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EMBEDDING MULTIPLE DESIGN STRUCTURES INTO DESIGN DEFINITIONS: A CASE STUDY OF A COLLISION AVOIDANCE ROBOT

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1. Introduction

The success of engineering firms in global markets depends on their ability to design new products that fulfill evolving customer needs within tight constraints of cost and time. Often, this involves re-using and adapting existing designs and tailoring them to include new functionalities and forms. A common issue is the interpretation of previous designers' thought processes that governed the structuring of the design definition being re-used [Chandrasegaran et al. 2013]. Other typical challenges include managing multiple digital definitions of the same product that emerge from different departments within the firm [McKay et al. 2015] and the need for engineers to have sufficient knowledge about existing designs to specify search criteria [Vollrath 1998]. In addition, the mangement of engineering design changes has economic consequences for technology firms [Kidd and Thompson 2000]. Although many product developers prefer to do work from scratch and develop tacit knowledge to enable quick iterations, design involves handling complex, interrelated relationships among coupled problems [Smith and Eppinger 1997], which in turn can be facilitated by tools that support iterative development processes. Even when a new design is created from scratch, it is useful, from an organizational perspective, to create design definitions that can be reused in the future.

Both situations, reusing existing designs and creating new ones, and the need to support downstream processes such as manufacturing, call for engineers to use multiple design structures within their design definitions [McKay et al. 2015]. Examples of design structures include function structures, design grammars and bills of materials (BOMs). While design structures have been successfully used in existing product development systems, they are usually integral parts of different digital definitions of the same product. This results in a need for careful design data management, which increases product development time and associated costs. While it has been argued that concurrent product development processes and integrated product development teams can be helpful in new product development systems [Ahmad et al. 2013], the optimization of project management practices alone cannot fully overcome technical data management issues. Indeed, given that designers spend 14% of their time seeking information [Robinson 2010], readily accessible embedded information of this nature would enable substantial time savings. Within the aerospace sector, for instance, companies develop gas turbine engines within product families, such as Rolls-Royce’s Trent range, by making minor evolutionary changes to a standardised general structure [Kerley et al. 2011]. The embedding of functional information into engine designs could substantially increase the efficiency with which subsequent designs are developed. Furthermore, aero engine manufacturers have recently changed business models, moving from providing a product to providing a service, through long-term service and maintenance contracts such as Rolls-Royce's "power-by-the-hour" agreements [Neely 2008]. The ability to embed component costs and in-service performance data into designs would increase efficiency and confer a major competitive advantage.

This paper introduces a case study design process and associated design structures, and uses them to demonstrate potential benefits of using embedding to manage design information. The case study process concerns the transformation of a robot designed for collision avoidance into a one that can follow a marked loop path. Experiments were carried out with annotation of lightweight models and the use of NVivo to embed multiple design structures within one or more design definitions and explore the pros and cons of doing so vis-à-vis current change management techniques. The results of the study show how embedding allows different design structures to be related to each other, and demonstrates benefits of embedding for design reuse when compared with conventional change management strategies.

2. Literature review

In this section, three areas of background literature are reviewed. Previous work on engineering design change processes is reviewed because the case study process is a form of design change. This is followed by a review of literature on design structures. In practice, the creation of design definitions, including structures, would need design representation schemes but these are not the focus of this paper. Finally, a summary of design data management techniques and their implementation is provided.

2.1 Design change processes

The effective management of change is an important part of engineering design. Changes can occur at any stage of the product lifecycle and arise for technical or logistical reasons [Jarratt et al. 2011]. Eckert et al. [2004] provide a classification of reasons for change initiation: emergent changes and initiated changes. Emergent changes arise from weaknesses in product development systems which create rework driven by needs for error correction and the resolution of product quality problems [Jarratt et al. 2011]. Initiated changes, on the other hand, result from changes in customer and other stakeholder needs and requirements. Design change processes themselves involve altering design definitions, typically in the form of drawings or 3D CAD models, that were previously released from a design process for use in manufacturing and through life [Jarratt et al. 2011]. These alterations can apply to any aspect of the design and have the potential to change interfaces to other parts and requirements on downstream processes [Jarratt et al. 2011].

An important management decision lies in deciding whether the response to a given change should be to adapt existing work or start anew. A key advantage of adapting existing designs to develop new products is reduction of time and cost [Cross 2008]. The effects of design changes in different business scenarios has been studied by many authors. For example, Coughlan [1992] studied the effect of the deployment of manufacturing engineering resources on change management during product development and found that newer products were more prone to changes related to manufacturability. A study on the effect of frequent changes on a materials requirements planning (MRP) system performance showed that performance degrades substantially with higher frequencies of changes which can, however, be mitigated by intelligent selection of lot sizing rules [Ho 1994]. In analyzing design changes and complexity, Earl et. al [2005] discuss how even experienced designers may find it difficult to predict how a simple change in a single part may propagate to other parts in the design, thereby increasing both time and cost required to effect the changes.

2.2 Design structures

Engineering design processes lead to the definition of physical artefacts and associated services and processes. The focus of this paper is on the designed artefact. The core definition of such artifacts includes shape and material information. Design structures are used to support the use of design definitions in manufacturing and life cycle processes [McKay et al. 2015]. For example, a bill of materials is a design structure well suited for purchasing and procurement activities whereas a function structure is better suited for use in functional analyses. Design requirements define the required functionality of a product. A product's functionality can be described through one or more function structures which relate different functions to each other. A function represents a transformation of inputs to outputs based on flows of energy, materials and signals [Pahl and Beitz 2013]. The function of a product can be broken down into sub-functions, which are less complex than the overall function. This breakdown helps in the search for solutions to design requirements and enables a clear definition of sub-systems required/present in the design. However, what constitutes a function is not yet agreed and, for this reason, function structures are not straight forward to define [Eckert 2013]. Vermaas [2013] discussed the ambiguity of the different functional descriptions of a product and provided responses to the coexistence of different meanings of function.

A BOM helps define the product structure by decomposing a whole into its parts. Plossl et al. [1994] used BOMs in the context of material requirements planning (MRP). McKay et al. [2004] developed a grid enabled product data viewer that illustrates this decomposition within a software prototype. In more recent work, Kashkoush et al. [2013] have worked on using tree reconciliation, a method from the biological sciences literature, to match BOMs and thereby cluster product variants into families. A BOM can be represented as a hierarchical graph structure, where the arrows indicate the relationship from the whole to its individual parts, as outlined in the systematic definition for design structures given by McKay et al. [2015].

2.3 Approaches to the management of design information

Product Data/Lifecycle Management system solutions support the management of design information, typically in the form of design objects such as files, through workflow processes. Anticipated benefits of integration across design objects themselves, and advances in design analysis, simulation and optimisation technologies and systems, have led to simulation-driven [Sandberg et al. 2013] and model-based engineering [Cloutier et al. 2015] solutions. Architecturally, such solutions involve tight integration of processes and tools around a single design definition. The feasibility of establishing the digital design models needed for full implementation is, however, questionable, especially when associated business risks such as reliability and affordability are considered. A key challenge in establishing such models lies in supporting the multiplicity of viewpoints needed throughout a product's life. In parallel with the development of data exchange standards such as IGES and STEP, numerous researchers have proposed underlying meta-models for different aspects of these digital design definitions. Common problems with the adoption of such models include their inflexibility in accommodating changing information requirements and in supporting multiple, sometimes conflicting, viewpoints of different types of user. More recently, applications of lightweight CAD models and annotations have been reported. For example, [Ding et al. 2009] and [Song and Chung 2009] report the use of lightweight approaches to create digital mock-ups of disparate CAD models. Annotation does, to some extent, support multiple viewpoints and changing information requirements, but is limited by the restricted structure of annotation data and an inability to annotate aspects of the design, such as functional information, that do not occur in a CAD model.

This paper explores the use of embedding as a way of relating different design structures to one or more design definitions. Embedding allows one instance of a mathematical construct to be superimposed on another [Wikipedia]. It has been documented since the 1930s in the mathematics literature. Descriptions of concrete applications are less common but do occur, e.g., in the shape computation literature [Stiny 2008]; methods to enable the robust implementation of embedding for use in real-world applications remains an open research issue [McKay et al. 2012]. The ultimate goal of the research reported in this paper is to explore the use of embedding as a way of allowing engineers to associate multiple design structures with a given design as and when such structures are needed. We report early results using NVivo 10 [QSR 2014], a qualitative data analysis software tool, and lightweight CAD models to embed design structures into design definitions.

3. Methodology

The goal of this research was to establish a small, desk-based case study that could be used to both communicate the potential value of embedding to end users and evaluate the feasibility of implementing embedding using currently available techniques. To this end, a robot was selected as the case study because (a) robotic systems incorporate complexities arising from multiple design perspectives, and associated structures, in relatively small systems, and (b) the data for the robot was availabe from previous work. The engineering scenario used was based on two iterations of the robot, where the robot underwent design changes in response to a change in functional requirements related to the robot performing in a new competition where the success criteria changed from collision avoidance to following a guide line. The case study is defined in Section 4. The selection of a pre-existing case study ensured independence between the case study, which reflects the engineering problem, and technical solution principles. Results from early experiments with computational methods, lightweight CAD models and NVivo, are reported in Section 5 and compared, in Section 6, with evaluations of design structure matrices and component-function analysis techniques.

4. Case study

The framework used to develop the case study is illustrated in Figure 1. It accommodates different people associated with the development of the product. These people typically use specific design structures that are relevant to their different roles in the development process. These structures, in turn, are associated with digital definitions of the product in formats generated by their creators. The digital definitions could be a 3D CAD model, an engineering drawing or other textual/visual material. By considering how multiple design structures may be embedded within a given design definition, the potential benefits of embedding can be explored. The structure of this section reflects this framework.

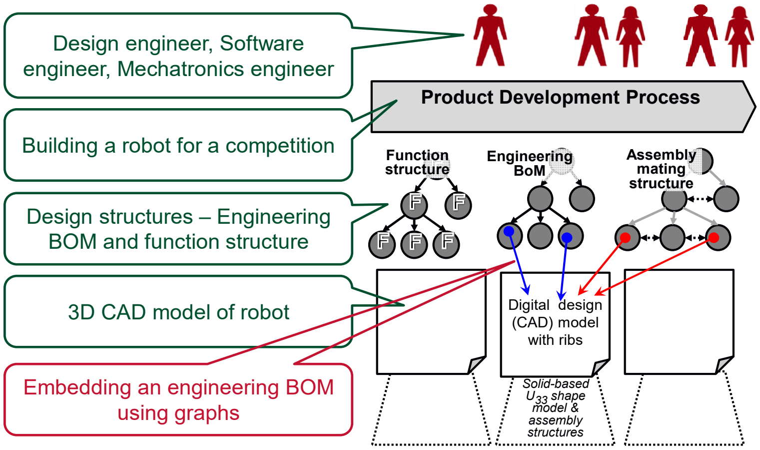


Figure 1. Case study structure

4.1 User scenario

The user scenario considered in this study involves a robot with a two wheel drive, shown in Figure 2. The robot was originally designed to navigate a specified area while avoiding collision with obstacles. Subequently, it participated in a competition where the goal for the robot was to follow a white track and return to the starting point indicated by a magnet. It can be seen from Figure 2, that there is no direct relationship between the design requirements and the physical design. As a result, if a design requirement changes, expert human intervention is needed to determine the impact of the change on the product itself and, therefore, downstream processes such as manufacturing. Suh et al. [1982] identify a need for mappings between representations of a design in both functional and physical domains to help interpret functional couplings. In this paper we show how, by relating design requirements and a function structure to each other, the relationships needed to support design decisions become available.

4.2 A function structure for the robot

Function structures were built by breaking down the robot's overall function into sub-functions. For the collision avoidance robot, a function structure has been created as shown in Figure 3. The overall function of the robot is to navigate from a start position 'A' to a target end position 'B', while avoiding

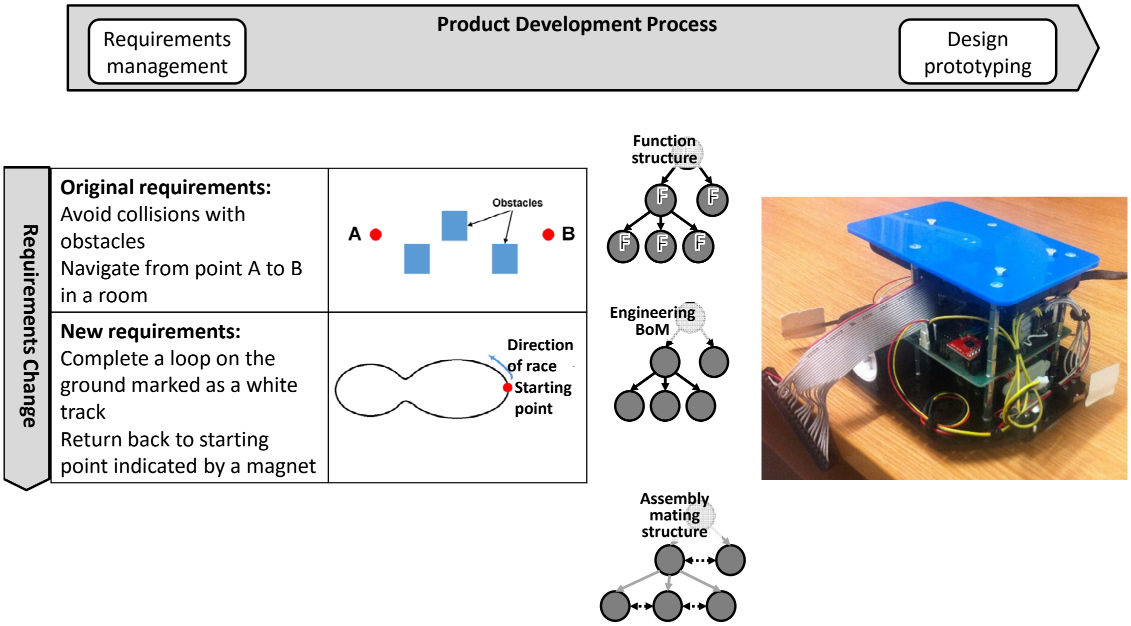


Figure 2. Case study product, associated design structures and change in requirements

obstacles. Assembly mating conditions connecting the components are necessary to create the assembled robot.

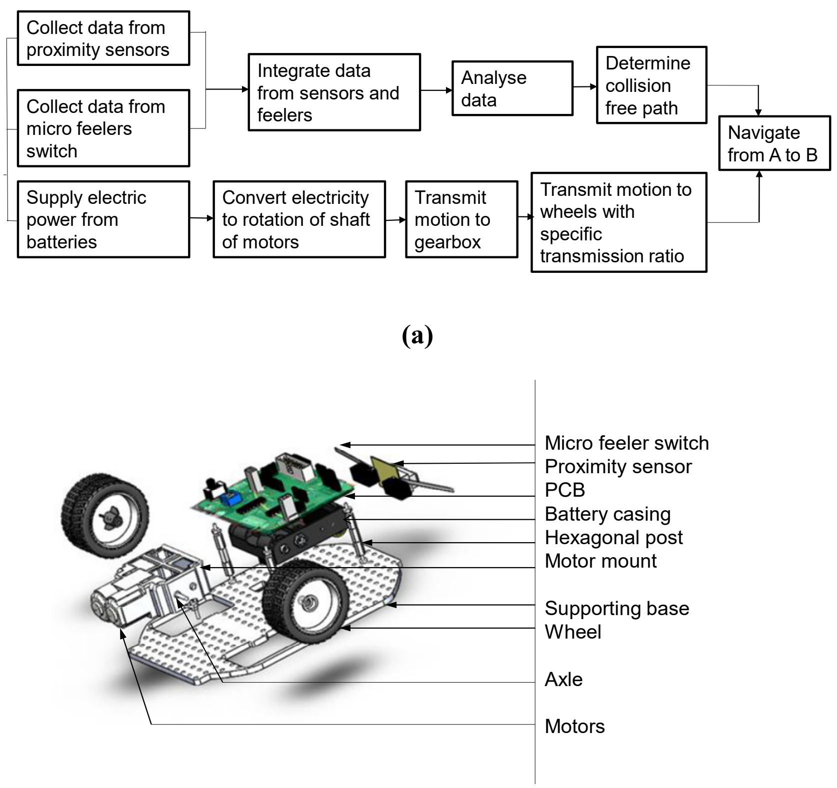
The basic function of navigation is implemented by supplying electric power from batteries. This power is converted to rotation of the shafts of the DC motors. The motion of the shaft is transmitted to the axle connecting the wheels of the robot after passing through a gearbox with a specific transmission ratio. While this is the basic function, the robot also needs to avoid collisions. To achieve this, it collects data from proximity sensors and micro feeler switches. This data is integrated and analyzed to determine whether or not there is an obstacle on the path. A collision-free path is thus determined and used to navigate the robot. It is noteworthy that building the function structure in Figure 3(b) required relationships to the physical domain (in the form of the exploded assembly shown in Figure 3(a)). This kind of mapping between domains is key to any design process [Kim et al. 1991] and this example shows how the presence of relevant design structures can assist this process.

4.3 Bill of materials for the robot

The robot was decomposed into its engineering BOM as shown in Figure 4. It should be noted that although wires and fasteners are included in the BOM, they are not always considered a part of the CAD model and, as a result, may not feature in the same. In particular, wires are usually not rigid elements and hence, often omitted from 3D CAD models.

4.4 Relationships between the design structures

The four different definitions for the robot design (requirements, function structure, shape model and BOM) were mapped to each other as shown in Figure 5. In mathematical terms, this kind of mapping can be classified as an embedding of one definition within another [Stiny 2008]. The mapping is injective and structure preserving. It represents a topological isomorphism between two sets and is a continuous function with a continuous inverse. Such a function preserves distinctness in the sense that every element in the co-domain of the function has only at the most one image in the domain [Bartle 1964].



(a)

(b)

Figure 3. Function structure for the collision avoidance robot: (a) relates to the individual components in the exploded view of the assembly shown in (b)

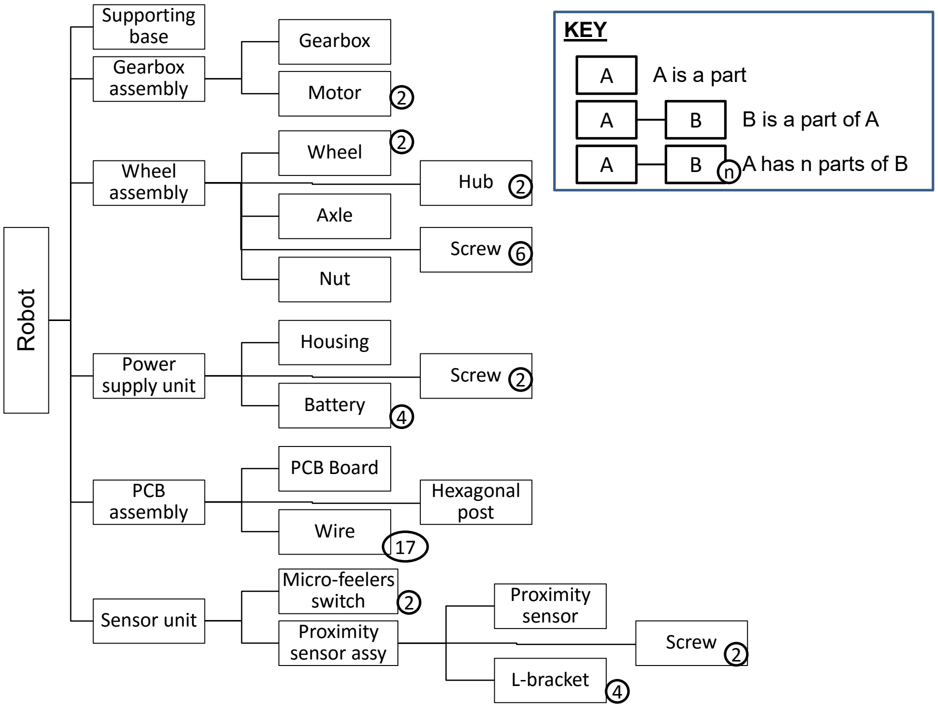


Figure 4. Physical structure of the robot's engineering BOM

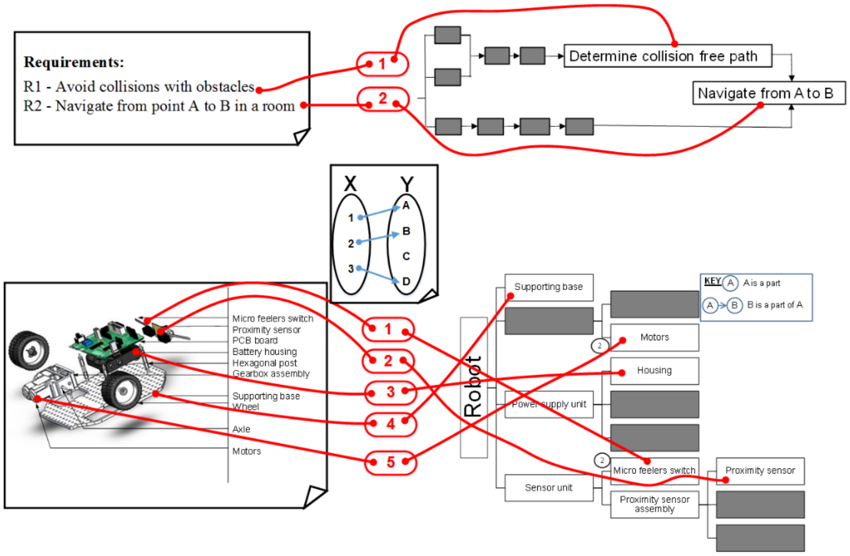


Figure 5. Relationships between different design definitions for the robot showing (top) how requirements are related to the function structure and (bottom) how the shape model is related to the bill of materials (inset) an injective mapping is evident from this relationship mapping

5. Results

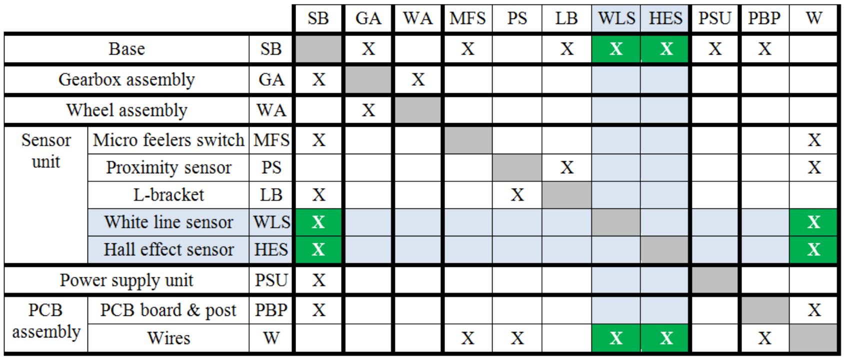
Results from early experiments exploring how the change in requirements in the case study might be accommodated in the design descriptions are reported in this section. The use of a Design Structure Matrix is outlined in Section 5.1, followed by examples from the annotation of a lightweight CAD model in Section 5.2 and the use of a qualitative research tool, NVivo, to establish relationships between the different design descriptions (Section 5.3).

5.1 Change management using Design Structure Matrix

Design Structure Matrix is a method used to organize the design of a physical system and capture flows, interactions and interdependencies between the elements that comprise the system [Steward 1981]. It helps relate entities of a given kind, such as parts, to each other [Lindemann 2009]. Tang et al. [2010] discuss how DSM can be used to assist designers in predicting the impact of changes on current solutions and their reuse on new projects. A component-based DSM was drawn up for the collision avoidance robot. The new requirement, to track a white mark on a dark backgound, was met by placing a white line sensor on the bottom of the robot. Likewise, the requirement to return to the starting point indicated by a magnet was met by using a Hall effect sensor. These additions were wired to the PCB assembly so that their outputs could be used in the logic required to meet the new requirements. This led to the DSM for the 'follow the line' robot in Figure 6. The shaded columns/ rows are additional for the 'follow the line' robot and the green boxes are the new interdependencies vis-à-vis the collision avoidance robot. It may be noted that sub-assemblies not involved in the change are shown as parts in this figure and fasteners are omitted to save space.

5.2 CAD lightweight experiment

Experiments with a lightweight CAD model used a Solidworks model that was exported as a 3DXML file and imported to eDrawings, a free Solidworks viewer provided by Dassault Systèmes. Different annotated markups were created showing individual components of the robot, and NVivo was used to incorporate image files of the BOM and function structure. These annotations were exported and stored as .markup files, for later use within eDrawings. The lightweight model together with the markups was also separately stored as a *.easm file. This approach makes it feasible to send markup files to project collaborators with change details mentioned without having to send an entire CAD model



			SB	GA	WA	MFS	PS	LB	WLS	HES	PSU	PBP	W
Base		SB		X		X		X	X	X	X	X	
Gearbox assembly		GA	X		X								
Wheel assembly		WA		X									
Sensor unit	Micro feelers switch	MFS	X										X
	Proximity sensor	PS						X					X
	L-bracket	LB	X				X						
	White line sensor	WLS	X										X
	Hall effect sensor	HES	X										X
Power supply unit		PSU	X										
PCB assembly	PCB board & post	PBP	X										X
	Wires	W				X	X		X	X		X	

Figure 6. DSM for the 'follow the line' robot

through, making change management a fast and visual process. The markup file can be used with any lightweight model derived from the original model, but is useful only if the absolute locations of the individual components have not been altered: the markup file has no intelligence about the CAD model from which it was generated. Functional information was captured by annotating relevant parts of the lightweight model using free-form text.

5.3 NVivo experiment

Image files from the lightweight experiment were imported into NVivo. Nodes representing elements of the design definitions from the case study were created and used to link individual elements of the BOM and function structure to the robot definition. This process enabled the embedding of information from design structures into the design definition so that, if changes to the design were reflected in the imported data, consequences of changes made to the robot design would be visible. Figure 7 shows how multiple design structures were linked up within the NVivo project environment to enable this. Figure 7 (a) shows a screenshot of the project showing nodes representing the definition and design structures in red boxes. The sub node for the proximity sensor shows three embedded relationships to an engineering BOM (b), an element in function structure (c), and the sensor highlighted by NVivo in an annotated image of the robot (d). In practice, there would need to be a live link between the design definitions in NVivo and the CAD system; this is the subject of current work.

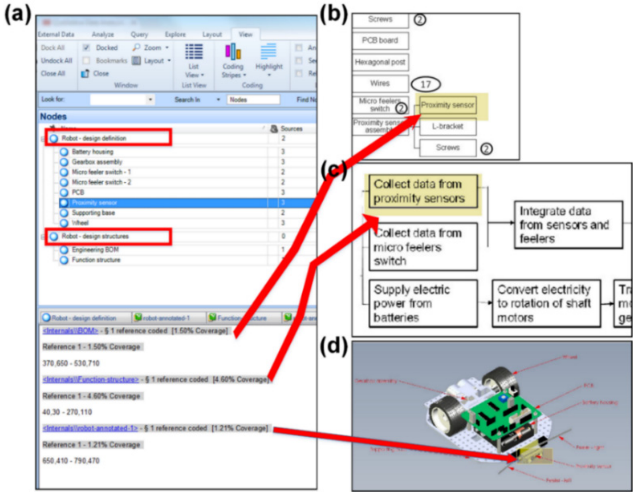


Figure 7. Experiment within NVivo

5.4 Summary

The addition of two new components to the robot resulted in eight new interdependencies to be analyzed. However, despite analyzing these interdependencies, there were issues with reusing the original design.

The DSM analysis did not reveal an important functional aspect of adding the white line sensor. The white line sensor had to be placed at an optimal distance on the bottom of the supporting base to maintain a specific clearance from the ground that enabled it to detect the white track. This functional characteristic could have been captured by embedding a new function structure for the 'follow the line' robot within the design definition. DSM does not have a framework to do this unless a domain mapping matrix had been used that could relate components to functions. The implementation of embedding was rudimentary but achieved its goal of allowing potential benefits to be evaluated. An important benefit of embedding, if implemented effectively, is that it allows shape models to be used to mediate different design structures that have been created and are used for different purposes. This could provide significant improvements for the planning and management of change management processes because managers would be able to visualise the impacts of changes.

6. Discussion and concluding remarks

This study demonstrated that current methods for reusing design definitions, such as DSM, become limited when the granularity of design definitions increases. Furthermore, with rapidly reducing product lifecycles, to stay competitive, product development-based companies need to be able to implement design changes quickly and reliably, ensuring that consequences of a change have been considered. Current matrix-based techniques can enable this, but with high storage requirements of complex designs and their definitions, it becomes costly to maintain multiple digital definitions of the same product in different parts of the company. Embedding design structures within a smaller collection of design definitions provides a potential solution by allowing shape models to mediate across design structures. Furthermore, capturing functional information, and relating it to design models, is critical for designing. The example of the gap between the white line sensor and the ground provides a simple example of how shape models such as 3D CAD files alone provide insufficient information for future designers.

This paper has reported research based on a single design case study and explorations of the potential benefits of embedding using currently available software tools. It was concluded that embedding offers significant advantages regarding change visualization and validation, data management, interpretation, querying, incorporation of hidden functionalities, design reuse and automation of change management. However, to realise this potential, significant further work is needed on the implementation of embedding and its integration with existing design solutions.

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