Product-driven Automation with Distributed Intelligence
with the ERRIC research infrastructure

"High-speed robot-vision system for Active Holon Entity aggregation and intelligent product inspection - CARTERV"

The acquisition of the CARTERV equipment in the ERRIC project was necessary to allow the development of research activities in the ERRIC scientific domain: "Cognitive and Collaborative Information Technologies in Robotics and Manufacturing" (CCIT_RM).

The CIMR team in the A&C faculty and its EU partner LARM from the University of Cassino - Italy are currently involved in the main research lines which are promoted in the ERRIC project:

1. Natural-like human-robot interaction systems for:
   - 1.1. Human-Personal Robot (HPR) communication: assisting people in special, difficult tasks; assisting aged / disabled people in everyday tasks;
   - 1.2. **Human-Industrial Robot (HIR) skills emulation**: learning from visual modelling and interpretation of gestures; cognitive learning for dexterous task reproducing
2. Intelligent control architectures for emergent types of robots: personal robots; parallel high-speed robots; open-chain precise robots; multiple-arm robot systems
   - 2.1. **Data fusion for constrained robot motion control**
   - 2.2. **Robot cooperation technologies**
   - 2.3. **Visual robot servoing from feature-based description of environment**
3. Robot sculpture:
   - 3.1. Robot-driven 3D digital shape reconstruction
   - 3.2. **$2^{1/2}$** and 3D **surface generation through procedural tool motion**: orthopaedic and surgery expert; **robot-based CARE and rapid prototyping**
4. Open manufacturing control with agile reconfiguring of robot services
   - 4.1. **Agent-Oriented robot coordination; integration in Holonic Manufacturing Execution Systems (HMES) and service orientation for global sustainable manufacturing**
   - 4.2. **Product-driven automation, semi-heterarchical production scheduling, intelligent embedded products**

Research activities at points 1.2, 2.1, 2.2 and 2.3, 3.2, 4.1 and 4.2 needed the high-speed accurate robot-vision system CARTERV, which was installed and integrated in the Holonic Service Execution Platform (HSEP) of the CIMR Laboratory of the A&C faculty, which operates with intelligent, self-organizing robots for sustainable manufacturing.

A mid-range **laser scanning equipment** has already been purchased by the CIMR Lab. in A&C, installed on a 6-d.o.f. anthropomorphic robot and connected to: the multitasking controller, a machine vision system with intelligent colour camera and the PC-based robot terminal. This equipment is necessary for the research activities:

- 1.1 - part of the Ambient Intelligence Laboratory
- 3.1 and 3.2 - information-based medicine (orthopaedic and surgery expert)

Details concerning the role of the CARTERV equipment to extend existing research facilities if the HSEP platform, are given below:

A shop-floor control framework is proposed in which one entity (e.g. a processing, transport or inspection resource, a product) can not only achieve its goal in terms of the system's objectives but also in terms of its own objectives. An entity can be a *resource* (e.g. a machine, a robot, vision system) or an active *product*. An **active product** or Active Holon Entity (AHE) is an aggregate entity able to inform, communicate, decide and act in order to reach its goals in solving resource allocation and routing problems (Fig. 1).

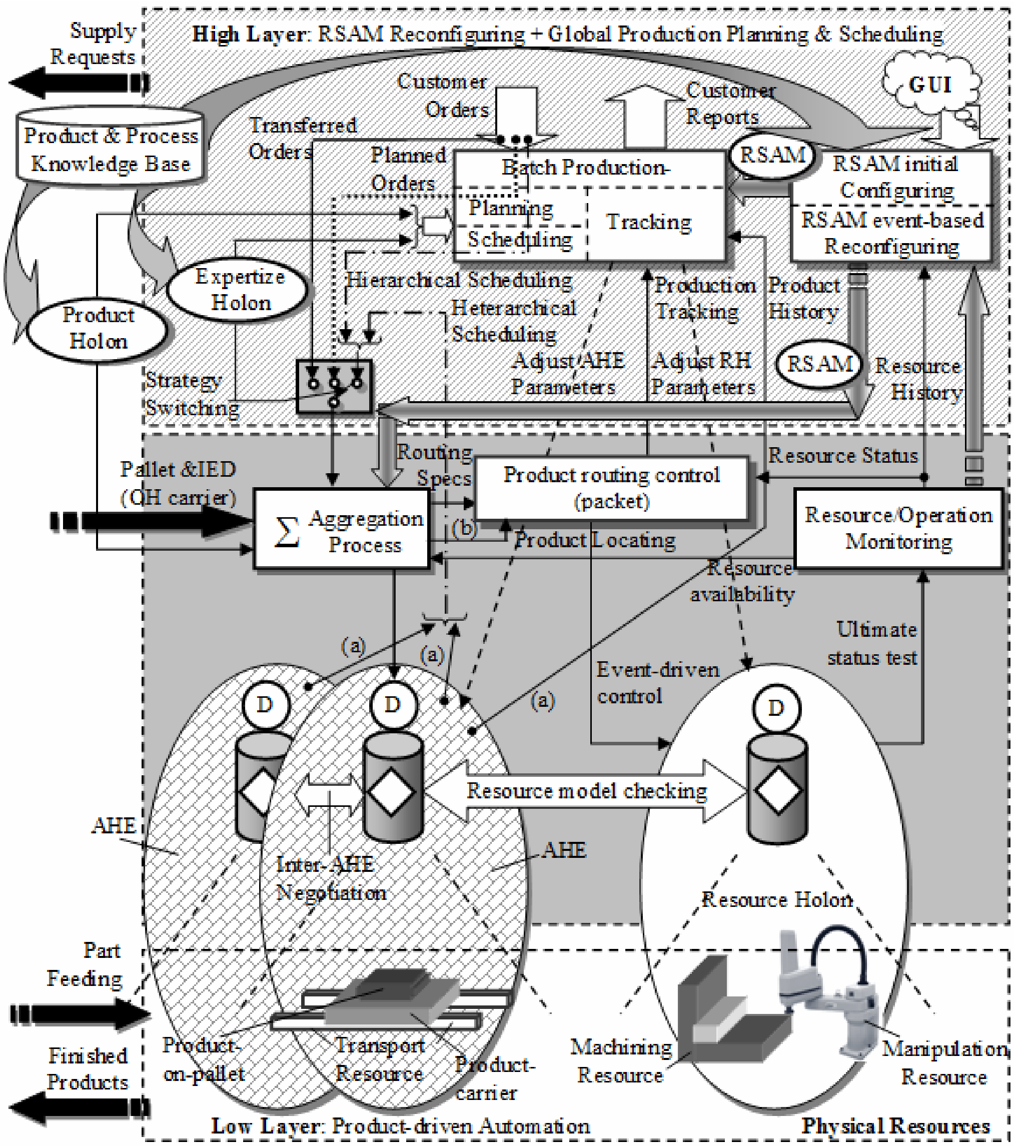

Fig. 1. The two-layer generic architecture proposed for dynamic (re)configuring a Resource Service Access Model (RSAM) for open, semi-heterarchic shop-floor control (planning, scheduling, controlling and tracking)

The target existing repetitive, discrete batch fabrication structure consists of several machine tool-, robot-, vision- and storage-workstations interconnected by a shop-floor conveyor. Each workstation contains one or more processing resources (CNC machines), a part handling & processing robot (accessing the cell conveyor) and product control unit (machine vision).

The products, which are placed on **pallets**, are progressively processed and assembled by physical resources, some of which are identical or have identical capabilities; some of the resources are different but offer similar services at different costs. Each pallet mounted on a carrier moving on the conveyor is equipped with an Intelligent Embedded Device (IED) which is capable of memorizing information, communicating over an ad-hoc network with peer devices and taking real-time decisions regarding *product scheduling* (allocating a resource to each operation on products), *product and resource tracking* (monitoring the operation's quality and the resource's performance, creating the product's "history").

Because **agility** is a main objective to be achieved by the open control structure, a generic multi-agent architecture is proposed to allow shop-floor reengineering; components of this architecture and their capabilities are configured initially (upon receiving customer's orders) and possibly reconfigured at run time in case disturbances occur (adding / removing one resource, performance decrease or breakdown of a resource).

A **Resource Service Access model** (RSAM) is thus created and maintained using generic properties:

- *Modularity*: a production system will be configured as a dynamic composition of modularized manufacturing units which become basic building blocks. Building blocks are developed on the basis of processes they are to cater for.
- *Configuring rather than programming*: the addition or removal of any manufacturing component (basic building block) should be done smoothly, without or with minimal programming effort. The system composition and its behaviour are established by configuring the relationships among modules, using contractual mechanisms.
- *High reusability*: the building blocks should be reused for as long as possible, and easily updated for further reuse.
- *Legacy systems migration*: legacy and heterogeneous controllers might be considered in any global architecture and a process must be developed to integrate them in the new agile architecture.

Two stages are considered in the creation of the shop-floor Resource Service Access Model:

1. <u>Initial creation</u> (*RSAM configuring*): using a Graphical User Interface (GUI in Fig. 1), resources are manually added to the working structure or team (responsible for producing a type of product), being thus created a map of services offered by the team, their costs and the way they can be accessed.
2. <u>Automatic update of resource status at run time</u> (*RSAM reconfiguring*): the resources are monitored by the Active Holon Entities during their lifecycle and the resource access model is updated with information about the real-time capacities of each resource, its availability and the penalty/bonus it received for the accomplished services.

Shop floor agile control / supervision can be achieved if the manufacturing system is abstracted as a composition of modularized manufacturing components that can be reused whenever necessary, and whose interactions are specified using reconfiguration rather than reprogramming. Consequently, a generic multi-agent system (MAS) was designed to create and automatically update the shop floor's service access model RSAM, because of its adequacy to create cooperative environments of heterogeneous entities.

Manufacturing components were *agentified* to become modules that can be (re)used to compose complex systems. The different types of manufacturing scenarios and batches were thus represented by coalitions or consortia of agentified manufacturing components, which are essentially societies of self-interested and heterogeneous agents whose behaviour is governed by contracts; contract negotiation is the configuration basis required whenever a supervision / control system needs to be changed or adapted.

Thus, a manufacturing component or module is seen as a physical piece of equipment that can perform a set of specific functions / basic production actions on the shop floor such as moving, transforming, handling or inspecting. To design the generic RSAM, images of the manufacturing were defined as:

- *Agentified manufacturing component*: composed of a manufacturing component and the agent that represents it. The agent's skills are those offered by the manufacturing component, connected to the agent through middleware.
- *Coalition* or *consortium*: a group of agentified manufactu-ring components, whose cooperation is regulated by a coalition *contract*, interacting in order to generate aggregated functionalities that, in some cases, are more complex than the simple addition of their individual capabilities.
- *Shop floor cluster*: a group of agentified manufacturing components which can participate in coalitions and share some relationships (belonging to the same manufacturing structure and possessing some form of technological compatibility). The different coalitions that can be created out of a cluster represent the different ways of exploiting / operating a manufacturing system.
- *Broker agent*: used to help the formation of coalitions to reduce the complexity of the individual agents in terms of coalition formation.

Once configured and operational the service access model of manufacturing resources, it was integrated into a 2-layer holonic semi-heterarchical control architecture for both high-level optimal batch products planning and scheduling and low-level real-time packet products (products currently in execution) scheduling. This self-organizing control topology is suitable for shop floor environments affected by disturbances (which is the real case in industry environments) like: resource unavailability due to breakdowns or maintenance operations, part stocks depletion due to limited storages, variable processing and transporting times. The proposed planning, scheduling and control models with their implementation frame are *generic*; the structuring of the decisional entities (Active Entity Holons) and the distributed decision making (based on holon autonomy and cooperation) do not rely on proprietary technologies.

The control part of the distributed system is composed of entities that are independently responsible for one aspect of fabrication such as technological planning (**product** recipe), **resource** capabilities, and logistics (production **order**). These components, being endowed with information processing skills (except for products) are encapsulated into autonomous and communicative entities called *holons*. The following holons were defined:

1. On the high level layer:
   - A set of **Expertise Holons** (**EH**): together with the application for global production planning, scheduling and tracking acts as a *Coordinator* of the high level control with its attributes, including the client interfaces.
2. On the low level layer:
   - A set of identical **Active Holon Entities (AHE)**: one AHE is an aggregate intelligent entity in charge of taking real-time decisions. It is composed of: (a) the product being fabricated, (b) the pallet carrier which transports it to the assigned (scheduled)

workstations where operations are executed upon according to the product recipe, and (c) an augmentation module, implemented as an *Intelligent Embedded Device* (IED) providing decisional capabilities. The maximal number of AHEs in the shop floor equals the dimension of the product packet in current execution.

- A set of **Resource Holons (RH)**: describe the physical resources (e.g. robot, conveyor), used for part processing or transporting, together with their controllers and sensors which communicate with the AHE for service granting and management.
- The **Product Holons** (**PH**) store the operations structure for all the types of ordered products, by retrieving info from a **Product** and **Process Knowledge Base** (PPKB**).**

In heterarchical production control mode, the AHE use the data from the PH to access, through communication with the RH, those available and cost-effective resources the image of which is permanently updated in the RSAM.

Active Holon Entity (AHE) and product-driven scheduling: the IED design approaches two essential problems in real-time, product-driven manufacturing control: (i) *product locating* and (ii) *decision making for resource allocation.* Both problems are influenced by the placement of the information part of the AHEs (taking decisions in the process of real time scheduling) with respect to the physical part (the product carrier) and by the synchronization solution between the two parts.

Intelligent Embedded Devices for AHE: in the present design, the augmentation module associated to the AHE comprises (see Fig. 3):

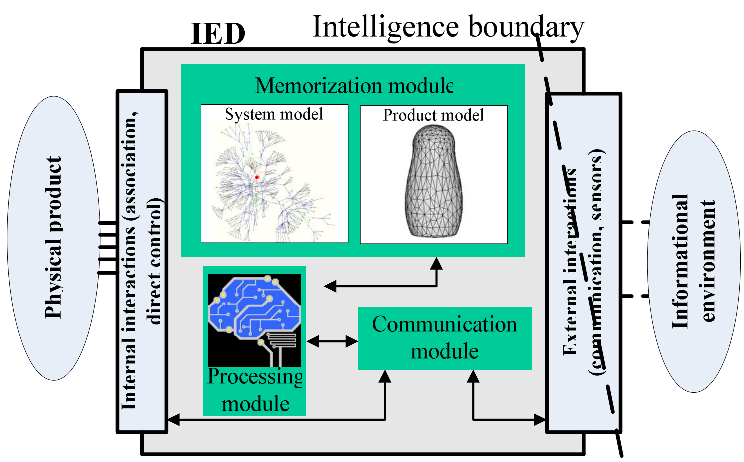

Fig. 2. Structure of the intelligent embedded device (IED) augmenting the OH with active behaviour to an AHE

- A *data storage module* memorizing the fabrication model of the product (operations to be done, their parameters and precedence between these operations – services to be obtained) and of the resource model (services provided by each resource and their costs, the current status of the resources and of the links between them – RSAM);
- A *module for communication* and
- A *decision module* (for real-time scheduling).

The augmenting entity is thus structured as **local (embedded) intelligence**, placed on the product carrier, which rends the AHE entity more autonomous and co operant. The decision-making process is more agile since decision is taken near the point of interest, and more fault tolerant because in the case of a local failure the rest of the entities can continue to work. The entities do not rely in this case on the communication of control information but on the synchronization between them. Product localization is done in this case by the IED which interprets the signals received from sensors placed on the conveyor in the proximity of resources. This solution allows implementing "product-driven automation" (or "intelligent product" method), providing *agility* in operation and *modular structure* easy to change *by reconfiguration*.

The physical implementation of the AHE (Fig.3) consists of:

- An Overo Air *processing module* (www.gumstix.net) based on an ARM processor, with WiFi communication, running Linux, configured for real-time applications;
- A *transportation pallet with RW RFID tag*: this is the carrier of the product to be progressively manufactured, offering it transportation services;
- *Product*: the part of the AHE being manufactured in a sequence of operations executed by assigned resources.

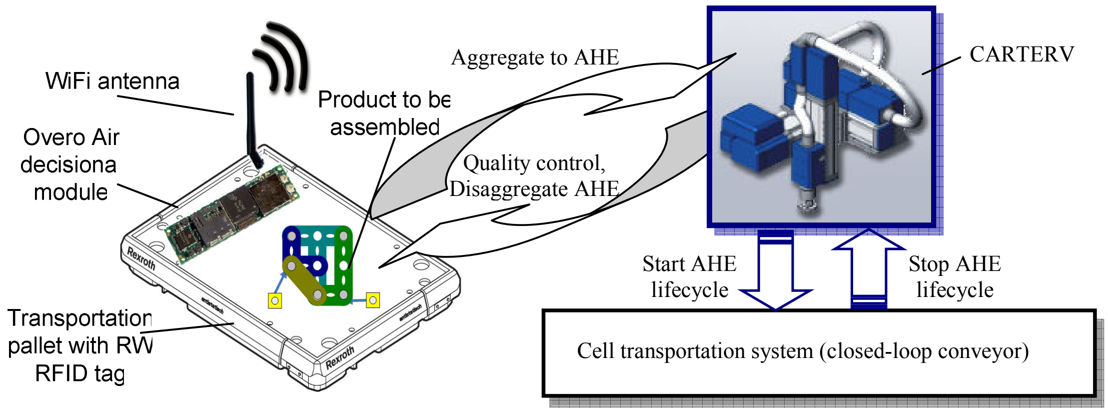

Fig. 3. Physical implementation, aggregation and disaggregating of an AHE

The lifecycle of any AHE is:

- **Initiated by the CARTERV controller**, which introduces the carrier of the intelligent product [the pallet carrier with an empty pallet] in the manufacturing cell, thus triggering the aggregation of a new AHE;
- **Terminated by the same CARTERV controller** which, upon visually inspecting (geometry) and validating the quality of the final product, outputs the entity "product-product carrier" from the manufacturing cell, thus triggering AHE disaggregating.

The *product routing control* (low level) is done by a PLC which receives from each AHE standard files decoded to command the conveyor devices (motors, diverting units, and stoppers) so that the product visits the allocated resources and gets processing services. Product localization is done by the PLC which reads the IDs of the pallets in fixed (e.g. conveyor diverting) places using a RFID system (*AHE Localization*), and offers this information to the exterior through a server. This information is then read by the AHEs which are continuously polling the PLC; when their own ID is detected by the PLC the location where the ID was read is associated with the corresponding pallet (*Raise event: Inform of localization* in Fig. 4).

The localization events trigger a decisional process on the AHE which sends its decision to the PLC (*Request service*), this entity being in charge of its realization (*Perform service*). After completion of the requested operation, the PLC informs the AHE on the result (*Inform*) and why the result is negative.

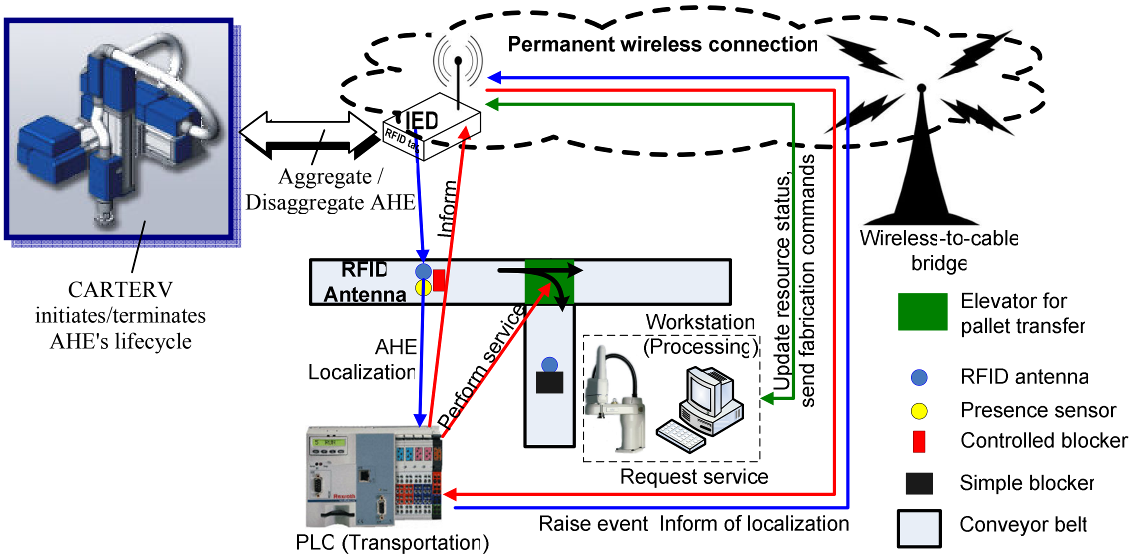

Fig. 4. Intelligent product localization and scheduling with aggregated AHE

The decisional software uses the Java Agent DEvelopment Framework. This framework is designed for developing MAS applications conforming to FIPA standards (www.fipa.org). It includes two main products: a FIPA-compliant distributed agent platform and a package to develop Java agents. The application provides the developer with an agent management system, a directory facilitator, an agent communication channel, debugging tools to aid developing multi agent applications, and intra-platform agent mobility.

Three important processes are implemented using the JADE environment and its facilities:

- **Individual schedules**, computed from the perspective of each product, will be implemented as one-shot behaviours triggered by discrete events which perturb the normal operation;
- **Resource service access configuring**, done through a combination of a proprietary server application running on the resource controller and a middleware running on a PC and connected to a generic resource agent. This is necessary since resources may be heterogeneous, coming from different manufacturers, with different operating systems and interconnecting solutions (e.g.: Ethernet, serial port). This approach allows creating an intelligent infrastructure in which the resources are easily integrated and accessed using a common interface (a JADE agent);
- **Communication** between intelligent embedded systems and resources is done by utilizing common ontologies and interaction protocols easily defined in JADE, and is supported by the uniformity amongst agents, which are all implemented as JADE applications. Two types of agents were defined in the project: *product agents* in charge of the execution of the associated client order, which are active entities in the decisional process of resource allocation, and *resource agents* in charge of resource automation. These agents communicate in a mix of wire and wireless networks, allowing a high degree of mobility both from information and physical point of view.

The CARTERV functionalities were developed and integrated by the experienced research team of the CIMR Centre in the framework of T3.8 of ERRIC WP3: "Cognitive and collaborative information technologies in robotics and quality inspection".

The integration of the CARTERV equipment (Cartesian robot, multitasking controller, firewire video camera and software licences - robot motion control, image processing library and API for visual motion planning) with the existing research infrastructure of the Holonic Service execution Platform HSEP is shown in Fig. 5.

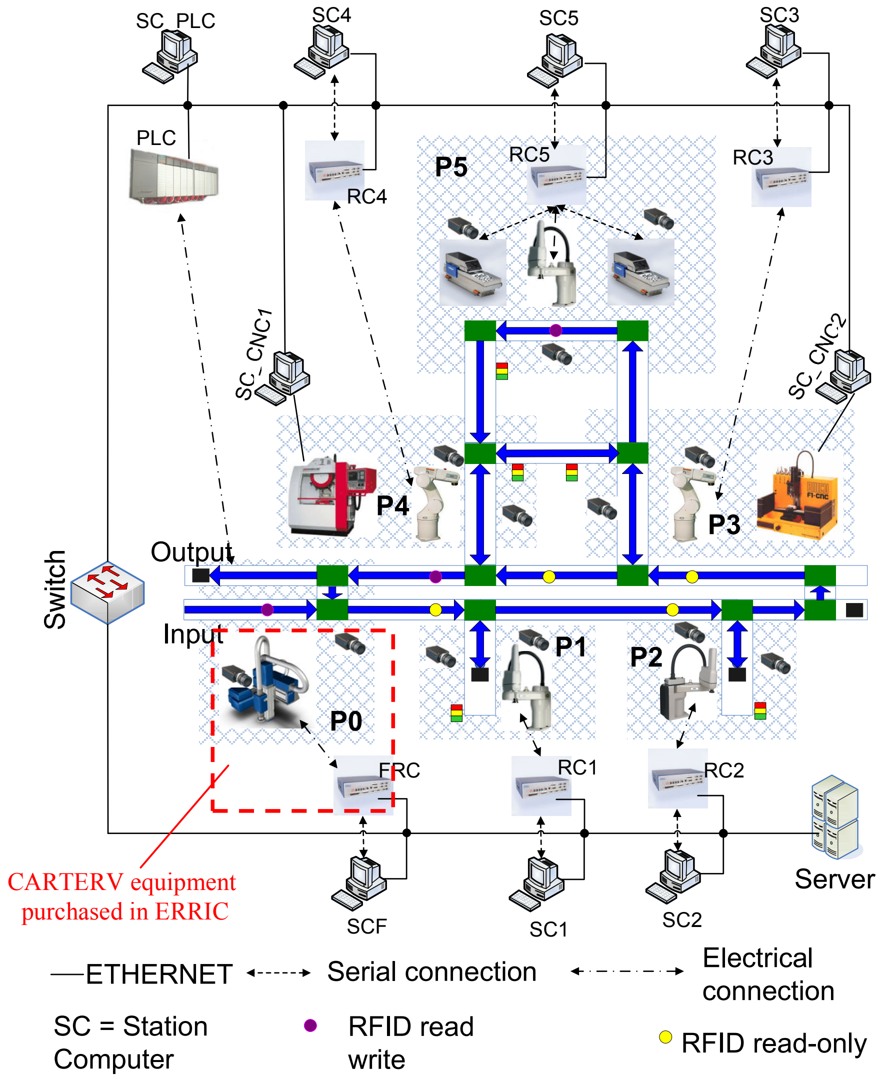

Fig. 5. Integration of the CARTERV equipment in the existing HSEP research infrastructure