THE EVOLUTION OF FUNCTION AND BEHAVIOR DURING MECHANICAL DESIGN

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ABSTRACT

This paper explores the meaning and evolution of function and behavior during mechanical design. The paper is based on an example from practice. The goal is to develop a model of the information developed during the design process and thus define the types of data inherent in mechanical design. Beyond the academic interest of defining function and behavior, this work is important to the development of representations for computer based design history and design rationale tools and techniques.

1. Introduction

This paper focuses on the evolution of information during the design process. For both original and redesign problems new physical objects are developed and modified to meet functional requirements. The development of these objects and the relationships between them bring with them behaviors that are intended to meet the requirements and other, unintentional behaviors. The definition and characterization of function, behavior, objects and relationships are important for a number of reasons. First, the terms *function and behavior* are used in many texts and papers without clear definition. This is pedagogically weak. Second, the traditional definition of function is inadequate as will be shown. Third, the terms defined here aid understanding the design process. This is important for the development of design aids. Forth, clear and complete definitions of terms are essential for the development of computer based design support tools. Currently there is strong interest in capturing design rationale and histories which requires precise definition of the types of information necessary to describe the evolving product. This paper is one step in that effort.

Consider the following example from practice. This example will be used throughout the paper. The example is based on a project in which the author was one member of the design team. As of this writing, the product is developed, patented and nearing production. The problem was to design an easy-to-use, effective securement system for mobility aids (e.g. wheelchairs, scooters, power bases) on transit vehicles, specifically buses and vans. Several types of mobility aids are shown in Figure 1. These represent only a few of the thousands of configurations available.

Currently a number of different types of securement systems are available. Most of these make use of three or four belts that hook onto the mobility aid and into the floor or wall of the transit vehicle. These systems were derived from hardware developed for the securement of cargo on aircraft. They require the driver or other assistant to hook each end of the belt, then tighten them to ensure that the mobility aid will not shift during normal operations and not break loose during accident conditions. These systems are time consuming to use and for many mobility aids there are no acceptable places on which to attach the belts.

In solving this problem the first step followed by the design team was to use the Quality Function Deployment Method (QFD) (Hauser and Clausing 88, Ullman 92) to develop a complete set of requirements. Using this method 54 customer's requirements and 72 engineering requirements were developed. These set the basis for the concept design effort.

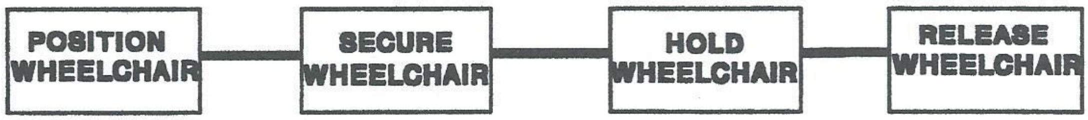

Figure 3: The Operational Steps for the Securement System

Behavior is often defined as "what a device does" or "how a device performs". Behavior is based on physical laws. In terms of Figure 2 behavior is the result of the function or action on the initial state. If the behavior of the system actually meets the functional requirements then the design activity has been successful. In terms of the example: if the hardware designed to meet the "secure" function can be shown through test or simulation to meet those requirements then the behavior of the system is as intended.

During design, concepts proposed to meet functional requirements result in intended and unintended behaviors. Intended behaviors are compared to the requirements as part of the evaluation process. Unintended behaviors, if recognized, may require new design activity to counteract. If not recognized, they may adversely affect the operation of the product. For example, one concept to secure the wheel chair was to use clamps on the wheels. The behavior of this concept was abstractly simulated in the mind of the designer. During this simulation the behavior of the concept relative to the requirements showed promise, but other behaviors not covered by the requirements left this concept in doubt (i.e. damage to wheels during normal operation).

Although the above discussion of function and behavior does clarify the concepts, it is insufficient to fully define the terms. Formal definitions will be given in Section 4.4 after further, needed terminology development.

3.0 Operations, Objects and Relations

In this section the categories of information that are needed to model product evolution are defined. They are the foundation of the remainder of the paper. It is intended that the information modeled here serve as a future basis for object oriented data base development.

3.1 Product Operation

Reconsider Figure 3 where the operation of the securement system was identified as consisting of four distinct steps. This operating sequence is part of the life cycle of the securement system. The general life cycle of a product is shown in Figure 4.

Every product goes through a series of transformations, operational steps or, more traditionally, phases during its life cycle. A product may have many different alternative uses and for each use there may be many alternative operating sequences.

During the design process all of the phases in the life cycle must be considered. However, the operating sequences that define the use of the product are always of key importance. Each operating sequence is punctuated by observations of the state of some objects and their relations. Between these observation points, the behavior of the system is usually continuous and considered as an operational step. As the product evolves there is the possibility that the operational steps or the sequence of them will be refined, or that operating sequences on subsystems of the product will be generated.

In Figure 3 the operational steps "position", "secure" and "release" all represent continuous activity with observable initial and final object and relation states. The relation between the mobility aid and the securement system changes during the "position" step. Before "position" the mobility aid is in the bus aisle some distance from the securement system. After "position" the mobility aid is in the proper position to be secured. Like-wise, "secure" implies a change in the relation between the mobility aid and the securement system. The same applies to "release". The operational step "hold" implies that the relationship between the objects and the state of the objects themselves remain in a constant state over some change in operating conditions. For the example problem there are two types of operational conditions: "normal operations" and "accident conditions".

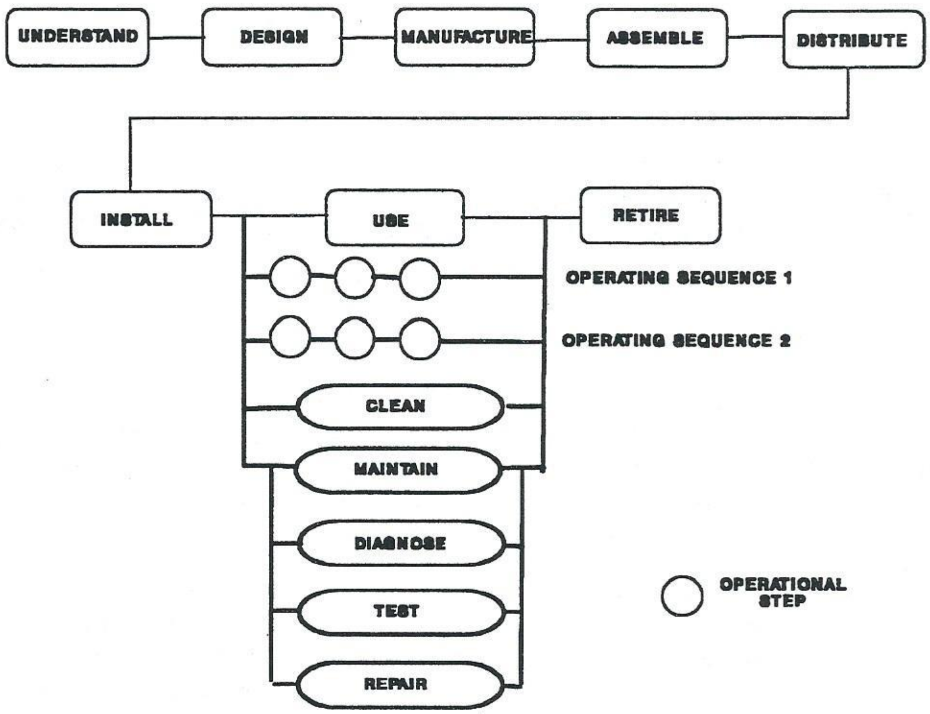

Figure 4: The Product Life Cycle

3.2 Objects

The physical building blocks that comprise the product and its surroundings will be called "objects". A general term like "object", "entity" or "actor" must be used as humans or other living things are usually part of a product's environment. In the Securement System example, some of the objects initially identified by the design team were "Mobility Aid", "Mobility Aid Passenger" and "Securement System".

The object "mobility aid" has a number of different variants as shown in Figure 1. Early in the design process each variant was fully described through measured information from examples and from the manufacturers data.

The object "Mobility Aid Passenger" represents the human who is in the mobility aid. The relationships between the humans who are to use the product, and the product itself can be very important, thus these humans must also be modeled.

Finally, the object "securement system" is the product that is to be designed. At the beginning of the project, it is an object in name only. Virtually nothing is known about it. By the end of the design process the "securement system" will be fully defined with drawings for all the assemblies and components, complete with manufacturing and assembly instructions.

> An object is defined as an assembly, a component, a feature, a human or other identifiable physical thing that is used to describe some physical aspect of the product being designed or its environment.

Although it was stated in the previous paragraph that virtually nothing was known about the securement system at the beginning of the project, this is not entirely true. Early in the project information was developed on requirements for the securement system and information was gathered on existing examples of securement systems currently in use. Thus, for each object (actually for any information about an object or relationship between objects) there may be three categories of information: examples, requirements and proposals. Initially, for the "securement system" there are the requirements developed using the QFD and examples identified during an evaluation of the competition, but no proposals. However, as soon as design work begins, design proposals are developed.

There are two main classes of objects considered during the design process: physical objects and human objects.

A physical object is defined by the seven classes of information is given below. Note that this information may be at any level of abstraction and may be represented by text, drawings or equations. Additionally, the information describing an object may be time and operational step dependent.

Object type

Physical objects can be undefined, a component, an assembly or the feature of a component or assembly. For example, the "securement system" initially is undefined as it is not known if it will become an assembly, a single component or the feature of an existing component or assembly. Even though its type may be undefined, other information about it such as some of its geometry may be known.

Object Relationships

All objects considered during the design process have relationships with other objects. It will be shown in fact that these relationships are major factors in designing the objects. There are two major pieces of information in this class of information: 1) relation identifiers and 2) object detail locations.

Each physical object must have a list of relations that interfaces it to other objects. Not all of these relations may be active all of the time. Additionally, some may be proposed relations while others represent requirements or examples. From the beginning of the solution of the securement system problem, it is known that the non-existent securement system must be related to the mobility aid and the transit vehicle at a minimum. Its relationship with the mobility aid changes during each operational step.

Objects relate to each other through specific geometric details. These details are part of the geometric definition of the object. They can be as abstract as the name of the object or as refined as the identification of specific surfaces, edges and centerlines (Lee and Gossard 1985). As the details evolve they determine critical aspects of an object's geometry. For example, early in the design of the securement system it was decided that it would interface with the rear of the mobility aid. Later this interface was refined to be much like a trailer hitch for an automobile. This refinement, therefore, defined the geometry of the objects that formed the interface.

Object Geometry

There are two main types of object geometry - object detail transformations (geometric coordinate transformation) and geometry of non-detail features. Since relationships between objects describe specific details on each object, the position of the details on the object must be defined. Thus there must be transformations between the object details and an object reference frame.

The geometry that is not associated directly with relationships to other objects is called non-detail or connecting geometry. This does not imply that it is not critical. On the contrary, the connecting geometry carries the flow of energy and information through the object from one object detail to others. If the energy is mechanical then the stresses developed in the object are a major determining factor of the geometry. Maximum stresses often do not occur at interfaces but at other locations in the body of the object.

Object energy, information and material state

Energy, information and working materials can be transferred between objects. The energy transmitted causes the objects to change state or to keep the same state under varying operating conditions. Information transferred between objects is usually for sensing and control purposes. An object may store information in a number of forms (e.g. digitally or physically).

Objects can also store or process a working fluid or stream of other materials. These flowing materials can be treated as separate objects that are affected during their processing by relationships with other objects.

Object Properties

There are two types of object properties that are important - physical properties and calculated properties. Certain physical properties directly describe the object based on its material, geometry and manufacturing process. These properties include density, yield strength, modulus of elasticity, opacity, reflectance etc. Other properties are calculated based on the physical properties, geometry and relations with other objects. Some of these properties are volume, deflection, stress, strain, etc.

Object Manufacturing Process Information

The manufacturing process information may be highly dependent on the material and geometry of the object. Besides the actual machinery used in the production of the object, the sequence of the process may be of equal importance (von Houten 91).

Object Cost/quantity

An obvious set of information is the cost and quantity of the object.

Besides physical objects, human objects are also important in the design process as many of the requirements are based on relationships between humans and existing or to-be-designed physical objects. Even though not all products spend their useful life in contact with humans, all must at least be assembled and possibly installed by humans. For humans there are four categories of information (Ullman 92): size (anthropometry), strength, sensing ability and controlling ability.

3.3 Relationships Between Objects

As stated before, relationships between objects are considered to be of key importance during the design process. Thus, the definition of a relation will be carefully developed in this section. Basically, a relation represents how one object interacts or interfaces with another. As with objects, relations may be required, proposed or examples. Additionally, the information may be described at any level of abstraction and as text, graphics or equations. Finally, the information may be time dependent. A relation is fully defined by five attributes:

> A relation (or relationship) is defined as the description of the interface between objects. This includes information on geometry, the flow of information, energy or materials and the nature of the connection between the objects.

Related Objects

The first pieces of information that must exist for all relations are the names of the two related objects. This information exists even if the objects are very abstract. For example, from the beginning of the design process it is known that the object "securement system" has some relationship to the object "mobility aid". The nature of this relation is not initially defined but becomes very detailed and concrete as the product evolves.

Position Relation

The second type of relation information is the relative position of the two objects. This information can range from abstract terms, like "near" or "on", to transformations between coordinate systems fixed to each object detail. These *transformations may require six values to fully define them plus additional values to convey the tolerances. The position relation can represent the fit, clearance, relative path or other relative geometric information.

Connection Relation

The third category of relation information concerns the connection between the objects. There are actually four pieces of information that define connection - degrees of freedom, type, rigidity and part-of. Information about the degrees of freedom can be closely tied to the position information. The term "pivot" implies one degree of freedom between objects (connection) on the same center line (position). The type of connection information relates the mechanical nature of the connection (i.e. welded, bolted, bonded etc.). This information can also be used to show that two objects have been combined into a single component. The rigidity information is to convey the slip-stick information in the plane of the surface details (Lee and Gossard 1985). Finally, part-of is a pointer to another object. This object is a higher level assembly. During the design process assemblies are decomposed into individual components and components are grouped into assemblie s. Sometimes the exact grouping of components in assemblies changes as the design progresses. In any case, assemblies are connective relations between components and/or sub-assemblies. Also, the pointer may be to a component implying that the two objects are features of the same component. Finally, this part-of information may be used to define mixtures of two liquid or particulate objects.

Transmission Relation

The forth type of relation information describes what is transferred between the objects, the flow of energy, material or information between them.

Relation Activity

The fifth type of relation information concerns a relation's activity during the operation of the device. A particular relation may only be active during some of the operational steps. The relationship between two objects may change non-linearly between steps. For example the nature of the relation of the mobility aid to the securement system is very different when comparing the positioning of the mobility aid for attachment to the securement system and when the mobility aid is being held by the securement system during the operation of the transit vehicle.

4. Function/Behavior: Realization

Now that objects and relations have been fully defined function and behavior can be refined. Specifically, it will be shown that function and behavior evolve with the development of objects and the relationships between them. This evolution is realized in one of three different ways.

4.1 Operational Function or Behavior

From the systems viewpoint (Figure 1) function is characterized by change or transformation during an operational step. Thus, operational function or behavior is defined as the transformation of objects or relations during an operational step or other life cycle phase. This definition is incomplete, as in the securement system example one operational step (Figure 3) is "hold". "Hold" implies that the relationship between the objects and the objects themselves remains in a constant state over some change in operating conditions.

> Operational function or behavior is defined as the transformation of objects or relations from their initial states to their final states during an operational step or other life cycle phase, or constant object and relation state with differing operating conditions.

4.2 Relational Function or Behavior

Relations contain information about the physical interface between two objects, their relative positions, and the energy, information and material transfer between them. It is the relationships between objects that are the primary cause of the operation of the product and as such enable the function or behavior. For example, the operational function "attach" was realized through a latching mechanism that evolved during the design process. This mechanism had a car door latch mounted in the securement system that engaged with a bar or pin mounted on the mobility aid. The relationship between the latch and the bar created the operational "attach" function. Further, once the latch was engaged it provided the operational "hold" function. Notice that there is a discontinuity between the objects' relationships during "attach" and "hold". The position, connection and energy flow are different in each of the steps. Also, during "hold", the state of the relations and objects remain constant while operating conditions may change. Note that the car door latch was chosen to meet the functional requirements of attaching, holding and releasing the mobility aid to the securement system. Its performance - its ability to provide those functions - was accessed by analyzing its behavior through dynamic and structural modeling.

> Relational function or behavior is defined as changes in the relationships between objects that <u>enable</u> the operational step state changes.

4.3 Object Function or Behavior

Generally functionality is realized through changes in relations as changes in an object's state usually require the interaction with another object. Sometimes however, state change is realized through an isolated change in an object's attributes. There are no examples of this in the development of the securement system. However, an example is the change in properties of a material due to aging.

> Object function or behavior is defined as changes in the object's properties that <u>enable</u> an operational step state change.

4.4 Function and Behavior Revisited

In light of the refinement of understanding function and behavior it is necessary to re-evaluate the function model shown in Figure 2 . The systems model of function is limited primarily in its inability to represent the relationships between objects and object attributes beyond energy, information and material states (Ullman 93). This is not to imply that the systems model is not useful. For simulating the behavior of a proposed configuration of objects it can be invaluable. However, for modeling the evolution of products with complexity, the systems method is too limiting.

> Behavior is defined to be the change of state of objects and their relationships as governed by physical laws.

> Function is defined as a human abstraction of behavior often implying intention. Function is described by: 1) the transformation of objects and the relationships between them during an operational step; 2) the changes in relationships that enable the transformations; or 3) the changes in object state that enable the transformations.

The definitions given here do not affect the link between function and behavior. Function still defines the intended action of the device and behavior is still the actual or resulting action. Now however, these actions can occur as operations on objects and relations, relations themselves or isolated object state changes.

5. The Evolution of a Product

In this section the example is continued. It will be shown that design progress and thus the evolution of form, function and behavior occurs through the development of objects and relationships between them. Regardless of the nature of the design problem - redesign or original design, system design or detail design, static or dynamic systems design - design progress can be modeled through the evolution of the objects and relations. This will be demonstrated through the securement system example.

This discussion will focus only on a small part of the securement system project. The important initial objects and their relations are shown in Figure 5. From the beginning of the project it was known that the objects called mobility aid, securement system and transit vehicle all had relationships with each other. In reviewing the requirements that were generated using the quality function deployment (QFD) method it was found that 63% of the customers' requirements were in terms of relationships between objects as were 73% of the engineering requirements

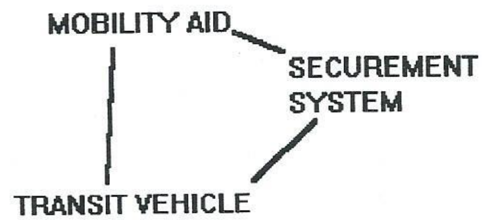

Figure 5: Initial Object/Relation Network for Securement System

Three design concepts were generated to refine relationship between the mobility aid and the securement system; belts, clamps on the wheels, and something similar to a common, automotive trailer hitch. Note that each of these require the addition of new objects and relations to enable the refinement of the object "securement system". The first two ideas were already well refined with products on the market. The third idea needed more extensive refinement in order to be comparable to the first two. In order to explore this third concept, the design team abstracted the idea of the trailer hitch to its basic purpose, that of having a common interface. Thus, an object the team called "the interface unit" was added to the system. The interface unit was intended to be like the part of a trailer hitch commonly attached to a car and was to be mounted on the mobility aid. Additionally, the securement system was then refined so that the still abstract geometry of the object detail of the securement system matched with that of the still undefined interface unit. The object/relation network then looked as shown in Figure 6, where the function of attaching and detaching has been focused on the relationship between the interface unit and securement system.

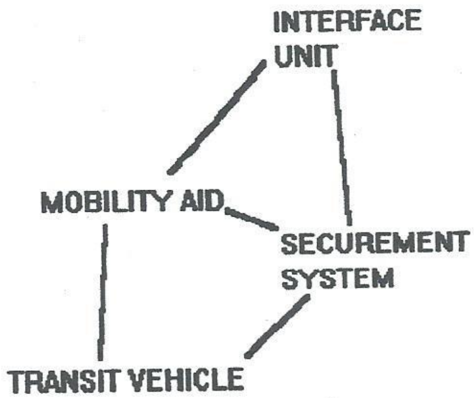

Figure 6 Modified Object/Relation Network for the Securement System

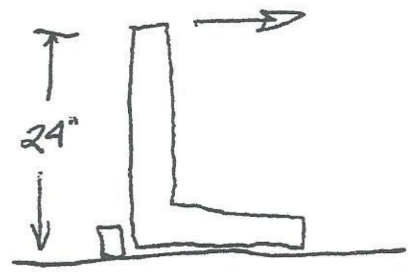

Figure 7 Assumed geometry of the Securement System

The design team then addressed where the interface unit should be mounted on the mobility aid (refining the position attribute of the mobility aid relation to the- interface unit). Three ideas were generated: on the bottom, on the back, or on the side(s). Arguments used to evaluate these were based on the position of the mobility aid center of gravity relative to the attachment point; ease of attachment to mobility aid; interference with ground; interference with luggage carried on the back of many mobility aids and interference with other passengers (All requirements developed in the QFD). A tentative decision to mount the system on the back was made and was reviewed many times during the project.

The team then considered the number of connection points between the mobility aid and the interface unit (refining the connection attribute). Ideas for one or two connection points and arguments were based on simplicity of the interface, ability to carry loads in all directions as determined by the operating conditions and finally potential for interference with mobility aid operation. Two connection points were decided to be best.

One functional requirement that the system had to satisfy was to hold the mobility aid in place during an accident. The team considered this function even though the objects were still just abstract text strings. They wanted to check the behavior of the system during the hold operational step. This consisted of checking that, with the rear attachment, the maximum stress in all the objects was reasonable. In order to calculate stress there had to be some assumed geometry. Thus, they refined the securement system geometry as shown in the sketch taken from one engineer's design notebook (Figure 7).

The 24" dimension shown in Figure 7 was the result of estimating the height of the securement system attachment point (the object detail geometry). This dimension was later refined to 14" after a number of mobility aids were measured and their centers of gravity determined. The 4650 lb load shown in Figure 7 was the result of an effort to refine the requirement on the energy transmitted between the interface unit and the securement system. This was calculated based on the severest operating condition (highest rate of deceleration) that occurred during the hold operating step and the heaviest mobility aid variant.

In making the sketch in Figure 7, there is the implied decomposition of the securement system into two parts; the one shown in the figure (which later became known as "the base") and the rest of the assembly. This "rest of the assembly" contained all of the functionality to connect, hold and release the interface unit, and thus, the mobility aid. This decomposition created new relations that would later need refining as shown in Figure 8.

In order to calculate the stress, the base had to be given some geometry. In this case the designers chose common extruded steel shapes available from a handbook. The ideas selected from this handbook were repeatedly modified until a number of commonly available - round, "I" beam and channel - shapes were identified that could handle the load given above with a reasonable assumed maximum stress.

Even though new objects were added and both objects and relations were refined, there was minimal commitment in this proposed design. It should also be noted that analysis for the "hold" operational step was only for the frontal impact accident operating condition. Later in the design process other operational steps and operating conditions were considered.

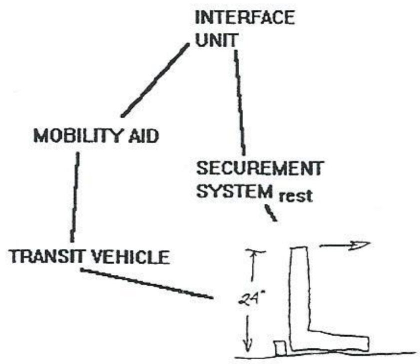

Figure 8 Refined Object/Relation Network for Securement System

The above issues represent about 5% of the total work accomplished during the conceptual design of the securement system. Much later in the conceptual design process, the sketch shown in Figure 9 was made.

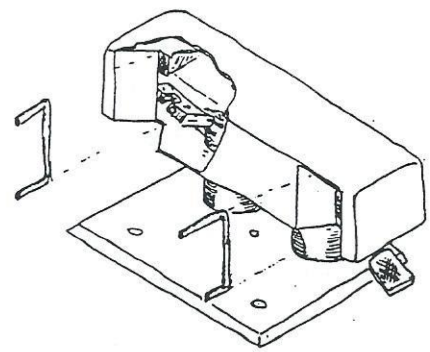

Figure 9 A Concept for the Securement System

This concept, which ultimately evolved into the final product, was actually one of nine generated. Some were only variations of others, however the group included five distinctly different concepts. The one shown in Figure 9 was chosen after repeated relative comparison between the concepts using the decision matrix technique (Pugh 91). The concept in Figure 9 can be shown in an object/relation network for different operational steps. In Figure 10a, the system is shown during "move mobility aid into position in securement system" and in Figure 10b the same system during "secure","hold" and "release" steps is shown. As can be seen, the active objects and relationships between them differ in each figure.

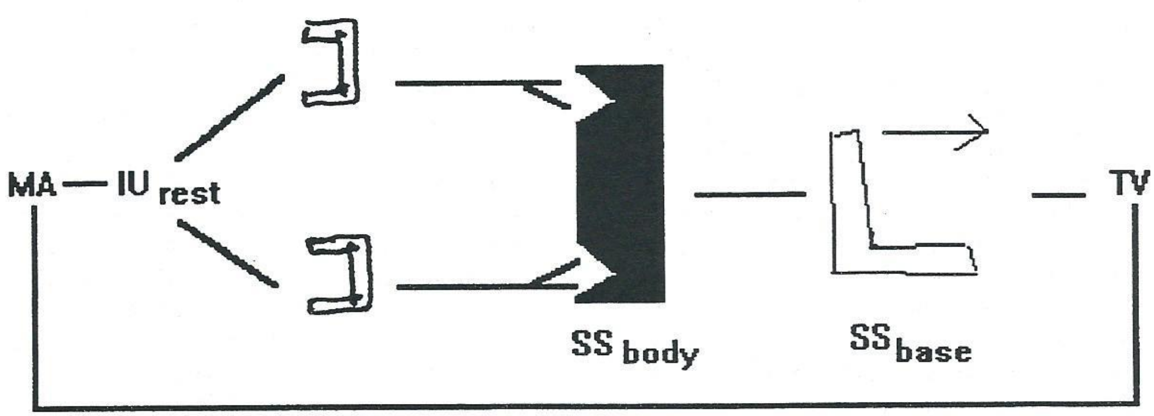

Figure 10a: Securement System Concept Object/Relation Network During "position" Operational Step.

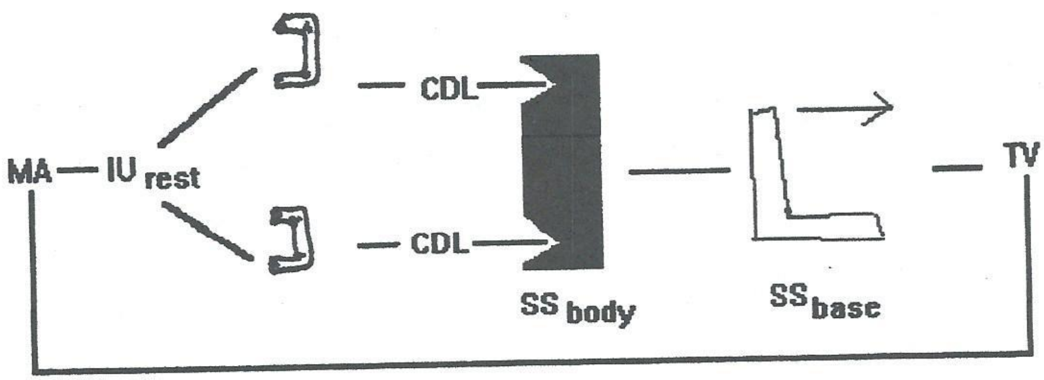

Figure 10b: Securement System Concept Object/Relation Network During "secure", "hold" and "release" Operational Steps.

In Figure 10a the interface unit (now refined to bent rods) interacts with the angled surfaces on the securement system body to align them (geometric details). The function of these surfaces is to enable the positioning operational step. Their behavior was modeled by simulating the forces generated when a mobility aid was misaligned with the securement system. This function is fulfilled through the position, connection and energy transmission relations between the angled surfaces and the interface unit. The angled surfaces are objects that may represent components or part of an assembly. This has not yet been decided. In fact the decision on this changed many times during the refinement of the concept. The form of these surfaces is very abstract here, merely sketched lines. However, this abstract form, indeed the very existence of the surfaces, evolved with the need for a relation between the interface unit and the securement system to aid during the positioning operational step. Further, as the design evolved, and the surfaces refined, i.e. their angle specified, the material chosen and the surface treatment determined, their functional relationship to the interface unit also matured. It should also be noted that it was not yet clear whether or not the objects in the figure were individual components or assemblies of components. This was yet to be determined.

In Figure 10b the object "car door latch" has been added. The car door latch is a catch mounted inside the securement system body that holds the interface unit. An actual car door latch was used in early experiments to establish behavior. An off-the-shelf latch designed for automotive use was also specified for the final product. The process of securing and releasing interface unit, is a refinement of the operational steps developed in Figure 3. This refinement was not possible until the objects were defined and refined as developed here. By this time in the design process, there was extensive commitment to these objects and their relationships.

6. Comparison to the Research of Others

The effort to understand and represent function has been the topic of many papers and books. This work has been dominated by a systems view as represented in Figure 2 and discussed in Ullman 93. As has been shown here this model can only represent part of the functionality evolving in a product.

A more sophisticated model has been developed by Umeda et.al (Umeda et.al. 90). In this model they call an "object" an "entity" (E) and define the attributes (A) of an entity in a similar manner as done here. Further, they define a relation (R) as "what relates attributes, entities, or relations". Unfortunately they never refine or expand this definition, but seem to have a more limited view of relations than given here. The definitions of function and behavior are similar to those given in Section 4.4. Thus, the work here can be seen as built on Umeda's with effort to refine the definition of a relation and through this extend the understanding of function and behavior.

Kannapan and Marshek (Kannapan and Marshek 91) have develop a synthetic reasoning system for developing concepts based on functional and geometric requirements of systems built of machine elements. In their model each "object" is called "system" or "machine element". These have relationships at "ports" (here called "object detail") as in bond graph analysis. This view emphasizes the flow of energy between objects. Tjalve (Tjalve 79) called the object details "functional surfaces". Kannapan defines "items" as what passes through these ports. Items are kinematic motions of translation and rotation which give some of the information contained in the position, connection and transmission relationships defined here. They have developed a predicate logic for transforming initial representations of the requirements into potential machine element structures that exhibit the same behavior and geometric relationships. Their system contains a very refined, formal representation of objects and relationships between them. Further it can automatically evolve the concept for many mechanical systems. The model is kinematic behavior oriented.

Another aspect of the model presented here is its implications on the design process. Common wisdom and education suggests that a good mechanical design methodology is one where geometry and structure are developed after a complete understanding of the its function (VDI-2221, Andreasen 92, Pahl and Beitz 84). It has been shown in cognitive studies (Ullman et.al. 88, Dylla 90) that the form and function of a device evolve concurrently. The model presented here supports those findings.

7. Conclusions

There are five important conclusions to be drawn from this paper:

I. Form, function and behavior co-evolve during the design process.

II. Function and behavior are realized through: 1) operations or transformations of objects and the relationships between them, 2) one object's relationship to another object, or 3) a single object's attributes.

III. Design progress and thus the evolution of form, function and behavior occurs through the development of objects and the relationships between them.

IV. Relationships between objects have attributes that must be modeled for a complete representation of the design process.

V. As the product evolves object/relation networks can be refined to keep track of the evolution of proposals for the product during each operational step. This evolution is effectively a history of design progress.

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