A FUNCTION-ORIENTED APPROACH FOR A MECHTRONIC MODULARIZATION OF A SENSOR-GUIDED MANUFACTURING SYSTEM

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ABSTRACT

Nowadays, the development of special machines still depends a lot on the experience and knowledge about mechanic design and construction. This paper presents an innovative approach for reusing mechatronic modules that are assigned to so called solution neutral functions. This way, the developer is able to conceive a modularized blueprint based on a description of the function of the special machine. Thereafter, the developers have to select matching modules from a catalog.

An important prerequisite is to modularize mechatronic system in such a way, that they can be resued in various machines. Therefore, machine systems are modularised by an extended *Axiomatic Design*. The resulting modules have to be assigned to solution-neutral functional descriptions and integrated into a database. In the present paper both, the approach for the modularization and to the development, will be presented and illustrated by examples.

Index Terms - Mechatronic Engineering, Functional Description, Mechatronic Modules, Mechatronic Units, Modularization, Axiomatic Design, Manufacturing Processes, Modular Machinery

1. INTRODUCTION

In the development of special machinery, customer requirements are always firstly analysed. Functions that meet these requirements are then derived by the process of customer mapping, which describes the application of functions. The developer searches suitable physical solution principles, which can realise these functions. Today searching of physical solution are always done by the knowledge and experience of the engineers with the help of creativity techniques. Finally, these components are described in detail in process mapping.

An alternative to the described procedure is to reuse and adapt the already known machineries. In order to reduce the adaptation effort a catalog with mechatronic units or modules could be developed that corresponds to the standard parts catalog. However, these modules alone do not help the developers to find solutions for new machinery. Therefore, solution-neutral functions are introduced that can be assigned to mechatronic modules. The developer will be assisted in finding appropriate modules by these relationships.

Figure 1 illustrates the approach for a mechatronic modularization of new machinery. Left is modularization of an existing machine, which illustrate the procedure of generating a database of mechatronic modules, while on the right is engineering of new machinery by using this database.

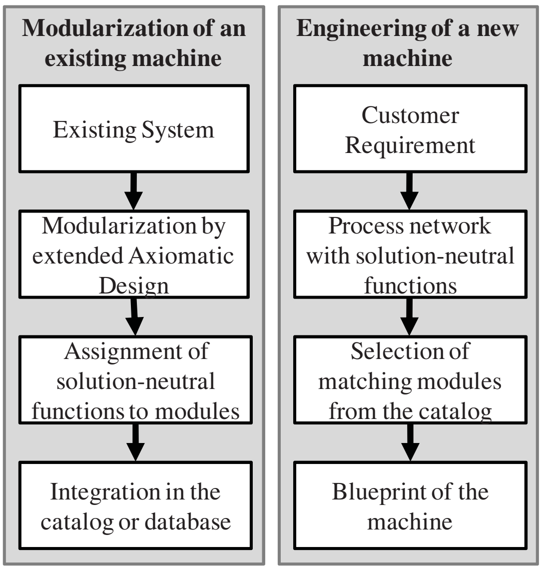


Figure 1. Procedure of modularization (left) and engineering (right).

The modularization is done by *extended Axiomatic Design.* Therefore, the modules´ complexity is important in order to ease the engineering process. If on the one hand the modules are too complex, the units cannot be reused or have to be adapted very much. On the other hand, the benefit of reusing mechatronic modules is reduced by low complexity.

2. STATE OF THE ART

A manufacturing system consists of different components which can be described as mechatronic units. Lüder et al. described a systematical engineering approach for manufacturing system with mechatronic units. Question of interfaces and complexity were discussed. In addition, Weyrich et al. presented a method for modularization of a mechatronic system [1, 2, 3, 4]. Further the function and the design of mechanical components in mechatronic systems and their simulation were described by Weber [5, 6].

An interdisciplinary process of collaboration during the development process is described as mechatronic engineering. The essence of these methods is a continuous and systematic description for coordination of requirements [7, 8]. In addition, the utilization of simulation software tools for providing a mechatronic models of high quality was described by Reuter et al. [9, 10]. These approaches correspond to the general design methodology [11].

The *Axiomatic Design* is a further approach for development of complex systems [12, 13, 14]. This approach can be employed for modularization of machines, e.g. in order to design them so that they are easier to be maintained [15]. A different aspect is a description of a *knowledge based and functional CAD model* [16]. The approach of *Axiomatic Design* is based on a sorting of design parameters by a sparse reverse Cuthill-McKee algorithm [17, 18]. In addition, there are other approaches to structuring and modularization of machinery and equipment, primarily aiming to reduce costs in the development of serial production with many variants [19].

Often symbols are introduced to indicate certain solution-neutral functions. In this paper, the symbols are from the guidelineVDI 2860 [20].

3. APPROACH

There are many engineering methods aiming at the optimization of production machines. In the design of special machines, however, the work of an engineer is not focused on the optimization of the system, but rather on the conception. Therefore the design of such systems and machinery should be supported methodically by the integration of known solutions in the form of mechatronic modules. On the one hand, existing systems have to be modularized in such a general way so that they can be reused in futher developmental processes. On the other hand, the selection of modules has to be integrated into the development process.

The general methodology of design is to divide the overall function into sub-functions, seek physical solutions, and develop alternative concepts through the solution combination. It provides the development of alternative concepts and the subsequent blueprint, both will be accelerated by the use of mechatronic modules.

During modularization of machine system raises the question, what complexity of the mechatronic modules should be employed in order to ease the engineering process. An excessive complexity means that the units cannot be reused or rarely used because they are designed for very specific tasks. Low complexity reduces benefits of mechatronic modules in the development process. Simple mechanical parts – such as standard parts – could be treated as mechatronic modules. However, this would only help to save little time, comparing to the time saved by the reuse of larger mechatronical assemblies or complete modules. The presented approach provides one way to modularize mechatronic systems. The resulting modules are suitable for reuse due to their proper complexity. Functions are assigned to these modules in order to categorize them and integrate them in the engineering process.

The aim of this modularization is to support the process of physical mapping. Matching modules should be recommended to the developer based on the functional requirements. As an information basis for the method existing machines need to be modularized according to the procedure described afterwards. Therefore these modules must be assigned to define, solution-neutral functional descriptions. A standardized catalog of those functions should be used to help structuring the modules.

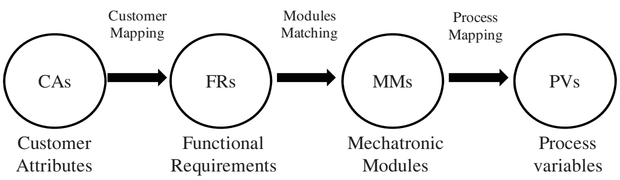


Figure 2. Extended Engineering Methodology.

The changes in the development process are shown in Figure 2. The physical mapping is replaced by a module matching. The developer conducts a customer mapping, whereby the functional requirements are derived from the customer requirements. The derived requirements are described by general and solution-neutral functional descriptions from a catalog, which is illustrated in Figure 12. In this catalog the functions are assigned to the module. The developer can choose different modules that met this function. Here, the developer may also be supported by graphical icons. Suitable solution modules for a function are stored in a database and are available to developers. Linked modules are recommended in addition to the selected modules. Finally, the developer needs to adapt the selected modules to the process.

The classical *Axiomatic Design* is a top-down process. Differ from the classical *Axiomatic Design*, the extended *Axiomatic Design*, introduced in this paper, comprises a top-down and bottom-up processes. The bottom-up view of the modular design approach is combined with the top down view of the *Axiomatic Design*. This allows creating a blue print of new machinery without detailed knowledge of components. This knowledge will be provided in the engineering process.

4. MODULARIZATION OF A SPECIAL MACHINERY

In the following, the modularization of a special machinery will be described. The differences between a modularization of the classical *Axiomatic Design* methodology and the extended *Axiomatic Design* perspective are demonstrated and compared o point out the feasibility and advantages of the improvement. This is illustrated by an inspection system.

4.1. Process network and blueprint of an example system

The objective of this system is to detect defects on the lateral surface of rotationally symmetric parts such as screws and bolts. The testing process is described in Figure 3 with solution-neutral symbols.

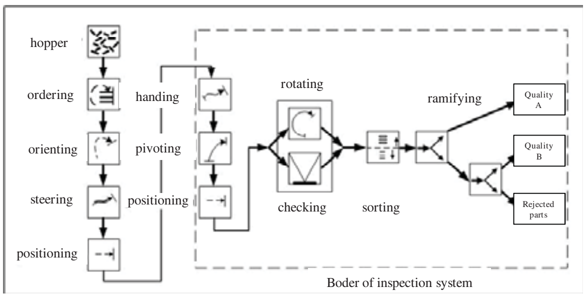


Figure 3. Process network of the exemplary testing system with solution-neutral functional symbols.

The system consists of a centrifugal feeders and the inspection system. Both are illustrated in Figure 4. The centrifugal feeder provides material which is separated by various slides. The separated objects are placed in an adaptor by a lifting and rotating unit. This adaptor is positioned by the rotary indexing table in front of the camera. Here, an image of the lateral surface is captured by rotating the test object in front of the camera. Finally, the objects are sorted based on the analysis result of these images into three classes - A quality, B quality and rejected parts.

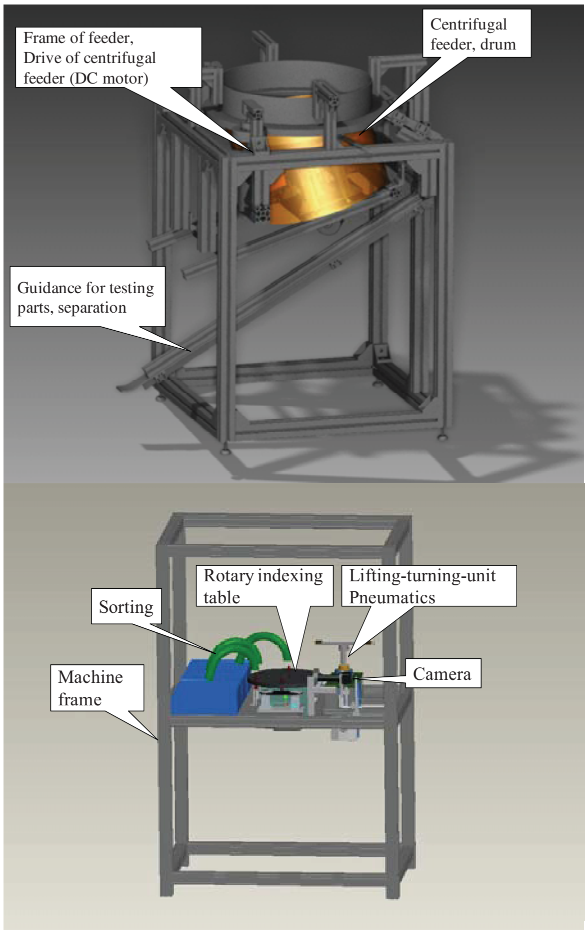


Figure 4. Example of the centrifugal feeder (upper) and the testing system (lower) and their components.

4.2. Modularization according to the classical Axiomatic Design

Firstly, the machine is modularized by the classical *Axiomatic Design*. The procedures of this method and its 4 domains have been illustrated in Figure 5.

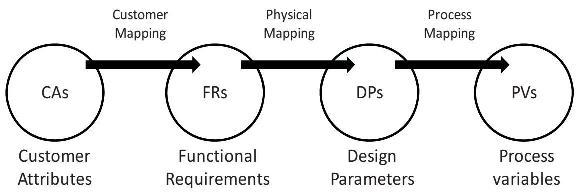


Figure 5. Axiomatic design domains.

A mapping process represents the interface between each. Based on the customer requirements, functional requirement are derived. These functions are assigned to design elements which should be adapted to the process.

Interaction	Weight
Required	2
Desired	1
Indifferent	0

Figure 6. Weighting of the Interaction of Design Elements according to function.

The functional relationships of these elements are scaled by the factors listed in Figure 6. These weighted relationships of the elements are illustrated in a matrix shown in Figure 7. The weight factor 2 indicates a strong dependency (required) between the concerned elements, whereas factor 1 indicates a week dependency (desired), and the factor 0 indicates independency. This relationship is referred to interaction here. The sparse reverse Cuthill-McKee algorithm is implemented in Matlab to cluster these relationships through the improved *Axiomatic Design*.

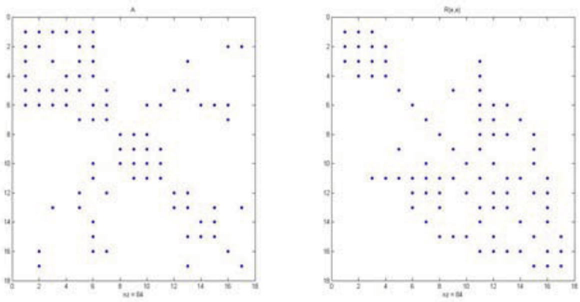


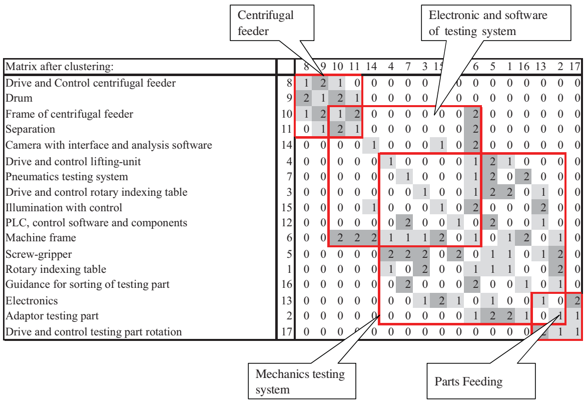
Figure 7. Design Matrix structure before (left) and after orientation (right).

Figure 7 and Figure 8 show the resulting weighted interactions of each element in comparison to other elements within a matrix. For simplicity, an interaction is represented by a point in Figure 6. Detailed presentation of sorting result is shown in Figure 8. The left matrix in Figure 6 shows interactions of the components, while the right shows the same matrix with the sorted interactions by means of reduction of bandwidth. This is a result of the Sparse reverse *Cuthill-McKee* algorithm.

By means of reordering the correlated design elements can be grouped into modules. For example, elements in Figure 8 are represented by the following 4 modules:

- Centrifugal feeder
- Electronic and software of testing system
- Mechanics of the testing system
- Parts feeding

The example shows a rough clustering of elements into modules. Some elements cannot clearly be assigned to a certain module. In addition, if a resulting module is too specific, then it can seldom be reused in subsequent development phases. For example, a specific module including all equipments of mechanics of the test system, as well as including PLC control, can only be reused in this specific machine.



Matrix after clustering:		8	9	10	11	14	4	7	3	15	[illegible]	6	5	1	16	13	2	17
Drive and Control centrifugal feeder	8	1	2	1	0	0	0	0	0	[illegible]	0	0	0	0	0	0	0	0
Drum	9	2	1	2	1	0	0	0	0	[illegible]	0	0	0	0	0	0	0	0
Frame of centrifugal feeder	10	1	2	1	2	0	0	0	0	0	0	2	0	0	0	0	0	0
Separation	11	0	1	2	1	0	0	0	0	0	0	2	0	0	0	0	0	0
Camera with interface and analysis software	14	0	0	0	0	1	0	0	0	1	0	2	0	0	0	0	0	0
Drive and control lifting-unit	4	0	0	0	0	0	1	0	0	0	0	1	2	1	0	0	0	0
Pneumatics testing system	7	0	0	0	0	0	0	1	0	0	0	1	2	0	2	0	0	0
Drive and control rotary indexing table	3	0	0	0	0	0	0	0	1	0	0	1	2	2	0	1	0	0
Illumination with control	15	0	0	0	0	1	0	0	0	1	0	2	0	0	0	2	0	0
PLC, control software and components	12	0	0	0	0	0	0	2	0	0	1	0	2	0	0	1	0	0
Machine frame	6	0	0	2	2	2	1	1	1	2	0	1	0	1	2	0	1	0
Screw-gripper	5	0	0	0	0	0	2	2	2	0	2	0	1	1	0	1	2	0
Rotary indexing table	1	0	0	0	0	0	1	0	2	0	0	1	1	1	0	0	2	0
Guidance for sorting of testing part	16	0	0	0	0	0	0	2	0	0	0	2	0	0	1	0	1	0
Electronics	13	0	0	0	0	0	0	0	1	2	1	0	1	0	0	1	0	2
Adaptor testing part	2	0	0	0	0	0	0	0	0	0	0	1	2	2	1	0	1	1
Drive and control testing part rotation	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1

Figure 8. Modularization according to the classical Axiomatic Design.

4.3. Modularization according to the extension of a mechatronic perspective

A new method, which is based on the *Axiomatic Design* and modularizes mechatronical system into modules with proper complexity, will be presented here. Firstly, an improvement to *Axiomatic Design* is distinguishing and clustering of the domain design parameters into three disciplines:

- Mechanic
- Electronic
- Software

Figure 9 illustrates the new expression of *Axiomatic Design*. In new expression, all modules can be represented in three disciplines. A module, which covers all three disciplines, is considered as a mechatronic module. Otherwise, the module is considered as a standalone module. Elements, which can be assigned to multiple modules, are links. This improved approach is used for the modularization of the test system.

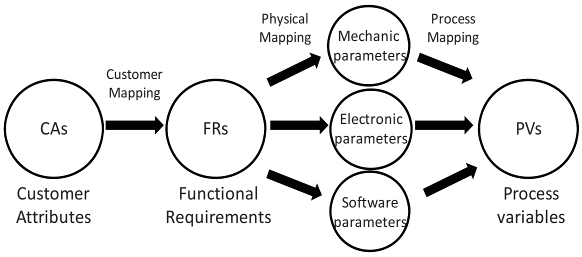


Figure 9. Mechatronical design structure.

The mechanical, electrical and software elements are combined into one matrix shown in Figure 10. In this way the correlations between these mechatronic modules can be considered. This allows for an identification of mechatronical links.

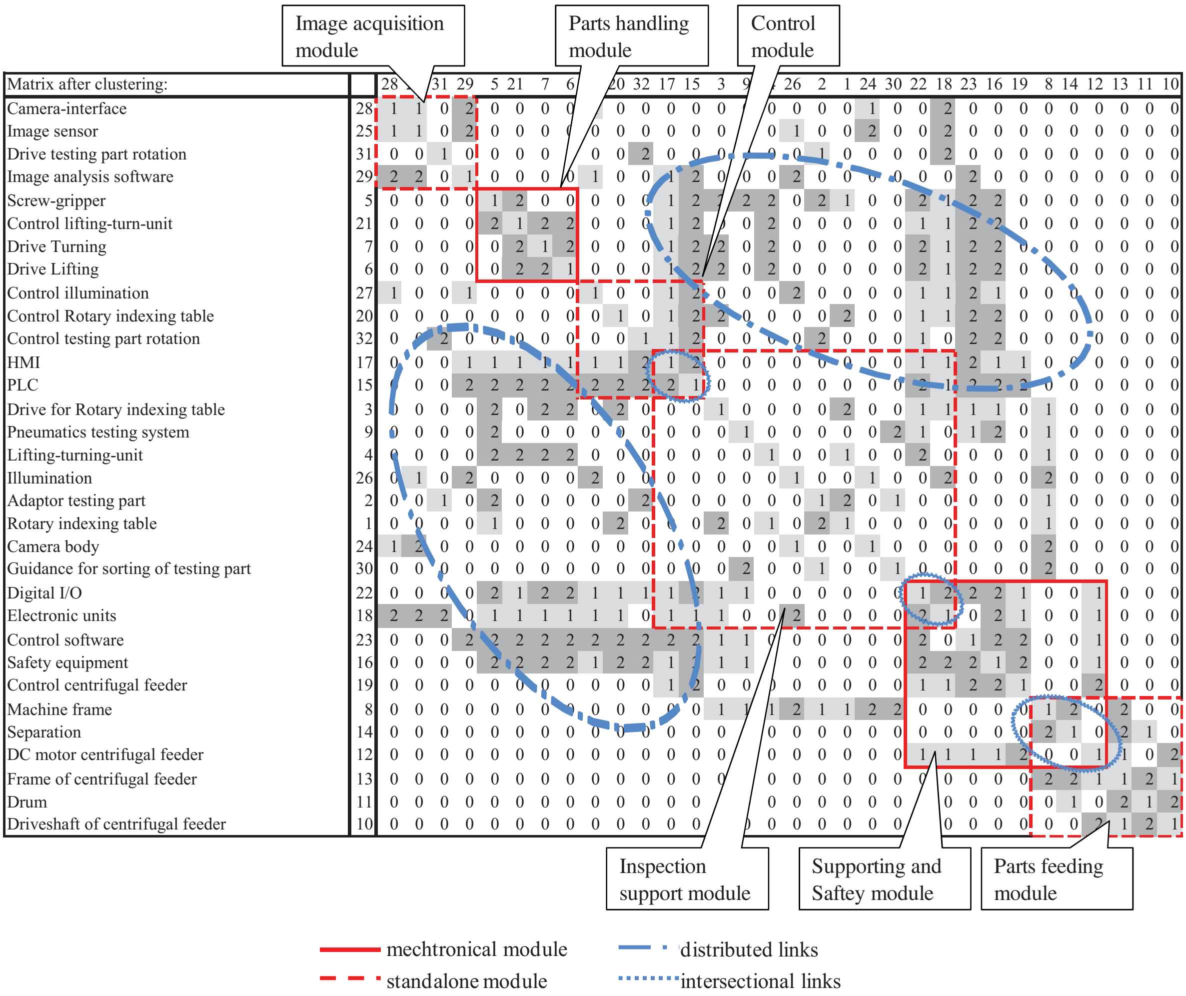


Figure 10. Modularization of mechatronic elements.

The matrix of the mechatronic elements is depicted in Figure 10. Six different modules resulting from the ordering of the correlations are: *Image acquisition, parts handling, control, inspection support, support and safety* and *parts feeding*. The modules *parts handling* and *support and safety* are considered as a mechatronic module, because they cover all three disciplines. In contrast, the modules *image acquisition, control, inspection support* and *parts feeding* are standalone modules. The links could be divided into distributed and intersectional links. The intersectional links are the elements in the intersection of two modules. The distributed links are the elements that cannot be clearly assigned to a certain module. The modularization of different disciplines shows that it is not worthwhile to generate a module for the narrow bandwidth (indicating a low correlation between the mechatronical elements) in the Design Structure Matrix. These elements must be adapted to specific tasks. In contrast, the summary of the elements in modules is worth at a wide band of the correlation matrix.

A module describes a functional and not necessarily a technological connection of components. Therefore, there might be a module with software but without electronics, which only means that the electronics do not need to be considered in this module.

In addition, two different kinds of links result from the described approach. Intersections between two modules are regarded as intersectional links. This means that elements, such as machine frame, separation and motor of the centrifugal feeder cannot clearly be assigned to only one module. These elements are both, *parts feeding* module and *safety and support* module and are examples of intersectional links. The elements that are neither integrated into modules nor the intersection between modules are regarded as distributed links.

These modules must be assigned to the functions that are described in Figure 3. The combination of the functions *hopper*, *ordering*, *orienting*, *steering* and *positioning* is met by the module *parts feeding*. The module *parts handling* is assigned to the functions *handling*, *pivoting* and *positioning*. The *image acquisitions* module meets the function *checking*. The *inspection support* module is assigned to the combination of the functions *rotation*, *sorting* and *ramifying*.

5. EXAMPLE FOR APPLICATION OF THE EXTEND ENGINERRING METHOD

In following the steps of the described extended engineering method should be illustrated with an example. These steps correspond to the procedure described in Figure 1. The aim of this method is to rapidly reach a conclusive concept for the system. In a first step, the functional requirements are derived based on the customer attributes.

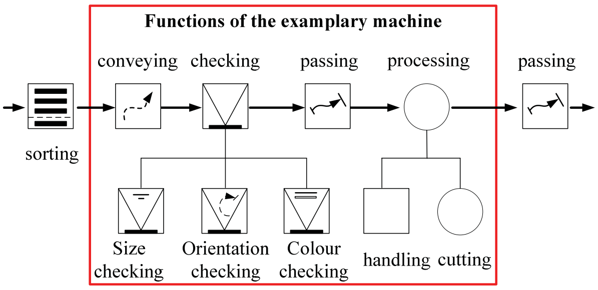


Figure 11. Process network of the exemplary machine with solution-neutral functional symbols.

The resulting description of the exemplary special machine is shown in Figure 11. The objective of this processing machine is inline detection and processing of defects on objects. This customer requirement is divided into conveying, checking, passing and processing. The checking and the processing can be specified by further functions. The size, the orientation and the color of the products are to be checked. The processing is realized by a guided cutting, it consist of a cutting and a handling function.

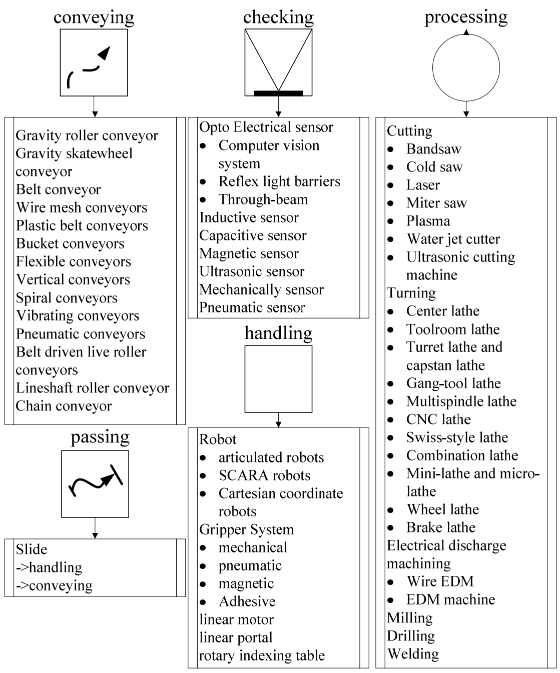


Figure 12. Examples of the catalog with solution-neutral functions and assigned modules.

As a next step, the developer must choose matching modules from a standardized modules catalog. Figure 12 shows an exemplary selection of the modules and their assigned functions. A module can also be assigned to various functions, such as the function passing shows. This function can be met by the modules that are assigned to *handling* and *conveying*. Other functions, such as the processing or checking module, are met by much modules so that a specification in partially functions may make sense. This specification is indicated by the division of the functions in Figure 11.

The task of the developer is to select matching modules. In this example, the conveying and passing functions are met by a wire mesh conveyor. An image processing system was chosen because of the specification of the function checking. Size, orientation and colour of the test object can be checked in one modul in this way. Water-jet cutting has been selected as the cutting process. A linear motor is selected to move the cutting valve.

The resulting sensor guided special manufacturing system is shown in Figure 11. The term "sensor-guided" indicates that this processing machine is actively controlled by a sensor information of the image analysis.

Modules that meet no direct function in the process might be complemented by linking. An example is the *support and safety* module from the above-described example of modularization. In addition, the links show, which topics should be taken into consideration during the detailed engineering of two or more modules. Therefore, this information can be directly integrated into the planning of the further development process.

Figure 13. The manufacturing system with the described solution modules.

6. CONCLUSION AND FUTURE WORK

The presented approach aims to support developer by the methodical integration of functional, mechatronic modules in order to reuse those. The developer should describe the customer requirements with defined solution-neutral functional descriptions. Mechatronic modules are assigned to these functions or a combination of several functions. Modules that meet the functions of the process description are provided to select them from a catalog in the form of a database. The developer may choose between matching modules.

The *Axiomatic Design* is suitable for the modularization of special machines. The functional orientation of the modularization is achieved by structuring the functional relationship of the components. In addition, the components are divided into their mechanical, electronic and information technological elements to realize mechatronic modules. The resulting mechatronic modules are in proper complexity, which is one prerequisite for resusing them in the engineering of a specific machinery.

Intersectional and disturbed links result from the modularization. The intersectional links can be used in order to link the modules in the catalog. The disturbed links can be considered as comprehensive functions in machinery – such as the control software (PLC).

The modules, which the developer can select, meet the assigned function. In addition, missing modules could be proposed by the links. An evaluation of the modules can be integrated into the database to optimize the selection of modules. Here, different perspectives on the product can be considered. The sales might optimize the configuration of the special machine in terms of cost, performance or delivery time. An optimization is also possible with regard to precision, efficiency or reliability of the system. Evaluation standards for comparison of the modules must be developed to allow this optimization. This evaluation can be made on basis of a fixed asset or on its dependencies from input variables.

7. ACKNOWLEDGEMENTS

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