FUNCTIONAL ANALYSIS AND SYNTHESIS OF MODULAR MANUFACTURING SYSTEMS USING THE HOLONIC THEORY: APPLICATION TO INTEGRATED ROBOTIC WORKCELLS

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Abstract - This paper investigates the application of the concept of holons in manufacturing and business organizations. Holons are defined as an identifiable term of a system that has a unique identity, yet is composed of subordinate parts and in turn, is part of a larger whole. The generality and simplicity of Koestler's pioneering ideas for holons and holarchies, triggered rather recently the interest of numerous researchers, who suggested their use for the development of a suitable framework for designing the architecture of next generation manufacturing systems. The holonic analysis approach as a first step to modular building of systems exhibits significant advantages, such as, faster application design, re-usability of components, optimized interface with the providers, and ability of the system to evolve. The holonic synthesis approach as the second step for synthesizing new systems also exhibits attractive advantages, such as, ability to generate applications by using elements from a continuously enriched design template, time and cost savings due to the determined consistencies and interfaces among the components, and ability to add new elements to the template, thus extending the design capabilities. This paper capitalizes on the theory of holons, thus taking full advantage of its generality, and investigates new fields where this theory can be applied effectively. The presented research investigates generic manufacturing and business aspects, such as the modular design of products, manufacturing cells and business process modeling, since it is estimated that the holonic organization can provide valuable innovative concepts and solutions for improving the efficiency of such systems. A real production system with embedded robot systems is examined to reveal the full potential of the proposed approach.

1. INTRODUCTION

Holons, were introduced by Koestler [7], in an attempt to develop a framework for analyzing the internal mechanisms of all living organisms in nature and to study the evolution and organization of life mainly in biological and in social systems; they were defined as an identifiable term of a system that has a unique identity, yet is composed of subordinate parts and in turn, is part of a larger whole. Holons exhibit both autonomy and the ability to

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The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35492-7_50

G. L. Kovács et al. (eds.), *Digital Enterprise Challenges*

cooperate; that is, they are able to produce and to execute decisions through mutual agreements and co-coordinated actions. Apart of being autonomous and self-contained units, holons may also come together in order to form hierarchically organized structures called *holarchies*. These result from the integration and co-operation of various holons to a system for performing a specific function.

The generality and simplicity of Koestler's pioneering ideas for holons and holarchies, triggered rather recently the interest of numerous researchers, who suggested their use for the development of a suitable framework for designing the architecture of next generation manufacturing systems. Several research projects, such as the HMS, investigated the synthesis of systems consisting of highly flexible, reusable, and modular units, able to reconfigure quickly and easily in order to produce various products. Similar research directions were adopted in the case of business systems, where products are substituted by services. The common denominator in all approaches is the intention, and thus ability, to provide customized products/services at a low cost, as dictated by the production trends of the 21st century.

The general approach of designing and constructing modular systems comprises of two main steps, namely, (a) the analysis of existing systems in order to reveal functionalities and to generate a "palette" of modular components, and (b) the development of a coherent methodology for interfacing and integrating such modules into new systems, which may execute different functions depending on the way modules are synthesized.

The holonic theory fits precisely in this philosophy: holons, being autonomous self-reliant units that exhibit co-operative capabilities, may be regarded as suitable blocks that can be synthesized in various ways to provide systems/holarchies with different degrees of complexity and size. The holonic analysis approach as a first step to modular building of systems exhibits significant advantages, such as, faster application design, re-usability of components, optimized interface with the providers, and ability of the system to evolve. The holonic synthesis approach as the second step for synthesizing new systems also exhibits attractive advantages, such as, ability to generate applications by using elements from a continuously enriched design template, time and cost savings due to the determined consistencies and interfaces among the components, and ability to add new elements to the template, thus extending the design capabilities.

The concepts of holons and modular systems and products, may also be well applied for designing generic products. The term is used to describe products designed in a generic Bill of Materials (BOM), which allows some flexibility over certain features of the generic product. Such an approach enables a corporation to deliver variable customized products, thus achieving product differentiation and higher customer satisfaction; nevertheless, the production of a very large variety of different products may cause significant problems in production planning and delivery times. These problems may be eliminated if: (a) a large number of common components is used, which facilitates production and materials requirement planning, and (b) if routing procedures are attached to each component of the end item. Both requirements are satisfied through the holonic approach; the routing procedures, in particular, may be expressed as interfacing rules.

This paper capitalizes on the theory of holons, thus taking full advantage of its generality, and investigates new fields where this theory can be applied effectively. Extensive research is carried out in the exploration of new potential application areas and a systematic approach is followed for the examination of the different facets of the holonic theory in a coherent manner. The presented research investigates generic manufacturing and business aspects, such as the modular design of products, manufacturing cells and business process modeling, since it is estimated that the holonic organization can provide valuable innovative concepts and solutions for improving the efficiency of such systems.

A real production system with embedded robot systems is further examined to reveal the full potential of the proposed approach. The methodology for obtaining a modular design template from which larger and more complicated, robot-integrated systems can be built is outlined herein, while sample rules for synthesizing such systems are exhibited. These systems are considered as the best paradigms for illustrating the feasibility and applicability of the holonic approach. The reason is that robotic work cells are typically composed of various components, which depend on the specific application to be handled. Such components are sensors, end-effectors, actuators, etc. Depending on the application, sensors may be used, for example, to measure proximity, force/torque, or to acquire an image; end-effectors may possess fingers or be simple grippers, while external actuators may be glue nozzles, welding torches, etc.

The use of the holonic approach permits the synthesis of various robotic applications by combining the distinct components, assuming of course, that their interface properties and technical specifications are known in advance. This is achieved if an appropriate "palette" is available a priori; such a palette may be created if certain basic robotic applications are analyzed and the holons that compose them are identified and described. This palette may then be enriched as new applications are examined and created.

2. HOLONIC MANUFACTURING SYSTEMS

The world of manufacturing has experienced radical changes during the twentieth century. The first thing to notice is *mass production and standardization of products*. After the Second World War, when world-wide capacity began to come into line with world-wide demand due to technology improvements, this situation changed. This caused a shift to manufacturing strategies, where manufacturers began to capture market share by differentiating their products in new way; thus, in addition to price, another competitive factor emerged, that of *product differentiation according to customer's needs*. The advance of technology led to the development of sophisticated manufacturing equipment, permitting production at significantly higher rates and lower cost. Additionally, manufacturing management techniques such as Just-in-Time and Total Quality, added to over-capacity by making manufacturing operations even more effective and efficient. At the end of the previous century, the manufacturing emphasis was thus to compete *on prices, choice and quality*. The above trends, justified the need to proceed through a review of the existing architectures for manufacturing systems so as to provide new solutions compatible to future expectations. In order to meet diverse customer requirements and maintain manufacturing competitiveness, next generation manufacturing systems must exhibit such features as *rapid development and deployment, flexibility with respect to product quantity and variety, and re-usability of manufacturing equipment and systems* [3,6]

In this environment, the concepts of open hierarchical systems (OHS), holons, holarchies, and holonic systems have been put forward as the key concepts for designing the architecture of the next generation manufacturing systems. Believers of the *Holonic Manufacturing Systems* (HMS) theory, believe that the best way to address the needs for next generation manufacturing systems is to *create open, distributed, intelligent, autonomous and co-operative manufacturing systems*. Such systems should be *highly flexible, reusable and modular manufacturing units* [4,5]. These units should also be able to reconfigure quickly and easily in order to produce various products, and to co-ordinate among themselves according to needs and to respond intelligently to unforeseen disturbances in the external environment, and to better maintain smooth and seamless production.

A **Holonic Manufacturing System** (HMS) is defined as *a highly decentralized manufacturing system consisting of co-operative, intelligent, autonomous modules, called "holons", that together yield an agile and self-organizing manufacturing system and support global optimization* An HMS is comprised of holons, people, communication network and methods for cooperation, including procedures for negotiation and resource sharing [8].

In a HMS, its key elements, such as machines, work centers, plants, parts, products, human operators, departments or divisions are regarded as holons. Yet, holons are elements which exhibit both autonomy and the ability to cooperate, that is, to make and carry out decisions through mutual agreements and coordinated actions. Therefore, each holon must have the data necessary for deciding its own actions, means of communicating with other holons, algorithms and procedures for negotiating and executing mutually agreed actions, and means of carrying out such algorithms, procedures and actions, whether by manual or automated means. For instance, a "virtual" (information only) product holon which needs to become an actual" (physical) product must be able to request other holons in the HMS to cooperate to carry out the manufacturing processes [9].

These necessary attributes for manufacturing holons lead to the conclusion that, in order to perform any actions, they need to exhibit intelligence and possess their own centralized command system [10]. Thus, *in a holonic manufacturing system, intelligence, information and control must be distributed among all holons*. This attribute differentiates HMS from other relevant manufacturing concepts, such as CIM, where the main control and intelligence resides mainly in the central computer, which controls the complete network; furthermore, this attribute is very useful to increase the capabilities of the entire system, because:

- Multiple, even conflicting goals can be achieved, since individual holons can be working on individual goals concurrently; and
- The system is readily extensible; a new holon can be added to an already working system, increasing the level of competence of the latter.

The issue of system's extensibility, establishes perhaps the greatest challenge for the HMS project. As a matter of fact, the vision of the HMS is the *design of highly decentralized architectures, built from a modular core of highly standardized, autonomous, co-operative and intelligent building blocks (holons)*. These modules exhibit all the attributes of holons; therefore, they are exchangeable, extendible and reusable and will exhibit skills such as self-diagnosis, self-repair, self-learning and self-control and organization [1,2].

Summarizing, the main distinguishing features of a HMS are: (a) the system is built from a modular core of highly standardized, autonomous, co-operative and intelligent building blocks (holons); (b) the elements are reusable; (c) the elements are self-configuring; (d) the system is developed from bottom to top; (e) the system is easily extendible; (f) a distributed database exists, containing goals for and state of, all holons updated in real-time; and (g) a communication network exists to allow information exchange with neighboring and remote holons.

3. APPLICATION

In this section, an industrial application which will be used as an example for the *analysis of a production system*, is described. The aim of this analysis is to develop a pool of hardware and software re-usable components to enable fast and efficient generation of new applications from the analysis of existing ones. A complete description of components should contain rules of composition/ interfacing, properties, technical characteristics, limitations, etc. The application examined herein has resulted from an effort to create a basis for systematic generation of robotic applications in automotive industry; these applications involve sensory feedback, as it is expected to provide significant profits such as, accuracy improvement, uniform quality, production increase, reduction of errors and of lost material, etc.

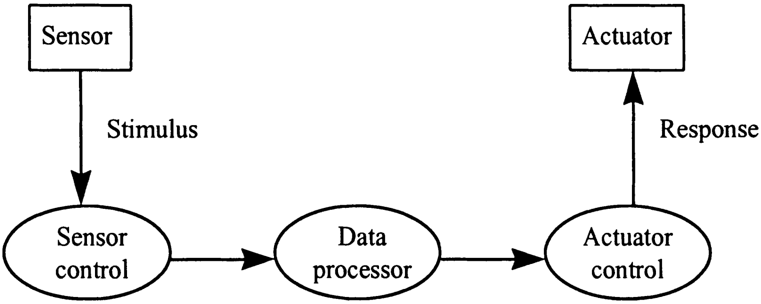


Figure 1: *Sensor-System-Actuator Model.*

The basis for applications generation is expected to have the form of a *blueprint*. The term blueprint is used to describe an aggregate of entities (hardware and software components) that are combined to form a robotic application. The description of the entities may contain properties, rules of composition/interfacing, technical characteristics, limitations, etc. As the analysis and study of the blueprint proceeds, the exact contents of the entities description will become clearer and more precise. In this context, an attempt will be made to generate a pilot blueprint in order to assess the feasibility of the concept and the evolution directions. The form of a blueprint for a robot system is based on the "sensor-system-actuator" model, depicted in Figure 1.

The implementation of a pilot blueprint proceeds through the following steps: (i) selection of a small number of robotic applications with visual feedback; (ii) first analysis of the applications into decomposable elements; (iii) further decomposition into primitive elements to the finest possible degree; (iv) identification of relationships of interaction and interfacing between the components; (v) identification of the common elements between applications and hierarchical composition of the common elements to groups; (vi) specification of the communication and interfacing rules between components; (vii) generation of a blueprint.

The blueprint generation in the final form will include the components, rules of composition, interfacing, etc. for a large number of applications. Among the profits of this implementation are the following:

(1) One will be able to generate new applications by using elements of the blueprint, so as to check for consistencies during generation, thus saving a large amount of time.
(2) New elements will be added to the blueprint if necessary. The blueprint will thus be enriched as new applications evolve.
(3) The need for new design and customized solutions from the providers will be minimized. Customization requests will be more specific. This will result to shorter implementation time and significant economy in development funds.
(4) The weak points of components, methods, etc. will be easier to identify and thus easier to correct, while the strong points will be more obvious and more easily estimated, and thus easier to profit.
(5) The time for application design and test will be minimized. This, in combination with the economic benefits of customized implementation, are expected to provide significant economic profits.
(6) The time for the implementation of a production line will be shortened. New products will enter the market sooner than expected, thus providing competitive advantages to the company.
(7) The applications will be more formally specified, described, and recorded. This will facilitate the development planning and will clarify the new research directions.

The application examined herein is the *sunroof placement application*. In this application, the workcell contains two industrial robot arms (IR1 and IR2), two conveyor belts (C1 and C2), and a glue nozzle (GN). Conveyor C1 brings the sunroof parts to the workcell, while conveyor (C2) brings the car bodies (Figure 2). The car bodies are assumed to be ready for the sunroof placement, that is, an appropriate opening has been created. The sunroof is placed in the inner part of the car body, that is, on the lower side of the opening. When the sunroof is positioned on the car body in order to be fixed, considerable pressure is exerted on the metal of the car body. This pressure may cause irreversible deflections to the car body. A rigid "negative" is positioned on the upper side of the sunroof opening, that is, in the outer part of the car body, n order to account for this deflecting pressure. Both the sunroof *and* the negative are pressed simultaneously, and for the same time period, against the car body in opposite directions and pressure magnitudes, so that fixation is performed without metal distortions.

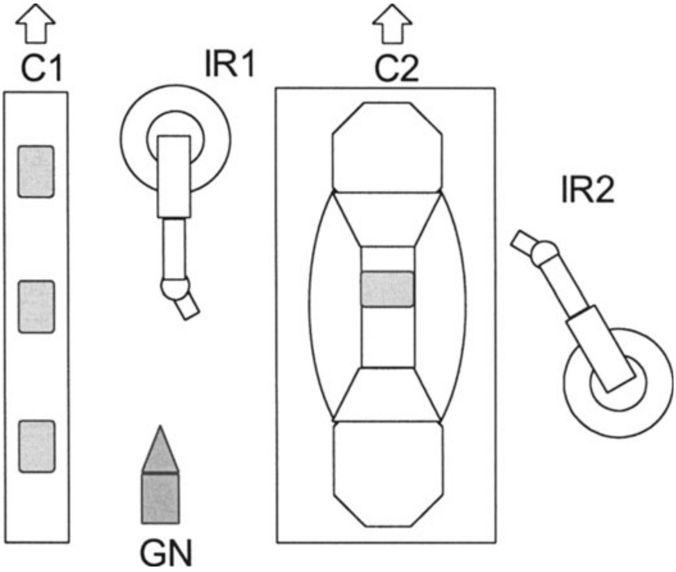


Figure 2: *Workcell Layout for the Sunroof Application.*

The work phases for this operation are separated to those performed by IR1 and by IR2. The work phases for IR1 are the following:

P1.1 *Pickup of the sunroof from conveyor C1*: The robot moves to the conveyor and picks up the sunroof. Proper grasp of the sunroof is ensured by the function the end-effector (EE1) of IR1. When the EE1 senses that the object is properly grasped, the robot picks up the object.
P1.2 *Glue application on the perimeter of the sunroof*: The robot moves the object close to the glue nozzle to begin gluing. Uniform and precise glue application is ensured by the use of a contour following sensor. When gluing finishes, IR1 removes the sunroof from the glue nozzle.
P1.3 *Placement of the sunroof on the car body*: The sunroof is moved close to the car body and placed to the opening. Precise placement is ensured by the use of visual sensors that monitor the sunroof position relatively to the opening and guide robot motion. After placement, the sunroof is fixed to the car body using clamps. After fixation, EE1 releases the sunroof and IR1 goes back to its initial position.

The manipulator IR2 has attached on its end the "negative" and clamps. There exists only one work phase for IR2:

P2.1 *Placement of the "negative" on the car body*: IR2 moves the "negative" close to the sunroof opening,and places it precisely using visual sensors to monitor the "negative's" position relative to the opening and to guide the robot's motion. After sunroof fixation on the car body, IR2 goes back to its initial position.

The analysis method that is used is the "Structured Analysis". This method is used for determining the requirements for a system, and to construct logical system models. These models are simplified depictions of the function of an object or the sequence of a process. They are easier, quicker and cheaper to create than the final system, and modifications can be effected here at a fraction of the cost required to alter a finished system. The tool that is used for creating Structured Analysis descriptions is ProMod, a CASE environment that contains a Structured Analysis tool.

Hierarchical structures are an integral part of the Structured Analysis method, enabling information to be represented on various levels of abstraction. All data can therefore be included without losing the diagram clarity, by successively "refining" diagram elements into further diagrams. In Structured Analysis Flow Diagrams are used. Flow diagrams model processes which transform data, and the interfaces between those processes. Diagrams are built up of *Nodes* (processes), *Stores*, *Terminators* and *Data Flows*.

- Data flows indicate the flow of data in a Flow Diagram to and from Nodes, Terminators and Stores.
- Nodes symbolise the processing of data. They transform incoming data into outgoing data. A Node representing a complex process can be additionally depicted in a separate Flow Diagram, its "child diagram". This process is called "refining", and is the basis for the system hierarchy.
- Stores hold data for use in more than one process (Node). Information is written to and read from Stores by Nodes. This is represented by incoming and outgoing Data Flows respectively.
- Terminators are data sources or sinks which show the exchange of information between the SA model and the "outside" world.

Structured Analysis in its simplest form represents the flow and transformation of data. A Flow Diagram does not take account of the chronological order in which events occur. Real Time elements can then be used in a Flow Diagram to model the system's dynamic behavior. These elements reveal the conditions under which the processes are triggered.

As regards the sunroof placement application, firstly, it is decomposed into two *robot systems*. Each robot system contains a robot (and eventually other actuators), sensors and the corresponding data processors, as shown in Figure 3. Each robot system is treated as an operational unit which performs a well defined task (production step). For example, a robot which grasps an object, applies glue on it, and then places it on another object is such a robot system.

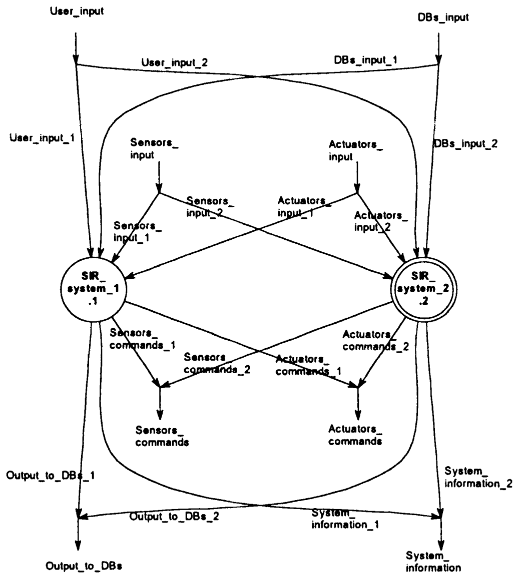


Figure 3: *Sunroof Placement Application.*

In the second decomposition step each robot system is described with a data processor, which communicates and exchanges data with the *control units* of sensors and actuators (Figure 4). The control units are the interfaces of sensors and actuators. The hardware capabilities are accessed through them. For each class of sensor, a corresponding sensor control unit class is introduced (Figure 5). For each sensor control unit class, there is a corresponding sensor processing entity (Figure 6). Such a flow diagram description does not imply that, in an implementation, for all sensor control units of a sensor class, only one sensor processing unit is used. It just describes the kind of data processing for a sensor class. In an implementation, more processing units of the same kind may be used in parallel.

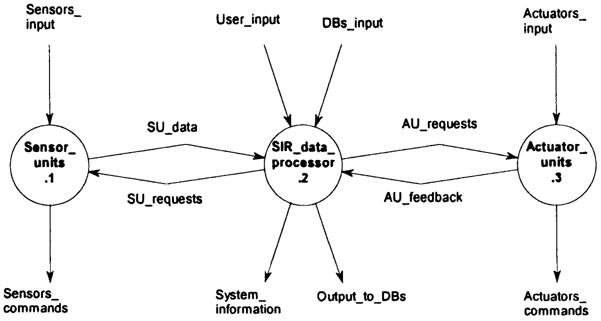


Figure 4: *Robot System Analysis.*

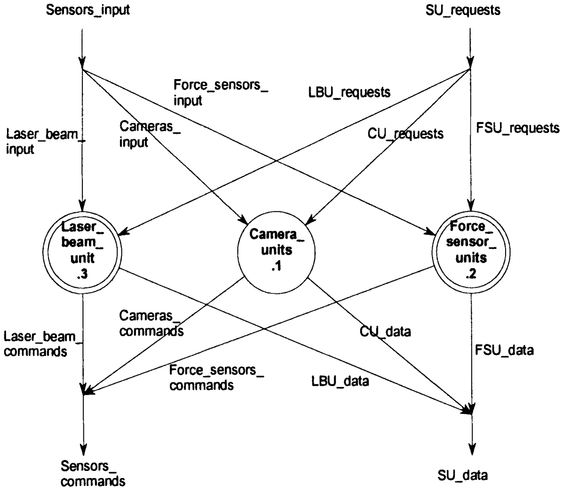
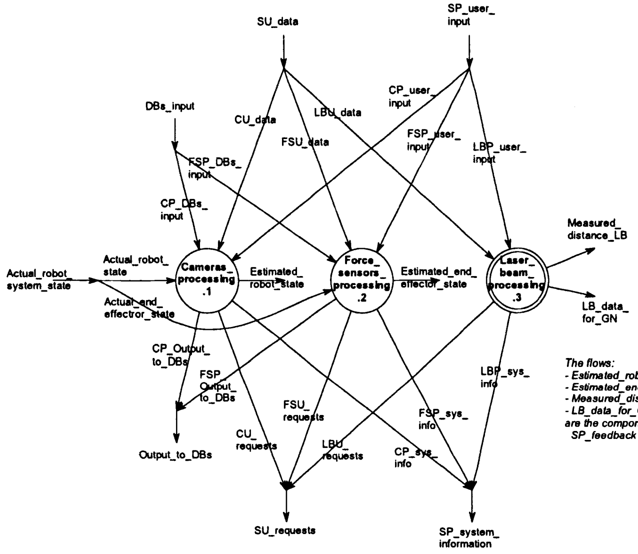


Figure 5: *Sensor Units.*



The flows:
- Estimated_robot_state
- Estimated_end_effector_state
- Measured_distance_LB
- LB_data_for_GN
are the components of the flow
SP_feedback

Figure 6: *Sensors Processing.*

4. CONCLUSIONS

From the previous analysis and the study in modular manufacturing systems using the holonic theory, the following conclusions result:

- The holonic architecture is a highly promising solution for the future, since it can combine the best features of hierarchical and heterarchical architectures is a flexible manner.
- The holonic architecture appears consistent to the needs for the design and organization of production systems and enterprises in the future.

- There exists a large number of possible applications of the holonic theory; however, the most promising areas seem to exist in designing modular production systems and products, in business organization of companies in holonic networks, in analyzing an enterprise to its business processes, and in biological systems.
- The holonic theory can be considered as a very effective framework for studying, analyzing and designing complex systems. The concepts of holonic organization can be exploited effectively for building a modular design template (*autonomy*) and the rules for synthesizing, later on, these modules in larger systems (*co-operation, interface rules*).

The contributions of this study include the following:

- development of a systematic basis for analyzing, structuring, and decomposing robotic applications with sensory feedback and formulation of a complete set of decomposition rules for these;
- establishment of the a CASE tool to analyze and structure robotic applications along with presentation of the holonic software concept and suggestion of parallelisation implementation;
- identification of the correspondences between software entities and system components.

BIBLIOGRAPHY

[1] Bongaerts L., Wyns J., Detand J., Brussel H.V., Valckenaers, "Identification of Manufacturing Holons", in *Proceedings of the European Workshop for Agent-Oriented Systems in Manufacturing*, pp. 55-73, Berlin, 1996.

[2] Bongaerts L., Valckenaers P., Brussel H.V., Peeters P., "Schedule Execution in Holonic Manufacturing Systems", in *Proceedings of the 29th CIRP International Seminar on Manufacturing Systems*, May 11-13, 1997, Osaka University, Japan.

[3] Carr D.K., Johansson H.J. *Best Practices in Reengineering*. McGraw-Hill, 1995.

[4] Fukuda T., Ueyama T., "Autonomous Behavior and Control", in *Proceedings of the IEEE International Conference on Robotics & Automation*, 1993.

[5] Huang C.C., Kusiak A., "Modularity in Design of Products and Systems", *IEEE Transactions on Systems, Man and Cybernetics*, **28**(1), January, 1998.

[6] Kidd P.T. *Agile Manufacturing: Forging New Frontiers*. Addison-Wesley, 1994.

[7] Koestler A. *The Ghost in the Machine*. Hutchinson & Co, London, 1967.

[8] McHugh P., Merli G., Wheeler W. *Beyond Business Process Reengineering: Towards the Holonic Enterprise*. John Wiley & Sons, 1995.

[9] Van Brussel H., "Holonic Manufacturing Systems, the Vision Matching the Problem", in *Proceedings of the First European Conference on Holonic Manufacturing Systems*, December 1994, Hanover, IFW-Hanover.

[10] Wyns J., Brussel H.V., Valckenaers P., Bongaerts L., "Workstation Architecture in Holonic Manufacturing Systems", in *Proceedings of the 28th CIRP International Seminar on Manufacturing Systems*, May 15-17, 1996, Johannesburg, South Africa.