. So, for example, the goal "TO_KEEP room_temperature at 18 ± 0.5 °C" is an instance of the composite goal type "TO_KEEP VAR at REFERENCE_VALUE ± Δ", where the purpose variable VAR is instantiated in the thermal domain and refers to the specific variable: room_temperature, while the setting parameter REFERENCE_VALUE has been set at the specific value of 18 °C and the tolerance Δ has been set to the value of 0.5 °C.

Usually, during a design activity a goal is associated to a system as a whole. In this case, since the system detailed structure is not yet known (in fact, this structure is the result of the "in fieri" design activity), the teleological model represents the specification of the requirements that the structure being designed should meet. On the other hand, when the system structure is known because the system already exists, the teleological model represents the goals associated to it and to its major subparts by the designer. The teleological model of the system may be hierarchically organized reflecting the different levels of aggregation of the structure of the device. Goals associated to components at one level are decomposed in subgoals associated to components at a lower level. However, in general, the teleological model meaningfully describes purposes associated to the higher aggregation levels of the structure (i.e., to the system as a whole and to its major components) since at lower levels it could be very difficult to assign purposes to elementary components: they have only functional roles.

5. USING TELEOLOGICAL KNOWLEDGE FOR DIAGNOSIS IN THE DYNAMIS SYSTEM

Teleological knowledge can be used in diagnostic tasks to support three main activities which are normally performed in the early stages of a diagnostic session:

- *operator diagnosis and guide*: teleological knowledge can be used to identify/exclude unproper use, i.e. abnormal operational conditions or non-admissible goals, as the cause of an unexpected behavior. If an unproper use of the system has been diagnosed, teleological knowledge can then be used to guide the user in the choice of the correct actions to perform;
- *diagnosis focusing*: teleological knowledge can be used to provide hints to focus the diagnostic activity. Knowing which expected goals are unachieved and exploiting the relationships existing between teleology, function and behavior allows to localize areas for diagnostic search in the behavioral and functional models.

In the following, we illustrate in more detail how these activities are performed by DYNAMIS, a prototype system developed in PROLOG to experiment the multi-modeling approach in a thermostat-controlled heating system diagnostic application.

Current approaches to diagnosis are generally based on the assumption that discrepancies between expected and observed behavior of a physical system are always explainable in terms of faulty components. However, there exists an additional aspect to consider which is often not taken into account appropriately by current approaches, i.e. the user. In real-world diagnosis technical service is often called to diagnose faults deriving from wrong use, instead of malfunctioning system components. Users often place systems in unproper environments or feed them unproperly or fail to set system settings as the pursued goal would require. Sometimes, users even try to operate the system to pursue goals not intended by its designer. These problems are dealt with in the first of the above mentioned tasks.

Operator diagnosis and guide starts when DYNAMIS is provided with a) actual operational conditions or b) a set of operator's goals in using the system. In both cases, DYNAMIS tries to validate operator's behavior using the teleological model where admissible goals and expected operational conditions of the system are described.

If the operator provides the system with actual operational conditions then DYNAMIS tries to deduce operator's goals. This is done following this abstract procedure:

1. select a goal in the teleological model of the system. If all goals have already been considered, then go to step 3.
2. match actual operational conditions against the expected operational conditions associated to the selected goal. If the matching succeeds then include the goal in a list of hypothesized operator's goals. Return to step 1.
3. validate the list of hypothesized operator's goals: if the list is empty then terminate operator diagnosis with a failure (this is the case of unproper use, both abnormal or novel) else verify each goal in the list asking the operator if he/she actually wants to pursue it, prevent it or if he/she considers it immaterial (this can be the case of lower level goals). In the case the operator wants actually to prevent some of the hypothesized goals or he/she judges the list incomplete, then terminate operator diagnosis with a failure (abnormal or novel use). Otherwise, terminate operator diagnosis (success) with validation of actual operational conditions.

Analogously, if operator diagnosis starts with the operator's goals as input, DYNAMIS deduces the operational conditions that would be necessary to achieve all the desired goals (hypothesized operational conditions). If the hypothesized operational conditions are not consistent (for example, a tap can be required to be open and closed at the same time), then operator diagnosis terminates with a failure (unproper use caused by non-admissible goals). If the hypothesized operational conditions are consistent, the operator is prompted to check if actual operational conditions matches the hypothesized one. If that is the case, operator diagnosis is completed successfully with validation of operator's goal. Otherwise, it terminates with a failure.

When an unproper use is detected during operator diagnosis and guide, teleological knowledge can be used i) to inform the operator about the proper system operational conditions required to achieve a specific goal, ii) to suggest which actions (e.g. settings, inputs, etc.) to correct after an abnormal use has been diagnosed, iii) to inform the operator about the admissible goals that are achievable by the system.

If operator diagnosis excludes that an unproper use of the system could be the cause of a missing or undesired behavior then teleological knowledge can be used to guide the diagnostic activity in other models (*diagnosis focusing*). In the case of a missing behavior, i.e. a behavior that is expected but not realized, diagnosis focusing is done by i) the identification of unachieved goal(s); and ii) the identification of the candidate phenomena.
Goal achievement is checked by DYNAMIS using the behavioral information represented by the purpose i.e. by comparing observed values of purpose variables with expected values. If the operational conditions are correct, but the purpose is not realized then the goal is considered unachieved. If a goal is unachieved and decomposable, its decomposition is followed and the achievement of its subgoals is assessed too.
The identification of the candidate phenomena is done by DYNAMIS by exploiting the relationship existing between goal types and phenomena in the functional model of the system. Given unachieved goals, the link allows to consider only those phenomena that are relevant to them and thus might be malfunctioning.

At this point diagnosis is carried on by DYNAMIS in the functional, behavioral and structural models using knowledge about the functional roles and the physical laws that underlaid the operation of components in missing processes. A more detailed description of these activities is given in (Chittaro et al.,89).

Note that undesired behaviors may not realize any explicit goal of the design; in this case, searching in the teleological model for unachieved goals is useless. Therefore, it is advisable to use structural and behavioral knowledge to possibly conjecture unforeseen phenomena.

6. CONCLUSIONS AND PERSPECTIVES

The main contributions of the present research are two-fold. First, it focuses on teleological modeling, an issue that has been faced so far in AI research only in a partial way. The paper illustrate the main components of our teleological model and discusses the relationship existing between teleology and function within the multi-modeling approach. The second contribution is to show how teleological knowledge can be used in diagnosis to perform three main activities i.e. operator diagnosis, operator guide and diagnosis focusing.

Future research efforts include the exploration of the use of teleological knowledge for design activities. We will explore the use of the link between goal type and phenomena to automate the proposal of an initial functional organization for an artifact starting from its stated goals as input.

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