Chapter

Modularity of Production Systems

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Abstract

From the theoretical point of view, the chapter focuses on the unification of views on the living (constantly changing) structure of the construction of flexible production systems, including its cooperating devices. It contains currently defined and designated technical terms in the field of flexible production systems. From the theoretical point of view, the existing structures of the “multiprofessional manufacturing robotic center” are enhanced with new elements, which also contributes to innovation and expansion of their applications. These structural structures served as the basis for building sophisticated modular structures. Modularity is an integrating element directed at highly customizable manufacturing engineering structures. It fully complies with the requirements of manufacturing practice and demanding market, in the framework of fully implemented Industry 4.0 (I4.0) under way.

Keywords: modularity, module, production systems, structure, platform

1. Introduction

Modular manufacturing systems, as an integrated part of flexible manufacturing systems, deserve an unmistakable merit in today’s rapidly changing manufacturing environment, characterized by developed competition in the global context and progressive changes in process technologies and in their structure according to market requirements. Such systems necessitate a rapid and factual integration of new technologies and new functions into both system and process relationships.

The Industry 4.0 (I4.0) trends and conditions and requirements require cyber and flexible production-oriented approach, enabling to build the following:

- A production capacity of production systems that is operatively adaptive to market requirements, i.e., obtaining new, rapidly viable products

- Fast integration of modern process technologies and new functions into existing production systems and their easy adaptation to dynamically changing batches of individual products

- Integrated production units with new service capabilities based on robust Industry Internet of Things (IIoT) data streams from individual work units and their accessibility for being processed from anywhere subject to Internet connection

2. Flexible manufacturing systems

Flexible manufacturing systems (FMS) enable flexible production of a product group in a single production system. Using modular principles, flexible manufacturing, which is the fundamental concept of cyber production systems, has recently become one of the major systems of production management. These arrangements are (and there are several of them) theoretically and methodically based on the search for a mathematically modeled component production center relationship that would guarantee different types of parts produced with a small number of pieces in the batch. The modular structure of the production systems enables links between machines, saving production time and space. The operation of the machines is synchronized via data stream, and the material flow is optimized (moving parts between machines is at an optimal distance). FMS utilizes many advantages of other types of production structures (**Table 1**) [1].

The dynamic development of computers, information science, data processing, control and managing systems, optical systems, drives, and materials, that is taking place in short cycles, significantly affects the growth rate (obsolescence) of the technical level of the systems in question. An efficient manufacturing system can become inefficient in a short time. In addition, the current customer-oriented market, as well as the environmental, energy and material issues, results in accelerated launch of new products. The adaptability of established manufacturing systems to new products may not have sufficient technical availability, and the introduction

Type of production	Structure definitions and objectives
Production line	The line is designed for the production of a (one) specific product, using the technology of gradual production with given tools and a fixed level of automation. The economic goal of production lines is to produce one particular type of product in large quantities and the required quality cost-effectively
Flexible manufacturing system (**FMS**)	The structure of a production system with fixed hardware and programmable software for affecting changes in the assortment produced according to current orders and changes in production plans with tools for several product types. The economic objective of **FMS** is to ensure an efficient production of several types of products, which may change over time with the respective changes taking up shorter time on the same production system, while maintaining the requirements for the production's prescribed scope and quality.
Reconfigurable manufacturing system (**RMS**)	A structure of the manufacturing system that can be created through multiple groupings of basic process configurations of changeable system modules (hardware and software). Reconfiguration allows for the addition, removal, or modification of specific process features, controls, control software, or machine structure to adapt the system's production capacity to changes in market demand or to the necessary and related technological changes. This system structure guarantees the flexibility of the system for a specific product group, while the system is technically ready for change so that it can be further improved, upgraded, and reconfigured and not merely replaced [2, 3]. The goal of **RMS** is to provide the functionality and capacity that is needed at any given time. In terms of the system composition, **RMS** configuration can be reserved or flexible or changeable as needed between these two properties. The **RMS** goals exceeds the **FMS** goals in terms of economy, allowing the following: • Shortening the time of introduction of innovative systems and reconfiguration of the existing ones • Immediate production adjustment and rapid integration of new technologies and new functions into existing production systems

Table 1.
Overview of basic production system structures.

of new technically available systems may take too long a time from the production availability point of view (machine tools approximately 2 years).

For these reasons, it is necessary to pay constant attention to flexible, modular, and reconfigurable production systems and consequently to improve them systematically and technically and adapt them to the needs of current production processes or to the needs of current engineering production [1, 2].

Generally, the best-selling article (or article with the highest investment value) of production technology are the CNC machine tools. Prof. Marek writes in [3] about the factors influencing the development of machine tools.

Forecasts focused on the position of modular technologies in the twenty-first century confirm their important place in both fully automated production plants (both engineering and nonengineering areas) and in non-production areas (service and maintenance activities).

Thus, the modularity and reconfigurability in terms of where the development is heading have the potential for further development in the future. Design of reliable (universal) modules or of the building nodes with a wider applicability is, and will always be, topical. This desired property can be achieved through experience, selection of suitable elements, and reliable design. In terms of reliability and reconfigurability, two areas need to be focused on:

- Design of machine tools (machine reconfiguration to another type of workpiece)
- Production (technology reconfiguration to another type of workpiece)

The concept of flexibility is also related to reconfigurability and structurelability. Flexibility can also be seen from the point of view of design and manufacturing development (**Figure 1**).

The possibilities and tools for increasing the performance of production machines in multifunction machinery are associated with the developed ability to fully perform several types of machining, e.g., turning and milling at the same time

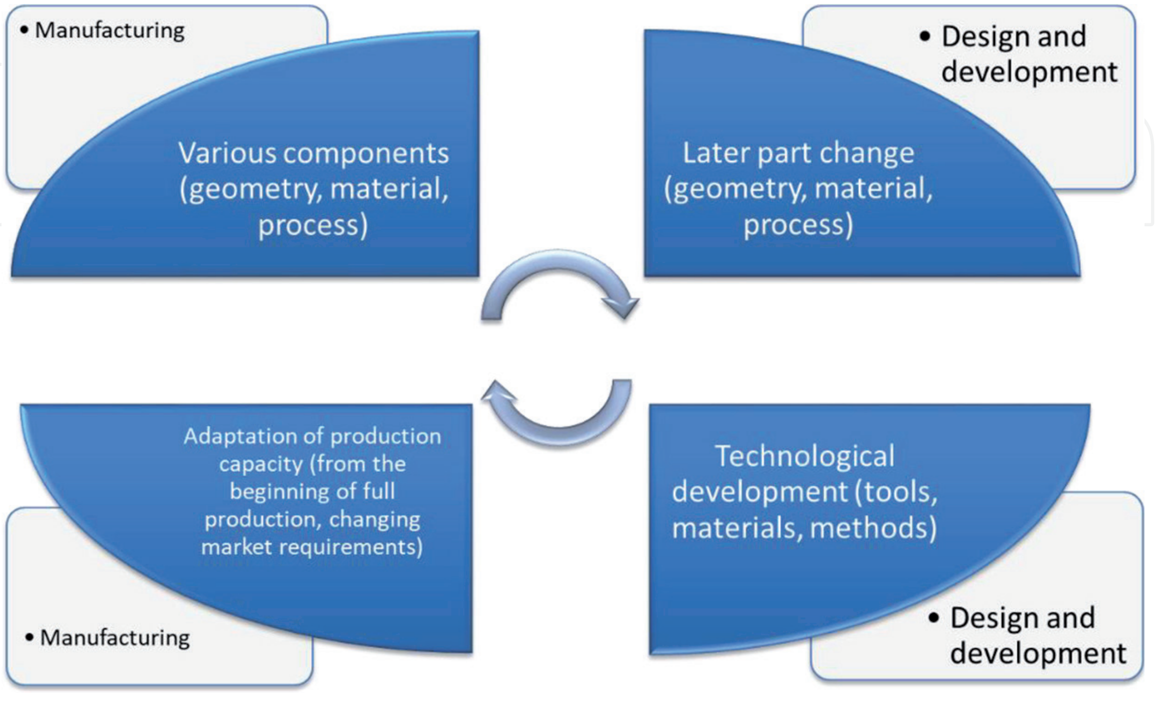

Figure 1.
An unconventional view of the "flexibility" concept.

or milling and grinding, etc. Reducing the number of machine tools for the production of one component, less handling, shortening the lead times, minimizing the recurrence of workpiece clamping, maximizing the concurrence of operations, as well as the development of machine components and machine concepts for maximum machine multifunctionality contribute to:

- Increased accuracy
- Increased production capacity
- Increased economy
- Reduced negative impacts on the environment

Unification of parts and components is implemented in order to minimize diversity of the components used, while maintaining very good static and dynamic properties of the machines and, at the same time:

- Increasing reliability
- Increasing economy

2.1 New approach to production systems classification

In the area of production systems, a number of terms are used with broader interpretation. This situation is related to approaches to and perspectives on this issue. A proposal for their general unification and effective classification is given in **Figure 2**.

Various definitions of production systems from different points of view are cited in various literature sources [1]. This has led to the need to harmonize these formulations so that they provide the most precise definitions, taking into account current knowledge in this area:

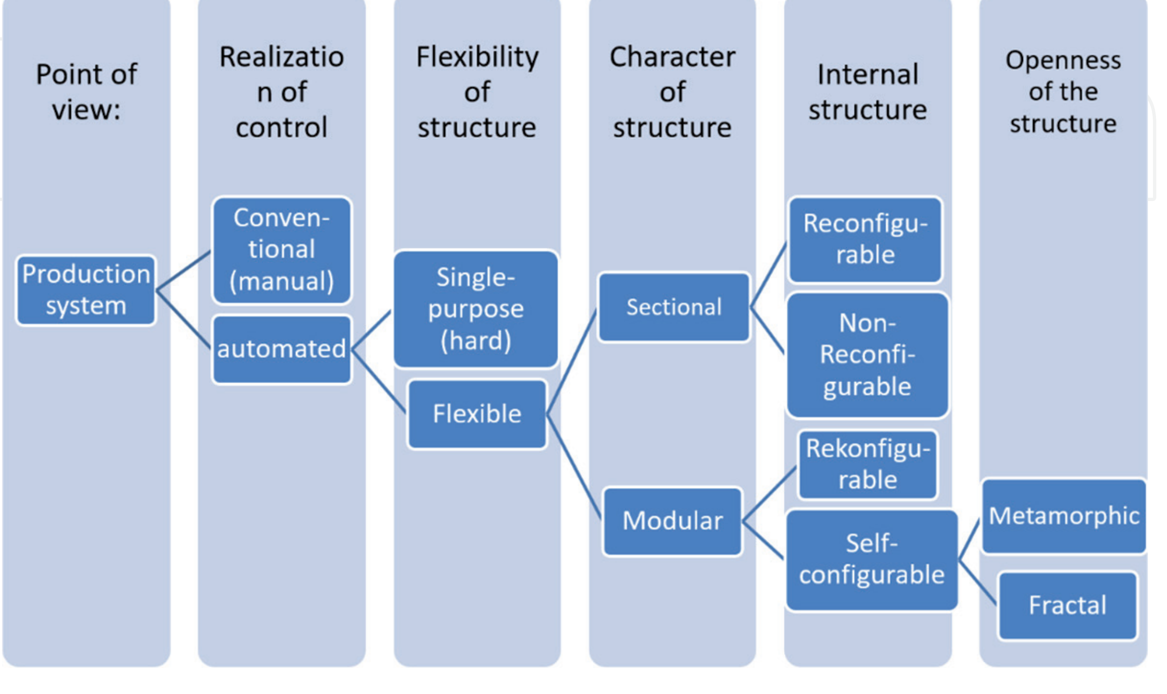

Figure 2.
Open proposal for production systems classification.

Flexible production system—a functional grouping of production facilities linked by material flow and information network, enabling the use of flexible change in production facilities due to the introduction of new products in relatively short time intervals, to produce small quantities efficiently.

Structural production system—flexible set of compatible elements (technological and positioning units, supporting frame, cooling system, etc.) and their mutual links, which can be expanded with new elements to change the system parameters.

Modular system—flexible set of unified modules (module—separately functional unit) in functionally logical (in terms of structure, system, concept, kinematics, etc.) arrangement into higher functional unit (meeting required parameters and working functions).

Reconfigurable system—a modular system with the possibility to change the arrangement of its own modules (in terms of structure, system, concept, kinematics, etc.) in order to create an innovated system with innovated properties.

Self-reconfigurable system—a reconfigurable system capable of independently reconfiguring its own modules (in terms of structure, system, concept, kinematics, etc.) to create an innovated system with innovated features.

Metamorphic system—a closed self-reconfigurable system to create an innovated system with innovated features (def. Inspired by [4]).

Fractal system—an open, self-reconfigurable system consisting of proactively behaving elements—fractals (their structure is recurrent) which pursue a common goal (def. Inspired by [5]).

2.2 Modular production centers

In the category of manufacturing technology, machining centers (MC) are defined as manufacturing machines designated for complex components machining with defined characteristics. According to the number and type of technological operations performed, machining centers are divided into:

- Multipurpose (multi-operation)—machines with a predominant technological operation (e.g., turning), i.e., they mostly enable one type of technology

- Multiprofessional (multiprofessional productions center (MPC))—machines on which various technological operations can be performed (e.g., turning, milling, drilling, etc.)

Production centers are conceptually built on the principles of modular systems or as modular single-purpose machines. In terms of design and structure, they are assembled from technological, handling, and auxiliary units (mechanical, electromechanical, hydraulic, pneumatic) integrated through a supporting element (frame) into one functional and structural unit. The highest integration of production centers is based on the automation of technological and handling operations. These are multiprofessional machine tools designed for complex machining of parts on one machine and, if possible, requiring one clamping. To machine a workpiece requiring one clamping, its rotation must be ensured (e.g., in the X-Y plane) and so must be its tilting. The machining centers are equipped with a tool magazine automatically replaced by a mechanical hand. Some tools feature their own drive, which makes drilling off the workpiece axis or its milling possible, especially on lathes. Machining centers represent the basic AVS production machines. They are mainly used in piece and small batch production. Machining centers are characterized by a high concentration of operations. The machining is often carried out with the component clamped only once. They are mostly equipped with tool magazines exchanged automatically as needed. The most common main feature of machining centers is the largest machined part dimension.

2.3 MPC and MPRC definitions

MPC—a set of working units (technological, handling, conveyors) integrated into one unit (frame), characterized by flexibly reprogrammable common control system, mostly with human operation. The nature and structure of the MPC construction classifies it under the group of modular reconfigurable production systems [1].

MPRC—a fully automated set of autonomous modules, integrated into a single unit (frame), with a common, flexibly reprogrammable control and the use of robotic devices performing the function of handling and technological work units [1, 6]. The nature and structure of the MPRC construction classifies it under the modular reconfigurable production systems.

MPRC characteristic features:

- The MPRC ensures the technological cycle of product manufacturing, i.e., MPRC may be considered a production system.

- The MPRC's design guarantees the automation of technological, handling, and control operations, i.e., MPRC may be deemed an autonomous automated production system.

- The MPRC is built on the principles of modularity, which allows the MPRC to be converted quickly and efficiently into a new product range, i.e., MPRC can be considered a flexible autonomous automated production system.

- By its structure, the MPRC is closest to that of the robotic cell.

Unlike the type-specific structures of automated production systems, the MPRC provides a fully automated multiprofessional technology cycle designed for complete workpiece production and has a simpler (fewer number of elements/modules) structure, less space requirements, and more integration of technological (handling) control functions.

3. Modularity and flexibility of production systems

The technical system is described by terminology which determines the procedures, tools, and methods for its description, understanding, and interpretation.

System—a purposefully defined set of at least two elements and a set of links between them, both sets specifying the properties of the whole. The links can be understood in terms of their physical or logical relationship. From the technical point of view, a system may be mechanical or functional. Each system is made up of individual elements. An important feature of the system is that its elements in relation to each other can work together as a whole. The manifestation and properties of the system represent more than a simple sum of the properties of its elements. The system as a whole may exhibit behavior that is missing in the behavior of its elements.

Subsystem—part of the system, which creates a relatively closed, separate functional unit within the system. As a rule, it consists of two components: elements and links. The links between elements are often called interfaces. The subsystems cooperate with each other in a system function algorithm. The subsystems can be viewed independently.

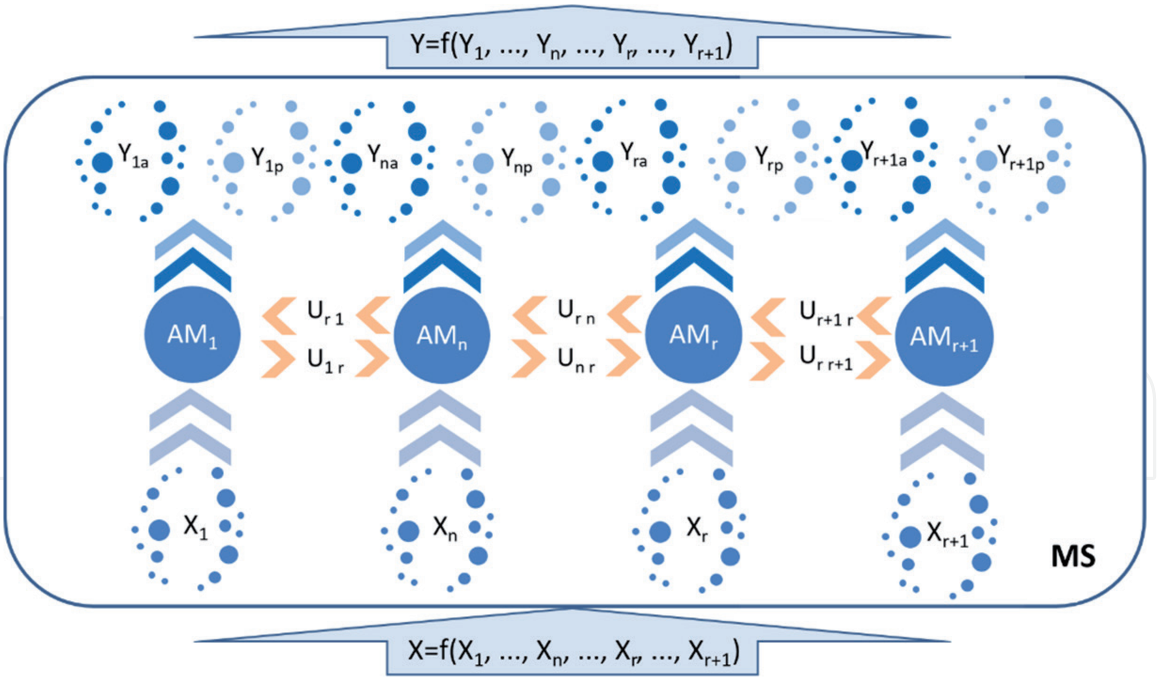

Figure 3.
Structure diagram of the general modular technical system.

Module—a basic building block of modular structure, which is a separate unit structurally, functionally, and in terms of design (a materialized implementation of the basic system function).

Modular system (MS)—complete set of modules (unified units, functional nodes, modular blocks, etc.) in functionally logical (in terms of structure, system, concept, kinematics, etc.) arrangement of a higher functional unit, featuring required parameters and working functions (**Figure 3**) [1].

Modularity—a feature of a technical system that allows its decomposition into a group of autonomous, loosely coupled elements—modules.

Modular system structure—a set of modules and their mutual links and configurations. Change in the interconnection/arrangement of modules results in the emergence of new delimited functional and kinematic system configurations.

Element designation:

MTS—Modular technical system.

AMi—Unified modular unit (functional node, modular block, etc.)

Ui—Mutual links (compatibility of ij module U_i to U_j, or of the ji module U_j to U_i).

X i—Module input parameters (set requirements).

Yi—Module output parameters (properties, operating functions), "a" active, "p" passive.

3.1 Functionality of the modular technical system structure

The mutual linking of AM modules is based on their arrangement in the technical structure of the system ψ. The possibilities of connecting the AM_i and AM_j modules are described by the matrix of the MTS_f system structure (matrix of the type n × n, where n is the number of modules AM = {AM1, AM2, ...,} AMn forming the MTS, while the set of binary links $x = \{x_{11}, x_{12}, \ldots, x_{nn}\}$ on the set AM expresses $x_{ij} = 1$, if there is a possibility of creating a link between AM_i and AM_j, or $x_{ij} = 0$, if there is no possibility of linking the modules):

$$MTS_f = [x_{ij}] \quad (1)$$

3.2 Assembly of modular technical system structure

By combining the modules AM ={AM_1, AM_2,..., $AM_{n,}$}, the MTS can be assembled with none or several degrees of freedom of motion. MTS motion options with respect to a defined coordinate system can be analyzed from the MTS_{pb} motion matrix (n x n matrix type, where n is the number of modules AM = {AM1, AM2,...,AMn,} forming the MTS, where b_{ij} = 0 if there is no connection between AM_i and AM_j, or b_{ij} = 0 if the modules are combined to form a unit without motion options, or b_{ij} = 1 if the modules are combined to form a unit with one degree of freedom of motion, b_{ij} = 2 with two degrees, etc.).

$$MTS_{pb} = [b_{ij}] \tag{2}$$

The AM module, a critical element of the MTS ψ structure, is defined as a unified unit, separate structurally, functionally, and in terms of design, composed of elements, elements E (e.g., mechanical module, servo drive, possibly also source, control, and communication module), with a specified level of function integration (main, secondary, auxiliary) and intelligence (control and information, control and decision function), capable of connecting with other modules mechanically, and in terms of control, creating functionally higher units in the technical structure of the system ψ:

$$MTS_{\psi} \approx \sum_{j=1}^{a} AM_j \approx \sum_{j=1}^{a}\sum_{i=1}^{e_j} E_{i,j} \tag{3}$$

AM_{r+1} inputs are X parameters of MTS task transformed to X_{r+1} parameters of X_{r+1} partial task and U_{rr+1} compatibility parameters transformed as interaction of directly linked downstream AM_r module in MTS structure. Outputs from the AM_{r+1} module are output parameters Y_{r+1u} and Y_{r+1p} of the AM_{r+1} module representing the performance of a partial task of the module transformed into output parameters Y of the MTS robot and the U_{r+1r} compatibility parameters, by which the AM_{r+1} module directly affects the subsequently linked module AM_r to the MTS structure (**Figure 4**).

$$X = f(X_1, \ldots, X_n, \ldots, X_r, \ldots, X_{r+1}) \tag{4}$$

$$Y = f(Y_{1u}, \ldots, Y_{nu}, \ldots, Y_{ru}, \ldots, Y_{r+1u}, \ldots, Y_{1p}, \ldots, Y_{np}, \ldots, Y_{r+1p}) \tag{5}$$

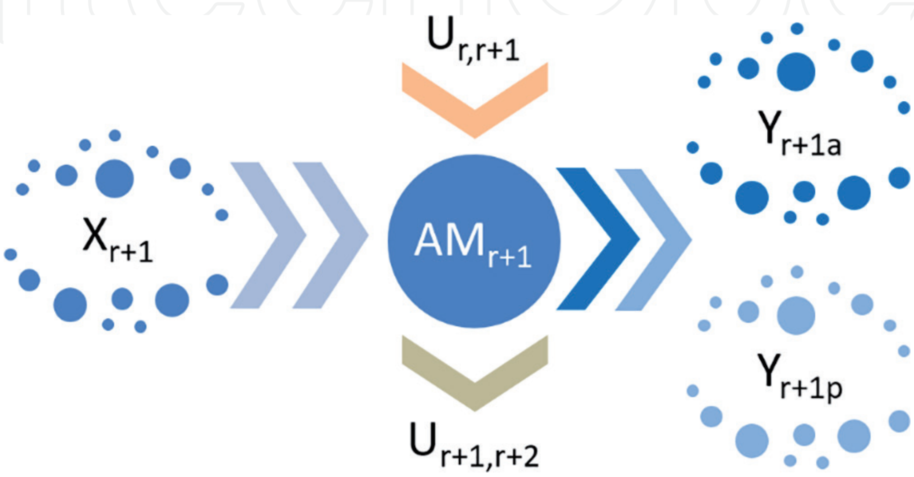

Figure 4.
Structure diagram of the general autonomous module (AM).

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AM modules—Depending on their importance for the MTS functions, they can be classified as the main active ones (ensure the main function, number l of total number m + l + a modules, e.g., motion modules), the secondary active/passive ones (ensure secondary support function, remaining number a out of total number m + l + a modules, e.g., a coupler module), and the auxiliary passive ones (ensure the auxiliary function, remaining number a out of the total number of m + l + a modules, e.g., a carrier). MTS can be described by an AM module set according to their importance to the MTS functions:

$$MTS_{\Psi} = \sum_{j-1}^{1} AM_j + \sum_{j-1+1}^{m} AM_j + \sum_{j-m+1}^{a} AM\,j \qquad (6)$$

3.3 Modular system properties

Unlike the conventional systems, modular systems have the following specific features (**Figure 5**):

3.4 Concepts of flexible technical systems

According to the breakdown in **Figure 2**, the flexible technical systems include modular and structural systems (STS). The difference between these systems is mainly in the autonomy or the sophistication of basic building elements.

The concept of MTS design is to create a complete set of modules (unified units, functional nodes, modular blocks, etc.) and their links in functionally logical (in terms of structure, system, concept, kinematics, etc.) arrangement into a higher functional unit, meeting the required parameters and working functions.

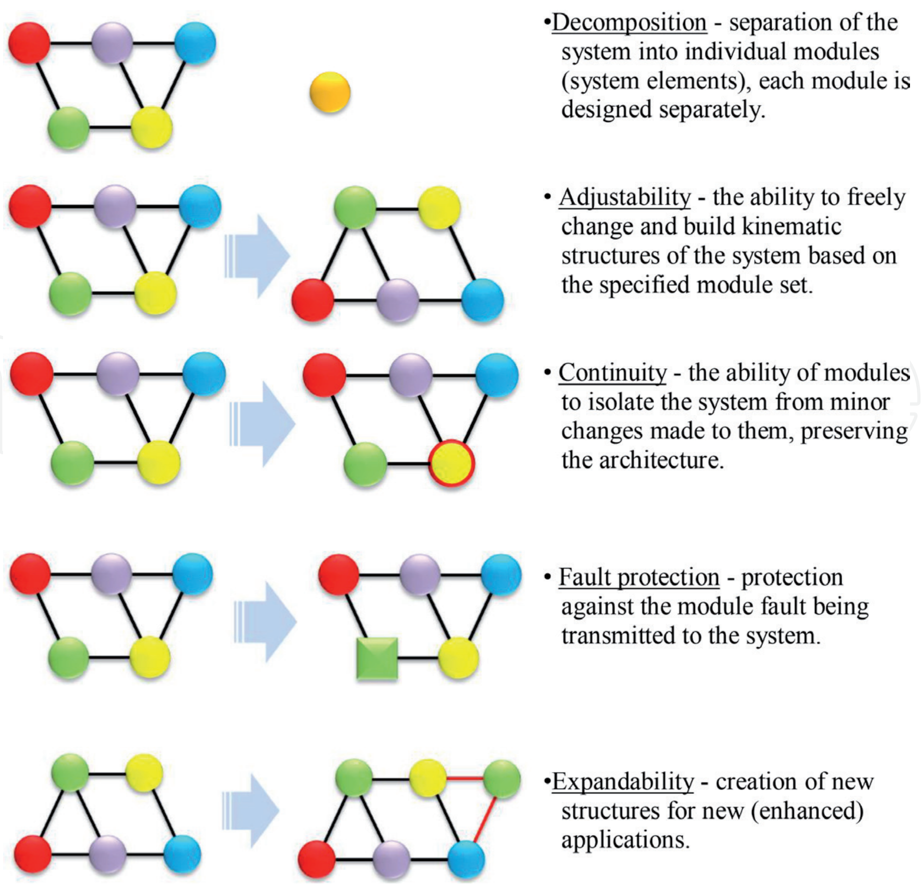

Figure 5.
An illustration of the modular systems' specificities.

Implementing interconnections—arrangement of the assembly of elements and a change of the same:

- *Fixed*—change by external activity, outside the structural system's operation: reconfiguration of kinematic and functional structure of the STS
- *Variables*—change through intrinsic activity in course of the structural system's operation: self-configuration leading to a change in the parameters of the kinematic and functional structure of the STS
- *Fixed*—change through external activity, outside the modular system's operation: reconfiguration of the kinematic and functional MTS structure
- *Variables*—change through intrinsic activity in course of the modular system's operation: self-configuration of the kinematical and the functional MST **structure**

Concept 1—Structural systems with fixed links, such as structural gripper heads by "SCHUNK" (**Figure 6**), STS assembly from a defined number and types of standardized elements (motion units, motion lines, building blocks, unified nodes, etc.), with the possibility of its mechanical conversion outside of operation into new functional and operational STS configurations [7].

Concept 2—Structural systems with variable links, e.g., a turret with multi-spindle heads from Riello Sistemi [8] (**Figure 7**), **STS** assembly from a defined number and types of elements (spindle heads, gripping units, structural blocks, unified nodes, etc.), with the possibility of its mechanical conversion in course of its operation into new functional and operational **STS** configurations.

Concept 3—Reconfigurable modular systems with fixed links, e.g., modules by Riello Sistemi (**Figure 8**), **MTS** assembly from a defined number and types of **AM** autonomous modules (motion units, motion modules, modular blocks, unified nodes, etc.), with the possibility of its mechanical conversion outside operation into new functional and operational **MTS** configurations.

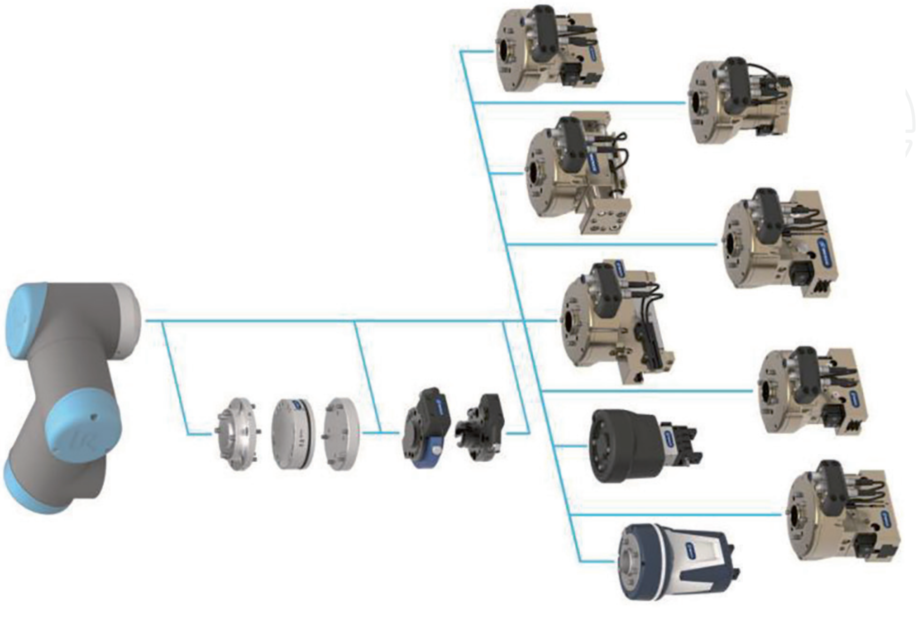

Figure 6.
STS rebuilding concept 1 with fixed links by SCHUNK.

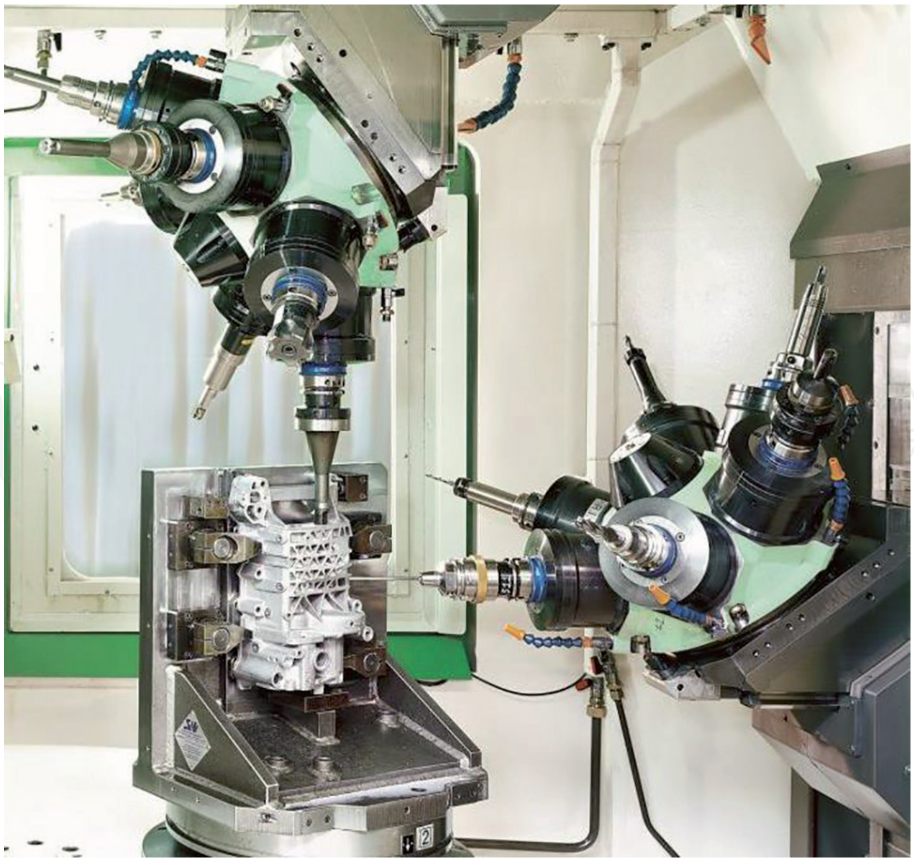

Figure 7.
Concept 2, reconfiguration by adding new elements to the assembly (in production technology, spindle heads) from Riello Sistemi.

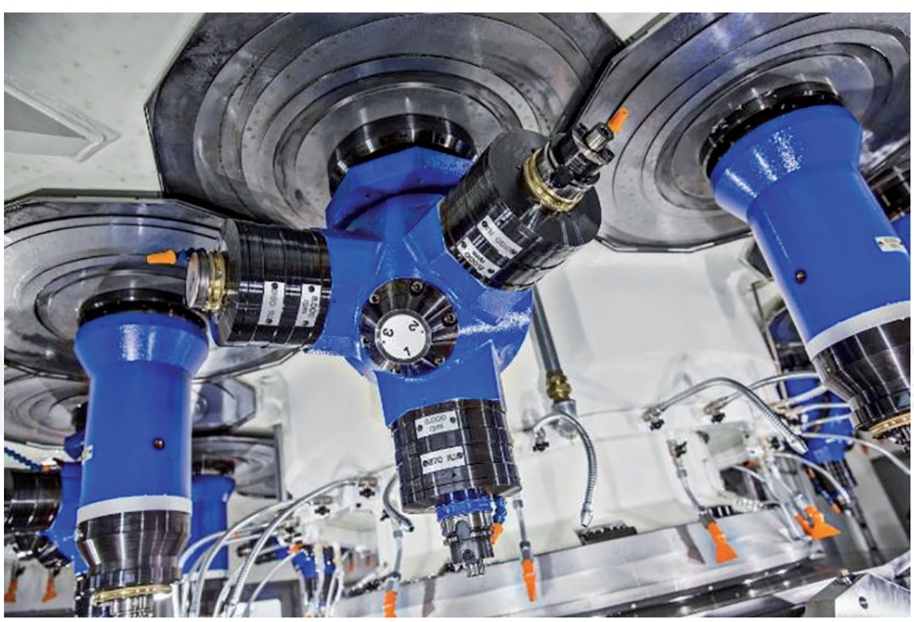

Figure 8.
Concept 3, reconfigurable modules by Riello Sistemi [8].

Concept 4—Self-configurable modular systems with variable links, e.g., modules from Riello Sistemi [8] (**Figure 9**) **MTS** assembly from variable number and types of autonomous **AM** modules (motion units, motion modules, modular blocks, unified nodes, etc.), with the possibility of self-conversion in course of the operation into new functional and operational **MTS** configurations.

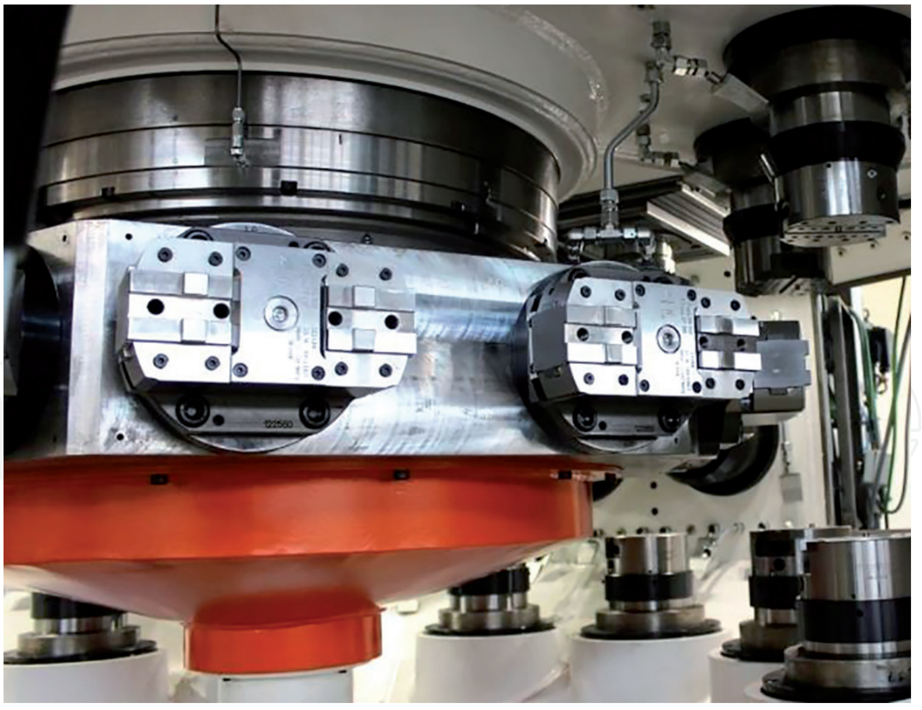

Figure 9.
Concept 4, self-reconfigurable module sets by Riello Sistemi.

3.5 Modularity of technical systems

A particular MTS architecture made up of AM modules should meet the technical requirements of the application, quality, durability, and safety.

In the MTS system, the AMs are interchangeable—links with other parts of the MTS system are ensured by standard (or special purpose) connectors (interfaces).

AM module features—type and shape of the AM_i module depend on its functionality in the MTS system configuration and parameterization of the resulting requirements (features):

- It can move on top of adjacent modules, or it can rotate or move adjacent modules.
- It may be heterogeneous or homogeneous.
- Depending on the type of positioning and coordination, it can be applied to parallel or serial MTS structure.
- The number of drives and the number of degrees of freedom determine its mobility.
- The type of interface applied determines the capabilities of its metamorphosis.
- An active AM can be built on the rotary or the linear principle of motion.
- Passive AM—connecting AM has no moving parts (the task is to link the active AMs).

The building module architecture is based on the need to appropriately group suitable modules into an MTS architecture that is recurrent for certain types of applications in the form of a structural base.

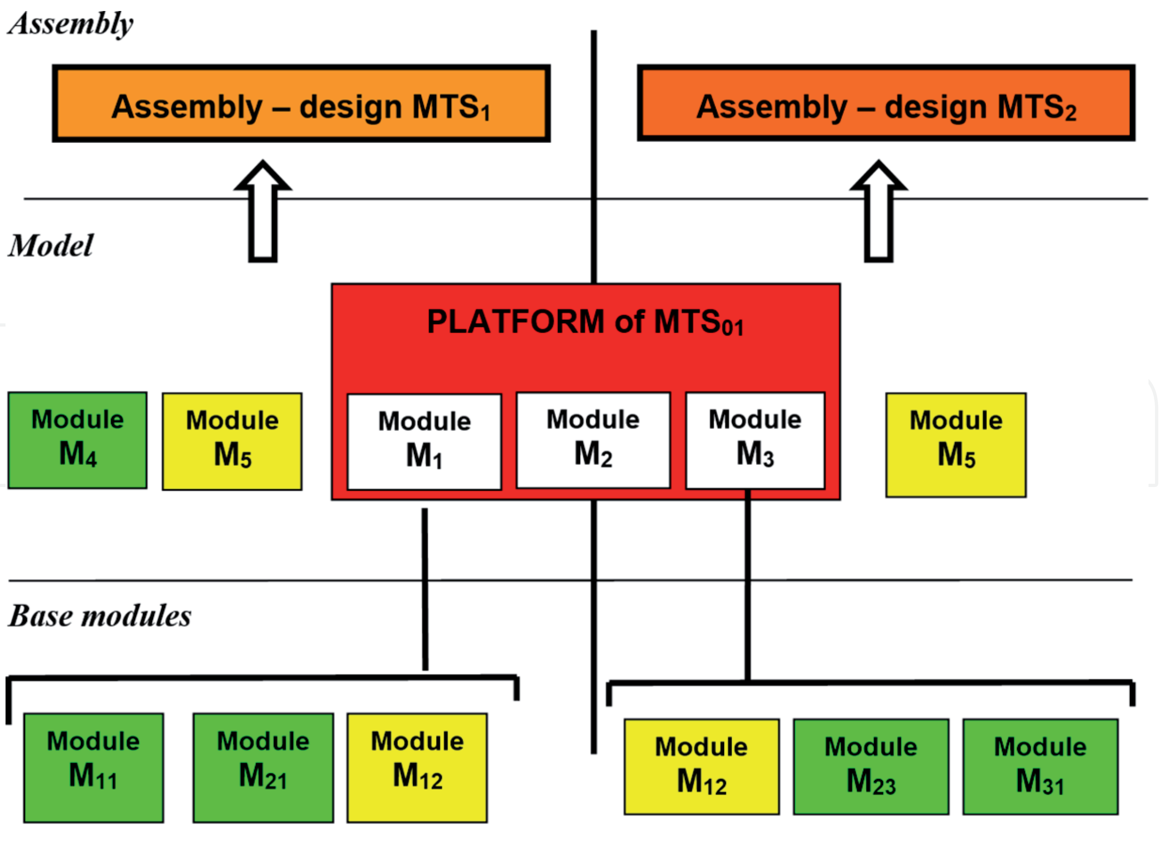

Figure 10.
Grouping of the modules into a platform in the general ***MTS structure****.*

Modules grouped in the MTS architecture (**Figure 10**):

- A *platform* is a set of modules used in multiple complete MTS (modules of platform (MP)) assemblies, e.g., MTS_{01}.
- A set of modules involved in multiple MTS sets (multimachine modules (MM)), e.g., M5.
- A set of modules involved in only one robot assembly (singlemachine modules (MS)), e.g., M4.

The degree of utilization of the unified building modules in the individual MTS design kit expresses the "degree of modularity." In general, the degree of modularity can assume a value of $k_M \in \langle 0, 1 \rangle$ [9].

It is recommended the structure of the MTS assemblies under consideration be compiled into the so-called modular system maps—a clear display of structures of individual assemblies and display of usage of individual building module options in the MTS assemblies.

3.6 Modularity of production technology, features, and characteristics

Assessing modularity—feasible from several points of view. For practical needs of design and operation of production systems, it is appropriate and sufficient to divide modularity into basic groups (in relation to the designed structure) (**Figure 11**).

Functional modularity—linked to the main MTS functions and features (mainly operational). Changing the AM module will change the MTS function (functionality).

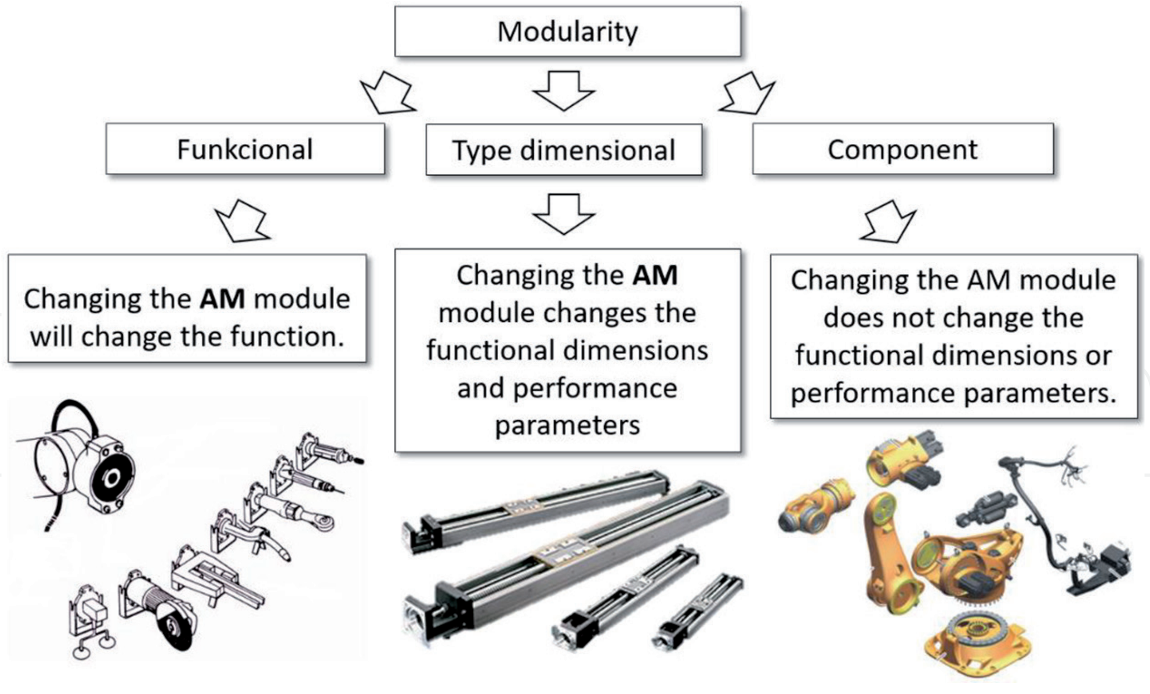

Figure 11.
Modularity breakdown.

Type-dimensional modularity—characterizes the MTS design, its flexible transformation view of another MTS-type series. By changing the AM module, the functional dimensions/performance parameters of the MTS design are changed.

The *AM-type series* (grading of AM parameters or specifying the AM type) is done by distinguishing the parameters as follows:

- Basic groups (typical for structural and functional groups: power, torque, etc.)
- Derived (critical for the user: output, speed, etc.)

Component modularity—characterizes the MTS design in terms of production, maintenance, and service. Changing the AM module does not change the functional dimensions or performance parameters of the MTS design. Such AM module replacement/application makes sense for streamlining the production, service, and maintenance.

AM elements—**components** of one type are physically similar. For this reason, once the conditions are met, the principles of similarity theory [1] can be applied.

Figure 12 shows a dual biaxial modular manipulator designed for varying degrees of load. If the modular assembly is subjected to maximum loads, it is necessary to reduce the motion dynamics to the recommended level or to choose a dimensional range of higher type for the construction of the handling equipment (**Figure 13**) [10].

3.7 Modular production machines

Currently, modular production machines represent advanced machine systems designed on the basis of a mechatronic approach to their design, with the predominant concept of their construction being a three-dimensional and functional modularity structurally built on fixed links.

Conceptually, these structures obey the principles of functional and type and dimension-specific modularity structurally built on fixed links.

Figure 12.
Güdel ZP-type biaxial portal linear motion modules.

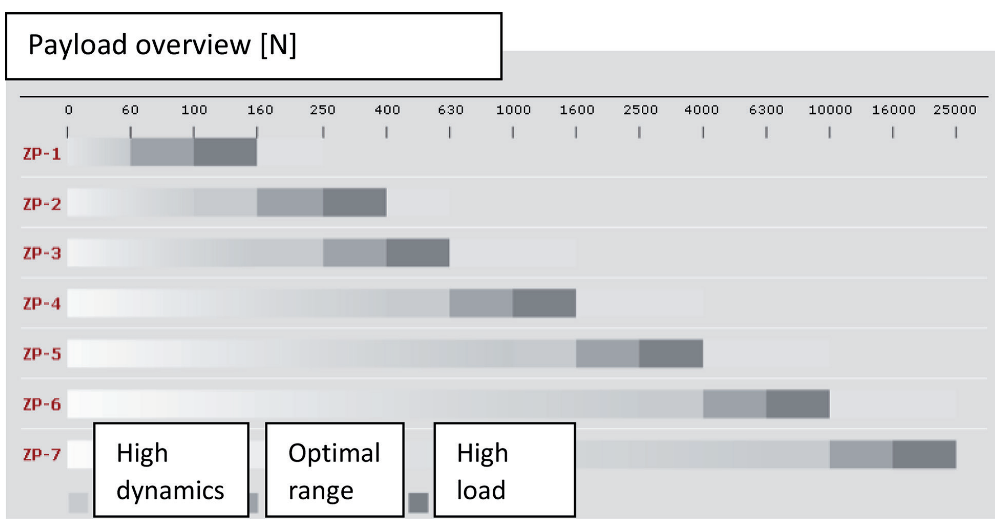

Figure 13.
Güdel type and size-specific linear portal modules of the ZP type.

An example of functional modularity is the IMG industry concept (**Figure 14**). Machining centers, production cells, and transfer lines of varying degrees of complexity can be built from the presented base of modules and platforms.

These two concepts are now strongly prevalent in the development of modular manufacturing technology. A feature of the application of these two concepts in the development of this technique is also their overlap in case of a certain degree of fuzziness of their boundaries or their combination. This direction is particularly pronounced in modular systems enabling the assembly of higher functional units such as machining centers, multiprofessional centers, and production cells.

3.8 Modular robotic systems

Industrial robots and manipulators are implemented as modular systems mainly due to the requirements of flexible automated production systems [4, 11, 12].

From a number of current designs (EPSON, SCHUNK, YAMAHA, KUKA, MOTOMAN, etc.), the solution by SCHUNK will be introduced (**Figure 15**), the

Figure 14.
Modular concept of EMAG production machines [13].

Figure 15.
Modular robot SCHUNK [7]. one- to three-finger gripping effector; 2, rotary module; 3, mechanical interface.

concept of which corresponds to the principles of functional modularity. The presented robot has 7 degrees of freedom when the required number of rotary motion modules can be linked in the series kinematic chain as required. In the design concept, rotary modules are arranged alternately perpendicular to each other, and linked modules are using complex shape interface, which is subject to demanding requirements of stiffness and low weight (a lighter metal material with sufficient strength). This concept is based on the complex structure of the modular system and the links of its elements. The advantage of this design is high flexibility and accommodation of a wide range of requirements of real applications.

4. Design of own universal rotary module with unlimited rotation (URM)

SCHUNK solution (**Figure 15**) can be improved with an innovative custom solution. The presented system of rotary modules called universal rotary module (URM) (**Figure 16**) has any number of degrees of freedom, within the rigidity, load-bearing, and precision characteristics of course. They can be connected to the required number of degrees of freedom (DOF) in the kinematic chain as required. The design concept is changed from the SCHUNK solution so that the rotary

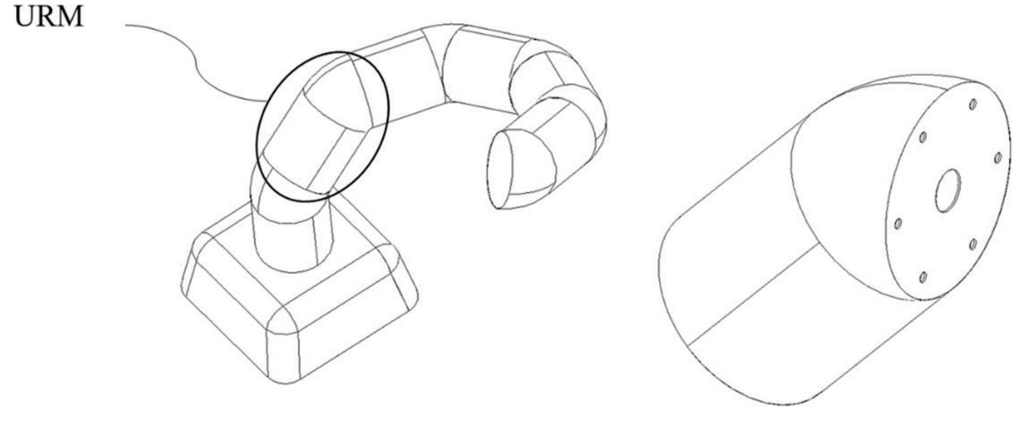

Figure 16.
Basic concept of universal rotational module (URM).

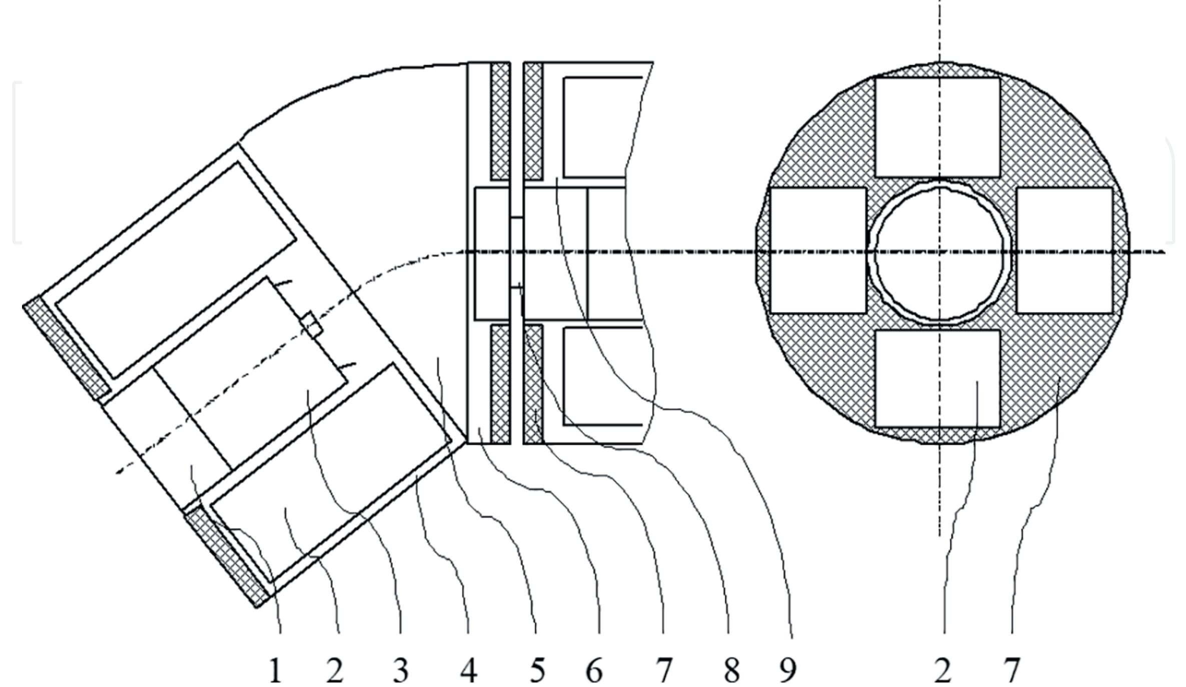

Figure 17.
Basic concept of standalone URM module and section of its structure. 1, reductor; 2, accumulators; 3, servomotor; 4, body; 5, interface; 6, connection panel; 7, coil winding; 8, rotational connection; 9, next URM.

modules are arranged at different angles in the range of 15 to 90° and not perpendicular to each other.

A simple interface is used to connect the modules (**Figure 17**, item 5) which by its curvature determine the extent and reach of the working space of the kinematic structure, which are subject to tough requirements of stiffness and low weight (material of lighter metal with sufficient strength). This concept is based on the complex structure of the modular system and its constraints. The advantage of the solution is high flexibility and coverage of a wide range of requirements of real applications.

Depending on the number of modules involved, a modular manipulator can be created with a working space of different ranges, positions, and shapes (**Figure 18**). The number of modules also determines the number of degrees of freedom of the manipulator. The design and construction of the URM allows the modules themselves to be modified so that their curvature angle may be different from the basic 45°, 90°, and the like. Subsequently, it is possible to assemble modified robot structures. Extension modules can be inserted between the modules to increase the reach of the manipulator arm while maintaining sufficient rigidity of the kinematic chain. All modifications to the mechanical part must be taken into account in the setup and programming of the robot control system.

The main benefits of designing URM-based modular structures are a pair of conveniences:

1. There is no cable bundle inside the modular structure. Neither data nor energy. This means that each module is capable of rotating without limiting the angle of rotation, as is the case of a machine tool spindle. The solution is absolutely wireless. No contact between the moving and the rotating mechanical parts occurs neither is there contact with a brush or carbon brush. Thus, the solution does not generate sparks and is, therefore, suitable to explosive or food handling environment.

2. The URM assembly has its own power accumulators inside each module. Thus, this kinematic structure is resistant to power outages. A certain short house can be operated without power. This is a benefit that other modular solutions do not yet have.

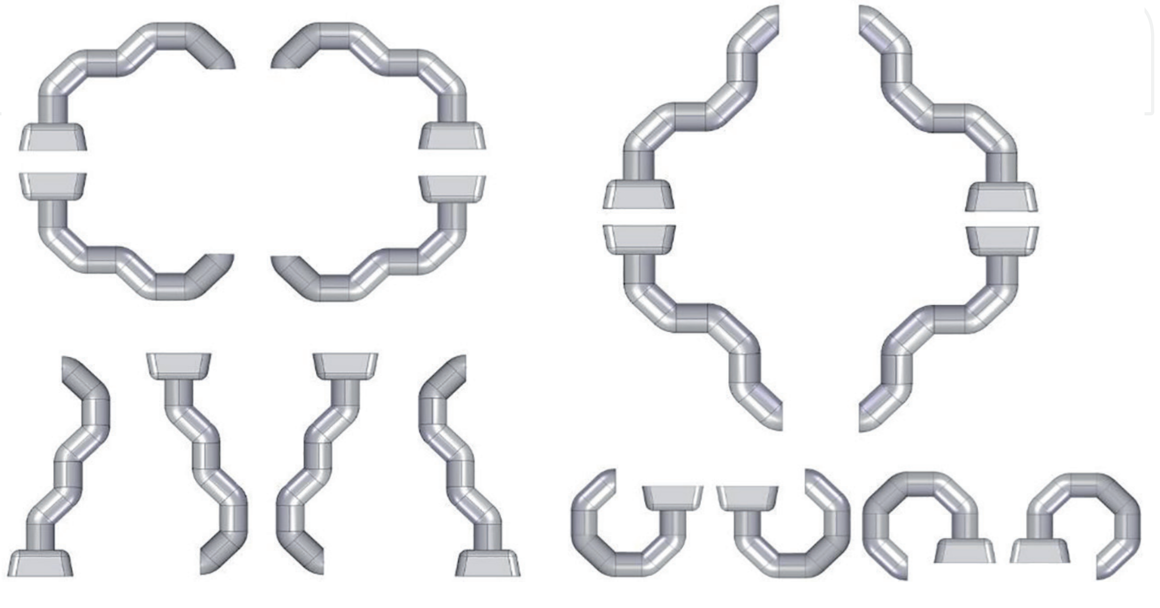

Figure 18.
Examples of reach of a modular assembly made of URM with 6 DOF.

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4.1 Design of URM prototype for robotic systems

The URM is developed by one department from Manufacturing Machinery, Faculty of Mechanical Engineering, Technical University of Košice. The result of this solution is a modular system that allows us to assemble modular robots, assembled from identical or type-identical URM01 with unlimited rotational motion. Machines and equipment constructed from these modules are designed to ensure the best possible working range and also to achieve the desired space in the work area (**Figure 19**).

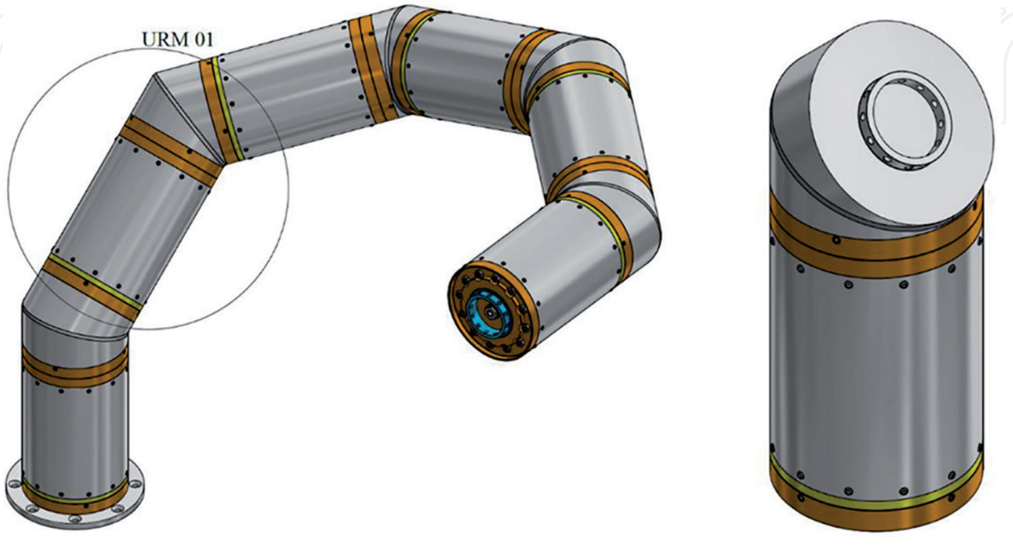

Figure 19.
Manipulator with 6 DOF of movement made of URM 01 modules.

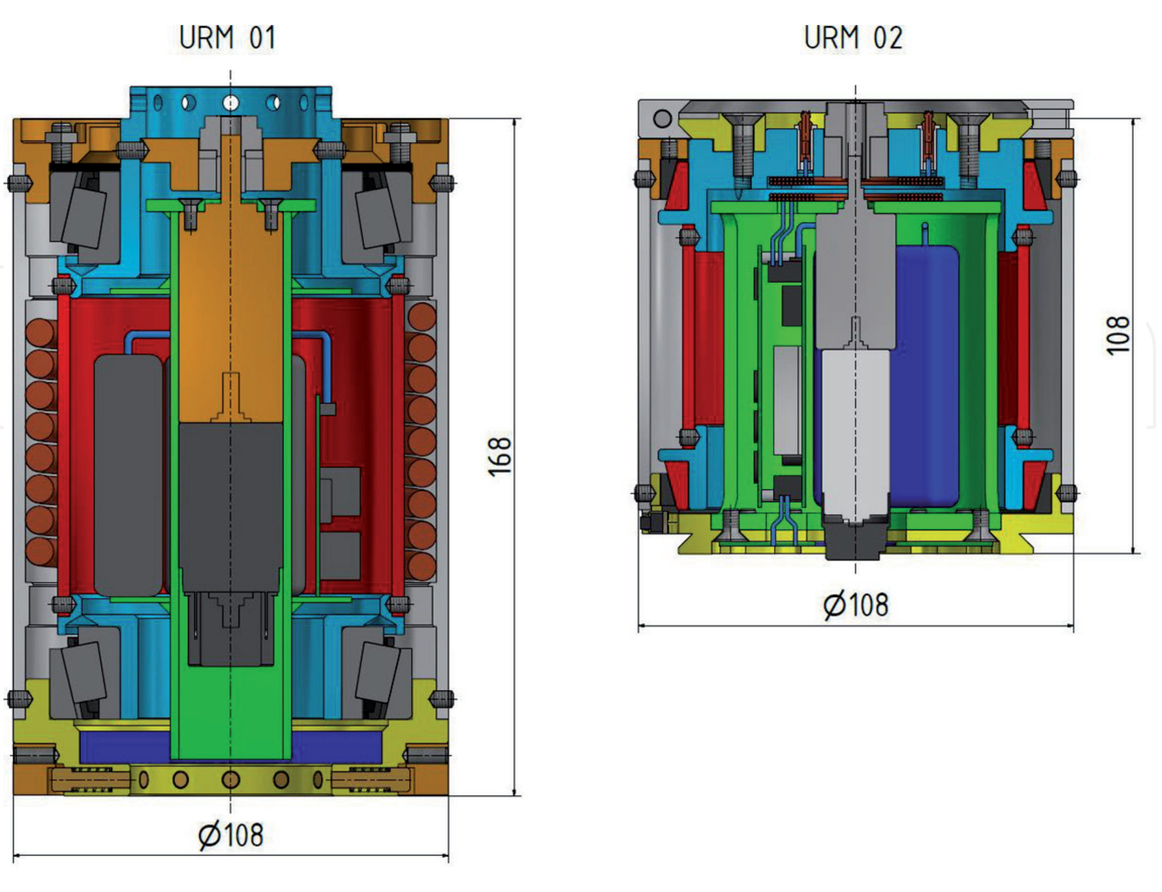

Figure 20.
The first version of the URM01 prototype (left) versus the second version of the proposed URM 02 prototype (right) with basic dimensions.

The main parameter of URM01 is the angle of curvature of the interconnectors. Since this is a homogeneous structure, the curvature of each manipulator module will be the same. A homogeneous structure with 5 DOF of movement was subjected to a series of simulation tests with different angles of curvature of the couplers. In the individual curves of the couplers, structures with interesting shapes are formed. The analysis of the working space of the individual series structures with different angles of curvature of the couplers has brought to light the fact that the more the angle of curvature of the coupler increases, the more the working space of the individual serial structures increases.

The best working space range in all axes has a series structure with 90° curvature of the coupler. This is similar to the standard solutions of SCHUNK, KUKA, etc. In our case, given the curvature of the spacer, it is necessary to consider the possibility of collision with the own modules. This problem can be addressed with the correct control algorithm or software-embedded software limit switches that alert the control system to the limit position of the axis and consequently prevent access beyond that limit.

The prototype URM02, which is conceptually based on the original first variant of URM01, is currently being completed (**Figure 20**). The development of the second-generation URM02 has brought many improvements and possibilities that its predecessor did not contain. Development has taken URM02 to a higher level, making it easier and more efficient to use it in industrial applications. As with any development, the aim was to achieve the best possible results based on the stated objectives and rules of previous research and testing.

5. Conclusions

Benefits of applying modularity to production systems:

- Modules can be developed, manufactured, and tested separately.
- Acceleration (paralleling) of development and production, production, and delivery to the customer.
- Higher component recurrence and simpler logistics.
- Higher level of design variability for the customer.
- Potential expandability.
- Higher flexibility of production volume and assortment (from the manufacturer's point of view).
- Simplification of organization and recycling.
- Acceleration of troubleshooting and service.
- Reduction of development and operating costs.

Disadvantages of applying modularity to production systems:

- Incompatibility with older production systems
- Higher acquisition price compared to conventional systems
- Lower overall efficiency in mass production

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This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-18-0413 and Research and development of rotary module with an unlimited degree rotation under Contract no. VEGA 1/0437/17.

Appendices and Nomenclature

FMS	flexible manufacturing system
RMS	reconfigurable production system
MTS	modular technical system
MC	machining center
MPC	multiprofessional productions center
MPRC	multiprofessional productions robotic center
AM_i	unified modular unit (functional node, modular block, etc.)
E_{ij}	basic building element of „$_{ij}$ “module
U_i	mutual relations (compatibility of ij module U_i to $U_{j,}$or of the ji module U_j to U_i)
X_i	module input parameters (set requirements)
Y_i	module output parameters (properties, operating functions), “a” active, “p” passive
x_{ij}	set of binary interconnections
k_M	degree of modularity
DOF	degrees of freedom

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