

THE OPEN-CONTROL CONCEPT FOR HOLONIC MANUFACTURING

Silviu RAILEANU * Thierry BERGER ** Yves SALLEZ **
Theodor BORANGIU * Damien TRENTESAUX **

* University Politechnica of Bucharest, Romania
** LAMIH-CNRS, University of Lille Nord of France, France

ABSTRACT

Nowadays, the advances in information technology and electronics made possible attaching devices with decisional and communicational capabilities to almost all of the entities present in a Flexible Manufacturing System. This allows the passage from the classic centralized control approach to a fully decentralized approach where each entity has its own objectives, making it very hard for the system as a whole to achieve a global objective like minimizing the production time (makespan). In this context the paper proposes a new control concept in which commands from a superior level are not sent in a rigid manner but rather as recommendations. Open-control, along with the holonic manufacturing concept tries to offer the tools needed to face the rising complexity of Flexible Manufacturing Systems. After introducing the open-control paradigm, we illustrate one possible implementation based upon the holonic approach applied to a job shop production system, containing multiple networked robot workstations.

Keywords: Open-control, holonic manufacturing systems, Contract Net Protocol

1 INTRODUCTION

To be competitive, manufacturing should adapt to changing conditions imposed by the market. The greater variety of products, the possible large fluctuations in demand, the shorter lifecycle of products expressed by a higher dynamics of new products, and the increased customer expectations in terms of quality and delivery time are challenges that manufacturing companies have to deal with to remain competitive. Besides these market-based challenges, manufacturing firms also need to be constantly flexible, adapt to newly developed processes and technologies and to rapidly changing environmental protection regulations, support innovation and continuous development processes [10]. Although the optimization of the production process remains a key aspect in the domain of fabrication systems, adaptive production gains more and more field [14]. Flexible manufacturing systems should be able to quickly adapt to new situations like machine breakdown, machine recovery due to physical failure or stock depletion and also face rush orders [1].

In recent decades, scientific developments in the field of production have defined new architectures including the heterarchical/non-hierarchical architectures that play a prominent role in FMS. This paper is an extension of the work in [12], describing an instantiation of the open-control paradigm, the societal implicit open-control, using the holonic manufacturing concept. This paradigm is an extension of the previous work in the domain of heterarchical control [15] and includes the concept of implicit control in addition to the traditional explicit control. The structure of the paper is: introduction of the open-control paradigm, its description and motivation in section 2, a detailed description of the static model of the fabrication system using the holonic concepts is presented in section 3; Section 4 gives the physical infrastructure, the experiments done and their results. The paper ends with the conclusions and perspectives resulted from the current work.

2 MOTIVATION

Traditional approach is mainly associated to the initial CIM (Computer Integrated Manufacturing) concept and usually leads to centralized or hierarchical control structures. Due to the complexity of manufacturing problems, the usual practice has been to split the overall problem into hierarchically-dependent functions that operate within

Contact author: Silviu RAILEANU¹

¹silviu@cimr.pub.ro.

decreasing time-ranges, such as planning, scheduling and control and monitoring. This traditional approach is known to provide near optimal solutions, but only when hard assumptions are met, for example, no external (e.g., rush orders) or internal (e.g., machine breakdowns) perturbations, well-known demands, and/or supplier reliability. Since reality is rarely so deterministic, this approach rapidly becomes inefficient when the system must deal with stochastic behaviour.

The above observations have led researchers to define a second approach to designing control architectures. These control architectures, also called emergent or self-organized, can be categorized in four types [3]: *bionic & bio-inspired*, as proposed by Okino [11] and Dorigo & Stützle [5]; *multi-agent*, as proposed by Maione & Naso [9]; *holonic*, as proposed by Van Brussel [17]; and *heterarchical*, as proposed by Trentesaux [16]. An analysis of the state-of-the-art has been recently published by Trentesaux [15]. His main conclusion is that the expected advantages of such architectures are related to agility: on short term, such architectures are reactive and on long term, they are able to adapt to their environment. However, these last control architectures suffer from the lack of long-term optimality, even when the environment remains deterministic, which can be called “myopic” behaviour. This is the main reason why such control architectures are not really used by industrialists at the moment.

The paper presents an extended model for the global control paradigm, in which traditional control is augmented by a new type of control: “implicit”. In this paradigm, entities can be strictly controlled hierarchically and, at the same time, they can be influenced heterarchically by their environment and/or by other entities. This paradigm would make it possible to design control systems that are both agile and globally optimized, thus reducing the myopic behaviour of self-organized architectures and increasing the agility of traditional architectures. Combining the two types of control in the same architecture causes new challenges since the two types of control must now be managed and integrated within the larger control paradigm.

The work in this paper focuses on the type of control in which an entity tries to achieve its own goals with respect to the global system objectives by the means of a dialogue with the other entities; the entities can be resources or active products, both equipped with decisional and communicational capacities. An *active product* is an entity that is able to inform, communicate, decide and act in order to reach its goals in solving resource allocation and routing problems. (For more details on the typology and advantages of active products see [19]).

The control principle briefly described above will be further called in this paper *open-control*, according to [13], because of the capacity of subordinate levels to receive orders from upper control levels through direct orders (explicit control) and recommendations (implicit control), in which case they exhibit local decisional capabilities to follow their own

objectives enabling thus the easy addition and removal of entities.

Based upon the relations between different control levels, Figure 1 shows the two kinds of control: the explicit control, in which the entities from lower levels are subordinated directly to entities on a higher level through an obligatory control relation (e.g., master-slave) and the implicit control, in which the entities at lower levels are influenced by an intermediary optimization mechanism but not necessarily controlled.

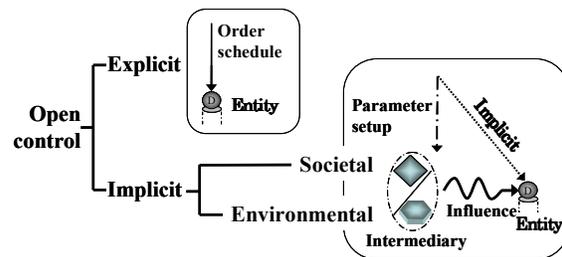


Figure 1 Control typologies present in the open-control concept

Implicit control involves influencing entity behaviour by setting up the parameters of the optimization mechanisms. This type of control works in two stages. First, through explicit control, the superior level directly affects an intermediate entity that plays a role in a societal or environmental optimization mechanism. The affected part of the intermediary entity can be either the decisional mechanism (represented by the diamond in Figure 1) which generates a societal type of control, or it can be a directly the environment which memorizes information (represented by the hexagon in Figure 1). Then, an information exchange (peer-to-peer dialogue or a diffusion process) influences the behaviour of the other entities on the same level.

Taking into account the way the upper control level influences the lower levels, implicit control is of two types:

1. **Implicit control via a Societal Optimization Mechanism (SOM).** In this case the upper level either fine-tunes the partial view of a collective property inside an entity, modifying its behaviour and then this entity influences the others through dialogue, or the upper level changes the dynamics of the dialogue in the SOM by modifying the dialogue parameters inside the entity. The key element of implicit control using a societal SOM is the dialogue between entities which leads to the two characteristics of holonic manufacturing systems: autonomy and cooperation [8]. This is why this concept offers good means of implementation for semi-heterarchical control systems which under normal conditions work under a hierarchical structure but when perturbations take place each entity uses its own decisional capacities to continue production (Ex.: staff holon proposed in PROSA, [17]).

Implicit control via an Environmental Optimization Mechanism (EOM). This type of control is performed using last minute information from the environment [2]. This environment is characterized by a memorization mechanism, which stores data or physical characteristics, and an optimization mechanism that acts upon the memorized information.

3 HOLONIC MODEL OF THE FABRICATION SYSTEM

Based on the PROSA reference model [17] and the production domains presented in [10] the following base elements were identified in a fabrication system: resources, products (blueprints) and orders in execution represented by the physical products which are currently fabricated. Because the entities in the fabrication system are almost all equipped with decisional capabilities we decided to structure the system according to the holonic principles and implement an implicit societal open-control which will confer both the adaptive and optimality characteristics in its operation. The following elements, presented in Figure 2, have resulted after applying the holonic scheme to the flexible manufacturing system: resource holons (RH), product holons, order holons (OH) and expertise holons (staff holon according to PROSA).

The **order holon**, the first key point of the fabrication system, represents the client's order in real-time and is composed of the following informational and physical parts: an augmentation module which enriches the holon with decisional (information processing), communicational (information transport) and memorization (information storage) capabilities, the pallet which associates with the

fabricated product along the production phase providing it transportation services and the passive product which is fabricated/assembled on the pallet. The structure of an order holon emphasizes the recursive propriety of a holon which can in turn be composed of other holons. In this case the order holon contains two resource holons, a pallet used for transportation with an augmentation module used to process information, and a product holon representing the blueprint containing the operations needed for execution.

Depending on the way the order holon connects to the informational network (RFID, WiFi, Bluetooth, IrDA, etc) and the computational capacities of the local augmentation module the OH intelligence can be divided as follows (Figure 2):

1. At distance, on a distant machine: in this case between the main control system and the physical part (the pallet) exists a synchronization so that the control system is always aware of the current state of the product. Usually this synchronization is done using RFID. In this case the OH is delimited by line 1 in Figure 3;
2. Locally: the main control system is located directly on the physical part. In this case the OH is delimited by line 2 in Figure 3;
3. Hybrid: the main control system runs on a distant dedicated machine and its role is to take high level decisions (ex.: processing resource allocation). Besides this high level control system there is a local control system dedicated to handling alarms, monitoring product status and taking local decisions like routing towards a goal established by the main control system. In this case the OH is delimited by line 3 in Figure 3.

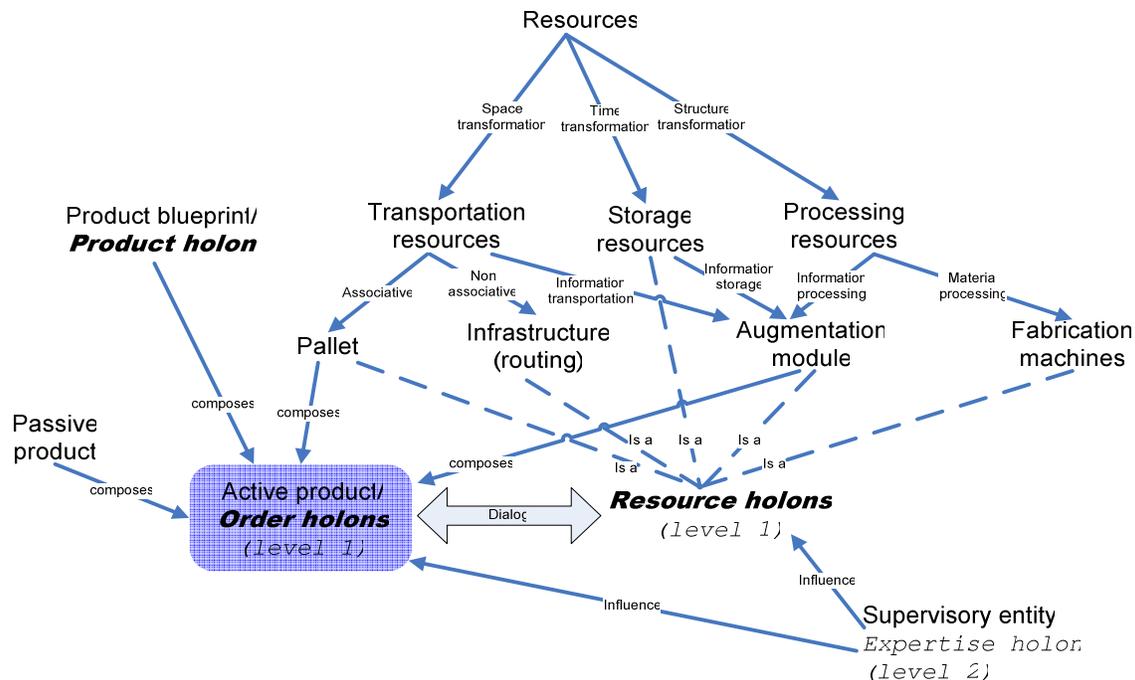


Figure 2 System components (static model)

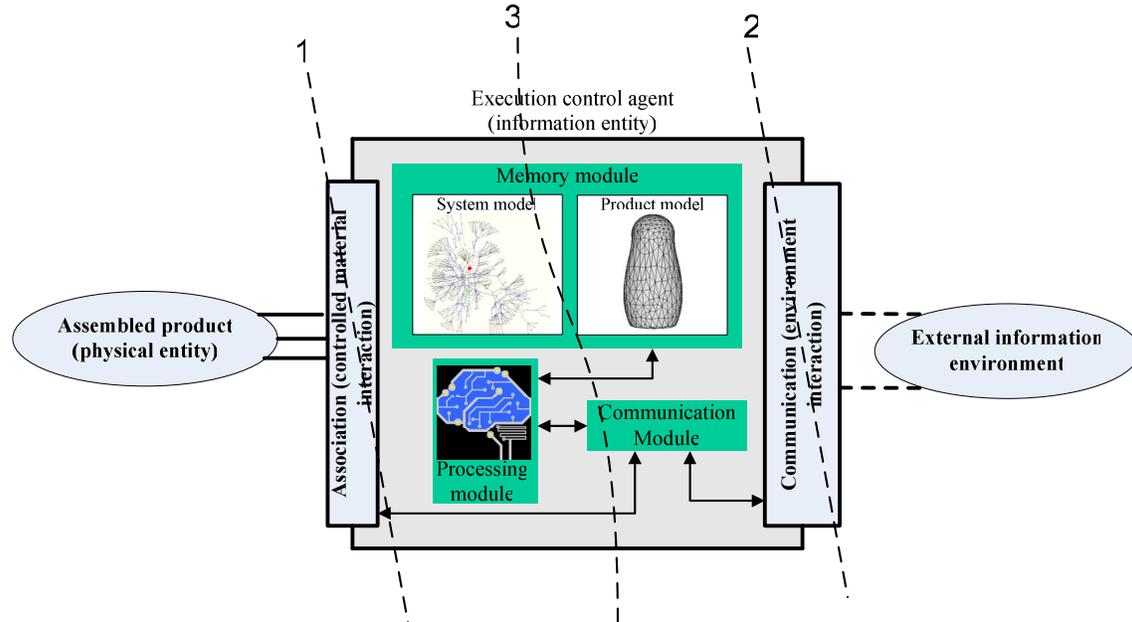


Figure 3 Location of an OH intelligence

The second key point of a fabrication system, the **resource holon**, is composed of an informational part responsible for decision making, control and communication and a physical part responsible with the physical processing (e.g.: mounting a piece on the product, image recording, etc). Depending on the type of operation performed by the resource the system is composed of the following basic types of resources: of processing type offering structural transformation services, of transportation type composed of motion infrastructure (ex.: conveyor belt or conveyor segment) and mobile entities (ex.: mobile shuttle/pallet) which together offer spatial displacement services and storage type offering time locating services. Moreover, each resource can be further classified, according to the entity upon the function is exercised, into information processing (as is the case of the augmentation module) and material processing (as is the case of an industrial robot working upon a product).

For the logical part of the system to be in conformity with the societal open-control concept proposed, the entities of the system are distributed on a 2 layer architecture, a low decisional level and a high decisional level. Usually a factory is composed of three levels [13]: strategic problem solving at the top (level 3), tactical problem solving in the middle (level 2) and operational problem solving at the bottom (level 1), our architecture taking into account level 1 and 2.

The low decisional level (level 1) is composed of autonomous entities, OHs and RHs, which communicate in order to optimize their production schemes. The high decisional level (level 2) is useful at providing general guidance, through the influence of the OM existing at level 1 (Ex.: explicitly modifying the local view of an entity, like

the set of corresponding entities to communicate with), in order to attain a global objective; otherwise the low decisional level might have an uncontrolled emergent behaviour. The high decisional level is represented here by the coordinator holon which besides general guidance offers a mean of integrating the fabrication system into the upper layers of the factory (Ex.: attaching client demands to order holons, supervision of the system, computing parameters describing the global behaviour of the system, etc).

Although an FMS is composed of transportation, processing and storage resources, for fabricating a product only the processing resources are mandatory; the others are just used to automate the transportation process. For this reason when executing a product the decisional module should provide an answer to the following questions: What is the next operation? What is the resource that will do that operation? How do I bring the product there? The last two questions are being considered together in order to minimize the sum of the processing and routing times. According to Figure 4 the general order execution process is composed of the following three subprocesses:

- First, an order (seen as an active decisional product) *updates its personal knowledge* about the possibilities of each resource from the system (A);
- Second, a *decision* that regards the three questions posed above is taken (operation, **R**esource for **P**rocessing (RP), **R**esource for **R**outing (RR)) (B);
- and third step, *execution* (C) takes place.

The extended process is a modified version of the Contract Net Protocol [7] and is described in Figure 5.

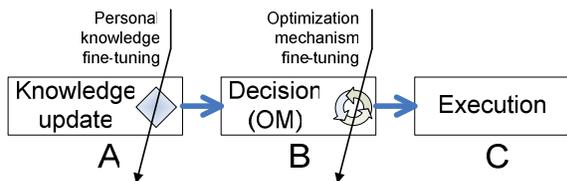


Figure 4 General order execution process

Figure 4 represents the dynamic interaction of the decisional entities presented in Figure 2 for optimizing the allocation and execution operations according to the implicit type of control. The choice for the product to be manufactured is done by the augmentation module in a

fixed location, the input/output of the system. Once a product is chosen it cannot be changed unless its production was completed or it was compromised in the manufacturing process. In order to find out what type of product should be attached to the pallet, the augmentation module interrogates the client's orders database, then the system resources and then, according to the products deadlines, to their complexities and also to the charge of the system a single product representing a production order is chosen for fabrication.

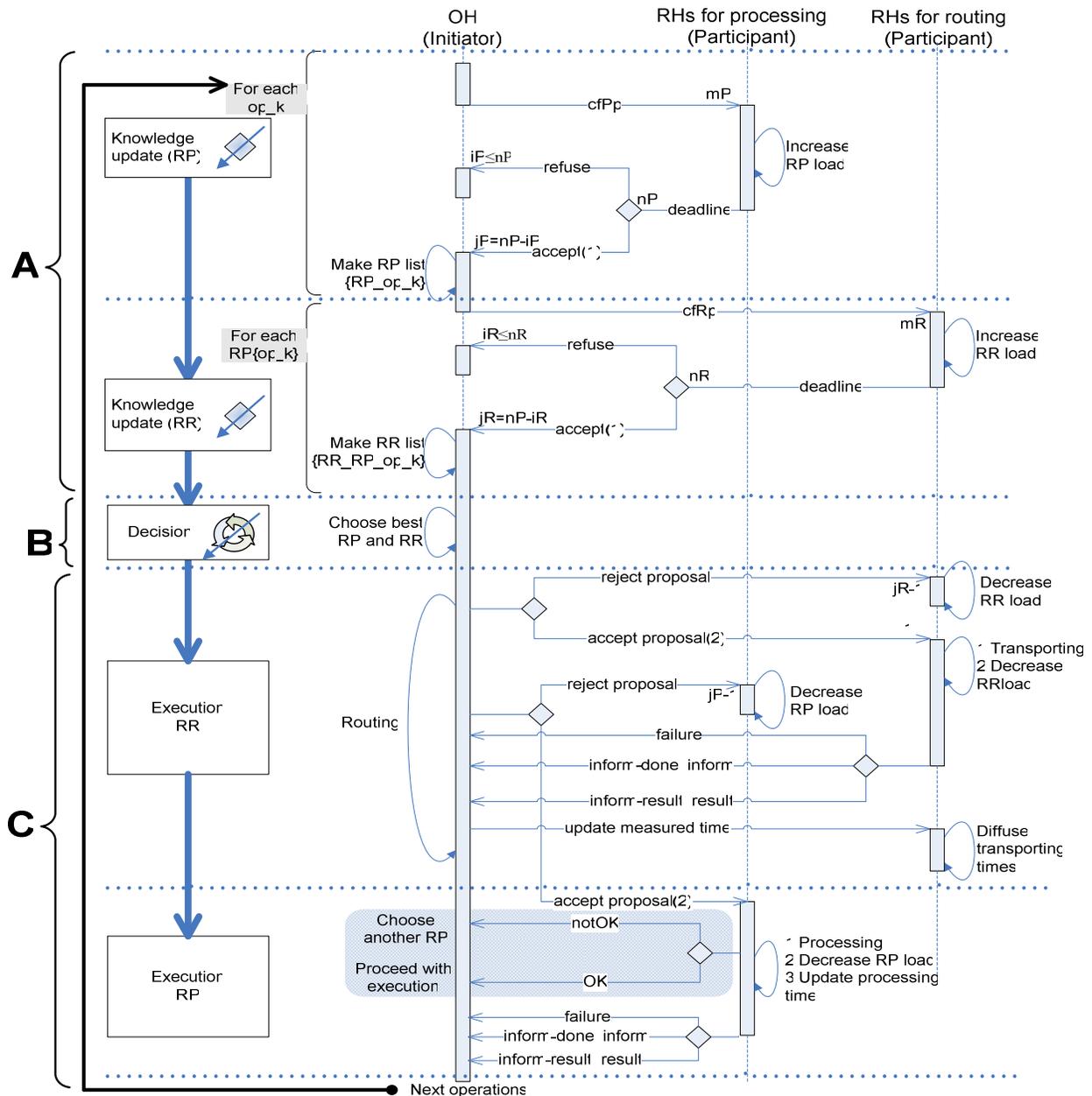


Figure 5 Interactions between order holons and resource holons for optimizing the allocation and execution operations

The interaction process between an OH and the RHs, representing the dialogue arrow in Figure 2, begins with the "knowledge update" stage during which each operation of the order (op_k, k=1:total_number_of_operations) is tested to see if there is a corresponding resource capable of executing it. Then, for each resource found capable of executing a processing operation a path towards it is searched (For each RP{op_k}). The knowledge update process takes place two times, the information exchanged and the way it is exchanged being almost the same except that it is done for different type of resources: update the processing model and update of the routing model.

The updating model process relies on the exchange of information between entities using messaging mechanism. The messages to resources are sent in the form of call for proposals (*cfPp* referring to calls made for processing resources and *cfRp* referring to calls made for routing resources) and because the dialogue is synchronous, in order not to block an order waiting for a response from a failed resource, timeouts for replies are imposed: if the resource does not respond in the established interval it is declared off-line and it is not taken into account during the decision making process. If the resource replies in this interval the answer can be negative or positive. The negative answer represented by the *refuse* arrow in Figure 4 indicates that the state of the resource does not permit to execute the requested operations because the resource is busy with other products, or the resource can not execute the requested operations; in both cases the resource is operational. The positive response is represented by the *accept* arrow that indicates the availability of the resource to execute the requested operation.

After the "knowledge update" process the model of the system is ready and the production order can begin taking decisions which regard the manufacturing process: what is the next operation, on what resource it's done and what is the path to the resource.

After the above decisions are taken, the workloads of the chosen routing and processing resources are increased. This process is represented on the diagram of the interactions in negative logic (to respect the standard Contract Net Protocol [7]), with the aid of the *proposal reject* message which is sent to all the resources that have participated in the dialogue and have not been chosen; in order not to increase and then decrease resource charge during each dialogue it was chosen to increase only once the charge, after the decision, when the chain of resources is finally chosen.

Figure 4 shows the case where only a single production order interacts with the resources of the manufacturing system. In the real case there are several products, the resources being able to face all of them.

The start of an operation, routing or processing, is marked by the *accept proposal* message, which in the case of processing resources may contain additional parameters (e.g.: the points between which an assembly operation is done). Before the production order enters the processing

resource a last dialogue takes place between it and the corresponding resource in order to confirm the production possibility. After the *accept proposal (2)* message, the chosen resource must send a message that contains either *OK*, the product can enter, or *notOK*, the resource has failed during the routing phase of the production order or another product is in production or there is no raw materials in the workplace, in which case the product jumps at the decision state, seeking another answer to the 3 above questions.

The end of an operation is marked by the reception of one of the following messages *inform-done*, *inform-result* or *failure*. *Inform-done* is a simple message sent if the resource has well finished the operation. If more information is required then the resource can send a detailed message of the execution, *inform-result*. *Failure* is a simple message sent by the resource to inform that the requested operation has failed (e.g.: the video inspection has not found the requested characteristics of the object).

For other production orders to take into account the transportation times in real-time (e.g.: instantaneous charge of a line between two resources) travel times are measured and then written to the destination transport resource with the aid of *update measured time* message; this time is then diffused to all the other transport resources via a broadcast mechanism.

The optimization mechanism (OM) is done using the dialogue between the entities of the system. The information exchanged in order to minimize the makespan is the charge of each resource.

4 EXPERIMENTAL RESULTS AND PERSPECTIVES

The open-control concept presented above is currently under deployment at the Flexible Manufacturing System at AIP PRIMECA Valenciennes, Figure 6, composed of a multi-path conveyor, self-propelled pallets with embedded decision capabilities, and flexible workstations with industrial robots and visual inspection cameras.

The transporting resources are composed of the underlying infrastructure on which the physical support of the order holons progress, along with the control represented by WAGO PLCs [18] that drive the transfer gates according to the commands received from the OH. The processing resources are represented by the corresponding resources and the PLCs that do the control, and consist of industrial robots. The interactions between resources and orders (Figure 7) take place in special places and via an Ethernet-IrDA bridge which aids to both communication and localisation. In our case the bridges consist of IrDa Clarinet systems ESB 101 [4] located for the transporting resources before the transfer gates and for the processing resources in the station workplace.

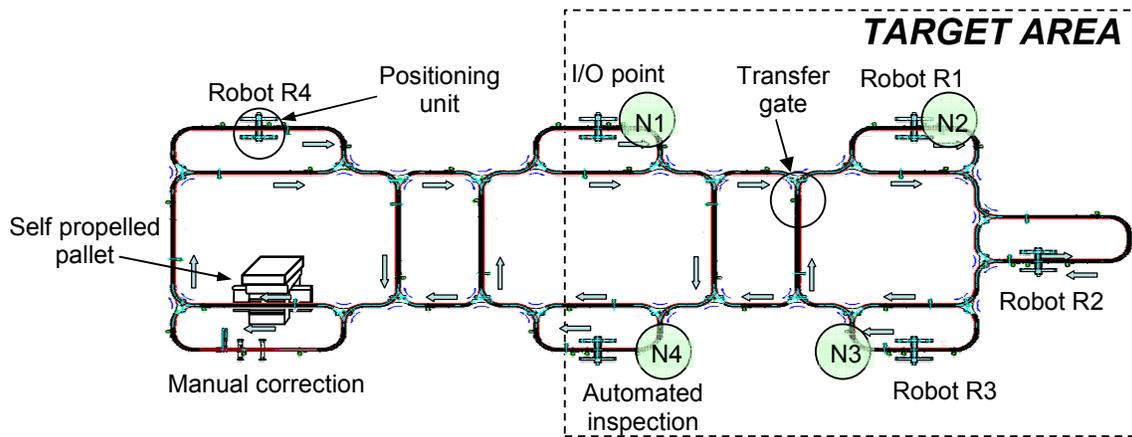


Figure 6 AIP cell system layout

The implementation of the routing part from the general interaction scheme, presented in detail in Figure 4, is done on a small scale model as depicted in Figure 6 making use of the MODBUS protocol which already exists on the PLC controlling the resources. On the down side the entities that participate at the dialogue are shown, the order holons and the resource holons; in the upper part an adaptation of the general dialogue, the routing with the allocation, from Figure 4 is presented.

Before starting execution, or after finishing an operation the online allocation of the next operation takes place as depicted in Figure 7. Afterwards, the routing towards the selected resource is done.

When the Order Holon arrives at a routing node, the following messages are exchanged after connection for the routing purpose:

- The OH transmits the measured time it took to travel from the previous node to the current one and the RH broadcasts it to the others RH updating in real-time the routing information;
- Information about the current resource is read from its control PLC;
- The transportation times are sent to the OH, which updates its routing model and chooses the best neighbor by locally applying the Dijkstra routing algorithm [6], work detailed in [19];
- The OH sends a routing demand to the current RH which acts upon the transfer gate.

The future developments to be considered are the implementation of the routing procedure and the online allocation procedure on the real FMS from Figure 6 and then do a comparison between a static (offline) allocation and the online allocation using the societal open-control concept and holonical approach.

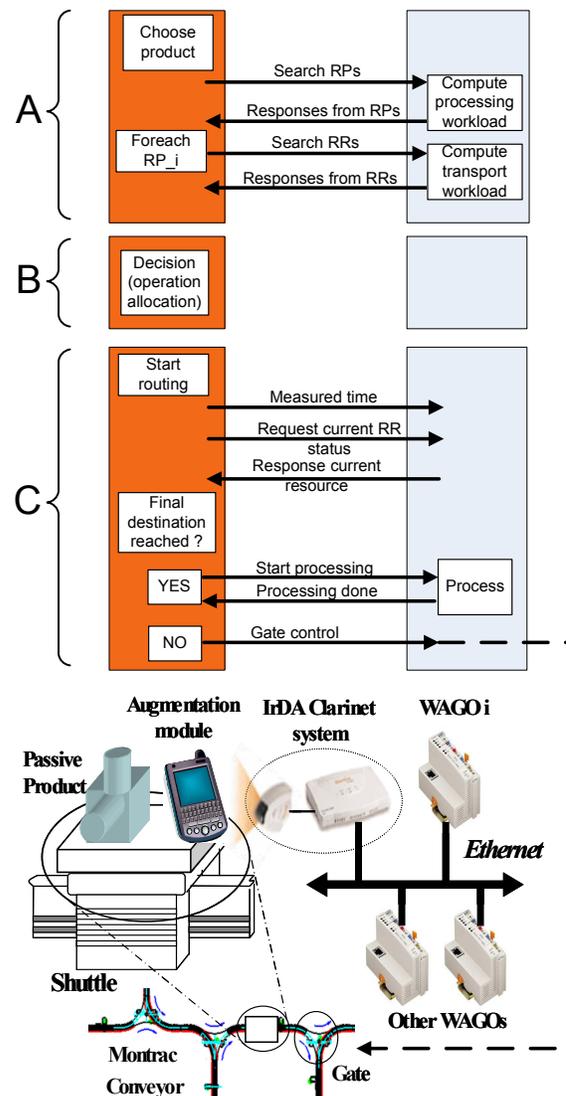


Figure 7 System architecture and order-resource interactions for routing and allocation

5 CONCLUSIONS

In this paper we have presented the societal open-control, a control paradigm well suited for decentralised FMS, which combines the advantages of “classical” control architectures, the possibility of hierarchical systems to achieve a global optimum, and the reactivity and easy maintenance due to easy removal and addition of composing elements of heterarchical systems. All these advantages induce a certain price in terms of extensive work and programming knowledge needed which are nevertheless justified if the designed fabrication system should offer an increased productivity and great flexibility.

Also, in this paper we tried to show that the open-control concept, and especially the implicit societal part, works very well into a holonic manufacturing system, since the proposed dialogue between entities is key element of the holonic theory.

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REFERENCES

- [1] Borangiu, T., Ivanescu, N., Raileanu, S., Rosu, A., Vision-Guided Part Feeding in a Holonic Manufacturing System with Networked Robots, RAAD 2008, Ancona, Italy
- [2] Borangiu, Th. and M. Dupas, Feature-Based Modelling in Robot Vision Tasks, Proc. of the Int. Conference on Feature Modeling and Advanced Design-For-The-Life-Cycle
- [3] Systems FEATS 2001, Valenciennes France, June 2001 Bousbia, S. and Trentesaux, D. Self-Organization in Distributed Manufacturing Control: state-of-the-art and future trends. In proc. of IEEE SMC'02, Tunisia, 2002
- [4] Clarinet System, Network Connectivity for Mobile Devices, <http://www.clarinetsys.com>, 2009
- [5] Dorigo, M., and Stützle, T. Ant Colony optimization. The MIT Press, 2004
- [6] Dijkstra E W, “A note on two problems in connexion with graphs”. *Numerische Mathematik*, 1:269,271., 1959
- [7] FIPA, 2002, FIPA Contract Net Interaction Specification, www.fipa.org, consulted in February 2009
- [8] Koestler, A. *The Ghost in the Machine*. Hutchinson publishing Group, London, 1967
- [9] Maione, G., and Naso, D. A soft computing approach for task contracting in multi-agent manufacturing control. *Computers in Industry*, 52, 199–219, 2003
- [10] Nylund H., Kai Salminen, Paul H Andersson, A multidimensional approach to digital manufacturing systems, 5th International Conference on Digital Enterprise Technology Nantes, France 2008
- [11] Okino, N. Bionic Manufacturing System in Flexible Manufacturing System: past – present – future. J. Peklenik (ed), CIRP, Paris, 73-95, 1993
- [12] Raileanu, S., Sallez, Y., Berger, T., Borangiu, T., Trentesaux, D., Holonic implementation of the open-control paradigm, IESM' 2009, May 13 - 15, 2009 Montreal, Canada
- [13] Sallez Y., Berger T., Trentesaux D., Open-control: a new paradigm for integrated product-driven manufacturing Control, 13th IFAC Symposium on Information Control Problems in Manufacturing (INCOM '09), Russia, June 3-5, 2009
- [14] Sauer O., Automated engineering of manufacturing execution systems – a contribution to “adaptivity” in manufacturing companies, 5th International Conference on Digital Enterprise Technology Nantes, France 2008
- [15] Trentesaux, D. Les systèmes de pilotage hétéroarchitecturaux : innovations réelles ou modèles stériles ?. *Journal Européen des Systèmes Automatisés*, 41 (9-10), 1165-1202, 2007
- [16] Trentesaux, D., Dindeleux, R. and Tahon, C. A MultiCriteria Decision Support System for Dynamic task Allocation in a Distributed Production Activity Control Structure. *Computer Integrated Manufacturing*, 11 (1), 3-17, 1998
- [17] Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L. and Peeters, L. Reference architecture for holonic manufacturing systems: PROSA. *Computers in Industry*, 37 (3), 255–274, 1998
- [18] Wago system, innovative connections, <http://www.wago.com>, 2009
- [19] Zbib, N., Raileanu, S., Sallez, Y., Berger, T. and Trentesaux, D. From Passive Products to Intelligent Products: the Augmentation Module Concept. 5th International Conference on Digital Enterprise Technology, Nantes, France, 2008