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Towards An Agent-oriented Smart Manufacturing System

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Abstract – As the impact of the recent recession is still evident in the slow recovery of industry, restructuring for total visibility and agility is inevitable to sustain a competitive edge and steady growth. Endowed with total visibility, smart automation is quite essential for responsive manufacturing and efficient supply chains. This work proposes a new model for building smart automation for manufacturing systems that blends flexible manufacturing with total visibility, distributed intelligence, rationality, collaboration and flow control. In this vein, the work exploits the coordinated, intelligent and rational aspects of smart tag and resource agents with RFID enabling technology. While smart tag agents manage visibility for an agile process flow and supply chain management, smart resource agents improve responsiveness in shop floors and across supply chains. A hybrid control model drives the smart manufacturing system that realizes a reactive-reflex control at the operations level and an agent-oriented deliberative control at the planning level. At the technology level, the system realizes the JADE development environment that hosts the smart controller layers.

Keywords- *smart manufacturing, tri-state control, RFID, smart tag agent, smart resource agent, collaborative architecture.*

I. INTRODUCTION

The flexible manufacturing system (FMS) is one of the contemporary industry technologies for delivering production flexibility using work cells of computer numerical controlled (CNC) machines connected to robotized transport systems and managed by computers that control machinery and optimize process flow. FMS, however, lacks dynamic reconfiguration flexibility essential for efficient productivity especially during unpredictable order changes or as a reaction to a disturbance. The hierarchical FMS control models have an abstractive lengthy planning process that makes it hard to react promptly to an emerging situation by the rescheduling of algorithms upon the existence of discrepancies [1]. Endowed with intelligence and rationality, the distributed agent-oriented (AO) FMS control offers more responsiveness, flexibility and adaptability, as it adapts and reconfigures, automatically when triggered by the dynamic changing world requirements or the system alerts to respond to the disturbances at real-time.

The AO decentralised computing paradigm is, furthermore,

a suitable framework for the modelling and development of self-interested, economically-inspired decentralised systems. Researchers often examined AO computing paradigms for problem modeling and solution approaches development and implementation of distributed AO systems for industrial job shops, enterprise integration, supply chains collaboration and management, in addition to manufacturing process planning, scheduling, and control in decentralised settings [2].

The recent emergence of economically feasible active and passive radio frequency identification (RFID) and wireless sensors solutions with tags that are extremely cheap, durable and with far reaching antennas, has commenced a new era of total visibility internally within the value chain and externally across supply chains networks. For instance, the massive deployment plan of RFID tags mandated by Wal-Mart [3] has created enormous strategic implications in industry with sweeping momentum for ubiquitous smart computing and supply chain management. Inspired by the industry potential of auto-ID tags and wireless sensors and multiagent systems enabling technologies, the smart manufacturing system (SMS) control paradigm extends the FMS production flow control visibility and management down to work pieces for responsive control of production and flow dynamics that extend to the internal value chain and across to the supply chain networks.

This work attempts to tackle the challenging collaboration problem among the competitively positioned and expanding manufacturing plants and supply chain networks that, driven by technology trends, may extend worldwide. Motivated by the momentum of RFID visibility technology and the chase for responsiveness and agility in manufacturing plants and supply chain networks, the work introduced a hybrid AO SMS controller based on the real-time smart resource agent (rt-SRA) with the tri-state action controller that improves the real-time performance of smart resource agents and consecutively the overall SMS controller. The tri-state engine operates as a multi-thread system triggered by the finite tri-state controller events. While the guaranteed real time property is still a research challenge mainly for adaptive agents [4], the work improved responsiveness of the physical robot agent in [5], using functional decomposition and

decoupling with the state driven actions of rt-SRA. In fact, the functional decompositions of the Multiagent System (MAS), often, deliver integration benefits and have a faster response [6] [2]. However, MAS efficient coordination is still a research issue. The proposed SMS introduced an AO decentralised multilayer computing model that tackles the coordination problem. The SMS furthermore uses the real-time smart tag agents (rt-STA) to manage the visibility and control of the work pieces throughout the product stages.

The SMS has a multilayer controller system that complements the *iShopFloor* in [7]. The *iShopFloor* facilitates distributed intelligent manufacturing at the process planning, scheduling, sensing, control, integration and supply chain levels, using internet and agent technologies. The SMS controller, however, facilitates total process and products visibility down to the shop floor machinery, while delivering a more responsive lower level smart automation - features that could extend *iShopFloor* functionality. Furthermore, SMS facilitates agent-based collaboration among decentralised entities across the supply chain network.

Considering the fact that much of the resources workload are often controlled by the reactive controller, while occasionally managed by either deliberative or reflex engines, the SMS architectures are designed as a hybrid model of deliberative manager, reactive control and rule-based reflex. Reflex, while operating occasionally, has an impact on system availability and reliability. The hybrid system senses the world and plans the next course of actions and optimal control strategies and reflex rules to accomplish each action or reflex, efficiently, on time.

Section 2 elaborates on the rt-SRA control architecture, while section 3 expands on the architecture of the rt-STA. Section 4 summarizes the distributive collaborative model. The details of the SMS architecture are presented in Section 5, while Section 6 reviews the implementation environment. Section 7 concludes with a highlight on the future work.

II. THE REAL-TIME SMART RESOURCE AGENT

The work exploited the coordinated, intelligent and rational (CIR) agent in [8] as a foundation for a real-time smart resource agent (rt-SRA) that drives smart manufacturing automation for decentralised and distributed shop floor and manufacturing resource settings. Its metaphorical architecture provides flexible primitive components as problem solver, pre-interaction, interaction and execution. The arrangement of components reflects the agent's mental state as related to its reasoning to realize its goals using coordination control and interaction. The component-based design of the CIR agent makes it more flexible, potentially improvable and internally well coordinated. The rt-SRA manages stationary and mobile SMS resources as automatic guided vehicles (AGV) based on our work in [5] for better management and responsiveness. As shown in Fig.1, the rt-SRA architecture has two main logical layers: cognitive (deliberative) and action layers. While the

deliberative layer supports the strategic view and reasoning capabilities of the resource, it interfaces with the action layer using the tri-state hybrid controller. As shown in Fig.3, agent behaviours in the state based action layer model the control actions. During normal operation the reactive controller manages the firing of control strategies as planned by the agent deliberative control and sensing of the world. The deliberative control may override to change the course of actions, change a schedule, or direct a command at persisting events. The reflex also may swiftly override, during alerts based on stimulus-action rules, fired based on imminent alerts and risks.

The two-layer model has been exploited over subsumption architecture in [6] as many dedicated modules might visualize the world differently leading to inconsistency in decision making. The TCA in [9] combines the deliberative function of the planner layer with the reactive capability of the behaviour and executive layers. The responsibilities of each layer are fuzzily defined. As well, the planner lacks access to the functional layer that parts the planner from information on functionality during planning. CLARATy in [10] presents a two-layer model: a decision layer that replaces the planner, executive TCA layers, and a functional layer, eliminating the dominance of multi-layers model and tightening the coupling between autonomy and control systems. CLARATy layers, however, are tightly coupled with the breadth of interactions at all granular levels that are meant for centralized deployment of resources and contrast to the loosely coupled layers of the rt-SRA meant for distributed deployment of physical resources.

Fig.1. Real-time Smart Resource Agent (rt-SRA)

The rt-SRA model attempts to decompose functionality based on the abstraction level of the supported responsibilities. It transfers certain knowledge and capabilities to the action layer to improve system performance. The rt-SRA is implemented as a two-layer model with a tri-state action layer. The goal is transformed by the problem solver

into course of actions that include selected control strategies and rules to be executed by the reactive controller. The reactive controller monitors the physical world through the sensors and combines the model of the world with the interaction models of the goals to apply the suitable control strategies. However, when critical issues are imminent, the reflex controller can be state triggered for actions consistent with the coordination models. The agent, while providing this autonomy to the controller, also monitors the progress towards the achievement of the goal. If it senses any change in the course of action, the agent transitions to the deliberation control state to reconfigure and decide the new course of actions that enables achieving the goal in the shortest possible time.

A. The rt-SRA Cognitive Layer

The cognitive layer supports the strategic view and the reasoning capabilities of the resource. It interfaces with the action layer through domain interface. The cognitive layer is the reasoning engine that deals with high-level tasks on behalf of the physical resource. Based on the CIR agent, the cognitive layer has a modular architecture that provides robust primitive components that facilitate coordination control and agent interaction. It provides a high level decision support to the rt-SRA. The internal implementation of the cognitive layer is shown in Fig.1. When making control decisions, the cognitive layer is responsible for reasoning about agent chosen actions by merging models of the world with present situations in the environment. The rt-SRA perceives the world by communicating with other agents and using the sensors at the action layer, which directly interfaces with the controller.

B. The Tri-state Hybrid Action Controller

The proposed tri-state hybrid action controller is the core of the rt-SRA architecture. Two aspects inspire the action controller design: the first aspect relates to the fact that, while more than 95% of processes workloads are managed by normal reactive control, less than 5% of the workload is managed by either the deliberative (cognitive) or the reflex control. The reactive control locally senses data and applies local control strategies to execute the planned course of actions. The deliberative control, however, senses the world models, plans the course of actions, and selects control strategies and reflex rules for the course of action, while the reflex operates based on stimulus-act couplings rules. The proposal extends the deliberative-reactive hybrid model in [11] to a tri-state hybrid control model of deliberative-reactive-reflexive that senses the world and plans the next course of actions and suitable control strategies to accomplish actions that execute per the reactive controller. At alerts, though, reflex uses stimulus-act arc rules. Although reflex fires only rarely, like safety alerts, it enhances availability and reliability while minimizing risk impacts. Fig.2, presents the tri-state hybrid control model.

Fig.2. Tristate Control Paradigm

The hybrid action-based control model has occurrences in the research space. The real-time system architecture in [12] consists of a set of task-specific perception-action behaviour modules that work concurrently to generate diverse actions with either reflex, reactive or cognitive qualities. However, deliberative coordination embodies a burden to the reflex capability due to the extra processing time needed for deliberation and interactions among the system entities to deliver the best solution. The decomposition of the system functions, the direct interaction with the world and the states' dynamics in rt-SRA allow for better responsiveness.

The second aspect relates to using the finite state machine (FSM) to model the dynamics of the agent hybrid controller. The breakaway is in realizing the reflex as a concurrent dynamic processor in the FSM behaviour selection engine. The FSM defines the logical state of the system responsible for system output behaviours, and not only for a combinational input or sequential input [13]. Both state transition conditions and the output conditions are functions of inputs and states. Fig.3 shows the proposed general tri-state model.

The state machine acts as a decision machine that describes behaviours mapped as state transitions with either entry, exit, or transition actions. State transitions triggers appropriate deliberative, reactive or reflexive controllers, while the action layer holds all related control knowledge and functionality - another breakaway that assumes a functional decomposition and a states' model of the rt-SRA for faster real-time delivery.

Fig.3. Tri-state FSM

C. The rt-SRA Action Layer:

The action layer, shown in Fig.1, is renovated to provide a higher decomposition and better decoupling of the two layer system functionalities for faster response. It is based, as well,

on a tri-state hybrid model for more responsiveness to world events. The action layer represents the operational subsystem of the agent but resides as close as possible to the actuators and the sensors of the resource. The agent transmits the set of actions through the action controller and monitors the progress of execution. However, the primary role of the controller is to keep abreast of the world models, translate high end views to the cognitive layer and perform the suitable actions based on the action layer states. The action layer is composed of state-based hybrid controllers, namely deliberative, reactive and reflex. The deliberative system translates the cognitive directives to both the controller and processes access for passing agent views and strategic direct controls. The reactive control connects to the cognitive engine and resource process interface. It consists of a repository of the reactive control strategies for the actuators which is selected through high level deliberation with the cognitive system. The reflex connects to the resource interface and cognition engine and holds tables of condition-action rules that are prioritised based on the resource operational environment and cognition interactions for rapid reflex to sudden alerts. The resource access also works as a device management layer for AO controllers. The sensing unit interfaces with resource sensors for data acquisition and works closely with the cognition layer to provide it with current world models.

III. THE REAL-TIME SMART TAG AGENT

The tireless chase of full visibility at manufacturing and enterprise business levels has initiated the innovation of a new generation of very cost-effective wireless sensors and an auto-ID solution. Driven by the emergence of very cheap, durable active and passive RFID tags and wireless sensors that have far reaching antennas, the integration between wireless technology and smart automation has led to capturing the visibility of products in real-time and sharing the information and intelligence with enterprise systems to influence the products' destiny through decision making. The auto-ID technology has eventually, enabled the evolution of smart products that have a substantial impact on leveraging a supply chains visibility [14].

The wireless tags and sensors, furthermore, have evolved recently into complicated ubiquitous computing technologies with functionality that ranges from passive RFID tags to Wi-Fi badges with large memory, System on a Chip, location tracking, I/O, and diverse sensors and multimode roles. As a new era of research has emerged smart products are empowered by fusing their tags with smart agents that collect intelligence, collaborate in decentralised settings and reason to take decisions on behalf of product(s). The real-time smart tag agent (rt-StA) architecture is proposed as shown in Fig.4.

As shown in Fig. 4, the generalized rt-StA action layer is rather basic compared to rt-SRA. The rt-StA captures and interacts mainly with the smart tag computing models through wireless communication, while holding the detailed profile intelligence and state knowledge of managed products,

whether tagged to raw material, work in progress or finished products. The objective, ultimately, is to facilitate interactive visibility and optimum management of the products' dynamics from the raw material to stocking to manufacturing processes, to logistics within the internal value chain and across the supply chain, down to the customer.

IV. THE DISTRIBUTED COLLABORATIVE MODEL

The collaboration between real time agents in decentralised settings is based on high-level interaction between their cognitive layers [5]. Coordinated control and handling of interdependencies are both carried out at a high level of abstraction. The agents negotiate on behalf of resources and smart tags to guide in rational decision-making and control.

Fig.4. Real-time Smart Tag Agent (rt-StA)

The abstract environment model can be viewed as a multi-agent system with N resources. The agents are situated on different frameworks forming a world of cognitive layers that support high-level interaction between the corresponding real-time agents. It also supports low level interaction between the cognitive layer of one agent and the action layer of its resource. The simplified architecture facilitates flexible integration of rt-SRA and r-StA with the interface present in the resources and tags. The agents, while participating in the control of resources, still participate in other roles depending on the challenge. Fig.5 shows the collaborative agent model.

Fig.5. Agent Distributed Collaborative Architecture

V. THE SMS CONTROL ARCHITECTURE

FMS control is essential in organizing the scheduling and synchronization of resource utilization. However, the increase in FMS control states and amount of process information has led to greater complexity in control which makes it vulnerable to abrupt changes. As such, FMS controllers are designed as a decentralized model due to the size and diversity of system functionalities and interactions. The AO system offers a better choice for controlling distributed systems for their cognitive, cooperation and synchronizing capabilities that enable hiding the complete functional domain of the production system. The smart tags attributes, furthermore, improve FMS visibility that extends to work pieces for better planning at shop floor and supply chain levels. In this vein the SMS AO controller is proposed as a decentralized AO hybrid model controller. The PABADIS in [15] is a hybrid model with a centralized part that can be attached to an ERP system and a decentralized part, implemented by the work piece agents that connect to resources for scheduling of a product. However, it restricts the agent assignment to production job orders. The FMS system in [16], on the other hand, is formulated of a two-level hierarchy: a high level regarded as the decision support and a low level that manages the optimal routes for all AGVs so that a high level optimality criterion is close to achievement. The system, so far, is domain specific with no preference to a time factor, while vulnerable to disturbances.

The SMS controller decouples the operation control from resource planning, while preserving the responsiveness and efficiency of reactive control and the swift action of reflex that acts during alerts. The AGV agent, for example, deliberates the routing course, while real-time activities are controlled by reactive control. The two layer model in [17] has an interactive layer for interpreting process data and agent interaction and a reactive layer that react according to the dynamic state of its resources in order to fix a malfunction and respond to other agents. Obviously, the two tier model has its practical aspect in small manufacturing systems where the

local controller manages operations while the planner coordinates workflow. However, such models lack enterprise visibility and planning, where multiple plants host many work cells to process massive and diverse amounts of parts and work pieces while collaborating with warehouses, suppliers, distributors, consumers and other stakeholders of the SMS supply chain in a coordinated manner.

A. SMS control Framework

As shown in Fig.6, SMS visibility architecture is based on a hybrid AO model, mainly, deliberative controller on top of reactive and reflexive action controllers. The deliberative control handles the reasoning, decision making and planning for the shop floor, work cell, resources and products, while the resources management layer manages the execution of production tasks and manufacturing processes as in CNC programs and AGV routing for optimal production of work pieces. The SMS, while facilitating interactions with planning and operations, transfers certain decision capabilities to the reactive layer for better responsiveness. Upper subsystems reflect increasing intelligence from process to reactive to deliberative. The SMS real-time notion, though, is manifested by delivering control schedules with process tolerance for absorbing the disturbance while preventing delays. The controller evaluates the absorption possibility with planned process tolerance. If it is impossible to absorb sudden disturbances, a reflex control is initiated to respond to an event with a limited time in a trade-off with quality.

At normal operations, though, work piece agents of tagged work pieces, as captured by rt-STA, auction off their tasks while resource agents bid for subtasks using an auctioneer broker agent leading to automatic self-organization [18]. The rt-STA complements the resources' visibility by capturing work pieces like parts, work in progress (WIP) and finished product intelligence. At the deliberative level, however, work cell, shop floor and controllers manage the scheduling and management of job orders, resources and processes while exchanging visible intelligence with the supply chains.

B. Smart Resource Control Agent (RCA)

The resource control agents like AGV agent, CNC resource agent, tags and wireless agents are responsible for capturing visibility and operational control of smart resources while executing tasks requested by the work cell controller (WCA). The resource process controller and resource control agents (RCA) manage resources. The resource controller executes the basic resource commands and core APIs while capturing the current state of the resource, delivered operations and the operations to be carried out. RCA interacts with higher control agents for utilization of resources and configuration updates.

RCA is based on the tri-state hybrid rt-SRA for real-time visibility and control of smart resources that shapes the low-level functionalities of SMS. RCAs bid for the work cell tasks based on their capabilities and get assigned the awarded

tasks. The smart tags' and wireless sensors' agents, though, work closely with work pieces and resource agents to complement the visibility of WCA capturing the status of parts, WIPs and finished products using rt-STAs for the visibility of buffers and process workflow.

C. Work cell Controller Agent (WCA)

The work cell controller handles the auction brokering service and process monitoring of work piece orders on work cell resources using WCA and the process database. For new job orders, work pieces are assigned to resources at the latest instance; given that the work pieces, the processing schedule and the resource availability are unknown until the work piece is introduced to the system. Work cell control agents (WCA) collect work piece orders from the subcontracted work piece agents as deployed by the shop floor controller agent (SCA), and auction off subtasks to the work cell resources monitored by work piece agents during their lifecycle. A capacity bottleneck automatically propagated in the opposite direction leading to self-organizing behaviour of the control system [18].

WCA reports to SCA, resources and work pieces production status using real-time rt-SRA for closed loop control of SCA. WCA controls work piece job orders deployed by SCA and subcontracted by work piece agents for production assurance based on the WCA online control of resources and production processes. WCA auctions tasks to resources, monitors the execution and completeness of work piece orders, and has the capability to alter or interrupt RCA tasks to absorb sudden disturbances and prevent delays. RCA, however, may halt reactive tasks at the reflex state driven by reflex condition-action rules. RCA evaluates the absorption possibility with the planned tolerance of WCA. If it is impossible to absorb disturbances into a process tolerance, a rule-based reflex process is selected.

WCA, while handling the process control of manufacturing resources, captures production process visibility of resources and processed parts in real-time. It exchanges visibility with the supply chain for agile management of manufacturing product inventories and resources, due to the agent's mobility that allows it to exchange product and resource visibility at all levels.

Fig.6. Proposed SMS Architecture and Environment

D. Shop floor Controller Agent (SCA)

The SCA breaks the production schedules deployed by the enterprise controller agent into job orders that translate further into work piece orders. The SCA creates temporary agents that manage the job and work piece production orders and are terminated at completion. It keeps track of production and monitors the delivery of subcontracted WCA assignments.

SCA and WCA interact and monitor assigned operations. SCA captures the job schedule that is communicated by the enterprise controller agent (ECA) and transforms it into a series of job and work piece order agents based on the process capabilities and status of work cells. It keeps a direct eye on the execution processing of scheduled jobs and work piece agents, captures visibility, archive and aggregate process data for forecasting and decision making. SCA, furthermore, formulates a visibility request for data from RCAs and work piece agents by telling the WCA which objects it wants. Responses work similarly, in that smart resource and work piece agents fetch the desired data using smart tags and sensors and present it to the WCA that formats the data into objects then they pass it to the SCA in a form native to its database. As clarified in a previous section, work piece agents auction off orders while WCA bid for them via the broker agent. The awarding rationale considers the work cells'

workload as well as the outgoing work pieces stream. If the work cell outgoing stream is blocked then the work cell will block its input stream as well. SCA resolves and updates job assignments at the deliberative state through interacting with the ECA for production order rescheduling. AO interaction is enabled for dynamic updates of variance and reassignment.

VI. IMPLEMENTATION ENVIRONMENT

The implementation of the SMS is multifaceted due to the large scale of the system scope. As such, the validation process was divided into multiple components implemented in stages. The smart shop floor layer operational control model, for instance, is already functional and validated in the context of a smart-space project. The smart-space is deployed using Apache tomcat and Axis 2.0 for real-time resource and event brokering services at the shop floor level. At deliberative control for decentralised settings, Java Agent Development Environment (JADE) [19] was deployed and validated for resources and smart tags control agents as JADE allows for the creation and interaction of multiple collaborative agents on different platforms using CORBA and FIPA that facilitate populating the distributed systems and agents. CORBA interoperability was exploited in modelling the SMS control systems. The approach adopted involves the modelling of the control functions as objects registered on the naming service to control resources. The prototype of the SMS is made up of Java simulated CNC machines deployed into PCs, mobile robots that simulate AGVs with routing and delivery capabilities and a smart tag and sensors reader that simulate the work pieces' ID and location. Fig.6 depicts a simplified model of development environment. The cognitive layers of the robots are composed of rt-SRA agents implemented on JADE while the action layers are built on a C++ library called Mobility running on the Linux providing CORBA interface for sensors and motion controls. RFID and wireless readers, while managed by rt-STAs that live on JADE with an action layer that holds the tag model, capture smart tags and sensors. The proof of concept validates the production scheduling and optimal routing of a few work cells with AGV robots and production resources to accomplish the tasks, facing possible dynamic events, such as parts shortages or breakdowns of resources. It has been validated that using the rt-SRA for the collaborative control and coordinated tasking of SMS resources has delivered better responsiveness due to the improved agent model. The rt-STA has facilitated, however, effective product management across the supply chain due to higher and smarter visibility. Integration was seamless between components. The working scenario has demonstrated that the SMS framework has potential in the future.

VII. CONCLUSION AND FUTURE WORK

This work introduces a new SMS controller architecture for building up a smart manufacturing system. It exploits RFID visibility enabling technology and collaborative AO models to support the work of decentralised systems in a smart, responsive and collaborative manner. The work outlines the

functional modules in the architecture with detailed descriptions. In fact, the emergence of cost effective auto-ID RFID devices and smart sensors has affected supply chains through closer integration of visibility and manufacturing systems. The decentralised SMS controller promises a variety of benefits ranging from total process and product visibility and smart flow to efficient resource utilization, high volume productivity and just in time delivery. The SMS visibility drilled down to the production resources, parts and work-pieces. The hybrid SMS AO model, while preserving the responsiveness of reactive control, improves performance of the distributed systems. The SMS real-time aspect is exploited through systems decoupling and closer integration that better manages normal operations and unpredictable events while agent-based models deliver a collaborative distributed intelligence and decision making for responsive delivery of system distributed functionalities. The work introduces, as well, a tristate-based hybrid real-time agent-computing model that improves system performance. This work is ongoing and paves the way for a research space that blends total visibility with contemporary manufacturing and collaborative supply chain management in decentralized smart networks driven by technology trends.

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