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CONTACT AND CHANNEL MODELLING TO SUPPORT EARLY DESIGN OF TECHNICAL SYSTEMS

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ABSTRACT

The early design of mechanical systems is critical because it constrains options later in the design process. In this early stage of the design process, designers must consider customer requirements, how they are related to system functionality and how these requirements and functions are implemented in the physical interactions between components and sub-systems. This paper proposes an approach by which the Contact and Channel Model (C&CM) can be applied to support this stage of embodiment design. The proposed approach is implemented in a computer support tool and illustrated through a simple example. A number of opportunities for further work to extend and evaluate the approach are identified. We argue that our approach offers a unique way to consider the functionality of a design alongside the parts, surfaces and physical effects which embody that functionality, and provides an intuitive representation which could help designers iteratively develop and express this relationship.

Keywords: Contact and Channel Model, Embodiment Design Process, Mechanism Design

1 INTRODUCTION

Even in relatively simple products design rarely begins from scratch; designers often have initial ideas and schemes in mind before beginning. One problem faced in this situation is embodying these ideas in sub-systems and components, decomposing the high-level requirements into interrelated functions, and localising these functions in mechanism parts and the interfaces between them in order to understand the detailed requirements for each component. In this paper we discuss a product modelling approach which we argue can support this aspect of conceptual/embodiment design. Our approach is based on the Contact and Channel Model (C&CM) developed by Albers and Matthiesen [1]. The C&CM approach offers a unique way to consider and visualise both functional and physical elements of a mechanical design concurrently. We show how a formalised version of the C&CM can be used to support the design process. We discuss an implementation of our approach in a computer tool to support the design process. The approach and design support tool are illustrated by example.

The paper is organised as follows. In Section 2 we review existing literature on the conceptual/embodiment design process and discuss tools and methods which have been proposed to support it. We then highlight some of the limitations of these approaches with respect to the specific problem outlined above, thus motivating the development of a new approach. Section 3 introduces the Contact and Channel Model, which forms the basis of our approach, and describes its current use to analyse technical systems. Section 4 shows how the C&CM model can support not only the analysis, but also the synthesis of technical systems, and introduces a design process which illustrates the steps of this C&CM-supported synthesis approach. Section 5 discusses a formalisation and implementation of the C&CM in a product modelling tool based on the ‘P3 Platform’ software, which provides computer support for the design process proposed in Section 4. Section 6 illustrates the process and software tool by application to design a servomotor. Section 7 reflects upon the main contributions of the paper, discusses strengths and weaknesses of our approach and highlights directions for future work. Section 8 concludes.

2 BACKGROUND

This section discusses literature which is relevant to the approach proposed in this paper. The review is organised into three sections, focusing respectively on the mechanical design process, the relationship between form and function in mechanical design, and tools and approaches to support the embodiment of functions in the design process.

2.1 Phases and stages in the mechanical design process

Many authors have described the mechanical design process and presented high-level models which aim to formalise and support it. For instance, Pahl and Beitz [8] state that the essential activity in both product development and solving problems can be viewed as repeating phases of analysis and synthesis, which can be seen as comprised from working steps and decision points. A general rule is to move from qualitative to quantitative understanding of the design, while reducing the space of possible solutions by becoming incrementally more specific. The process may also be viewed as a progression of higher-level stages. Although precise definitions vary from model to model, the general consensus model includes the stages of planning (clarifying the task), conception (defining functions and sub-functions and identifying how these are divided among main sub-systems of the design), embodiment design (developing increasingly detailed physical layouts of individual parts) and elaboration (creating the detail required for manufacturing and assembly instructions). The approach proposed in this paper aims to support the design activity between conception and embodiment design – in other words, the identification of functions and their localisation within and the assignment to parts and sub-systems of the physical layout.

2.2 The relationship between form and function in mechanical design

“Function” can be viewed as an intermediate concept which links requirements to the form of a design. Functions can be viewed as verb-object pairs [6] – for instance, a seatbelt may include the function ‘arrest-motion’ or a power supply ‘provide-power’. It is possible to distinguish between desired functions, associated with primary requirements, and other, possibly undesired functions which emerge from the design (such as ‘conduct electricity’). Different functions may also be required for operation in different life-cycle phases – for instance, geometry definition must take into account the needs of manufacturing, assembly, maintenance and recycling as well as the operation of a device.

The relationship between function and form has been studied extensively and a number of related concepts proposed in the literature to clarify this relationship. For instance, the chromosome model of Andreasen et al. [4] uses the concept of organs as an intermediary between function and form. In the chromosome model, operation requires certain functions, which are decomposed into organs, which are embodied in physical parts. Hubka [7] defines organs as the spaces, surfaces or lines on the collection of components which define the localities where necessary effects to realise the function take place. Umeda et al. [13] discuss how function is related to the ‘behaviour’ (eg. oscillation of a part) with which it is associated, commenting that this is a subjective and many-to-many relationship.

The activity of realising function and form is viewed as one of the most difficult creative steps in the mechanical design process and has been researched in detail in the mechanical design literature (see, e.g., [14] for a review). Many of these approaches suggest a linear progression from function structures to their embodiment. In practice, however, this is often not possible as functions and form are tied together and must emerge together during design. It may not therefore be possible in many cases to define function without also considering form simultaneously. This complex interrelationship is recognised by the definitions of concepts such as organs and wirk elements.

2.3 Design approaches, methods and tools to support function embodiment

According to Hirtz et al. [6], conceptualising an artefact in terms of function is a fundamental part of the engineering design process. Building on this understanding of function embodiment as a fundamental part of design, various authors have devised approaches and support tools aiming to support the process of function embodiment in mechanical design. These approaches commonly recognise the need for design iteration as a fundamental part of the embodiment process. For instance, as part of the axiomatic design methodology, Lee and Suh [10] describe a ‘zig-zagging’ approach, in which requirements are embodied in components, which in turn generate new sub-requirements which must be addressed by further detailing the component designs. Bracewell et al. [5] describe a package of software tools called Schemebuilder developed to support the conceptual and embodiment stages of mechatronic and mechanical systems design. The software helps the designer generate alternative schemes by using a database of working principles and decomposition principles in the development of a function-means tree-like information structure. In their approach, the designer must start with a basic decomposition of the problem statement into functional sub-systems which can solve it – Bracewell et al. give the example of a refrigerator, which can be decomposed at the highest level into a compressor, an evaporator, and so on. Each element can then be embodied in one or more ways, generating a set of alternative schemes which in turn have additional function requirements which must be further detailed by selecting more embodiments. For instance, selecting a compressor powered by an electric motor requires a power source and possibly a cooling device, which in turn might be provided by a transformer and an airflow. In this way the initial scheme is incrementally embodied into a tree of alternatives, where each node comprises a choice between different embodiment approaches.

Although these types of approach have many useful applications, they do not directly assist in the localisation of function with parts, their surfaces, and physical effects. In this paper we propose that a design approach which addresses this limitation could better support engineering design in very early stages of the product development process. One approach which supports the consideration of function and form simultaneously is the 'Contact and Channel' modelling approach (C&CM). This forms the basis of the present paper and is therefore described in detail in Section 3 below.

3 THE C&CM APPROACH

Within the embodiment design stage, a design must be decomposed into parts and their design objectives elaborated. These objectives can be viewed as describing issues deduced from the artefact's functionality. Making the step from a functional description of a system behaviour to its components and their detailed design objectives is a challenging task which can be supported by the Contact and Channel Model (C&CM) introduced by Albers and Matthiesen in 2002 [1]. In this section, we review the C&CM approach prior to describing its application to support this activity.

3.1 Overview of the C&CM modelling approach

Conventionally engineering products are modelled by components with defined geometry, which are grouped into systems and sub-systems. The C&CM approach takes a different approach to describing geometry through Working Surface Pairs (WSPs) which carry out functions and Channel and Support Structures (CSSs) which connect the WSPs. Albers and Matthiesen [1] propose that the concepts defined below are sufficient to describe systems with any functionality:

1. **Working Surface Pairs (WSP)** are pair-wise interfaces between components, or between a component and its environment. These interfaces can be between solid surfaces of bodies or boundaries with surfaces of liquids, gases or fields which are in permanent or occasional contact with the Working Surfaces (WSs) of a part. They take part in the exchange of energy, material and information within the technical system.
2. **Channel and Support Structures (CSS)** are physical components or volumes of liquids, gases or spaces which connect exactly two WSPs. They do not only transfer the system variables energy, material and information from one WSP to the other but they can also store them (e.g. the moment of momentum associated with a rotating gear).

Using this approach, a mechanical system can be decomposed into its components and sub-components down to the level of single surfaces. It is then possible to identify the functions that are realised between the surface pairs in order to create a better understanding of the whole system's functionality. Albers and Matthiesen argued that at least two WSPs and one CSS are necessary to describe a function.

The Contact and Channel Model is illustrated in Figure 1 using a simple example of a conventional planetary gear. A sun gear drives the planets rolling along a fixed hollow wheel (function 1 with blue, green and purple CSSs). After the transformation, the torque is discharged by the planet carrier (function 2, red CSS).

This is a very simple example. In practice the design of a technical system can satisfy large numbers of constraints and has been developed giving consideration to various difficulties which are not obvious to the casual observer. In order to develop an understanding of these constraints and difficulties it is usually necessary to first consider the system at an abstract level, and to develop a C&CM model which becomes progressively more detailed as more information is uncovered and understanding is generated. This analytical process is well-established through many applications of the C&CM approach to date, mainly in lectures at Universität Karlsruhe (TH).

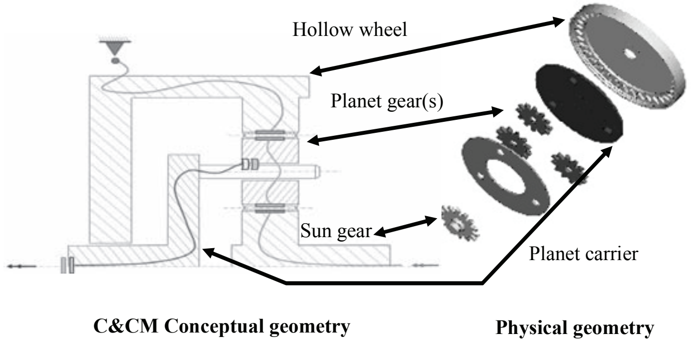

Figure 1. Planetary gear modelled using C&CM

3.2 Applications of the C&CM approach

Today the C&CM approach is successfully in use to help to support the modelling of technical functions (according to VDI 2221 [11]), physical design and system environment by providing an improved and collective understanding of the artefact. This conceptual unification leads to a better cooperation of designers in engineering practice.

Research being undertaken at Karlsruhe has led to production of a guideline for the application of the C&CM to analyse existing technical systems [2]. The guideline includes the following activities, which can be repeated in a process of iterative convergence:

1. **Determine the relevant part of the system and its borders** which will be analysed.
2. **Determine locations of special interest in function accomplishment**, either starting from functions of interest and localising the WSPs and CSS or starting with the design and assigning functions to WSPs that carry out effects.
3. **Use adaptive zoom** (described as a 'comb approach' by Albers et al. [2]) – enhance the detail of description to zoom in further on only those locations where functionality is not yet clarified.
4. **Use a 'sequence model' to describe dynamic systems** in which the functions change over time. This essentially decomposes the system in different ways as appropriate to different modes of operation in the sequence.

One key point is that the C&CM approach does not require the full decomposition of a complex system in order to identify the causes of its behaviour; the system can be decomposed from a functional point of view in order to identify the components, surfaces and effects which participate in the functions which are under consideration to understand and solve a given technical problem. Three example applications of the approach are given below.

- A project was undertaken with Hilti Deutschland GmbH focusing on the development of drywall screws. This illustrated application of the guideline's steps in detail, and is reported in Albers et al. [2]. One conclusion of the study was that application of the guideline led to a guided and detailed analysis and the enhanced understanding of designers was believed to improve their work.
- In engineering education, experience of using the C&CM approach in undergraduate teaching at Karlsruhe has found that students find technical problem-solving easy to learn through applying the C&CM. In this context the approach provides a systematic way to look at a technical system with which the analyst is unfamiliar, and helps to ensure a common comprehension of that system among multiple participants in the modelling exercise.
- Schyr [9] combined the C&CM with the simulation language Modelica. The basic concept is to mathematically define the physical properties within Modelica. Schyr describes a Behavioral Mock-Up in which the WSs of the C&CM are enhanced with the properties of Modelica Connectors. Similarly, the physical properties of CSSs are modelled and described by equations. Schyr then showed how typical problems in the validation of drive trains can be handled by linking WSPs and CSSs enhanced in this way.

In summary, these applications illustrate how the C&CM approach can be applied to support the analysis, validation and improvement of existing systems. The following sections extend this work by showing how the C&CM approach can also be used to support synthesis of new designs.

4 APPLYING THE C&CM APPROACH TO SUPPORT THE DESIGN PROCESS

The process of applying the C&CM approach to support embodiment design is illustrated in Figure 2. This approach is based on viewing the system being designed from two complementary perspectives. According to this view, a system being designed consists of the hierarchy of functions it must satisfy on the one hand, and of the sub-systems and parts by which the functions are realised on the other hand. The component's structures and surfaces must have attributes which allow the required physical effects for the functions to take place. The main objective of the process outlined below is to help designers identify and localise these structures, surfaces and effects.

In common with other design approaches, this process involves a number of steps which are revisited iteratively in a process of disordered convergence upon a design solution. The focus of attention at each step is governed by the insights gained in the previous activity. In the following sub-sections, we discuss the objectives and procedures associated with each of the main steps.

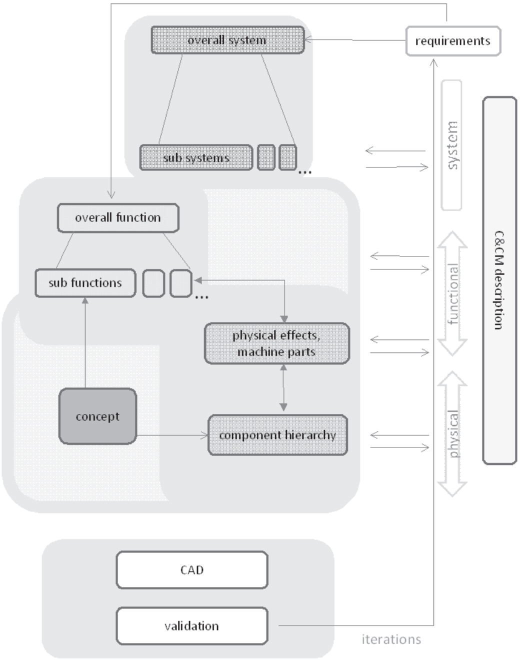

Figure 2. Design process using C&CM

4.1 Decompose concept into sub-systems and main components

In this first stage, the overall function and the rough design space (limitative dimensions, target weight, etc.) must be defined on a very abstract level. This first "concept in mind" can be decomposed to a certain level without detailing specifications or geometric aspects. At this level, the designer can use a "black box" notation in which flows of material, energy and/or signal are used to indicate the interactions between virtual sub-systems. In this context, virtual sub-systems could include concepts such as drive unit, controller, etc. This does not indicate a physical unit, but rather an element of the design which provides a required aspect of functionality. The result of this step is an energy-material-signal flow model of the type discussed in detail in the engineering design literature (e.g. [8]). The required behaviour of each sub-system can be viewed as the difference between the output and input flow values. It is not necessary to consider how this change is realised at this level of abstraction.

4.2 Decompose requirements into functions and localise start/end points

Having identified a preliminary system decomposition, the designer must define a set of functions which together realise the demands specified in the high-level system requirements. Each of these functions must have start and end points which are localised within the emerging mechanism design. For instance, the function 'create-torque' of an electric drive might be specified with a start point on the mounting point of the motor casing and an end point on the motor's output shaft. This then allows identification of a path through the sub-systems through which torque must be 'created' and transmitted. In this case, the main sub-system of interest can be identified as the 'motor', further consideration of which indicates the need for a 'supply-power' function and a 'supply-control' function. By developing a set of functions and associating them with the decomposed sub-systems in this way, the designer can progressively create a hierarchy of functions that specifies the artefact's behaviour. While this occurs, a high-level definition of the physical layout emerges concurrently through the same process. This will be illustrated by example in Section 6.

4.3 Identify machine elements to satisfy functions

Once the composition of functional interrelationships has been identified it is possible to search for machine elements and principle solutions which will carry out the functions. Since the functions have been described at a very abstract but still distinct way and also the decisive requirements are available, it is possible to look for known mechanisms with the help of catalogues. One could also think of a software tool that assists the designer in searching for possible realisations.

In case there are no known solutions or if specific constraints require a new design (e.g. with lower cost), it is still possible to use the information about the functions and their specifications by defining physical effects that carry out the desired functionality. These general effects – such as "heat transmission" or "friction" – can again be taken from lists as given, for example, in Altschuller [3]. These effects take place in a sub-system's WSPs and propagate via, or respectively affect CSSs. If necessary, the chosen principle solution can then be modelled using the C&CM elements within the sub-system. It is also possible to describe multiple ideas for implementing a sub-system and to compare them to identify the best solution according to the requirements. Selecting the best option where multiple solutions exist can often be considered aside from the main design problem when working at a high level of abstraction. According to the "black box" model, each of these sub-problems remains embedded in the context of the emerging system as their boundaries – in this case the working surfaces – remain the same and thus restrict the design space. This modularity allows many pending decisions to be left open until the surrounding system is sufficiently developed to resolve them appropriately.

When all the components for realising the functions have been found, a complete C&CM modelling of the product can take place. In different levels of abstraction, the functions can be assigned within the sub systems by "mapping" them onto paths along the WSPs and CSSs. This step still occurs at an abstract level before the final geometry is defined in detail – but nevertheless the whole system with its functions, behaviour and high-level layout can be described.

4.4 Complete design using other simulation and analysis approaches

This data developed through application of the C&CM-supported approach as outlined above delivers the input variables for subsequent stages of the design process, in which the geometric shape is fully defined (normally using a CAD system). These later stages of design use requirements which flow down from the C&CM modelling – namely information about the required properties of surfaces and structures, and definitions of sub-system boundaries alongside the nature and magnitude of interfaces (defined in terms of 'flows'). The C&CM approach can thus help designers determine precise sub-system and component requirements in the context of the system's functional hierarchy. In turn, this can lead to an improved understanding of the design which can be shared amongst participants in the detail design process, thereby leading to fewer design mistakes and ultimately to less time spent in unnecessary rework.

The C&CM approach can support validation processes as well as detail design. Here numerical methods and specialised software may be used alongside conventional engineering calculations. The approach can support such activities by providing an overview of product structure and functionality which assists all relevant people in co-ordinating their activities. Since the systems are described in the context of their functions, this can reduce the need to search for additional information, stored in external documents, for example to consider questions about stiffness or surface quality requirements. The relevant data is archived directly in the product model and can be accessed when needed.

In any design process, it is likely that iteration and redesign will be required as new information is created through detailing and testing, revealing shortcomings in earlier design decisions. Redesign may also be required if high-level requirements change, either following detection of unconsidered problems or if customers change their specification. Therefore the C&CM-supported design process is iterative in nature (cp. Section 2.1). Here again, the function-based product data model makes the required information available for making informed decisions and hence helps to save time and effort.

5 IMPLEMENTATION

This section discusses the formalisation and implementation of the C&CM approach in a computer tool, which supports its application using the design process outlined above.

5.1 The need for software support

A critical part of the methodology proposed above is the recognition of the highly iterative nature of design, as the solution structure is progressively detailed through a repeating process of generation, evaluation and modification. Paper-based methods are unsuited to support these design iterations for even a moderately complex system, whose C&CM model could comprise several different perspectives of tens of components and subsystems alongside tens or even hundreds of WSs. To apply the process we propose, it is therefore necessary to provide a support tool which allows the construction and manipulation of complex, hierarchical C&CM models in a familiar and intuitive way.

5.2 Implementation overview

The approach was implemented in the ‘P3 Platform’ software [12]. P3 is a software tool for constructing diagrammatic linkage models capturing the elements in one or more domains and the relationships between them. It can be configured for different modelling approaches using ‘linkage meta-models’, which describe the types of element allowed in a model and the types of linkage allowed between them. This is ideal for C&CM models of the type shown in Figure 1, in which Working Surfaces can be viewed as elements and CSSs as the linkages between them.

Figure 3 shows an overview of the classes and relationships which comprise the C&CM modelling framework, as formalised for the purposes of this paper and as configured in the P3 linkage meta-model. The meta-model requires the modelling of working surface pairs as two individual working surfaces, each associated with a single component or sub-system, and linked via a working surface pair. To assist interpretation of diagrams using the P3 tool, each working surface comprises inner geometry (facing into the component) and outer geometry (facing out of the component). Thus, a working surface pair can only be used to connect between the outer geometry of two surfaces of adjacent components. A channel and support structure can only be used to connect the inner geometry of two surfaces of the same component.

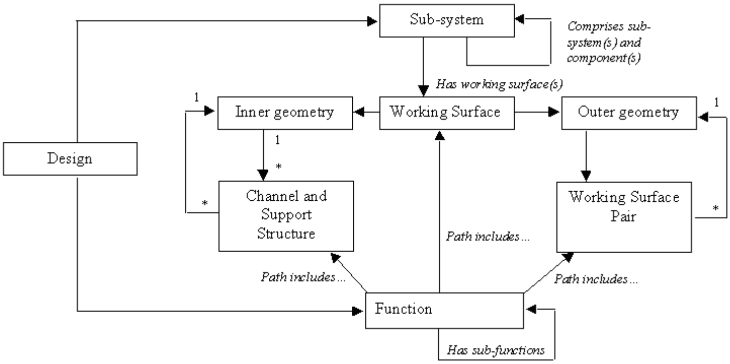

Figure 3. Data model of the C&CM approach as implemented in this paper

The P3 software provides diagramming features for all meta-models which are useful to support the development of large and complex models. For instance, the sub-systems can be individually opened and closed per double-click, and the software expands and contracts the grid appropriately to ensure that all other sub-systems in the model remain appropriately located above, below, to the left or to the right of one another. This allows the mechanism geometry to remain similar regardless of which aspects the user is ‘focusing’ on at any time. It thereby allows the practical decomposition of complex mechanical systems into many levels of sub-systems, while only showing those which are the modeller's current focus of attention.

Functions are implemented using the 'classification schemes' provided by P3 for all meta-models. Classification schemes are a painting tool which allows the user to construct a hierarchy of types and assign individual nodes and edges to one or more of these types. It is then possible to filter the display, for instance to highlight those working surfaces, CSSs and WSPs involved in the 'transmit-torque' function in different colors.

An example of the C&CM modelling tool configured using the linkage meta-model of Figure 3 is shown in Figure 4. This screenshot shows the components of the planetary gear discussed in Section 3.1. The individual components of the planetary gear are indicated by the large green rectangles. Within each rectangle, the conceptualised geometry of the component is sketched and overlaid by the WSs of that component. The circles indicate the inner geometry of each WS. Black lines indicate CSSs (within components – eg. Transfer load), whereas red lines indicate working surface pairs (between components – eg. Friction fit).

The implementation also allows creation of multiple views of the system being designed. This is necessary in many cases as the number of surfaces, connections and functions involved in a product of any complexity is significant. It is also necessary where the system has geometry that must be considered from different perspectives in order to present all WSs involved in its function.

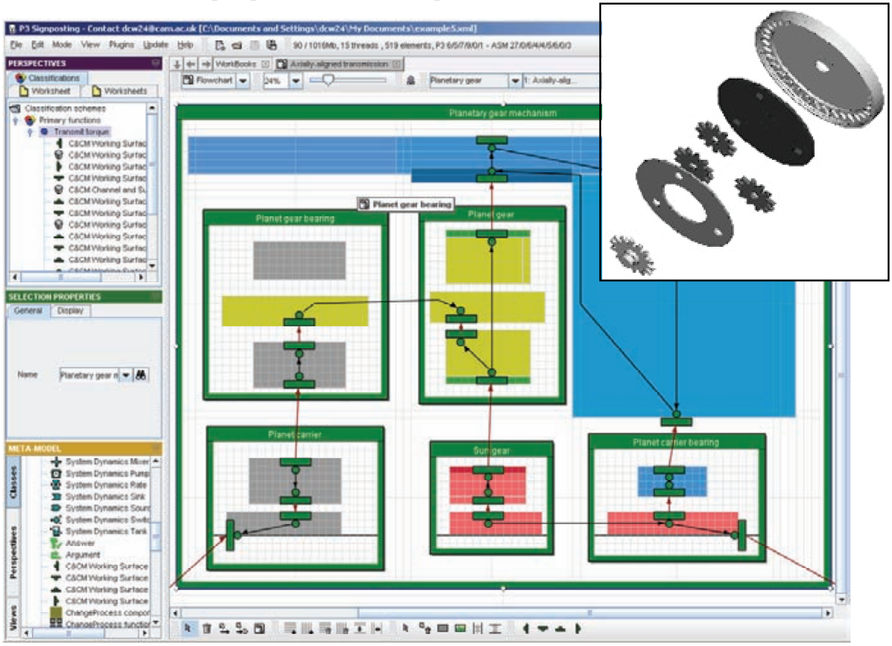

Figure 4. Screenshot of the P3-C&CM design support tool described in this paper, showing the components of the planetary gear described in Section 3

6 ILLUSTRATIVE EXAMPLE

This section illustrates the proposed design process and software tool using a very simple example of servomotor design. The objective of the illustrative, hypothetical design process considered here is to design such a motor for a given set of requirements. In the hypothetical example, we assume the designer has conducted some preliminary research on such devices and thus has some understanding of how the mechanism operates. Nevertheless, within this high-level concept it is possible to envisage different layouts for the device, for instance in the arrangement of gearing or the location and orientation of the drive motor. The objective of the hypothetical design process is therefore to determine a configuration and to decompose the high-level requirements for the servomotor into detailed functional requirements for the individual components. This would then allow the components to be designed individually or selected from catalogues as appropriate.

6.1 Applying the approach in iterative design

From basic research into similar devices, it was first identified that the motor should comprise the following functional sub-systems: the *casing and mounts*, a *controller*, an *electric drive*, a *gearing system*, an *output shaft*, a *sensor* providing position feedback from the shaft to the controller, and an *arm* by which the motor is connected to some part of a higher-level system which it controls. At this point it was clear that several alternative arrangements could provide the same basic functionality, but no design rationale was immediately apparent to suggest a single obvious layout. A preliminary layout of the virtual sub-systems was therefore selected with no initial justification, and subsequently modelled within the P3-C&CM tool as indicated in Figure 5 (left).

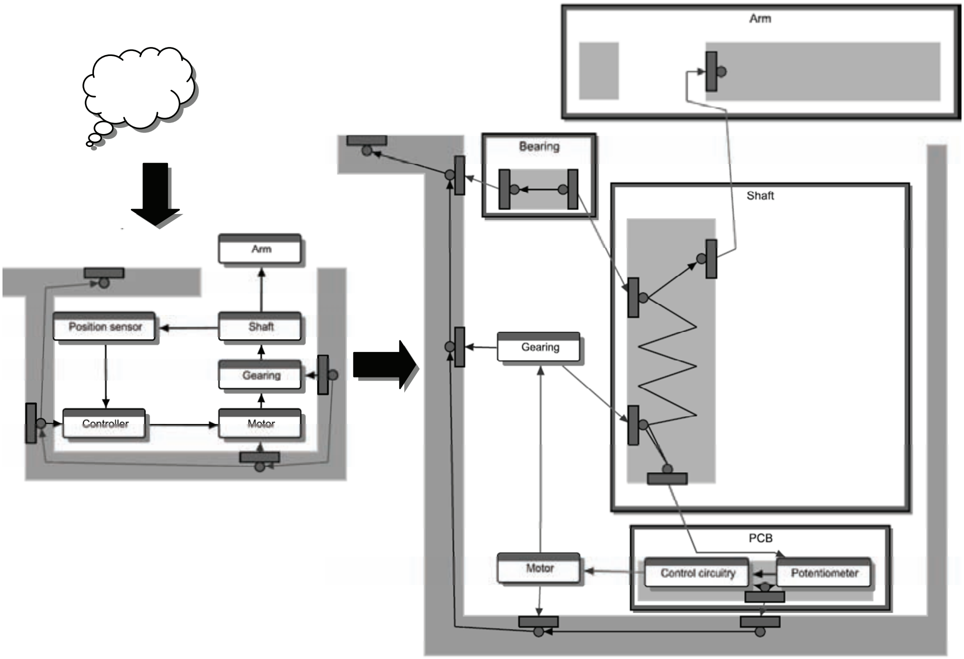

Figure 5. Preliminary layout of the servomotor design using the P3-C&CM tool

The following main functions for the servomotor were then identified:

- Provide-AngularVelocity of at least X degrees per second on average for a 90 degree rotation.
- Provide-Torque of up to Y Nm.
- Transfer-Load up to Z N applied vertically to the shaft through the casing and into the mounts.
- Localise-AngularPosition within W degrees.

Consideration of these functions indicated a number of additional aspects of the design which were not immediately apparent. Firstly, a bearing is necessary to allow the output shaft to rotate relative to the casing and mount. This led to the addition of an additional component to the scheme, as shown in the right-hand diagram of Figure 5. Secondly, focusing on the ‘Localise-AngularPosition’ function required qualitatitive consideration of how the position of the output shaft could be measured to the desired accuracy, using the simplest possible sensor and arrangement. This led to selection of a simple potentiometer aligned axially at the bottom of the output shaft and which for ease of assembly could be located on the same printed circuit board (PCB) as the control circuitry. In turn this required the motor to be offset from the shaft, necessitating a different gearing arrangement as shown in Figure 6 (right). It also highlighted the need to resist vertical load on the shaft, which placed additional requirements either on the potentiometer and PCB (vertical load transferred through potentiometer and PCB into casing) or required some additional vertical support mechanism, possibly through the main bearing or gear train. In the hypothetical example, the vertical load was expected to be small and thus the first option was chosen to minimize complexity. Further consideration of the potentiometer arrangement indicated a new requirement – a maximum limit on the angle of rotation – which was previously known but not made explicit.

The next step in this process would be to expand the gearing assembly, and continue iteratively decomposing until the designer was confident that s/he understood how all requirements were satisfied by the parts and their arrangements. It would then be possible to progress to detail design.

6.2 Summary of the example application

Although this example is limited in scope and sophistication due to the space constraints of this paper, it does illustrate the approach and show how it allows the progressive and iterative convergence of an initial design solution through the consideration of requirements, which in turn highlight the need for further functions which place additional constraints on the design. The key benefit of the approach lies in assisting visualisation of the functions and the locations involved in their embodiment, thereby allowing the designer to easily identify where additional effects and parts are required or what the consequences of a proposed change in the layout might be.

7 DISCUSSION AND REFLECTION

The example has shown how it is possible to combine both functional and physical aspects of a design in one graphical interpretation using the C&CM approach. By assigning each function to WSP and CSS elements, the product model is complemented with behavioural information and the technical properties and requirements of the components are explained. For example, the surface of a bush bearing may have different 'quality', e.g. being polished or tempered. Describing this surface as a WS of a WSP involved in a function such as "allow relative movement" highlights the need to consider this property and suggests possible choices. Additionally, using the relation between the function and its defining requirements, it is possible to envisage component property values being calculated automatically. For instance, the requirement for heat dissipation from the servomotor drive could be estimated automatically from torque and speed requirements.

Another advantage of the approach is the possibility to highlight previously neglected aspects of the design problem. Using the example of the bush bearing again, it is obvious that a WSP that requires a special treatment of the surfaces only makes sense if both of the WSs are featured with the same quality standard. Even if the designer had overlooked the need to include such a bearing between shearing components, this omission would be highlighted when the relative motion of these components was uncovered as part of a function and localised.

A key benefit of the approach is its ability to support an iterative and fundamentally disordered stage of the design process by providing a structured way of thinking about a design alongside a flexible representation for expressing this structure. For implementation in a computer tool, however, it is necessary to consider in detail the elements of the modelling approach and formalise how they can be interconnected and decomposed. While this offers potential for more analytical support and more clearly-defined procedures for applying the model, it also compromises to some extent the pragmatic simplicity and flexibility of the basic approach as described in Section 3.1. For this reason we prefer to view the formalism and computer implementation presented in this paper as one possible interpretation of the more generic C&CM approach – an interpretation developed to meet the particular objective of supporting the function embodiment process.

A number of opportunities for future work arose from this paper. These include:

1. **Integration of a part library.** The selection of machine parts to realise functions –e.g. "bush bearing", "roller bearing", etc. – could be supported by catalogues. Further on, these libraries could also be used as checklists to ensure that all required functions are fulfilled. For instance, a catalog would indicate the need for lubrication or cooling systems if the requirements for a bearing show that significant amounts of friction heat are to be expected.
2. **Functional basis.** The authors propose the introduction of a functional basis such as described in Hirtz et al. [6] to assist modellers in using a common terminology at the lowest possible level of description of functions. In this approach, flows are described in three classes (material, signal and energy) with respectively five, two or thirteen secondary and an expanded list of tertiary categories such as "Energy – Mechanical – Translational" for instant. The reconciled function set is divided in class (primary), secondary, tertiary and Correspondents. E.g. "Control Magnitude – Regulate – Decrease – interrupt". Use of such a scheme within the C&CM would further assist

communication and re-use of models, as well as to help define 'best practice' examples of how models should be constructed.

3. **Additional means for hierarchical decomposition.** The hierarchical decomposition in the current implementation is based upon physical decomposition – that of systems into sub-systems, sub-systems into parts, and parts into working surfaces and CSSs. However, it may also be necessary to allow the decomposition of CSSs and WSPs. For instance, considering the example of Figure 4, the WSPs representing gear pair interactions could be decomposed to indicate the need for lubrication in the mechanism. On the other hand, while this level of decomposition does indicate how physical effects can be incorporated in the model, and could thereby be used to analyse problems in the transmission, it is unclear whether this detail would be necessary to support the design process as proposed in this paper. Further research is required to explore this.
4. **Analytical support.** Since the approach is based on a formal model of the emerging design, this raises the possibility of further analytical support for the design process. Two such opportunities are: 1) the identification of 'unanticipated functions' such as electrical conductivity between two surfaces by processing the connectivity chains within a model, and 2) the use of simple parametric models embedded within a part library to provide further guidance to the designer, similar to the approach of Schyr described in Section 3.2. For instance, the electrical power requirement and rate of heat generation by a motor could be estimated automatically if the torque and speed of the output shaft were specified in the motor's CSS, thereby indicating to the designer what type of power supply and cooling mechanism might be appropriate. Such functions could provide additional guidance to help ensure aspects such as cooling are not overlooked during early design, and could be especially helpful to novice designers.
5. **Experimental validation.** The proposed design approach has been evaluated in the laboratory setting by the researchers, with promising results. However, it is necessary to design and perform a more rigorous evaluation study to show whether, and to what degree our approach can provide benefits over the unsupported design process. Designing and conducting such an experiment is our main focus for further work to extend the present paper.

8 CONCLUSIONS

In order to design mechanical systems, it is necessary to decompose the requirements for the whole system into the functions and understand how these functions are embodied in and must be supported by the design of individual parts. This must be achieved early in the design process, so that the detail design of parts and sub-systems can proceed with a good understanding of local design objectives. Supporting this decomposition process could help avoid expensive and time-consuming iteration, which can occur if misunderstandings of design objectives are identified in later phases of design.

The main contributions of this paper are twofold. Firstly, we have shown how the Contact and Channel Model (C&CM), an established method which has previously been applied mainly to analyse existing technical systems, can also support embodiment design through a model-based process in which functions and their localisation in components and the working surfaces between them are iteratively detailed. Secondly, we have discussed a formalisation of the C&CM approach and its implementation in a software tool developed to support this proposed design process. Our approach was illustrated by example and opportunities to enhance and evaluate it were identified.

In conclusion, the approach and software tool presented in this paper provide a unique way to support the mechanism design process by visualising requirements and functions alongside a simplified conceptualisation of the physical components which embody them. This new application of the C&CM approach is in a relatively early stage and requires further research to fully develop and evaluate. However, initial applications indicate the proposed approach has potential to provide concrete support for a difficult step of the mechanical design process: the progression from high-level functions to their decomposed localisation across physical parts with detailed design objectives.

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