NOVEL ARCHITECTURE OF INTELLIGENT AXES FOR FAST INTEGRATION INTO RECONFIGURABLE ROBOT MANIPULATORS: A STEP TOWARDS SUSTAINABLE MANUFACTURING

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Abstract. Sustainable manufacturing processes are defined as the totality of direct and related actions of goods creation which involve a reduced negative impact to environment, sufficient economical income together with society satisfaction, all of them linked in a long term commitment. A perspective on how fast integration of intelligent units into industrial robot manipulators can help to achieve future sustainable manufacturing is introduced in this paper. By combining the key characteristics of reconfiguration with the key issues of sustainability, a design model of fast reconfigurable robot manipulators is here proposed. To prove its potential, an experimental test bench was constructed around a plug-and-play intelligent electro-mechanical axis. The ongoing research work is focused on finding possibilities of how to endow usual robot manipulators with distributed intelligence and thus to extend equipment capabilities and performance in order to get closer to the goal of reconfiguration for sustainable manufacturing. Preventive maintenance, configuration options, self-integration and diagnosability together with a work record database have been implemented inside the experimental test bench. Results have concluded that plug-and-play intelligent axes are feasible for fast building of reconfigurable robot manipulators. Furthermore, an idea of how manufacturing environment should manage and use intelligent reconfigurable robot manipulators is also presented.

Key words: sustainable manufacturing, intelligent robot manipulator, distributed intelligence, reconfiguration, plug-and-play.

1. INTRODUCTION

Aspects related to the concept of sustainability, its links to the manufacturing environment, as well as the importance of achieving sustainability of the manufacturing processes are introduced in this section. Sustainable development has been defined by the World Commission on Environment and Development (WCED) in a complex report from 1978 called "Our Future" as the "development that meets the needs of the present without compromising the ability of future

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generations to meet their own needs” [1]. Sustainability can be visualized as the balance between three interconnected pillars: environmental protection, social responsibility and economic growth [2].

The close connection between sustainability and manufacturing was underlined since manufacturing was identified by the European Union and United States official reports [3–5] as being one of the most important driving force of the economy and society and thus capable to stimulate all the related sectors in the process of value creation [6]. Sustainable manufacturing has evolved from the concept of sustainable development since society understood that the manufacturing industry has a significant and an uneven distributed impact on all of the sustainability pillars.

Overtime, manufacturing environment was forced to change its approach in order to meet emerging market requirements, from mass production to mass customization [7]. Moreover, especially in the developed countries, society is becoming conscious and aware about the continuous deterioration of the global environment, climate change, shortage of natural resources and upcoming risks [6]; thus, once again manufacturing environment is facing a new demand, *sustainability of the manufacturing processes*. An emerging trend towards supporting sustainable manufacturing and mass customization is expressed by the paradigm of reconfiguration; that is reconfigurable manufacturing systems and *reconfigurable equipment* [6–10].

Despite the potential of reconfigurable manufacturing for the forthcoming manufacturing challenges, researches in the field are still at an incipient phase [11–13]. Scientific progresses related to reconfiguration are done in relation to the mechanical systems’ architectures [13–17]. However, key performance characteristics of reconfigurable equipment are related to the capacity of fast combination, removal, addition and recombination of various kinematic axes to meet the goal of reconfiguration: what is needed, no more no less, at the time is needed. This capability requires embedded intelligence in the kinematic axes, as well as spontaneous transfer of information from each axis to the master system and between the kinematic axes.

In these scientific boundaries, the purpose of this work is to present a control architecture that is capable to perform fast integration, configuration, inter-linking and information exchange between smart (intelligent) axes (units and sensors). The architecture is based on embedded systems, communication protocols and buffering units. It is not restrictive to the technologies selected for building the physical system. One of the possible physical solutions was built for concept demonstration. Selection of the appropriate technologies was done by means of content aware web searching tools and innovative problem solving methods (TRIZ [18, 19], CSDT [18]). The authors’ view of how smart axes can be employed for truly development of reconfigurable robot manipulators is also introduced in the end part of the paper.

The rest of the paper is organized as follows. In section 2, a short review of major control architectures and basic information about reconfiguration are provided. Section 3 introduces the specific problem that is going to be approached by this research. In section 4, the methodology applied for conceptualizing the innovative architecture is described. Section 5 addresses the application of the methodology for setting up a physical demonstrator of the architecture and of the intelligent axis. Tests and results on the intelligent axis are put into evidence in section 6. Discussions on the results, as well as their extrapolation on building reconfigurable robot manipulators are the subject of section 7. Section 8 completes the paper with some concluding remarks.

2. BACKGROUND

Control architectures and their logic have evolved in line with the evolution of specific processes that required automation (Fig. 1). The ideal control architecture is the one that provides best performances and is capable to suit any process, at any time, and at the desired level of quality [20]. From here, the control architecture of the future seems to be the one that has the highest level of reconfigurability and is capable of real-time reconfiguration of its resources in order to fit any process needs [21, 22].

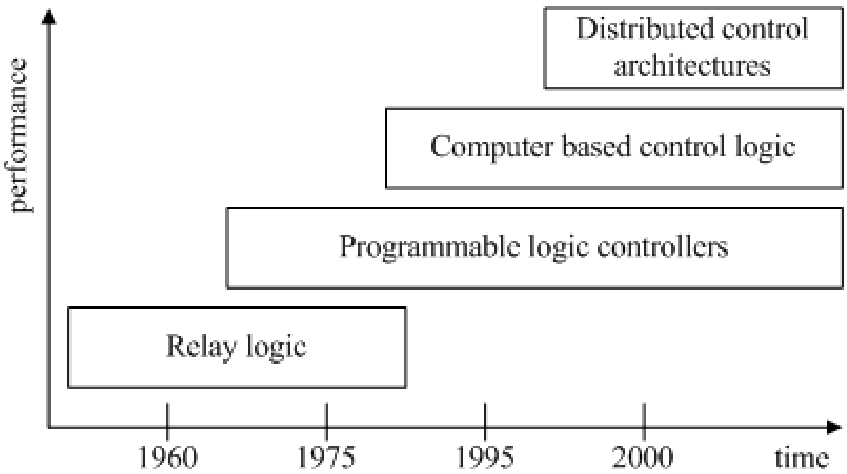

Fig. 1 – Major control logics.

Current control architectures are designed to have a certain degree of reconfigurability; however, the important issue is the easiness of gaining advantages from this reconfigurability, in terms of ramp up time, time to market, costs, complexity, feasibility, efficiency, environment impact and further unknown factors [15].

The relay logic control architecture marked the beginning of the manufacturing industry and was designed under the philosophy of product oriented mass manufacturing systems. Being a wired logic, it is widespread, hard to debug, complex to understand even for skilled personnel and inefficient. Even though it is reconfigurable by hardware means, it is also extremely time consuming even for trained personnel [23, 24].

Developments in the fields of electronics and computers gave birth to the first PLC in 1968, of whose architecture is based on hardware and software enhancements [25]. By using microprocessors and software algorithms, replacement of the relay logic was possible. This control architecture represents an advanced version of the relay logic, but it is less hardware-reconfigurable then the relay logic since the connection to the external world is predefined and requires trained personnel. Still, it brings valuable advantages like: reduced execution time, easy to debug, software reconfigurable, easy to update, change or expand, more efficient and reliable than relay control logic [25].

The transition from local to globalized markets, characterized by continuously increasing demands regarding product varieties and unpredictable batch sizes, made manufacturing environment understand that being client oriented is the only way an enterprise can achieve success and survive onto the market. On the background of this philosophy the paradigm of flexible manufacturing systems was developed and implemented throughout CNC machines. The architecture of these machines is based on computer control in order to meet market's needs regarding the product variety and batches sizes [26, 27]. Although such control architecture is both hardware and software reconfigurable within the range of products for which it was designed, it is still rigid because of its centralized and complex structure and very difficult to debug or upgrade. Among major drawbacks are the expenses and time required to develop the design with all its possible options included. Thus, the probability that devices and equipments built on such architecture to become subject to obsolescence before even being released is quite high [28, 29].

Challenges in the manufacturing environment require developing simple, sustainable, cost effective and easy to use decentralized control architectures for an increased efficiency and reliability. Such control architectures are based on distributed control and intelligent equipment [30, 31].

Reconfiguration paradigm applied on manufacturing systems refers to the ability of the manufacturing system to quickly reconfigure its resources in order to obtain a reliable system with a desired functionality as a response to market changes or other requirements [10, 32]. The reconfigurable manufacturing paradigm is based on six core functions.

- *Modularity* is a key enabler of reconfigurable manufacturing systems (RMS) and reconfigurable manufacturing equipment (RME) and refers to a system's property that would allow building complex systems out of basic hardware and software modules.
- *Integrability* represents the ability of RMS and RME to reliably cooperate with actual and future developed technologies regardless the producer.
- *Convertibility* is the ability of a RMS or RME to manage their resources to quickly changeover production, between existing products (and tasks) or shortly adapt to upcoming products (and tasks).
- *Diagnosability* is a core function that allows tracking down and troubleshooting manufacturing problems that are related to equipments. Self-diagnosis is an important extension of this core function.
- *Customization* represents the ability of RMS or RME to continuously adapt to product varieties and batches in order to quickly respond to market requirements.
- *Scalability* is the propriety that allows adding or removing components or functionalities reliably.

Employing the above mentioned core functions it is possible to obtain an advanced control architecture containing simple, intelligent units (equipments), with valuable characteristics. The type and evolution of these units is subject to the control architecture that was used for process control. Up to now, these units were more or less the same, having usual functionality and mainly, experiencing increase of performances from the mechanical point of view [15]. Built-in controllers endowed with a diversity of hardware, software functionalities and options are capable to enhance equipments' intelligence to meet high levels of performance [33–35]. They definitely represent the future of manufacturing systems since they can be programmed to work as needed [35, 36]. Simple intelligent equipments can be joined and configured to act as a whole in order to solve more complex goals or tasks. This is possible by employing advanced information management systems, efficient communication and software control algorithms.

Intelligent RME are the result of extrapolating and implementing the above mentioned six core functions on manufacturing equipments. Their goal is to optimally enhance usual equipments performances with additional functionalities and configuration options by hardware and software means, with respect to a set of constraints [37]. From the six core functions, scalability, convertibility and integrability are a must in order to successfully deploy the reconfigurable manufacturing paradigm [2, 7, 8, 9].

Extrapolating the benefits of manufacturing processes that are designed on the background of RMS's core functions together with the advantages brought by intelligent equipments, it is expected to reach higher levels of sustainability of the manufacturing processes.

3. THE PROBLEM

Building RME is not a simple task. RME should not be confused with modular manufacturing equipments. Far beyond modularity and fast connecting mechanical joints, RME must possess the ability to quasi-instantaneously transfer information between its modules and from each module to the master controller continuously or at least periodically, when this is required. Information is complex, it referring to several issues like: relative position and orientation of each module relative to those that are interfacing with, history of each module in terms of the previous use, current state in terms of failure monitoring and control, geometric, kinematic and dynamic data, accuracy data and calibration requirements, etc. Moreover, the master controller must possess the ability of scalability and convertibility. These aspects clearly require local embedded smartness, by using hardware and software means, as well as adequate algorithms and communication protocols to effectively build intelligence into the system. In this specific topic of reconfiguration, very few notable results are reported [13].

Beyond these issues, in integrated manufacturing enterprises, long distance service and maintenance is another significant challenge [12, 38]. Effective links between robot manipulator (robotic cell/RME) producers and robot users will be done via tele-engineering mechanisms (including remote monitoring and control, remote maintenance, remote service).

This requires implementation of adaptive sensory systems to the level of robot kinematic axes, optimal placement strategies of the sensors, efficient data compression and pre-processing stages to support the monitoring agents (watch dogs) performing simple, on-line and real-time process change detection, clever methodologies for information management, use of information for self-learning purposes, on-line adjustments to maintain accuracy instead of simply monitoring degradation, simplified diagnosis algorithms, etc.

4. DESIGN METHODOLOGY

Shown in Fig. 2 is the methodology formulated in this research work for supporting the design process of highly reconfigurable control architectures of intelligent axes. There are several tasks for design planning and a task for conceptualization and innovative problem solving. Design planning is done concurrently with respect to four blocks of the system: control architecture, control panel, smart sensors and other smart units (*e.g.* smart motors).

For each block of the system, weighted requirements are firstly defined. Relationship matrices are used to establish the relevance of the performance metrics in relation to requirements. Results are further deployed to establish the relevance of the generic modules of each block of the overall system in meeting the performance metrics.

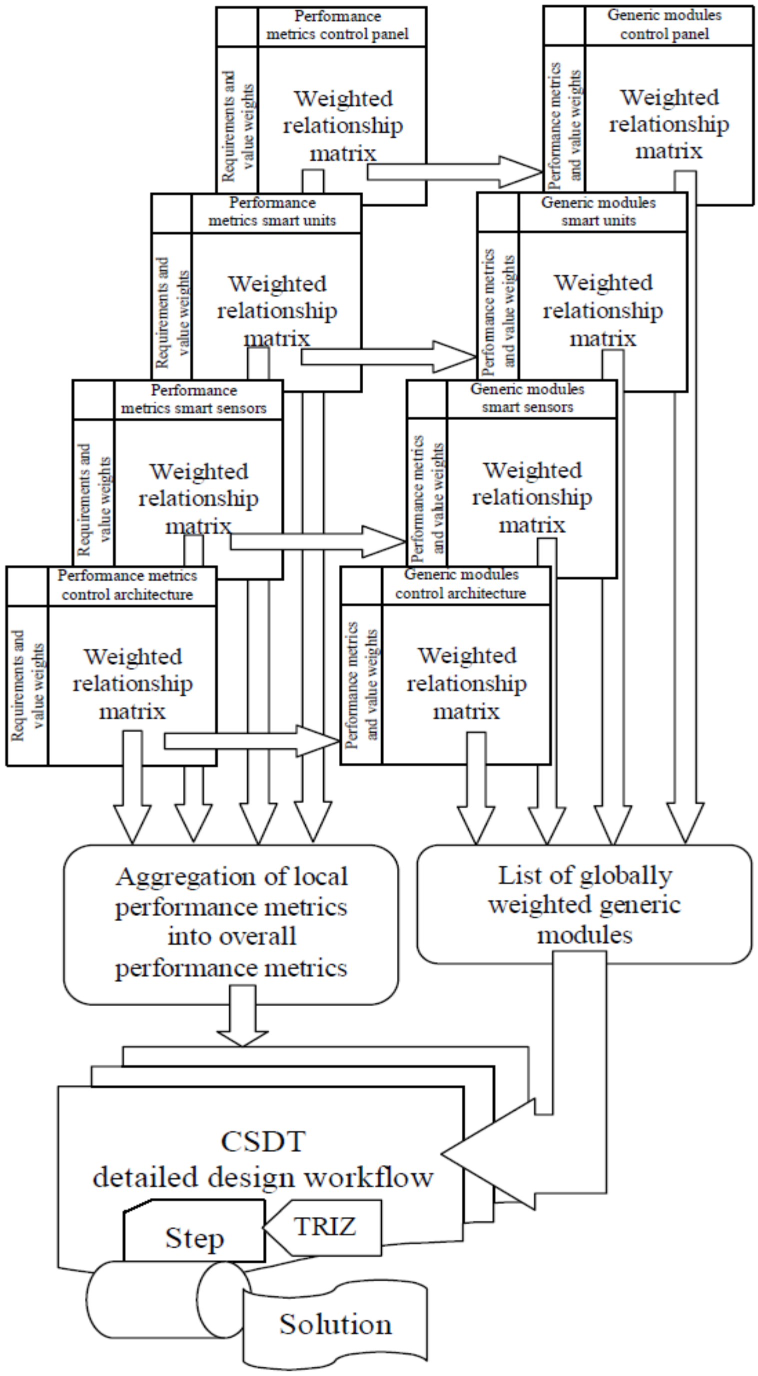

Fig. 2 – Design methodology.

Applying the methodology from Fig. 2, it is revealed that the most impacting generic module of the control architecture is the information management system, immediately followed by the control algorithms and the interface with process. For the block of smart sensors, the highest impact is brought by the interface between the configuration options and the operating protocols, close followed by the operating algorithms and the interface with the communication protocol. For the control panel, the most important modules are the remote control and configuration interface and the physical user interface. For other smart units (*e.g.* smart motors) the focus should be on the normal operating rules and the interface between the algorithms leading the normal operating rules. A global weight is further calculated for each generic module. Results are introduced in the CSDT framework [18]. CSDT method led to the concept presented in Fig. 3. TRIZ method [19] was further used to tackle with two general design conflicts:

- Conflict 1: increased reconfiguration while keeping low costs integration;
- Conflict 2: increased adaptability while keeping low costs integration.

For the first conflict, the innovation proposed by TRIZ is to change the concentration of functions and modularity. For the second conflict, three areas of interventions are proposed by TRIZ: to change the concentration of functions, to develop non-uniform structures and to make some characteristics of the components changing in time and/or space. Therefore, the idea was on developing sensors, motors and other units that are self-intelligent, able to carry information about their own past events, and information about their geometric, kinematic and dynamic characteristics (including offsets). Moreover, these intelligent units have to change some of their functions (by means of software algorithms and data). In addition, they have to incorporate an interface for communicating quasi-instantaneously with other intelligent units for self-reconfiguration in the new geometrical configurations of the RME. The idea to use buffers for avoiding the loose of information brings huge benefits in terms of system reconfiguration during its running. These ideas are reflected in the physical solution presented in Fig. 4. The software algorithms are not illustrated here, they being reflected in an upcoming paperwork of the authors.

5. APPLICATION EXAMPLE

Based on the design methodology, the demonstrator of the novel control architecture, together with a smart electro-mechanical axis, smart sensors and a human machine interface (HMI), has been developed and employed in order to underline possibilities for building complex equipments in the structure of reconfigurable manufacturing systems. The conceptual overview of the control architecture is presented in Fig. 3.

A high performance Atmel ATUC3B series microcontroller capable to run at frequencies up to 60 MHz is enclosed into an embedded design, forming the main control unit. All equipments have their microcontrollers that contain characteristic information. A communication protocol is employed for information transfer between the main control unit and other process equipments. Based on both, hardware and software designs, it was possible to endow the main control unit with scalability, configurability, plug-and-play and diagnosability.

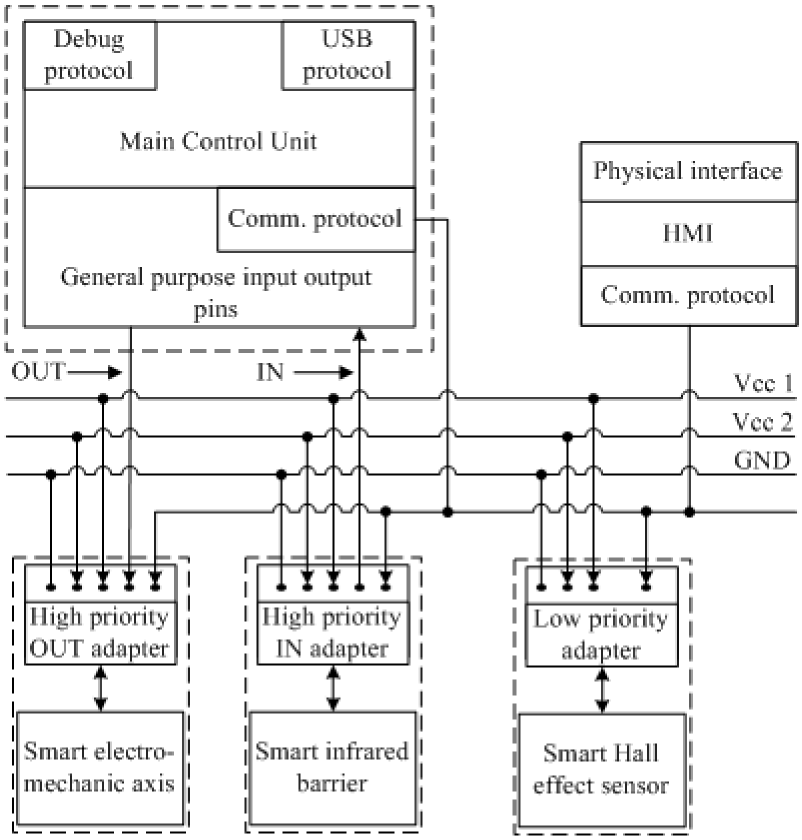

Fig. 3 – Conceptual overview of the experimental architecture.

Considering the main control unit's physical restrictions, for the selected technology to build-up the architecture from Fig. 3 a maximum number of 25 equipments can be directly connected to the general purpose input/output pins of the main control unit. Achieving an increased level of scalability requires the usage of the communication protocol, dividing equipments into high and low priority, and data management algorithms. Equipment priority is established by its role in the served process and provided by the used adapter. A high priority adapter provides equipment's connection to the communication protocol lines and a direct connection to an input/output pin on the main control unit, thus only 25 high priority equipments can be connected. High priority input equipments are capable to quickly trigger specific actions on the main control unit side; on the other hand, specific actions can be quickly triggered on the high priority output equipments' side. A low priority adapter connects equipment only on the communication protocol lines. Concerned to equipment's actions, they might suffer small delays due to data management algorithms and communication protocol performances. Still, since they are connected to the main control unit only throughout the communication protocol, the number of low priority equipments that can be connected is theoretically unlimited. However, timing aspects of the served process should be considered.

Based on hardware design, software creative algorithms and plug-and-play support, the main control unit has the ability to real-time configure the direction of its connections to the outside world with respect to the connected intelligent equipment and the type of high priority adapter used (input or output).

The main control unit offers plug-and-play support, a similar feature which can also be found in computer world, in order to quickly auto-integrate the connected intelligent equipments. The auto-integration process is based on the information stored inside the distributed intelligence of the microcontroller belonging to each smart-equipment, which is implemented by software means, and by the ability of the main control unit to manage this information.

Diagnosability is a software feature with direct impact on system functionality. It is based on the ability of the main control unit to gather and manage information from the connected smart equipments and identify incompatibilities between equipments. The human operator is alerted through the human machine interface in case of incompatibilities or other problems.

Smart equipments are embedded designs, which by hardware and software means are capable to provide additional functionalities and increase sensors or units performances. Each smart-equipment is characterized by a certain degree of distributed intelligence, which can be implemented inside its own microcontroller. The number of functionalities and configuration options that can be implemented in the microcontroller are limited only by hardware constraints and programming abilities. Using the HMI, the operator has the ability to select between equipment functionalities and configuration options in order to fit process needs.

Endowing usual equipments (*e.g.* electro-mechanical axis, infrared barriers, magnetic sensors, etc.), with distributed intelligence is possible if the above presented concept and design of smart equipments is employed.

Thus, by software means with respect to hardware constraints it was possible to develop functionalities and features like self-integration, preventive maintenance, configuration options, diagnosability and others.

Self-integration is based on to the plug-and-play capability of the connected smart equipments and is meant to reduce to a minimum the effort of the operator when adding or removing smart equipments from and to the process.

Plug-and-play has the role to cooperate with the main control unit to integrate any connected smart equipment by sending required information and safely remove the wanted equipment without disturbing other smart equipments.

Preventive maintenance was achieved by storing technical information related to each equipment datasheet inside microcontroller's memory and by advance information management algorithms. This feature is used for alerting the operator about equipment condition in order to take maintenance actions and thus, avoiding equipment failure, raw material and financial losses.

Once the smart equipment is integrated, the main control unit has all the information required to start the configuration process. Based on the implemented functionalities and configuration options, the operator has to configure the equipment to act accordingly to process needs, using the human machine interface. Some of the configuration options are presented in the next chapter.

Regarding the main control unit, diagnosability represents a feature that is capable to detect incompatibilities between connected equipment and to stop any attempt of driving the concerned equipments since malfunctions or even damages can occur. Self-diagnosis is smart equipments' ability to check for their health status and report back to the main control unit. This process is based on identifying data inconsistencies, misleading or bad control parameters.

6. TESTS AND RESULTS

Fig. 4 presents an experimental testing bench for testing the feasibility of the above presented concept and contains a main control unit (1), a power and signal distribution unit (2), a high priority smart electro-mechanical axis unit (3), a high priority smart infrared barriers unit (4), a low priority smart magnetic field sensing unit (5) and a human-machine interface (6). All devices are connected using a serial communication protocol to the main control unit (1).

The main control unit (1) is capable to support up to twenty-five high priority smart equipments and, theoretically, an unlimited number of low priority smart equipments and the distribution unit (2) can accommodate up to twelve smart equipments. Since each smart-equipment has its own ATmega32 microcontroller, a certain degree of distributed intelligence was implemented and filled by software means with specific control and monitoring algorithms relative to hardware and microcontroller's performances constraints.

Applying power to the experimental testing bench, the initialization sequence of the available equipments starts and internal modules like timers, communications, analog to digital converters, interrupts and others are configured.

After the initialization sequence, the main control unit (1) starts searching periodically for newly connected equipments. If a smart-equipment, as (4) or (5), is connected to the power and signal distribution unit (2), the main control unit (1) identifies it and establishes a link to the newly connected smart-equipment for the auto-integration and configuration processes.

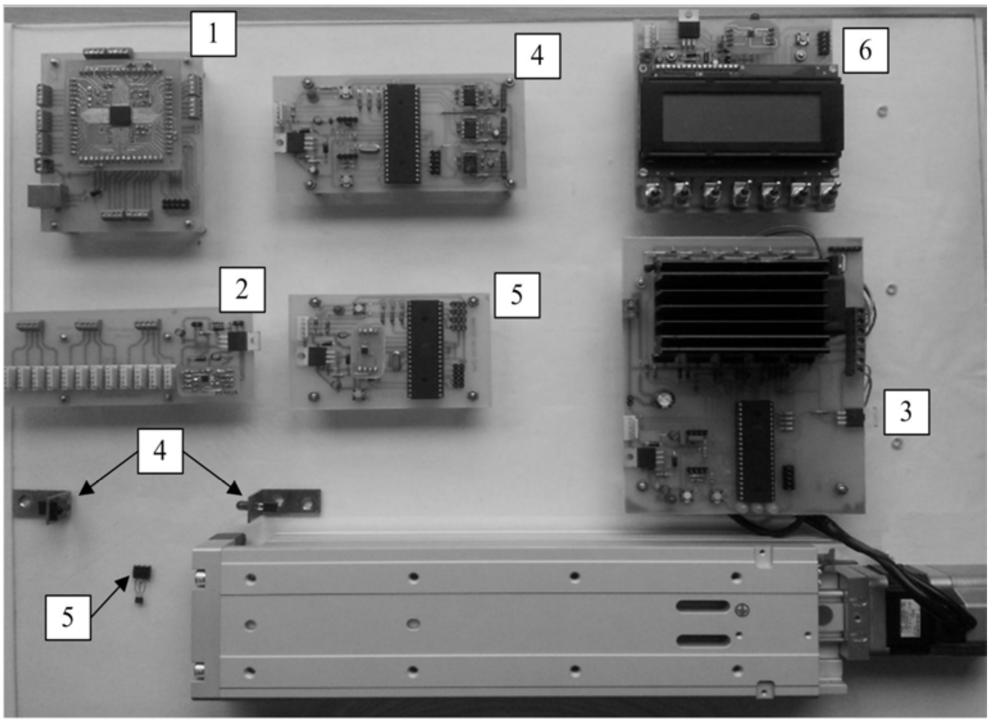

Fig. 4 – Experimental testing bench (without connecting wires).

By auto-integration of the smart-equipment, the main control unit has access to all available information stored inside the newly connected smart-equipment. Some of this information is sent to the human-machine interface (6) and it is used to configure the smart-equipment by the operator, in such a way to meet the process needs. Afterwards, information is sent back to the corresponding equipment in order to reconfigure its functionality and characteristics, accordingly to operator's actions. Some of the configuration options that have been implemented and experienced are presented below.

The smart infrared barriers unit (4) can accommodate up to three pairs of infrared emitters and receptors, which can be used for different purposes, starting from fulfilling process needs up to assuring safety. The following configuration options are available and accessible to the operator:

- Configuration options for smart IR barriers unit:
    - Define the priority of the smart IR barriers unit (high or low),
    - Choose the type of emitter and receptor,
    - Specify the number of emitter-receptor pairs (up to three).
- Configure the functionality of the smart IR barriers unit:
    - Detect object presence (Minimum one emitter-receptor pair required),
    - Count parts (Minimum one emitter-receptor pair required),
    - Identify the direction of moving part (At least two emitter-receptor pairs required),
    - Identify the direction of moving part (At least two emitter-receptor pairs required),
    - Alert the main control unit if barriers are trespassed (If the IR barriers are of high priority).

For this test bench, the smart magnetic field sensing unit (5) is used for identifying the position of the sliding part of the electro-mechanical axis (3) which has a magnet placed on the bottom of the sliding part. The sensing unit can accommodate up to four Hall-effect sensors. Bellow, the configuration options (which are implemented and available to the operator) are presented:

- Configuration options for the smart magnetic field sensing unit:
    - Define the priority of the smart sensing magnetic unit (high or low),
    - Choose the type of sensing elements,
    - Specify the number of sensing elements (up to four),
    - Select the resolution of the analog to digital converter (8 or 10 bits),
    - Specify the sampling rate of the analog to digital converter (up to 7.5 kSPS at a resolution of 10 bits).
- Configure the functionality of the smart IR barriers unit:
    - Identify the position of the sliding part (At least one Hall-effect sensors required),
    - Identify the direction of the sliding part (At least two Hall-effect sensors required),
    - Calculate the speed of the sliding part (At least two Hall-effect sensors required),
    - Disable or enable Hall-effect sensors (Select between available ones),
    - Assign smart sensing unit to an equipment (Select between available equipments, *e.g.* smart electro-mechanical axis).

The smart electro-mechanical axis equipment (3) can accommodate and control one SMC electric actuator. In this specific case, the electric actuator is driven by a 24 VDC stepper motor with windings in pentagon connection with a rated current of 0.75 Amps per phase and a step of 0.72º. The following configuration options are available and accessible to the operator for this smart equipment:

- Configuration options for the smart electro-mechanical axis equipment:
  - Keep track of working hours,
  - Monitor electric parameters.
- Configure the functionality of the smart electro-mechanical axis equipment:
  - Select default stepping mode,
  - Select default speed,
  - Allow remote control of the electro-mechanical equipment,
  - Allow learning of moves and working sequences,
  - Allow independent decision taking,
  - Assign smart sensors (Select between available smart equipments, *e.g.* smart IR barriers equipment, smart magnetic field sensing equipment),
  - Alert operator when maintenance has to be done.

By means of an advanced information management system and efficient coding (not detailed in this paper), the above mentioned configuration options were implemented into specific hardware designs and the control architecture was the subject of intensive testing in order to find out its performance.

From the tests on the proposed control architecture encouraging results have been obtained. A network of five intelligent equipments was considered for all testing phases. The speed of the communication protocol under which sending data packets, reliably reaches to the intelligent equipments under the action of continuously adding and removing equipments to the communication protocol was tested in the first phase. Table 1 summarizes the results of the first testing phase.

Table 1

Test results

	Data packets	
Communication speed	Fail	Pass
10 kbit/s	80%	20%
25 kbit/s	66%	33%
50 kbit/s	41%	59%
100 kbit/s	38%	62%
200 kbit/s	25%	75%

Table 1 presents the mean values when data packets are placed on the communication protocol and equipment is continuously added or removed by hardware or software means. Results show that, at higher speeds, an increased number of data packets are reached to smart equipments, but still the percent is not acceptable since the communication protocol is of great importance to distributed control architectures.

In order to overcome this disadvantage, an additional hot swappable communication buffer was added to the hardware design of equipments. Afterwards, all data packets sent by the main control unit have been received by the connected equipments regardless the frequency of adding or removing the fifth equipment to the communication protocol.

The second testing phase is related to the time required by the main control unit to identify, auto-integrate and display to the operator the configuration options of the recent connected equipment. An average of up to 3 seconds is needed if the speed of the communication protocol is from 10 kbit/s up to 50 kbit/s, 1.5 seconds for speeds from 100 kbit/s up to 200 kbit/s, and less than 1 seconds for 400 kbit/s speed. Still this time is dependent to the number of already connected equipments. Regarding this aspect, it is considered that no further enhancements are needed. Also, the mean time required to configure intelligent equipments is about 5 minutes for an inexperienced operator.

The third testing phase goal was meant to identify the total time delay introduced by using low priority equipments, which communicate with the main control unit only using the communication protocol. The longest time delay experienced is up to 5 seconds. This delay increases if the computational effort at the main control unit is higher or if a high number of low priority equipments are connected. In order to obtain better performances, the speed of the communication protocol should be increased to 400 kbit per second. Alternatively, a better communication protocol should be employed.

7. DISCUSSIONS

The concept of the proposed control architecture and smart equipments is based on the core functions of the reconfigurable manufacturing paradigm and this can be observed in the experimental test bench and its results. The traditionally centralized control architecture and its inconveniences are replaced with a decentralized one, in which smart equipments can be configured to work together, resulting in shorter control loops, together with a reduced computational effort on the main control unit's side. The usage of a communication network led to an increased number of connected smart equipments together with the possibility to assign a smart-equipment to another one in order to fit process needs in an efficient way. Each smart-equipment is a standalone fully functional equipment built from simple, but upgradable, hardware and software modules with abilities like plug-and-play for easy integration and self-diagnosis for troubleshooting problems. Reconfiguration properties are present in the proposed control architecture as follows:

- *Modularity* is achieved by the ability of the independent intelligent equipments to cooperate and act as a whole. The hardware design process of smart sensors and units is based on selecting the suitable module (power, communication, etc.) from the available ones. Software modules have the ability to enable, disable and make use of specific algorithms and hardware circuitry in order to achieve the desired level of performance and soft functions.

- *Scalability* is reached by means of the communication protocol where, theoretically, an unlimited number of low priority equipment could be connected. The number of high priority equipments is not subject to scalability since they are constrained by the number of available pins of the main control unit.
- *Convertibility* and *customization* are accomplished at a certain level by the ability to configure on request and real-time the functionality of an intelligent equipment. Customization is implemented at the level of the main control unit pins, since they can change their direction (input or output) to fit with the type of high priority smart equipment connected. To the authors' knowledge, this feature is not yet available on actual control architectures.
- *Integrability* is achieved by implementing an open-source philosophy. Thus, the stability and the compatibility between old and new hardware modules and software packages would reach a higher level.
- *Diagnosability* is solved by the ability of the main control unit to gather information from the connected equipments, to identify incompatibilities, to cancel commands to the concerned equipment and to alert the operator about the identified issues.

In order to develop a complex robot manipulator from a set of intelligent kinematic axes, besides the required fast coupling solutions, employment of reconfigurable control architectures is a must. A network of intelligent sensors placed within the structure of the kinematic axis is needed for real-time identification, control and virtually representation of the geometrical structure of the built manipulator. When the network of intelligent sensorics identifies a connection between two or more axes, the operator is asked to confirm the connection between them and specify the main kinematic axis.

Successful control and usage of such a complex device, built out of intelligent modular equipments, requires real-time information transfer about position, orientation and mechanical characteristics of the modules. In this respect, an advanced information management system is required, together with a powerful communication protocol.

A rapid solution would be to use the same communication protocol, in which the main control unit reserves the communication protocol for communication between the kinematic axes to exchange information regarding to their specific properties. Afterwards, the main kinematic axis becomes a local control unit for the interconnected kinematic axes and a second master of the communication protocol.

The main kinematic axis is responsible for the coordination and control of the interconnected kinematic axes and reports directly to the main control unit.

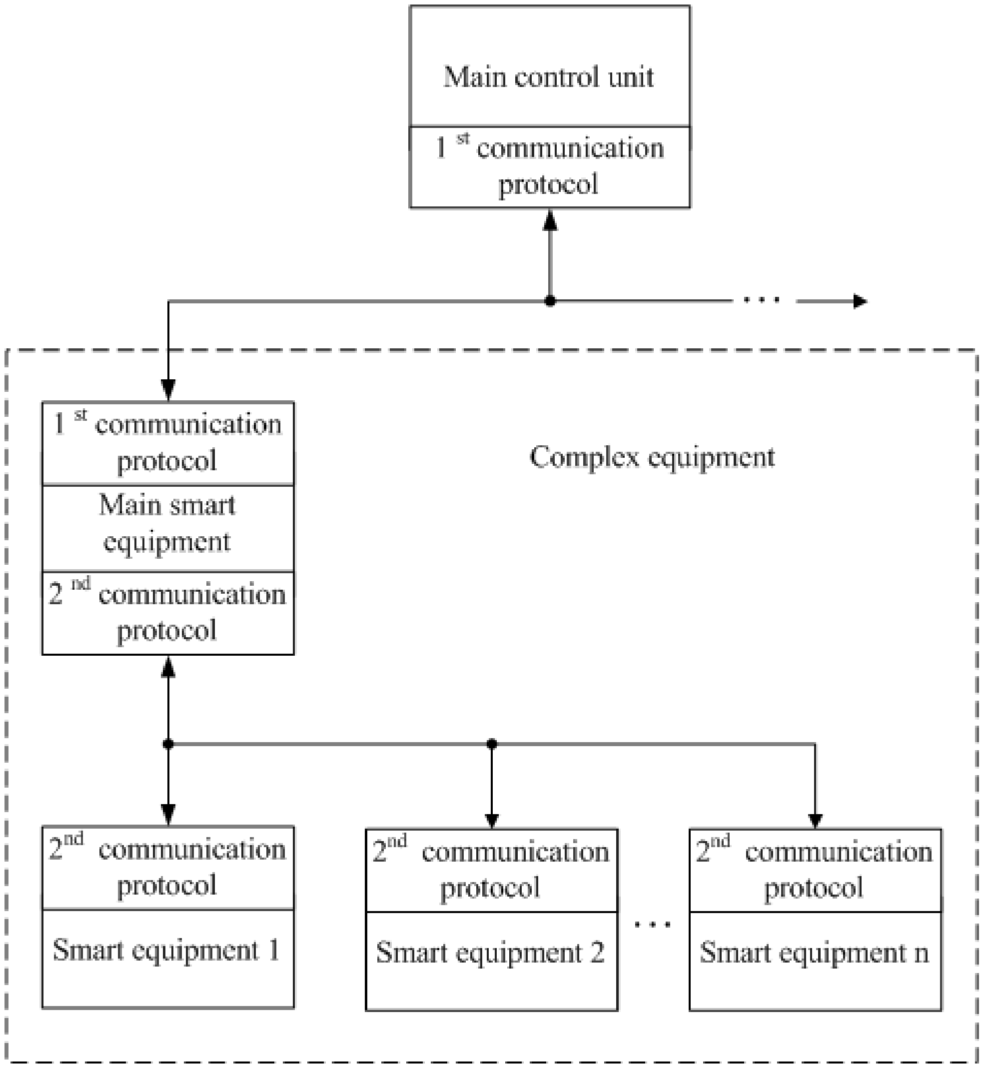

Fig. 5 – Simplified control solution for complex smart equipments.

Communication conflicts between multi-masters, the main control unit and the main kinematic axis are solved using the arbitration process of the communication protocol. Wining the arbitration process is based on the content of the sent message. The master which losses the arbitration process automatically restarts the transmission of the same information or data package after the previous transmission ends.

A second novel solution would be the one where the embedded design of smart equipments is built around microcontrollers that have at least two identical communication protocols. Thus, simple, intelligent equipments composing complex equipments will have their own communication protocol, which is driven by the chosen master unit. The master unit reports to the main control unit using the second communication protocol, as it can be seen in Fig. 5. Even if this solution requires additional hardware and software efforts it has better performances considering time response and stability.

Starting from the experimental testing bench and considering that further required software functionalities are implemented and smart equipments are available, the authors provide an example of how different robot manipulators can be built in order to adapt to process changes using reconfigurable equipments by extrapolating to a generic form the concept presented in this paperwork.

In the case of an electro-mechanical axis (Fig. 6), specific information about the distance between fastening elements on the sliding part, but not only, can be extracted from producer datasheet and/or drawings.

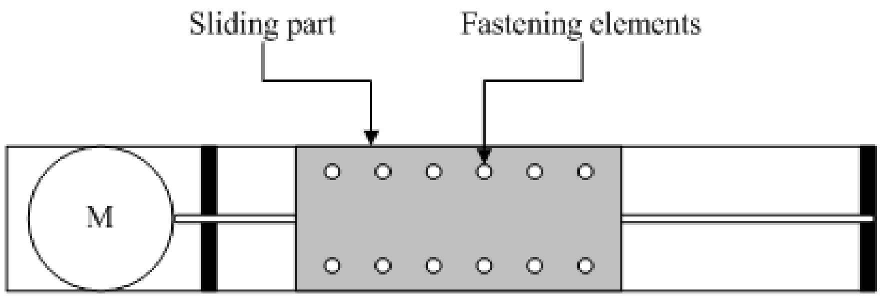

Fig. 6 – Simplified representation of the electro-mechanical axis.

Introducing this information inside the embedded design, and using information from various sensors placed within the structure of the kinematic axis (inside the mounting area) in order to detect if an additional element or equipment is being fastened, the master control unit is able to identify and build a new virtual model of the new kinematic structure.

If the served process requires another equipment to be mounted on the sliding part (Fig. 7), the sensors will detect its position and send this information throughout the communication protocol to the main control unit. When the new mounted equipment is connected to the communication protocol, the master control unit will identify it and its characteristics and provide the available configuration options to the operator. Based on this information, mathematic models are used to adapt the working characteristics of the robotic manipulator in order to keep it safe.

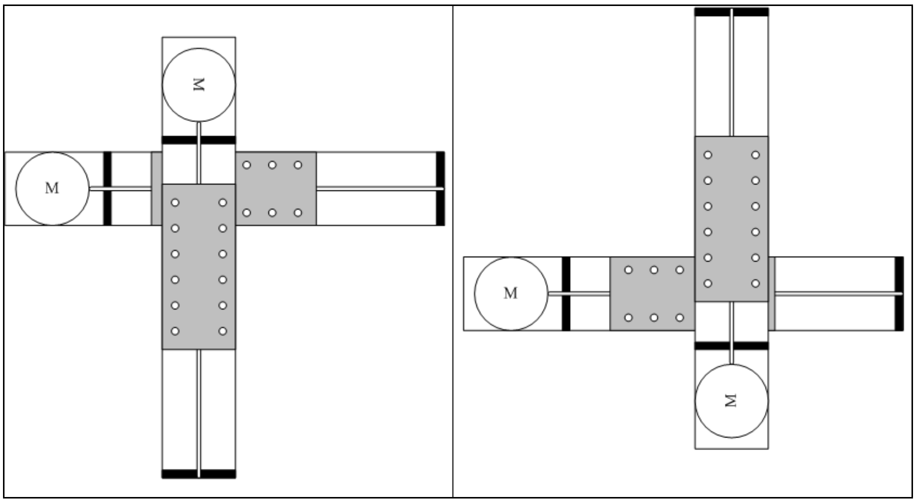

Fig. 7 – Two possible ways to link two electro-mechanical axis in order to respond to process needs.

8. CONCLUSIONS

Implementing reconfigurability-related features within a kinematic axis is a complex task. The major challenge is around information management and control in a fast and flexible way. This requires smart "watch dogs" integrated in the kinematic axis, with extended capabilities for handling complex information and communication with external "watch dogs" belonging to other kinematic axes. The flexibility and advantages of the concept proposed in this paper could be taken into account for building complex reconfigurable robot manipulators by using smart equipments since they can led, besides technical capabilities, to economic benefits like cost reduction, reusability and efficient usage of available resources.

Extrapolating the benefits and advantages of a reconfigurable robot manipulator based on the presented concept, many requirements that stand for sustainable manufacturing are fulfilled at a certain level. Thus, the presented concept contributes to the goal of sustainable manufacturing.

Based on the encouraging results, additional research directions were defined in order to exploit the full potential of this concept. The first research will be directed towards development of a PC-based human machine interface by using the USB communication protocol of the main control unit, in order to achieve an even simpler interaction between the served process and the operator. The second research direction will be focused on a new and more powerful communication protocol, like CAN or FlexRay, to investigate the possibility of achieving even better communication performances.

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