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MIRA: Enabler of Mass Customization through Agent-Based Development of Intelligent Manufacturing Systems

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Abstract-This research proposes an innovative agent-based design method known as "MIRA" (Modular, Intelligent and Real-time Agent) to represent products as well as mechatronic components in manufacturing systems. The new agent exploits semantic knowledge representation of its capabilities, tasks and surroundings, and upon which performs rule-based reasoning leading to generation of the IEC 61499 Function Blocks for real time and distributed control of production systems. This approach facilitates product's mass customization through development of intelligent mechatronic systems. Furthermore, the MIRA approach is exemplified in a food production case study.

I. INTRODUCTION

Jack welch, the "Manager of the Century" (named by Fortune magazine-1999) and the former CEO of the General Electric describes companies with many management layers as "wedding cake hierarchies" and not only believed that their structure can strangle them, but also he essentially put an end to the notion that organizations are obliged to be ruled by hierarchies [1]. In a similar manner, the hierarchical design and centralized control nature of current manufacturing systems have drastically failed to confront ever increasing challenges toward responding to numerous customer demands and lack fundamental properties, such as scalability, flexibility, handling complexity, and failure avoidance.

As one of the prominent solutions in this domain, multi-agent and Holonic manufacturing paradigms have conquered many of the aforementioned concerns and provided decentralization of control as well as increasing robustness, intelligence and flexibility to the manufacturing control systems. However, in spite of these advantages, the number of industrial use cases that are fully implemented using agents are still very limited and lack of simplicity can be the key reason for their deficiency, as at the present there is no methodology that can be applied by an engineer without sufficient experience in agent design while being mature enough to satisfy manufacturing systems' expectations [2].Therefore, to tackle the above shortcomings, this paper proposes an innovative multi-agent development method known as MIRA to represent both products and mechatronic components in manufacturing systems through symbiosis of semantic knowledge and rule-based reasoning as high level control, with the IEC 61499 Function Blocks as real-time and distributed control of machineries and processes.

The paper is structured as follows. Section two gives an overview of the focal objectives pursued in current researches in the agent-based manufacturing domain. Section 3 elaborates on MIRA approach and its development process. Section 4 exemplifies MIRA concept in a customized production test case. Finally, conclusions are made and the future research directions are discussed.

II. MAIN EXPECTATIONS FROM AGENTS

It has been more than two decades that Agent-based manufacturing systems have gained significant research interest. So far, various expectations from agents have been mentioned, and every research group has attempted to focus on one or more aspects of them, some of which are elucidated below.

Vallee et al. [3] propose a multi-agent control architecture for transportation systems which is enriched with ontological representation of knowledge and reasoning [4]. The results of this study have shown increased agility, robustness and fault resistance. Researchers in [5] have targeted reconfiguration as a pivotal issue in the manufacturing domain, and for that purpose, have chosen the IEC 61499 standard for distributed control of physical components. Furthermore, they developed an ontology to represent low-level control functionalities at the high level and suggest a creative structure that enables reconfiguration of the control system on the fly. Obitko et al. [6] proposed a general ontology consisting of three main modules which embodies specification of customer requirement, production planning and material handling, and emphasized on extensibility, modularity and flexibility as the main advantages of integrating multi-agent systems with ontologies. A comprehensive review of the past, present and future trend of agent-based technology development and the way it evolved over almost two decades is given in [7]. Moreover, the authors shed light on some of the future challenges ahead of agents, such as modular, object/service oriented and real-time control software design [7].

Reviewing most of the literatures about agent-based manufacturing systems, one can notice that there are various characteristics envisaged for agents, some of which listed below.

Table 1 Agent's expectations with their root causes

Desired Feature/Expectation	Root cause		
	M	I	R
Reconfigurability	●	●	
Scalability	●	●	
Adaptability		●	
Failure avoidance	●	●	●
Agility		●	●
Reliability		●	
Reasoning-ability		●	
Design simplicity	●		
Robustness		●	●
Reusability	●		
Distribution ability	●		●
Plug-and-Play	●	●	●

M: Modularity I: Intelligence R: Real time behavior

By analyzing each of the above attributes one can realize that they all can be derived from three main characteristics: *Modularity*, *Intelligence* and *Real-time* behavior. For instance, reusability can be considered as a fruit of modularity. Similarly, in order to have a reliable, robust and failure tolerant manufacturing system, it would be adequate to develop a modular, intelligent and real time agent system which can conveniently foresee probable failures in the system and dynamically react on their occurrence by removing the faulty agents and substituting them with their redundant counterpart. Moreover, distribution ability of the control system is another inevitable benefit derived from the modularized software design.

III. PROPOSED METHODOLOGY

A. *MIRA design approach*

MIRA brings together the three aforementioned features in a single entity. It undoubtedly inherits many of its features from current approaches, particularly those who used ontology for agent's knowledge representation such as [6, 8, 9]. However, the overall aim of MIRA is enhancing simplicity and user acceptability [10] of control system design which will result in significant reduction in the development costs and time. In addition, this approach distinguishes between different sources of knowledge that agents require for decision-making, identifies how they should be provided to them ,while an inter ontology mapping and data exchange [11] between existing agent implementations and MIRA is also possible. The other benefit of MIRA is the usage of semantic knowledge and rule-based reasoning to determine the compatibility of modular software as well as hardware components in various manufacturing conditions to achieve the appropriate solution. This is to accomplish rapid product customization through utilization of new or existing mechatronic devices in a flexible, decentralized and dynamic control arrangement.

MIRA approach considers a trio of main role players (Fig. 1) in an intelligent manufacturing system: *Human*, *Operator (O)* and *Client (C) MIRA,* and particular tasks are dedicated to each of them. Each MIRA can either take part individually in a manufacturing plant, or be grouped with other MIRAs and build a more capable (composite) MIRA.

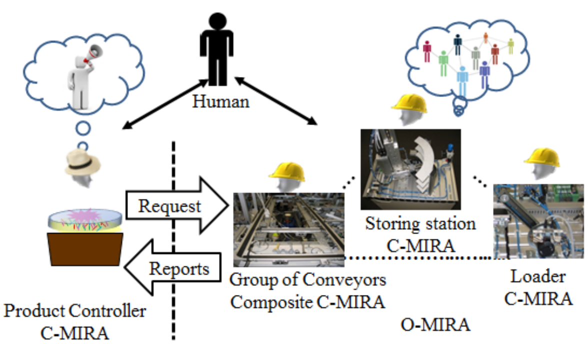

Figure 1 Trio of main role players in MIRA approach

1) HUMAN: Although the aim of using agents in manufacturing systems is to minimize humans' needed time and effort on such systems, their considerable role in the design can neither be neglected nor underestimated, at least for near future. Human can be engaged in the decision making process to provide a deeper knowledge of the problem domain that is not already captured by the agents and as well, adapt the system if problem specifications have altered over time [12]. It is evident that humans can always play a valuable monitoring role and take part in decision-making whenever needed to overrule MIRAs decisions as they are always given a higher priority than MIRAs. Apart from the aforementioned roles, human can act as an operator/technician supporting the system with different activities (i.e. maintenance, supplying raw material, etc.).

2) O-MIRA: It represents one or a group of mechatronic components including sensors, actuators, software components, controllers and power sources (Fig. 2). The knowledge representation of the O-MIRA is captured in a semantic way (Fig. 3). Each O-MIRA has two plug types (software and power) that enable it to be

rapidly plugged into an existing design. However, it is essential for every two or more collaborating O-MIRAs to ensure that both their physical and software components match with each other. For every two communicating MIRAs, their level of authority in decision-making is defined in two communication patterns: *Peer to Peer* and *Master-Slave* [13]. These negotiation methods can be either set manually or determined through reasoning, but their correctness needs to be formally verified as was reported in [14]. Finally, if some changes are made in one O-MIRA's ontology, it will result in propagating to all its dependent MIRAs and will affect their respective operations accordingly.

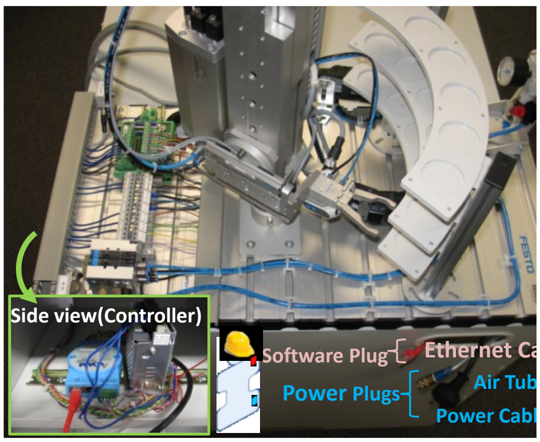

Figure 2 A modular storing station (from FESTO Co.) as an example of a C-MIRA

3) C-MIRA: It is an intelligent product in a sense that it has thorough knowledge representation of the constituent materials, recipe and other details of the product. C-MIRA takes part in negotiation with the available O-MIRAs weighing the cost of employing them with the services they provide to arrive to the most proper compromise which not only is within its budget limit, but is also feasible to transit the product from a concept up to full realization of it.

B. *MIRA Internal structure*

Similar to some agent architectures in manufacturing control [15-17], MIRA can be seen in three layers of high level control (HLC), low level control (LLC), and the physical components layer. Here, the term "Agent" is used for MIRA merely to define it as an autonomous entity (product or a mechatronic component), though there are other definitions of agents which solely refer to the high level control of the physical components. The HLC works as a "mind" for the agent and fully controls the agent behavior based on its world model representation. The low level control can be seen as a "brain" which directly interacts in real-time with sensors and actuators in O-MIRAs or RFID-tagged products in C-MIRAs, and controls the physical component as the "body" of the agent [16].

1) HLC development through STEP method

The way how MIRA's semantic knowledge is shaped is inspired by human behavior in an analogous work environment and is called STEP (*Self, Task and Environment Perception*) method and in fact it is considered as "the first *step* toward agent design".

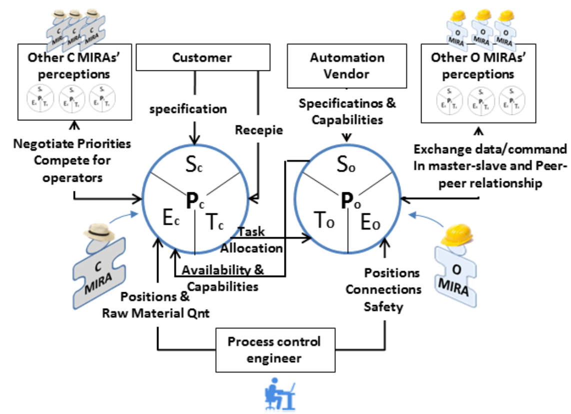

Figure 3 Knowledge representation of manufacturing system based on MIRA approach

STEP describes how knowledge must be captured and who should provide each part of it as ontology to a MIRA, so that the integrated knowledge can be easily utilized, shared and updated through all manufacturing life-cycle from the design level, up to fault avoidance and reconfiguration level. However, the "perception" term used in this context does not convey any kind of cognition as expected from human and solely refers to the semantic knowledge and rule-based reasoning ability of a MIRA. with which, it can achieve its desired goals. The three constituent elements of STEP are as follow (Fig. 3):

- Self-Perception (SP): In order that a MIRA be able to perform its duties, at first it must have a thorough understanding of itself. This knowledge known as "SP" consists of all material, mechanical, electrical and software characteristics and capabilities of MIRA's constituent components (e.g. dimensions, cost, sensor types, actuators capabilities, power source, IO info, etc.). This type of knowledge is assumed to be provided to the MIRAs either by customers (for C-MIRA), or by vendors (for O-MIRA) and then converted to semantic ontology. SP characterizes a general-purpose agent that can be later on tailored to various applications and environments. This method also respects the developers' intellectual property as they do not have to reveal their software implementation in detail and instead, they merely develop SP of their own MIRAS as "black boxes" [7] with clear interfaces and hidden complexity at the background, while leaving minor configurations to the process control engineers.

- Task Perception (TP): It consists of the semantic knowledge that specifies which tasks are to be managed by an O-MIRA or which processes a C-MIRA has to undergo in order to achieve the product as its intended goal. TP in C-MIRA is provided by product engineer or translated from customer order into ontology language. As for O-MIRA, TP is generally provided by C-MIRA and then the C-MIRA reasoner will break it down to detailed tasks to be accomplished. For instance, if a "placing cap" task is assigned to a Pick and place (PnP) robot, the reasoner initially checks whether it is feasible based on its SP and EP and then creates a set of detailed tasks (e.g. extend/retract cylinder or vacuum on/off, etc.) to achieve that goal.

- Environment Perception: Apart from SP and TP, each MIRA requires to have enough information about the environment it is being utilized at, such as its location, raw materials and finished products positions, whether human is present or not and if so, how to maintain their safety, with which MIRAs it is collaborating, and so on. Some of this information has to be provided manually by the process control engineer (e.g. positions) as they are specific to that manufacturing environment. However some of the other EP software/hardware compatibility check and establishment of distributed control patterns between O-MIRAs could be performed by human or generated within each O-MIRA through the reasoning process.

Once a MIRA has gained a comprehensive "S", "T", and "E" Perception at the HLC layer, it will result in generating the appropriate FBs for real-time execution of operations as explained below. It is clear that any alteration in any of the three aforementioned perceptions will have impact on MIRA's behavior in a manufacturing system.

2) LLC: IEC 61499 FB for distributed control

One of the crucial expectations from agents in manufacturing systems is their real-time behaviour; however, the HLC cannot guarantee this feature in certain circumstances. Thus to resolve this issue, it is coupled with the LLC which will be deployed to the PLCs or other industrial controllers[18] . Among the current industrial programming standards for industrial controllers, the emerging IEC 61499 [19] promises significant advantages to the users in terms of modularity, simplicity of system level design, and more importantly, the possibility of distributing low level control programs over a variety of distributed hardware and throughout the entire network [20]. These features make it an ideal solution for being employed in MIRA's real-time control layer.

One prominent aspect of MIRA which distinguishes its performance from other agents is that not only the physical compatibility of agents is checked prior to operation, but also the software compatibility among interacting agents is being taken into account at an execution level. For this purpose, two control design patterns (e.g. master-slave and peer to peer) for their communication has been considered and a uniform FB interface (Fig. 4) is proposed in [13] to facilitate derivation of LLC code from the STEP method while their ultimate functionalities are verified formally prior to operation [14].

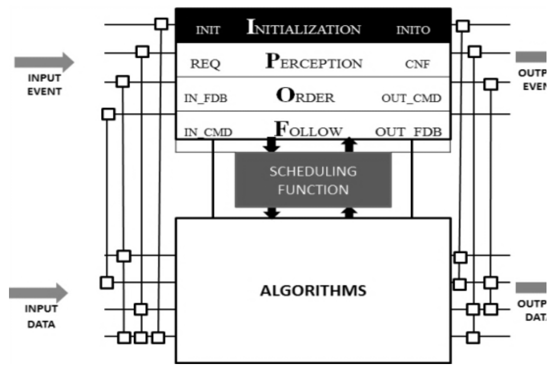

Figure 4 Proposal for a unified FB interface

3) Hardware components, Products, and Physical components

In terms of hardware platform for executing agents, in general the HLC part has been separated from LLC running on PCs, while the LLC was executed on PLCs or embedded controllers [18]. However, with the recent advances in making embedded controllers, it is envisaged that the future agent implementations could conveniently execute HLC and LLC on single runtime environments [7].

In C-MIRAS, use of RFID technology is helpful to enable them track the location and completion progress of the products, though this method is not applied in our case study. In O-MIRAs, the physical components (sensors and actuators) constantly exchange information in real-time with the industrial controllers to fulfill the desired tasks.

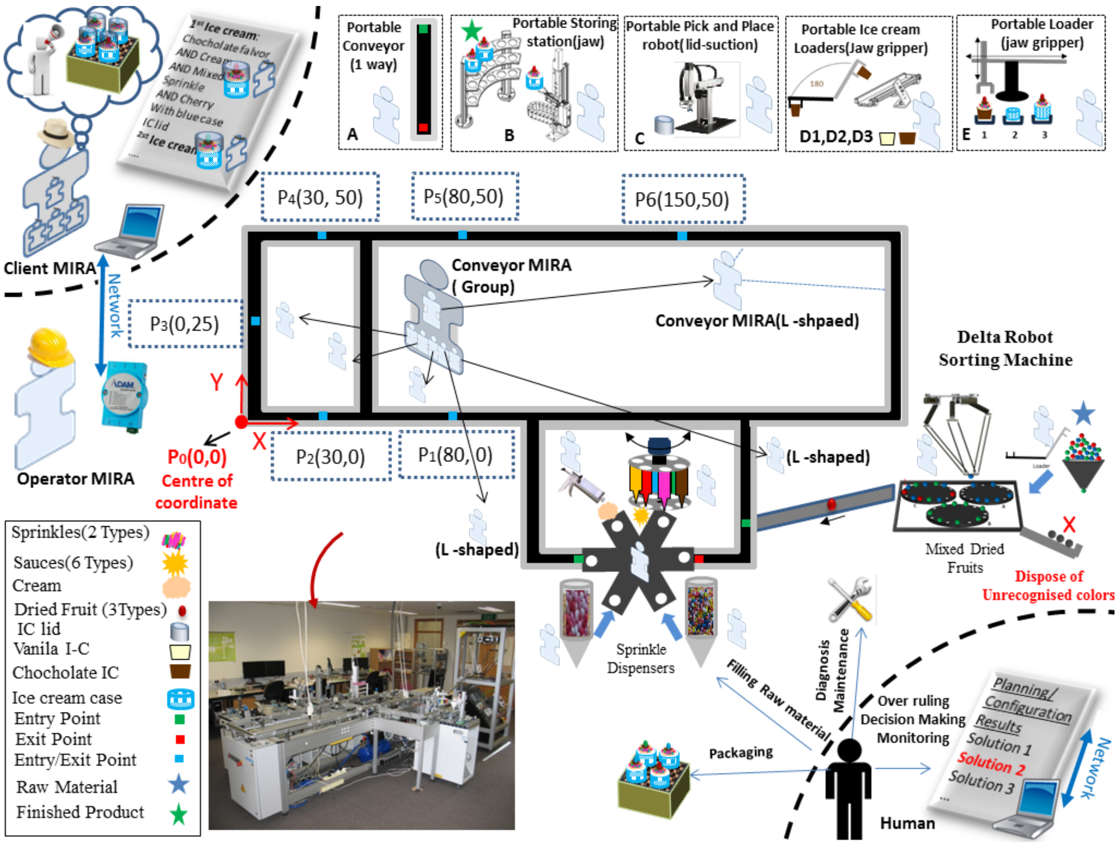

Figure 5 The Customized IC production implemented as a case study in the laboratory environment

IV. CASE STUDY

This case study was inspired by an innovative and futuristic ice cream (IC) shop called iCream [21] that enables their customers order from endless combinations of ICs while observing them being made right before their eyes. The MIRA approach has been pursued for formulation and implementation of this exemplified factory. Using available equipment in the Industrial Informatics lab of the University of Auckland, the factory environment has been simulated (Fig. 5) which enables customers to choose among numerous combinations.

The materials used for this IC include two vanilla and chocolate IC types, cream, two sprinkle types, three fruit toppings, six sauce types, the cup lid and finally an IC case. The choices for a customer may range from the simplest (and the cheapest) IC including an IC with lid up to the most complete IC which is dressed with a cup case and has all the available toppings. Every time a customer orders a specific IC through an API, the order is translated into ontology and creates a new C-MIRA that has a different STEP than the other C-MIRAs.

As a consequence, a unique sequence of steps will be generated for producing that particular IC. The mechatronic components utilized in this case study are of two types: *Stationary* and *Portable.* The stationary parts are assumed to be permanently available in the manufacturing process. They include a delta robot for sorting fruit, two sprinkle dispensers, a rotary sauce dispenser, one cream dispenser, a rotary table, three L-shaped conveyors, and 3 normal conveyors. All fixed conveyors have made a group conveyor MIRA. As shown in Fig. 5, there are 6 positions on conveyors (blue squares P1-P6) that have optic sensors, allowing them to be used as entry or exit connection points for the portable devices (Fig. 5 A-E). Apart from the inherited flexibility in choice that is provided to customers, on the manufacturing side, each portable O-MIRA can change location around the fixed conveyor track and be connected to any entry/exit point and this change will affect its EP as a result of the change in location and association with new C-MIRAs. In each of the possible circumstances, the C-MIRA pursues production of an IC while minimizing the cost (i.e. minimum IC travel distance). Among the employed C-MIRAs, only the Delta robot has "hazardous" specification in its EP and if a human is present at manufacturing environment, the associated C-MIRA will only allow it to operate if the light curtain sensor is enabled according to its SP.

Since the search process for the plant design is thoroughly automated, numerous options (e.g. selecting vendors, properties, prices) can be evaluated by the rule-based reasoner and different restrictive conditions can be added as production requirements.

The semantic knowledge of the MIRAs that were employed in this case study has been implemented using Protégé [22] which is an open-source ontology development tool along with two of its plug-ins (SWRL [23] and SPARQL[24]) for rule development and querying the inferred solutions from the ontology. As for LLC design, NxtStudio v1.5 [25] tool is used which is complaint with the IEC 61499 FB standard.

V. CONCLUSIONS AND FUTURE WORK

This paper identified the three key challenges ahead of agent-based manufacturing control systems and based on that introduced the concept of MIRA with the main direction of integrating an intuitive human inspired knowledge representation and rule based decision-making with the IEC 61499. Furthermore, this research was an attempt toward removing the burden from the software experts and enhancing comprehension and collaboration of ordinary automation engineers in developing applications employing intelligent mechatronic components.

In spite of the presented benefits of this approach, its immediate use in wide range of applications is still limited due to the manual process of defining rules and semantic knowledge for each client and operator MIRA.

Work is in progress to publish in the forthcoming literature the detailed specification of knowledge and rule development techniques for MIRA operation and communication. Also, as part of this continuing research, it is being investigated how to formally verify the intended behavior, safety and properties of MIRAs in a manufacturing system.

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