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A METHOD TO DEFINE A PRODUCT ARCHITECTURE EARLY IN PRODUCT DEVELOPMENT USING A CONTACT AND CHANNEL MODEL

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ABSTRACT

Defining a product architecture is one of the most important decisions during product development. Most researches in this field are focused on the modification of a product architecture, meaning that the design process is carried out based on the predefined architecture. Consequently, the obtained results are difficult to be used. This paper focuses on the determination of the product architecture in the early phase of product development, in which the product architecture is often developed intuitively. In this paper, a model to describe a relationship between a function and embodiment, the Contact and Channel Model (C&CM), a method to define a product architecture and its corresponding implementation will be presented. After a principle solution has been selected, the system is modeled with C&CM elements. An integration analysis using Design Structure Matrix (DSM) can be performed in parallel with the use of a search algorithm. The analysis result is a guideline for an optimal architecture. This helps designers to decide the product architecture prior to the launch of embodiment design. This method is implemented in the development of a robot forearm for the humanoid robot ARMAR III.

Keywords: Product architecture, Contact and Channel Model, Design Structure Matrix

1 INTRODUCTION

1.1 Paper Structure

The first section presents an overview of the product architecture background, the characteristics of a modular and an integral product as well as the motivation for this research. The state of the art necessary to define the product architecture in the early stage of product development, problems and the research objectives will be discussed in section 2. A concept and a description of the approach with Contact & Channel Model (C&CM) used in this research will be explained in section 3. This method includes the evaluation of the interactions between Channel and Support Structures (I_{CSS}) and a measure of the degree of satisfaction. An implementation and the result of the method will be shown in section 4. The final section includes a conclusion as well as proposals for the future work.

1.2 Background and Motivation

Product architecture is a hierarchical structure that illustrates the arrangement of all product parts and product assemblies. Product architecture can influence product properties and production processes, in which cost, quality, production time and business complexity are dependent massively upon [1]. Hence, developing the product architecture is a key phase in a design and development process [2]. Product architectures can be classified into modular and integral architectures. Modular product architectures generally consist of various detachable groups of component. One way to characterize a modular product is to consider the interactions between physical components. In this case, a dependency matrix [3] is normally applied as an analysis tool to identify the groups of physical components that have more internal than external interactions. These are known as “modules”.
It is ambiguous to decide which product architecture is better since modular and integral architectures possess particular advantages. The question then arises: Which product architecture can meet the requirements under the specified constraints and target system [4] better? It is of great importance to determine how modular the product architecture should be. The design constraints and the target

system that a designer needs to consider are, for example, the product requirements (i.e. weight, dimensions, etc.) and the process conditions (i.e. assignment of tasks, production, and manufacturing), which can be commonly found in the requirement list.
As a summary, a module in this paper means a group of components that:

- can perform a function by itself.
- has more internal than external interactions (functional interactions with suitability values).
- can be detachable.

2 STATE OF THE ART AND RESEARCH OBJECTIVE

Numerous researches to optimize product architecture can be found in many publications, nevertheless, only an analysis of the existing product to enhance the architecture using analysis tools such as Design Structure Matrix (DSM) [5] or Modular Function Deployment (MFD) [6] is in focus. The result of the analysis cannot be appropriately applied to the current product, since once the product architecture is presumably defined, the embodiment design is already finished and the product works. There is a strong temptation to get it into production [7] since the modification of the architecture on the finished design can cost a lot of effort and time. Based on the presumed architecture, a significant advantage of the optimal architecture can be lost. To avoid such situations, the analysis must be carried out in the early phase of the product development before the start of the embodiment design.

The idea to define the product architecture in the early phase (the conceptual phase and the beginning stage of embodiment design), is not unprecedented. It has been included in several well-known development processes and also published in some research papers. They can be classified into two types of approaches as followed:

- intuitive approaches using both function information and a layout of a system
- quantitative approaches based on integration analysis of function information

The approaches in the first group are applied without any quantitative computation. Examples include the methods from VDI 2221, Ulrich/Eppinger and Van Wie. Design guideline VDI 2221 [8] proposes a step to determine the product architecture by grouping elements in the principle solution. Various aspects through product life cycle have to be considered to determine the product architecture. Similarly, Ulrich and Eppinger [9] recommend "a four steps method" to decide the product architecture in the conceptual design. Function elements in a function structure are clustered into chunks, from which the modules in the architecture are derived. Likewise, Van Wie [10] applies function information and many types of diagrams to describe the system and to determine the architecture. Due to their simplicity and their use of both the function information and the layout information, many advantages can be gained, such as an increase in their application flexibility as well as a reduction in implementing time and effort. Nevertheless, they should only be carried out by experienced designers.

In the second approach, the methods are mainly based on the quantitative integration analysis of the function elements in function structure. This group includes the approaches from Hölttä, Stone and Allen. Hölttä [11] analyzes the integration of the system functions using Dendogram. Stone [12] suggests three Heuristics methods with an analysis of the function integration based on customer-need evaluation to make a decision on product architecture. In the same way, Allen [13] decides the architecture through an analysis of the function integration as well as product architectures of the products from previous generations and the development team. In comparison to the methods base on the intuitive approach, the advantage of the method with quantitative approaches is that it is able to search for the optimal solution, in which a comparison of various architectures can be numerically determined even if the designers are inexperienced.

So far, both alternatives are operated independently and gained different leverages in their own manner, however, the approaches from the first group could lead to some difficulties to decide the architecture without any measurable value especially in the case of many concerning factors or when the architecture is developed by non-experienced designers. On the other hand, the approaches in the second group are not very suitable for analyzing the geometry information. This can cause a conflict between the analyzed result and the geometry constraint. Two main causes leading to the difficulties mentioned earlier can be identified as follow:

- Geometry information and function information are either separated or not sufficiently connected.
- The architecture definition is non-quantitatively determined when the geometry information is concerned.

The objective of the research is to develop a new method that eliminates both of these problems and combines the advantages of both groups of existing approaches mentioned earlier.

3 APPROACH WITH C&CM

3.1 Approach Concept

Our concept to solve these problems will be subdivided into two parts as shown in figure 1, namely i) connecting geometry information and function information and ii) integration analysis. In the first part, the elements and their corresponding hypothesis based on the Contact and Channel [14] (more detail in section 3.2) to generate the element connections are used to link the function information and the geometry information together. This link might also be created other comparable elements such as by "function carrier" or "interaction". Nevertheless, using C&CM takes advantages of the systematic generating process, for which its supporting representation is currently being developed. This representation supports a system understanding by expressing a position of function. With this kind of representation, both types of information will be simultaneously expressed.

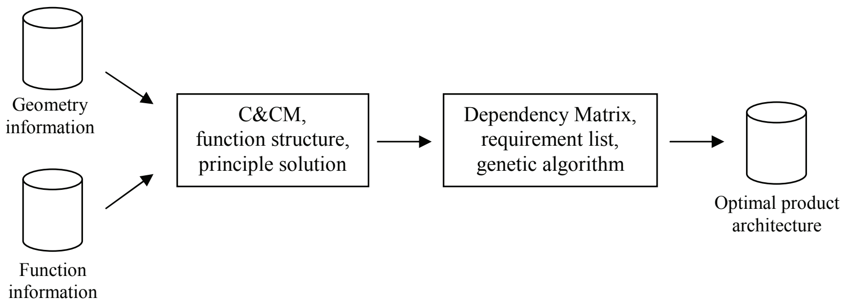


Figure 1. Approach concept

The second part will focus on the search for the optimal architecture which is based on a generated C&CM model from the first part. A matrix representation, an evaluation and a genetic algorithm are used together to obtain the optimal solution.
The following section provides an overview on C&CM and a description for the approach will be concretely explained step by step in section 3.3.

3.2 Contact and Channel Model (C&CM)

C&CM is an elementary design model which has been developed at the Institute of Product Development (IPEK). Technical products have been conventionally modeled with defined geometries which are grouped into sub-systems. The C&CM approach models the products by using two basic elements - Working Surface Pairs (WSP) and Channel and Support Structures (CSS). These can be defined as follows [15]:

- "WSP" are pairwise interfaces between two components or between a component and its environment. Working surfaces can be a solid surface of a body or a boundary, a surface of liquid, gas or field which comes into permanent or occasional contact with the Working Surface (WS). They take part in the interchange of energy, material or information within the technical system.
- "CSS" are a physical component, a volume of liquid, gas or space containing field which links exactly two WSPs. They do not only participate in a transfer of energy, material and information from one WSP to another but they can also store them (e.g. the mass inertia).

The model C&CM is a way of explaining technical systems with a reference to their geometries and functions simultaneously. C&CM bridges the non-connected functional and component-level descriptions without the need to switch between them [16]. There are some applications that use this element model to support designers to analyze and to synthesize a technical system. Examples include an application in the development of a bolt connection and an application in a synthesis exemplified on the friction contact between pin and disc of a Continuously Variable Transmission (CVT).

To model the C&CM, the following hypothesis [17] have to be met:

„To realize a function in a technical system one Channel and Support Structure and at least two Working Surface Pairs are necessary"

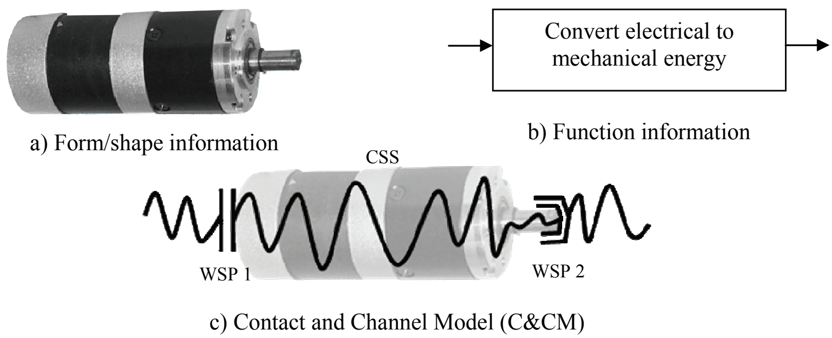


Figure 2. Example of C&CM, a combination of function information and embodiment information

Figure 2a shows physical characteristics of a motor, which are necessary to decide a position, a connection, orientation, etc. From another viewpoint of the same system, the function information of the motor underlines the task "convert electrical to mechanical energy" of the motor without any physical characteristics of the motor (e.g. size, shape). A C&CM connects both viewpoints of the motor as illustrated in figure 2c. It does not show more information than those from figure 2a and 2b, but it connects both viewpoints together by locating a CSS and defining two WSPs, which fulfill the function, into the geometry layout of the system. The location of the function can be clearly noticed by C&CM.

3.3 Description of the approach

The concept to define product architecture in the early stage of product development using C&CM can be divided into three steps, namely generating a C&CM Dependency Matrix (CDM), evaluation of CDM and analysis of clusters in the CDM as shown in figure 3. An academic example of a development of a universal joint will be explained in this section.

<u>Step 1: Generating a C&CM Dependency Matrix (CDM)</u>

Firstly, the relevant parts of the target system for the product architecture has to be determined. Normally, they are predefined in the requirement list for various aspects of "Design for X" (e.g. design for assembly or design for maintenance). Their importance factors are subsequently defined. These are scaled from 0 to 1. After the requirements and boundary conditions are defined, a specific function structure with a corresponding principle solution is needed. A function structure used to create ideas in the conceptual phase [18] has to be modified and detailed. Especially for the original design, only the rough function structure (i.e. Figure 8) containing main tasks to be fulfilled by a system are created. It has insufficient detail to be used for the integral analysis in our approach. To provide a reasonable detail to this function structure, the principle solution detail will be used as a reference.

Normally, the function structure of the product is a combination of basic and auxiliary functions. In the C&CM, the functions and their interactions are modeled as CSSs and WSPs. A complex technical system is usually composed of numerous CSSs and WSPs. This makes the system representation relatively unorganized and not suitable to analyze the integration. For this reason, another representation is required.

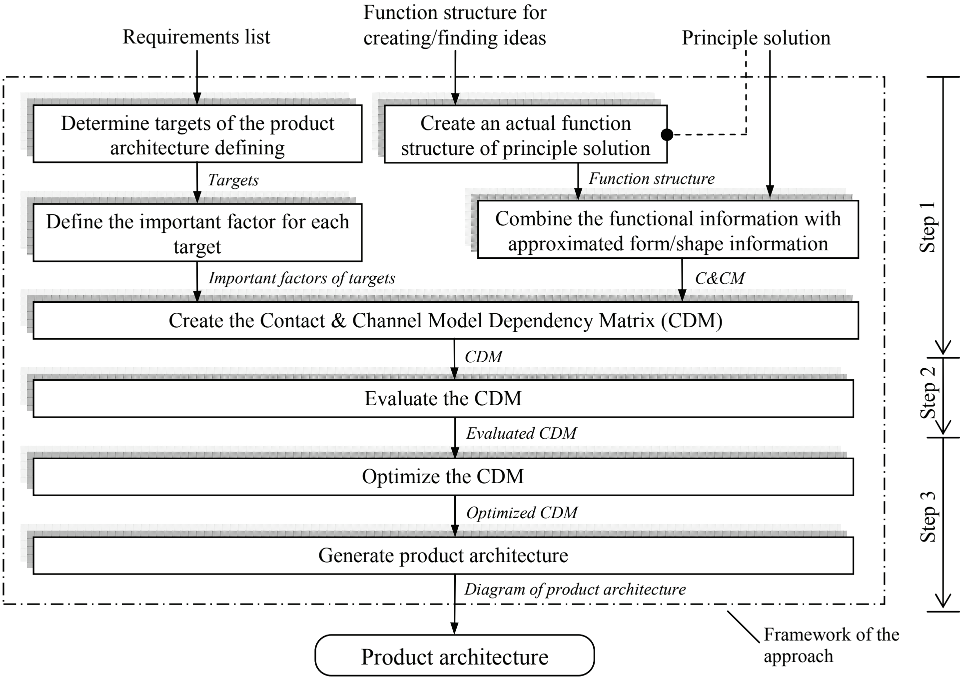
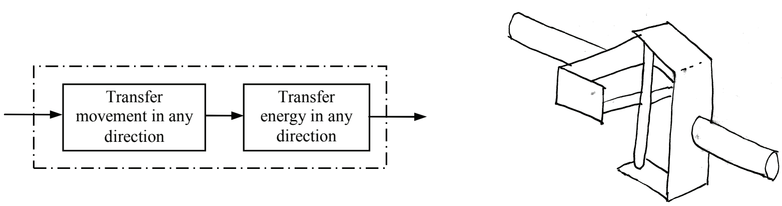


Figure 3. Approach for defining a product architecture with C&CM

A dependency matrix or a design structure matrix is matched to this condition. A C&CM Dependency Matrix (CDM) is a diagonal matrix containing CSSs which are all listed on the matrix headers. The CSSs are subsequently mapped to each other through their corresponding WSPs which are entered into the matrix to illustrate this relationship.



a) function structure for finding idea　　b) selected principle solution

Figure 4. An example system of a joint

A simple function structure of a joint is shown in figure 4. The joint must perform two main functions; transfer movement and energy in any direction. After many solutions were created, one solution similar to figure 4b was selected. In our approach, the embodiment design has not yet started. Initially, the target system is analyzed. In this example, we assume that the system has two targets; Design for A (3 modules) and Design for B (2 modules), for which their important factors are given as 0.3. Comparing which architecture is better may prove to be difficult for the designers. Therefore, the solution which compromises both requirements has to be found. Afterward, the C&CM model of the system is generated as illustrated in figure 5. The model consists of ten CSSs for ten sub-functions. This model will be used as a basis to create a CDM by listing all CSSs into a matrix, in which the evaluation of the interactions is taken as an input for the second step.

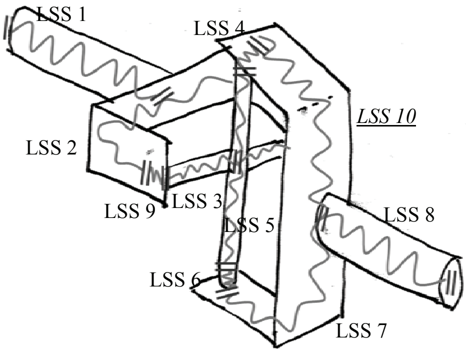


Figure 5 A C&CM model of the system

Step 2: Evaluation of CDM

In this approach, the CDM matrix with the evaluated interactions (I_{CSS}) is the main integration analysis tool. The interactions are evaluated in terms of the functional interactions and the suitability values and subsequently grouped into modules. The satisfaction index (Z) can then be computed based on this matrix. After the computation, the CSSs in the CDM are clustered and result in a matrix with the maximum satisfaction index.

Two main calculations in this approach are the evaluation of the "interactions between CSS" (I_{CSS}) and the determination of the satisfaction index. The evaluation of each interaction between CSSs requires two sets of parameter including the "influencing parameters of the WSP" (W_{WSP}) and the "suitable parameter for CSS" (S_{CSS}). I_{CSS} is the sum of "S_{CSS_i}" and "W_{WSP_i}". W_{WSP_i} concerns three functional interactions (force, energy, information) [19]. "S_{CSS_i}" illustrates the suitability between two CSSs which should be grouped together into the same module according to their suitability perspectives. For example, the durability of two CSSs which is expected to be equal can be suitably grouped into the same module because of the simplification of the recycling process. The evaluated equation has a maximum value of 1 for each I_{CSS} and can be formulated as shown in equation (1).

The values of the mentioned parameters above are influenced by the significance of each aspect in the product requirements. This step should be carefully considered since the result of the search for product architecture in the next step strongly depends on this selection.

$$I_{CSS} = \sum_{i=1}^{3} W_{WSP_i} + \sum_{i=1}^{m} S_{CSS_i} \tag{1}$$

where: W_{WSP} = weight factor of each functional interaction (energy, material and information)
S_{CSS} = weight factor of each product architecture purpose
m = number of product architecture purpose

All I_{CSS} are then entered into CDM. The Z value can be subsequently computed according to the definition of module which is similar to a computing of degree of modularity as follows:

$$Z = \frac{\left(\frac{\sum I_{CSS}}{\sum I_{CSS,\max}}\right)_{\text{inside module}} - \left(\frac{\sum I_{CSS}}{\sum I_{CSS,\max}}\right)_{\text{outside module}}}{\text{Numbers of modules}} \tag{2}$$

In the case for CDM, this can be formulated as followed [20]:

$$Z = \frac{\sum_{k=1}^{N_m} \frac{\sum_{i=n_k}^{m_k}\sum_{j=n_k}^{m_k} I_{CSS_{ij}}}{(m_k - n_k + 1)^2}}{N_m} - \frac{2\times\sum_{k=1}^{N_m}\sum_{p=k+1}^{N_m} \frac{\sum_{i=n_k}^{m_k}\sum_{j=n_p}^{m_p} I_{CSS_{ij}}}{(m_p - n_p + 1)(m_k - n_k + 1)}}{N_m} \tag{3}$$

where: n_k , n_p = index of the first CSS in k[th] module and p[th] module
m_k , m_p = index of the last CSS in k[th] module and p[th] module
N_m = total number of modules in the product
I_{CSSij} = evaluated value of matrix element (row i and column j in the matrix).

One configuration of the product architecture delivers one value of Z.

For example, if we continue our approach with the evaluation of the I_{CSS} values in the CDM of the joint in figure 5, which are configured in both cases as shown in Table 1. Each value is calculated from the equation (1). Taking one example for I_{CSS} between CSS 3 and CSS 9, the computation can be executed as $I_{CSS39}= W_{WSP39} + S_{CSS39A} + S_{CSS39B}$ = 0.4 + 0 + 0.3 = 0.7. After the evaluation of all I_{CSS}, the CDM (as shown in figure 6) is now prepared for the integral analysis in the next step.

Table 1 Member of CSS in each design target and their important factor

	Important factor	**CSS in module 1**	**CSS in module 2**	**CSS in module 3**
Functional interaction	0.4	-		
Design for A	0.3	3, 5	4, 6, 7, 8	1, 2, 9, 10
Design for B	0.3	4, 5, 6, 7, 8	1, 2, 3, 9, 10	-

	1	2	3	4	5	6	7	8	9	10
CSS 1	0,0	1,0	0,3						0,6	0,6
CSS 2	1,0		0,3						1,0	1,0
CSS 3	0,3	0,3			0,7				0,7	0,7
CSS 4					0,7	0,6	1,0	0,6		
CSS 5			0,7	0,7		0,7	0,3	0,3		
CSS 6				0,6	0,7		1,0	0,6		
CSS 7				1,0	0,3	1,0		1,0		
CSS 8				0,6	0,3	0,6	1,0			
CSS 9	0,6	1,0	0,7							0,6
CSS 10	0,6	1,0	0,7						0,6	

Figure 6. The evaluated CDM of the system

<u>Step 3: Analysis of clusters in the CDM</u>

The Z value shows how much the product architecture can satisfy its purposes. In this research, this value is to be maximized in order to obtain the optimal architecture under the given constraints. In this step, the main purpose is to determine the architecture which delivers the maximum satisfaction index (Z_{max}). This value is the function of the entire set of variables from equation (3). Due to the complexity of the calculation, it is not possible to use the analytical way to find out this maximum value. A search technique is to be used in this step. In this research, a Genetic Algorithm (GA) [21] with an integer encoding is selected. Its aim is to search for the optimal number of modules and the best arrangement of all CSSs. After a matrix containing Z_{max} is determined, the product architecture can be easily sketched by the conversion from the matrix representation to the C&CM representation. The layout of the product architecture can then be illustrated.

With this result, optimal product architecture can be established and visualized in the C&CM nomenclature. The following points should be considered:

- Number of modules of the product
- Functions or CSSs included in each module
- Boundaries of each module and interactions with other modules
- Detachability and connecting positions
- Rough product layout to assist the design of connecting components.

For example; the Z value can be calculated as Z_B = 0.5[2×(13.6/25) - 2×(0.7/25)] = 0,516. The GA searching provides 0.516 as the maximum value. The configuration as in figure 7b could be subsequently suggested as the product architecture in the embodiment design step. The architecture in the case A delivers the value of only 0.183 and a compromising architecture of both conditions in figure 7c provides a relatively high value with 0.425. With the approach using C&CM, the designer receives the guiding architecture information prior to the start of the embodiment design. Two examples for this case include:

- Two modules system
- Detachability concerning the WFP between CSS 3 and 5.

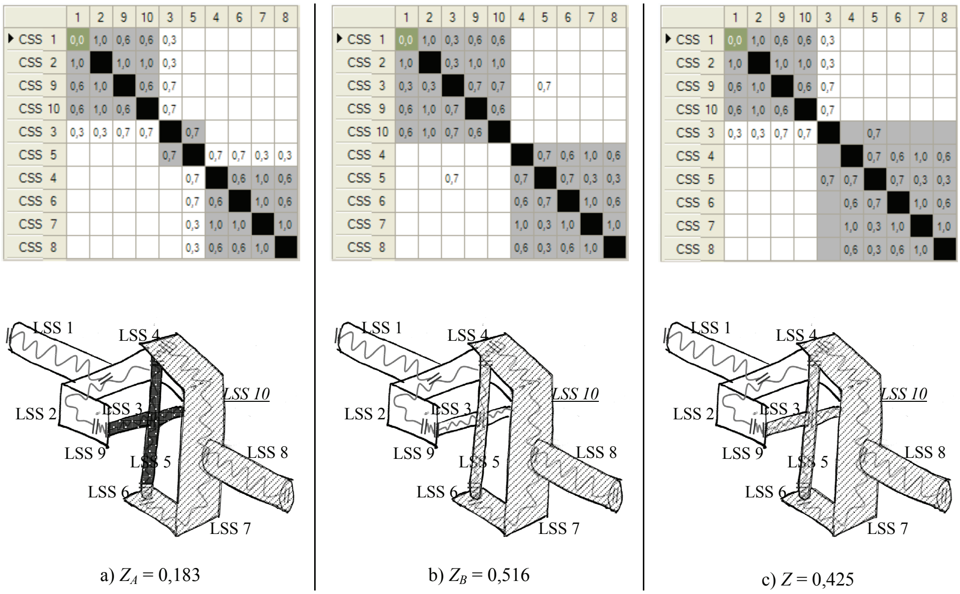


Figure 7. Compare of three product architectures

In the next section, an application for a more complex system will be presented step-by-step.

4 APPLICATION

The development of the forearm of the humanoid robot ARMAR III from the collaborative research center (SFB) 588 "Humanoid Robots" [22] is taken as a reference application in this research. Our approach focuses on the stage after the conceptual phase. A function structure was generated in the conceptual phase to find ideas, which are represented by four functions in figure 8. One side of the forearm is attached to the elbow while the other side is connected to the hand. Information and energy are exchanged between the forearm and the hand and also between the forearm and the elbow. The main function of the forearm is to realize the motion of the hand which duplicating the motion of the actual human wrist.

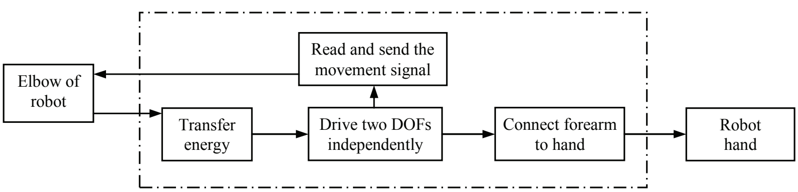


Figure 8. Function structure for finding ideas in conceptual phase

After many solutions have been created, the solution shown in figure 9 was selected as a principle solution. After that, the function structure was particularized based on this principle solution as presented in figure 10. The forearm fulfills 22 basic functions with 28 functional interactions. In this step, all the basic functions and the interactions are assigned into C&CM nomenclature.

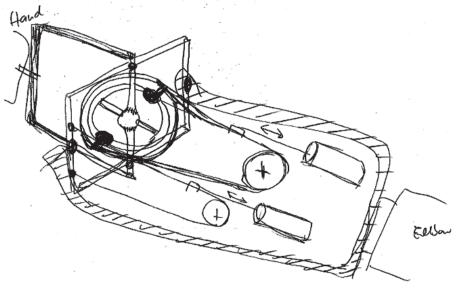


Figure 9. Selected principle solution

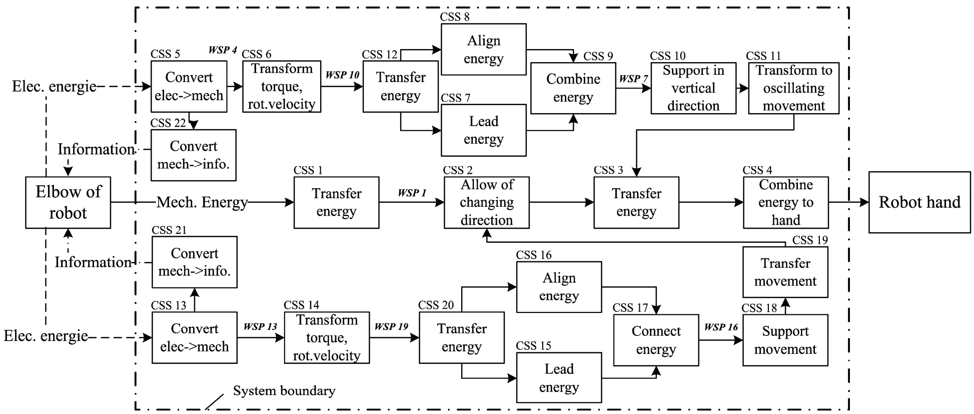


Figure 10. Function structure of robot forearm relied on principle solution

Modified function structure and geometry information from the sketch of the system are connected together with C&CM. All CSSs and WSPs are located into the sketch of the principle solution, as shown in figure 11.

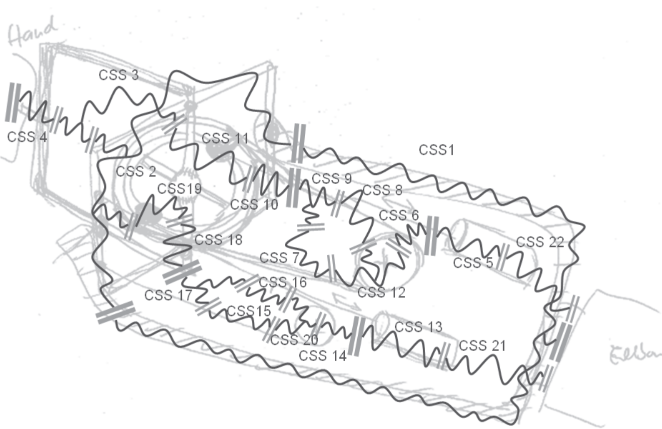


Figure 11. C&CM of robot forearm

In this example, the energy interaction as well as the service and the upgrade aspects are essential. The importance factors equal to 0.6 for functional interaction and 0.4 for the service/upgrade aspects are given. After the beginning of C&CM modeling, the CDM matrix is created.
Afterward, all CSS interactions are quantitatively evaluated in order to prepare the matrix for the cluster analysis as shown in figure 12a. In this initial stage, the value of Z is 0.135. The optimal product architecture can then be searched with the genetic algorithm. The objective function to be maximized is the satisfaction index. In this case, the result is that Z_{max} is equal to 0.446 when the forearm consists of four modules (figure 12b).

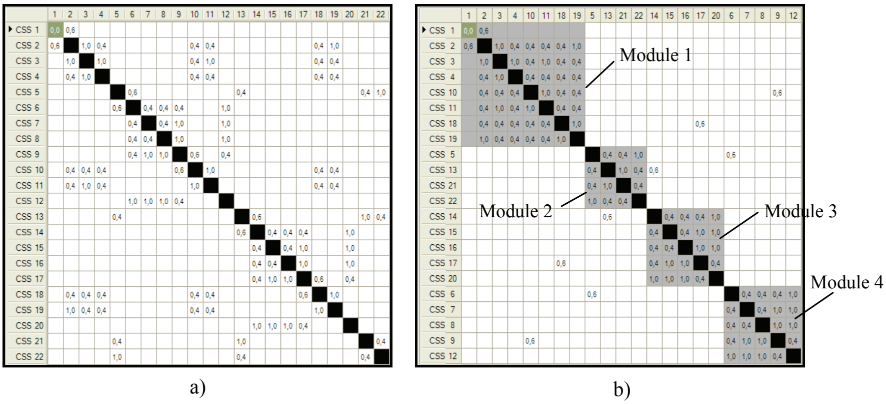


Figure 12. a) CDM before (Z=0.135) and b) after clustering (Z_{max}=0.446)

Without any analysis, the layout of the product architecture might be totally integral. The result of the analysis has shown several important points which are useful in the embodiment design phase. This robot forearm should have four modules which contain CSSs as shown in figure 13.

a)

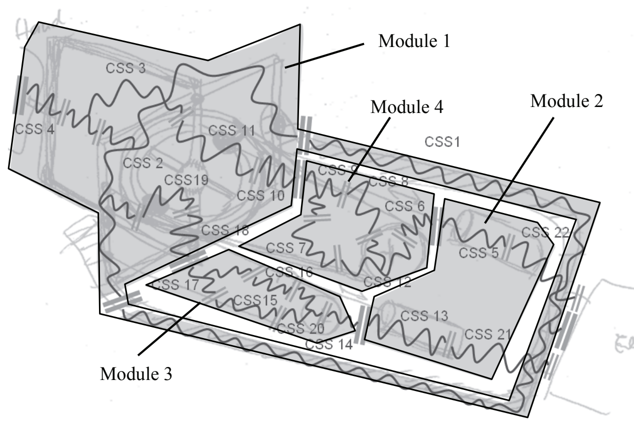


Figure 13. Result of the approach

The detachability of the connecting surface of the modules (WSP 4, 7, 13 and 16) has to be considered. The auxiliary connecting elements involving these WSPs should be detachable in these WSPs. The internal structure of each module can be constructed in an integral manner. This suggested layout of the product architecture was further implemented in the embodiment design phase. The actual design is illustrated in figure 14.

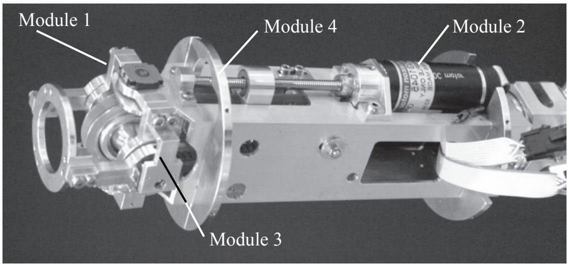


Figure 14. The real design of the robot forearm

5 CONCLUSION AND FUTURE WORK

In this paper, some approaches to decide the product architecture in the early phase and the corresponding implementation problems are presented. Although many advantages have long been apparent during the embodiment design phase, an approach using geometry and function information and their suitable supporting tool have not been existed. Clustering analysis with C&CM is suggested in this paper as a problem-solving tool with the aim of defining the optimal product architecture early in the design/development process. A Genetic Algorithm was used to search for the configuration of CDM which provides the maximum satisfaction index. An application of the approach in the development of a robot forearm in the early phase has been shown. This architecture is optimized according to the functional, service and upgradeability aspects. The result helps the designers to define the layout of product architecture which supports the further development of the embodiment design process.

Future work comprises the development of an easy-to-use software tool, the implementation of an efficient search algorithm, an improvement of the approach for the case of multiple restrictions. The application of the approach on a 3D-CAD sketch model, the analysis of sensitivity as well as the defining of the importance factors must be further studied.

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