Smart Units to Support Competitive Design of Control Systems in Surgical Robotics

S. Brad and M. Murar

Abstract Surgical robots consist of complex mechanical and control architectures in order to ensure high precision and safety in operation. Advanced force and torque feedback control is indispensable in this respect; therefore, enhanced embedded intelligence is necessary within surgical robotic systems. Smart units (sensors, actuators, etc.), able to intelligently interact with the process, as well as to communicate between them accordingly, should be part of this construction. A novel concept of building inexpensive smart units by integrating software and basic hardware (electronic) structures, that are further networked in master–slave architectures of microcontrollers, and with capabilities of plug-and-play, fast self-configuration, reconfiguration and upgrading in both hardware and intelligence, is introduced in this paper. This allows engineers to design and shape new reliable surgical robot systems in a time and cost effective manner by using the "probe (rapid prototype)-test-evaluate-learn-refine" methodology. A case study exemplifies the innovative concept of smart unit network. The results on the prototype verify that engineers can rely on this solution for constructing and testing in a competitive way (shorter time, lower costs, and higher quality) different design variants of surgical robot topologies and control systems they sketch, model and simulate in the conceptual phase.

Keywords Smart sensors · Smart actuators · Plug-and-play · Fast adaptable control unit · Embedded intelligence · Surgical robotics · Competitive design · PTELR methodology

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D. Pisla et al. (eds.), *New Trends in Medical and Service Robots*,
Mechanisms and Machine Science 16, DOI: 10.1007/978-3-319-01592-7_2,

1 Introduction

Surgical robotics is a growing interdisciplinary field of complex mechatronic systems in general and robotics in particular. Important research achievements in the field of surgical robots are reported today (Kuo et al. 2012; Marcus et al. 2013; Pisla et al. 2013). Surgical robots have already moved from the research labs into the real world. Commercial solutions of surgical and rehabilitation robots are available onto the market (Balaphas et al. 2013; Buchs et al. 2010; Li et al. 2012). In 1998, the first surgical intervention for heart bypass was assisted at the Leipzig Heart Centre by the da Vinci Robot Surgical System (Iranmanesh et al. 2013).

Surgical robots incorporate key functions to support surgeons in complex interventions, providing high accuracy and minimizing the wound due to less invasive actions (Melek and Goldenberg 2003; Moustris et al. 2011). In most of the cases, surgical robots are tele-robots, they being remotely controlled by surgeons (Balaphas et al. 2013; Buchs et al. 2010). However, modern approaches use computer assistance to control the robot (Moustris et al. 2011). In such cases, the surgeon has the possibility to make interventions from any place in the world, using internet facilities to control the robot (Vaccarella et al. 2012). The master console is used by the surgeon to control both the robot arms and the end-tool that act on the patient.

The enhanced surgical robotic architectures that combine tele-manipulation and computer control systems can provide much higher accuracy than the human hand can achieve (Buchs et al. 2010). Surgeons' actions are taken by the robot and further reproduced at the end-tool with high accuracy (Iranmanesh et al. 2013). High accuracy and safety in operation require precise mechanisms (e.g. parallel structures with high ratio speed reducers (Li et al. 2012) and advanced force and torque feedback control incorporated into the robotic system (Vaccarella et al. 2012).

Advanced force feedback control requires the integration of smart units within the robotic architecture, including smart sensors, smart servomotors, smart circuit breakers, and smart contacts, etc.; that is, surgical robots necessitates enhanced embedded intelligence (Li et al. 2012; Vaccarella et al. 2012).

Designing a robotic system for surgical operations is a difficult task, because a complex set of requirements related to safety, usability, accuracy, reliability, serviceability, manipulability, and cost effectiveness has to be taken into account. Moreover, fast customization and calibration of the robotic system for each medical case should be considered. In such cases, competitive engineering tools and approaches are useful to obtain reliable results in an economical and timely manner (Brad 2004).

To overcome these challenges, various possible concepts should be built, tested and improved incrementally (if necessary) very fast, with low costs, and with the capability to extract reliable and comprehensive information about various key performances required by the design specifications. The existence of plug-and-play, fast reconfigurable multi-type smart units (i.e. networked smart sensors, smart actuators, smart couplings, etc.) as part of the robot control system can significantly help in this demarche.

Thus, the objective of this paper is to investigate the possibility of designing such smart networked units for helping engineers to test in a competitive way their designs when switching from the drawing-board to the prototype construction and experimental tests. We propose a novel architecture and the related logic and algorithms that together are capable to theoretically integrate and self-configure an unlimited number of plug-and-play intelligent equipments (units). This gives designers the chance to explore various concepts by evaluating the prototype, making fast and easy-to-implement improvements by adding, replacing, adjusting, enhancing, repositioning, recalibrating, reducing, rethinking the logic, etc. of the network of intelligent units and further retesting the new version and refining it or even replacing the current concept with a new one without complications around the reconstruction of the control system (which is one of the most expensive parts of the surgical robots) in terms of time and costs.

The article is organized as follows. In Sect. 2, main highlights on current developments of smart equipments and their networking are considered. Section 3 introduces the scientific gap that requires new ways of thinking the problem of networking intelligent units. The research methodology is presented in Sect. 4. It is based on competitive engineering planning methodologies and innovative problem solving tools. Section 5 is dedicated for describing the proposed concept of the reconfigurable architecture, and the logic of the smart units. In Sect. 6, an experimental demonstrator of the concept is shown. Basic technological data are also revealed, together with solutions to build up the plug-and-play characteristic and intelligence for self-configuration of the system. Section 7 is dedicated to discussions around the preliminary results, to conclusions, as well as ideas for future researches.

2 The Background

Researches for developing smart sensors, as well as smart actuators or other types of generic smart equipments are not new. References in the field are since the end of’70. However, the scientific progress in the field has been strongly related to technology development (e.g. microprocessors, communication protocols, and communication interfaces, etc.) (Anderl et al. 2013; Butler 2002; Cook and Das 2007; Schmalzel et al. 2005; Smadi 2012; Spencer et al. 2004; Vaccarella et al. 2012).

It is not the purpose of this paper to analyze these developments, but rather to highlight the up-to-date relevant concepts of networking intelligent components into flexible architectures, and to see their main strengths and drawbacks such as to understand where are the major challenges for building up reliable solutions to meet requirements for complex systems, as surgical robots are.

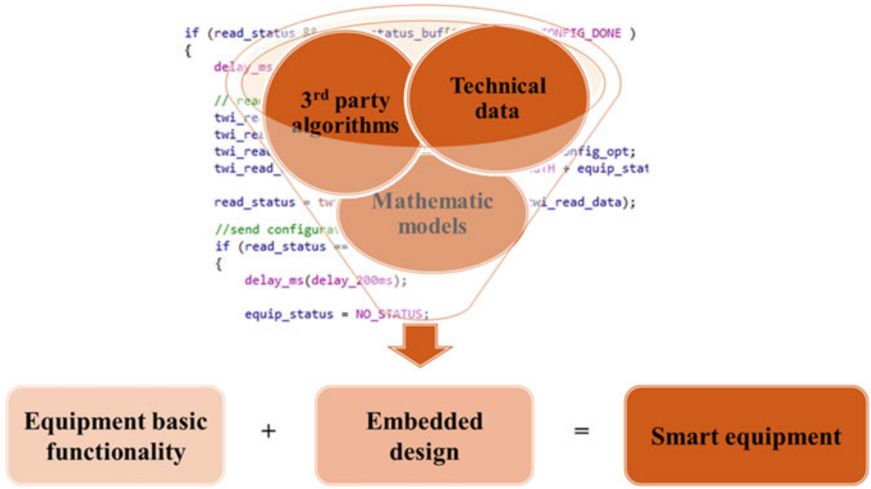

Fig. 1 The conceptual model of smart equipment

Basic equipments (e.g. sensors, actuators) by themselves do not provide any information in the system. This is why they have to be interfaced through a variety of data acquisition modules (Brajovic and Kanade 2004). By contrary, the so-called smart equipments (or intelligent equipments) are standalone units that can provide various data and information according to what is embedded in their software components (see the conceptual model in Fig. 1). For example, a smart sensor should make available analog filtering, data conversion, compensation, self-calibration, digital information processing, as well as digital communication processing (Anderl et al. 2013; Spencer et al. 2004; Vaccarella et al. 2012).

Because the intelligent tasks are performed by microcontrollers, any device that combines a classical unit with a microcontroller is called intelligent or smart equipment (Spencer et al. 2004). Capability of having enhanced built-in intelligence is another major strength of smart units. Proprietary customized algorithms are able to analyze data on key parameters to optimize the operation, as well as the operation of other components in the network (Schmalzel et al. 2005). Hence, smart units can be defined as autonomous computing units inside extensive intelligent equipments (e.g. intelligent surgical robotic systems).

A look on the state of the art in smart environments is done by Cook and Das (2007). They reveal the challenges in setting up more context-based intelligence and networking capabilities of the smart units. The need for smart sensing distributed technologies (e.g. smart sensors) is relatively recent re-emphasized by Spencer et al. (2004). They highlight the need for developing distributed computing paradigms to process information coming from the network of smart sensors. The majority of current algorithms centrally collect information and process it (Spencer et al. 2004). This approach needs additional resources in the central unit and it is rigid in terms of scalability and reconfigurability. A solution for integrated intelligent control architecture with application in robotics is introduced by Moon and Kuc (Moon and Kuc 2004). Their solution consists of an intelligent hybrid robot controller and a network of sensors with microcontrollers to perform a distributed sensing and information transmission. The solution formulated in this research considers a limited capability and simple signal processing engine of each sensor node. Communication between sensors is wireless. A network attached shared memory increases the capability of a group of sensors nodes to take effective decisions in real time, but they are limited to navigation tasks. From these perspectives, such types of architectures are not proper for applications in surgical robotics. A possible architecture for intelligent systems, based on networked smart sensors, is also described by Schmalzel et al. in 2005 (Schmalzel et al. 2005). In this case, sensors are integrated via a central knowledge-driven environment. An imbued intelligence for self-diagnosis at the level of each sensor is researched in this work, as well as the participation of sensors in a hierarchy to the decision making process. The architecture and algorithms introduced in 2005 (Schmalzel et al. 2005) still lack of solutions when the problem of self-configuration and reconfiguration is taken into account. Literature search in the area of reconfigurable robots reveals some developments of intelligent reconfigurable control architectures. The work done by Melek and Goldenberg (2003) led to such kind of architecture, but mainly focused on robot positioning by using fuzzy gain tuning for the PID parameters and neural network logic to improve control by learning. In the case of surgical robotics this solution is less relevant, due to the mode of robot operation. Self-reconfigurable robots are studied by Murata and Kurokawa (2007). They highlight the importance of networked smart units in the robot structure and work around the concept of cellular robots, which can be built with off-the-shelf technologies of microcontrollers, sensors, servo-drive units, etc. Similar results are provided by Bojinov et al. (2000), Butler et al. (2002), Shen et al. (2002), as well as Yim et al. (2007). However, such concepts are not quite suitable for surgical robots. A methodology for realizing intelligent task-based reconfiguration of the computational hardware in the case of robot controllers is introduced by Commuri et al. (2007). It is inspirational for the case of surgical robots but still not fitting the specific requirements in surgery, as long as the solution is oriented towards mobile robots for task management in a dynamic environment. Evolvable hardware, which is capable of reconfiguring its architectures unlimited time, based on artificial evolution techniques, is analyzed from different points of view by Tan et al. (2004), including description of advantages and limitations. Despite the possibilities this concept could bring in robot control, still no practical solution is proposed.

3 The Problem

Literature review leads to the conclusion that new methods for enhancing the reconfigurability performance of simple equipments (e.g. sensors, actuators, couplings, kinematic mechanisms, etc.), intelligence for self-configuration, plug-and-play capability at any time, without corrupting data transmission which may take place at that moment, and usability for non-specialized personnel, still raise up both scientific and technological challenges. Enhanced local intelligence and communication capabilities in the distributed network between heterogeneous smart equipments are still open issues.

This requires unconventional ways to think the control architectures, such as the evolution of technologies not making the system obsolete, but rather easy upgradeable and with capabilities for instantaneous transfer of information and historical data and states from the old unit to the new one. Local behavioral models (e.g. kinematics, dynamics, failure mode and failure/fault monitoring and self-diagnosis, etc.) and global behavioral models should be embedded in the extended intelligent equipment (e.g. the robotic system). Collaboration and cooperative support between the smart units is also necessary. Fast and synthetized information transfer from and to the operator (e.g. the surgeon) is a key performance characteristic, too.

The smart architecture should also ensure development and easy integration of adaptive sensory systems to the level of robot kinematic axes (positioning mechanism, orientation mechanism, and tooling mechanism), optimal placement strategies of the sensors in the constrain space given by the mechanical structure, efficient data compression and pre-processing stages to support the monitoring agents for performing simple, and real-time change detection, reliable methodologies for aggregated information management, use of local information for self-learning purposes, on-line adjustments to maintain accuracy, simplified diagnosis algorithms, etc. (Brad 2004).

4 Outline of the Research Framework

The research framework starts from the premises that the main characteristics of the developed embedded solution must include the followings: rapid customization, high scalability, integrability (based on the plug-and-play concept), diagnosability, convertibility, and modularity. In order to implement these characteristics some barriers need to be surpassed.

Thus, a conflict between the speed to which personalization of the system to a particular case is realized and the stability of the system has to be solved if rapid customization should be implemented. The classical TRIZ matrix of contradictions (Brad 2004) leads to the following lines of innovation: segmentation of the system for easy disassembly, generation of structured fields (e.g. for communication) and application of homogeneous solutions (e.g. for configuration). Scalability requires innovative solutions to surpass the conflict between productivity and the risk of losing information. The principle of qualitative change from the TRIZ method suggests asymmetrical division of the system. The TRIZ matrix of contradiction proposes to design the dynamic modules. Integrability could be innovatively designed by solving the conflict between versatility and complexity. A possible line of evolution is towards movable fields at the level of interface, as the TRIZ matrix of contradiction reveals. Convertibility involves several challenges like: adaptability versus productivity, easiness of operation versus capability, etc. This requires incorporation of multiple functions in each module, functions that are able to expand or contract, depending of the particular case, as well as software-based functions instead of hardware-based functions. To incorporate diagnosability potentials, the capability of fault detection must be increased without involving too many smart units. TRIZ suggests that this challenge could be exceeded by changing the degree of information concentration and introducing external "motivators". This could be done by software means, models and mathematical algorithms for better understanding local behaviors and exchange of information between the smart units within the system.

Each vector of innovation above presented (e.g. segmentation, asymmetrical division, configuration homogeneity, structured fields for communication, dynamicity of interfaces, multiple-function enrollment, external motivators, etc.) is taken independently and conceptualized within the architecture by using a PTELR cycle (probe-test-evaluate-learn-refine). This means, iteration starts with the design of each vector of innovation into a practical solution. All local solutions are analyzed in pairs. Conflicting problems that might occur are evaluated and indications for improvement are formulated (e.g. by means of TRIZ method). The lessons learned are further used to refine the local solutions until a mature global solution is finally designed.

5 Concept Descriptions

Based on the methodological chain proposed in Sect. 4, a potential smart control architecture has been developed. Its block scheme is illustrated in Fig. 2.

The proposed control architecture (Fig. 2) includes: the main control unit (1), high priority output equipments (2), high priority input equipments (3), low priority output equipments (4), low priority input equipments (5), together with the input adapter (6) and the output adapter (7) for high priority input and output equipments. Low priority equipments (4) and (5) are connected to the main control unit (1), through adapters (8). Troubleshooting and development actions are done by means of a specific interface (9). The interface between the operator and the automation system is realized by a human–machine interface (10), through the main control unit (1).

All intelligent equipments (2), (3), (4), and (5), regardless their priority, have a logic and distributed intelligence part (11) that contains information about the equipment itself, specific equipment and process control algorithms and configuration options related to the desired equipment functionalities (which are built-in by software means). Output intelligent equipments (2) and (4) have a part of output signals and power circuitry (12), designed for equipment control (e.g. pups, blowers, etc.) and/or for generating output signals having specific electric parameters. Input intelligent equipments (3) and (5) are characterized by a part of

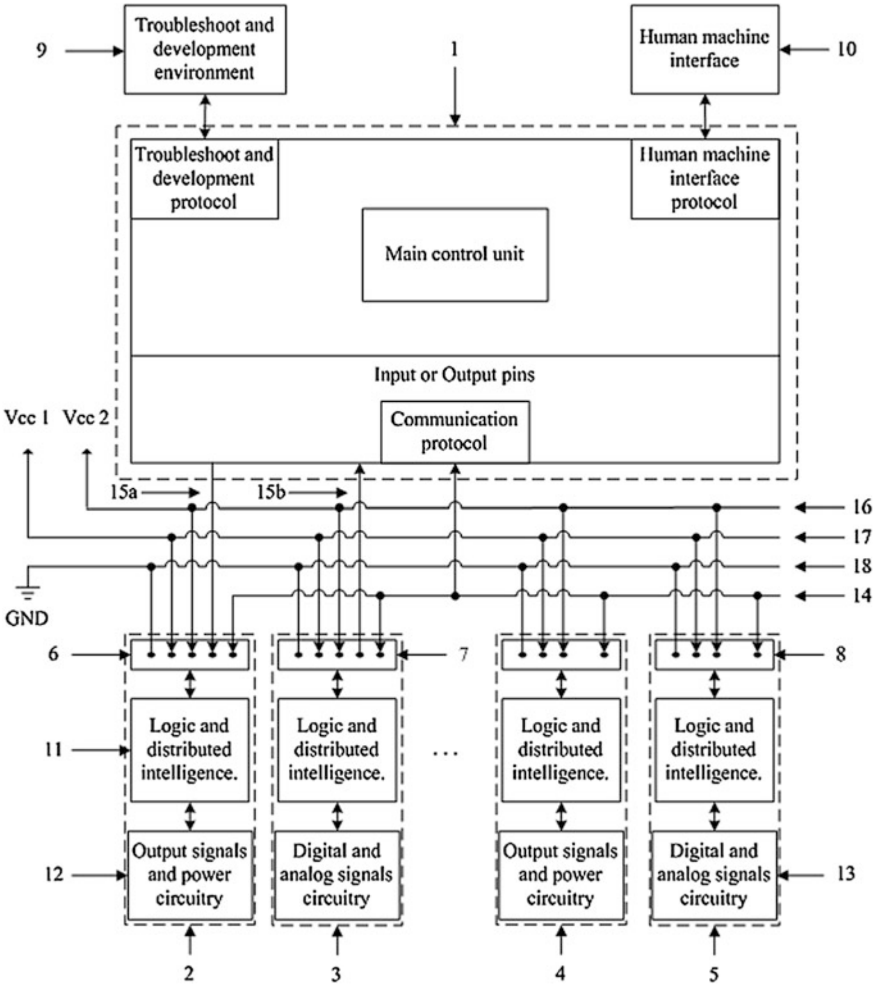

Fig. 2 The conceptual diagram of the smart control architecture

digital and analog signals circuitry (13), designed to gather information from input equipments (e.g. sensors or transducers).

The main control unit (1) uses the communication protocol (14) to physically connect and exchange data with high priority intelligent equipments (2), (3), and low priority intelligent equipments (4) and (5). Direct connections to the main control unit are ensured for the high priority smart units (15a, 15b). Adapters (see (6), (7) and (8) in Fig. 2) assign priorities to the smart equipments, supply with power the logic and distributed intelligence unit (11) of the intelligent equipments (2), (3), (4) and (5) from the power lines (16), (17) and (18), connect intelligent equipments to the communication network, ensuring in the same time the technical

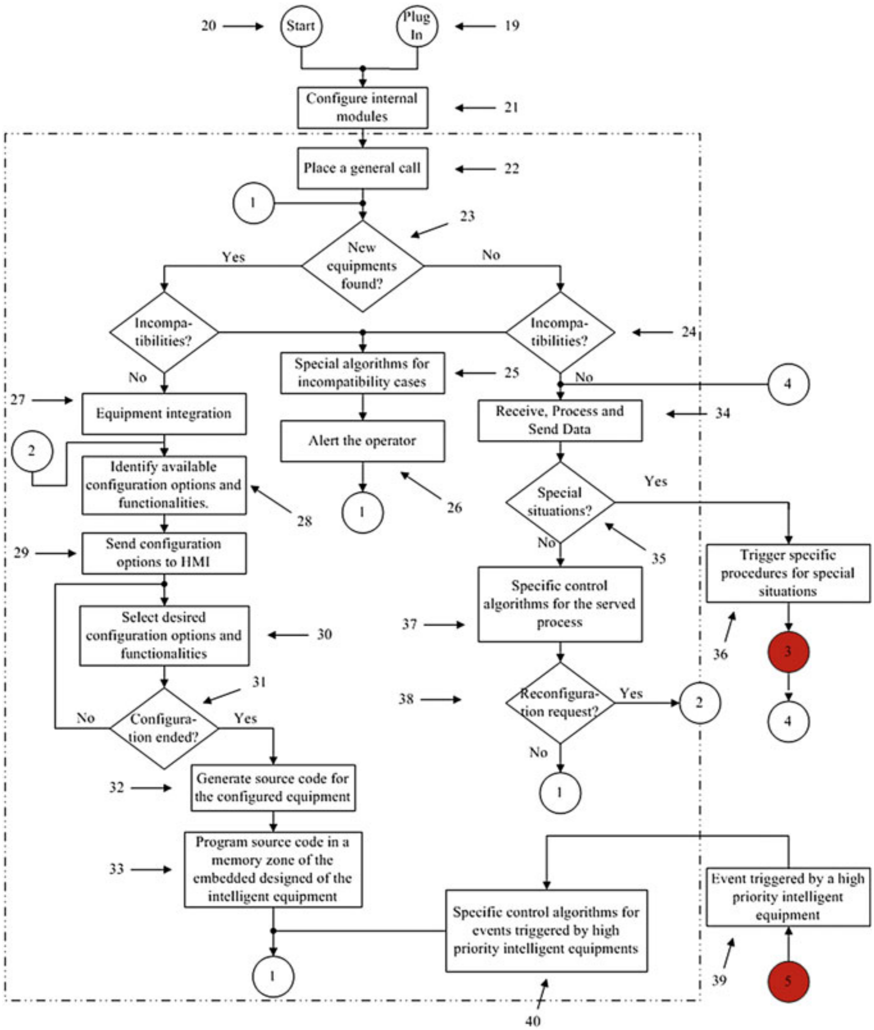

Fig. 3 The basic logic of the main control unit

requirements needed by the communication protocol to provide the desired level of functionality and performances.

Figure 3 illustrates the logic of the master unit and Fig. 4 the logic of the slave smart equipments. In Fig. 3, numbers from 19 to 50 are simply the indexes of the blocks. The same significance is for numbers from 41 to 59 in Fig. 4. Communication between the master and slaves is illustrated in Figs. 3 and 4 by the red-colored connectors 3 and 5.

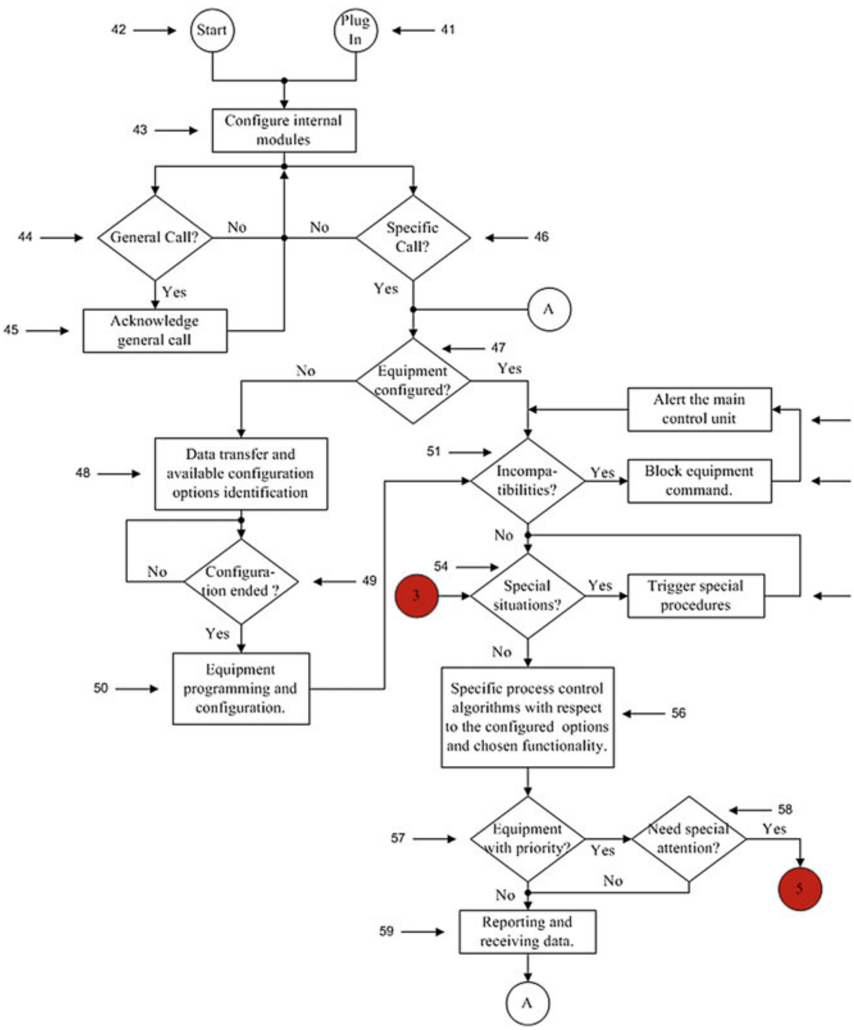

Fig. 4 The basic logic of the intelligent equipment

6 Prototype Development, Testing and Results

A demonstrator of the novel 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 intelligent equipments. A high performance Atmel ATUC3B series microcontroller that runs at frequencies up to 60 MHz is enclosed into the embedded design, forming the main control unit. All smart equipments have their microcontrollers. Specific information is embedded by means of software logic. Based on both hardware and software design the master unit is endowed with scalability, configurability, plug -and-play and diagnosability.

In this demonstrator, the technology used to build the master unit limits the maximum number of high priority smart equipments to 25. A higher level of scalability is ensured by the communication protocol, by integrating low priority smart equipments. Priority is given by the role the equipment has in the system. It is done via adapters. A high priority adapter provides equipment's connection to the communication protocol lines and a direct connection to an input/output pin on the master unit. Low priority equipments might suffer very small delays in communication due to data management algorithms and communication protocol performances. The number of low priority equipments that can be connected is theoretically unlimited. However, timing aspects should be considered.

Based on hardware design, software creative algorithms, as well as plug-and-play capability, the master unit can configure in real time the direction of its connections to the outside world, depending on the connected intelligent equipments and the type of priority adapters (I/O). The self-integration process is based on the information stored inside the distributed intelligence of the microcontrollers belonging to the smart equipments, as well as by the ability of the master unit to manage this information. All these functionalities are achieved by means of embedded models and mathematical algorithms. A fragment from the code embedded into the master unit for identifying new equipments that are connected in the smart distributed network is exemplified in Fig. 5.

```
{
        volatile char equip_addr          = TWI_HMI_ADDRESS;
        volatile char conn_strength_result = NO_STATUS;
        volatile int equip_responded      = NO_STATUS;
        volatile char equip_found         = 0;
        for (uint8_t i = 0; i < DATABASE_SIZE; i++)
        {       equip_addr += 2;
                if (!equipments[i].SE_Idendified && !equipments[i].SE_Configured  &&
equip_addr != TWI_HMI_ADDRESS)
                {       equip_responded = NO_STATUS;
                        equip_responded =
check_equip_status(equip_addr,3,delay_100ms);
                        // check if equipment at that specific address is available and
equipment connection was not checked
                        if (equip_responded && !equipments[i].SE_Conn_check)
                        {       //update database with equipments info
                                equipments[i].SE_Address = equip_addr;
                                equipments[i].SE_Idendified = TRUE;
                                equip_found++;
                                equip_responded = NO_STATUS;
                        }
                }
                delay_ms(delay_50ms);
        }
……..
```

Fig. 5 Fragment of code for identifying new equipments by the smart master unit

The number of functionalities and configuration options that can be implemented in the microcontrollers of the smart equipments 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. On the software side it is possible to develop functionalities and features like self-integration, preventive maintenance, configuration options, diagnosability and others, despite hardware restrictions.

Preventive maintenance was achieved by storing technical information related to each equipment datasheet inside its local microcontroller, together with advanced information management algorithms. This feature is used for alerting the operator about equipment condition. Once the smart equipment is integrated, the master unit has all information required to start the configuration process. Based on the implemented functionalities and configuration options, the operator can configure the equipment to act accordingly to process needs, using the human machine interface. Self-diagnosis is based on identifying data inconsistencies, misleading or bad control parameters. When an intelligent component fails, the master unit is informed. In principle, functions of the failed component can be taken automatically by other similar intelligent unit (there is no limitation from software/intelligence possibilities) only in the case the respective unit acts as a redundant element in the system (e.g. the same role and hardware capabilities). For example, an optical smart sensor can be replaced only by another optical smart sensor that exists in the system and is positioned such as it can take the required information from the system. The test bench is illustrated in Fig. 6. It includes the master unit, the power and signal distribution unit, a high priority smart electro-mechanical axis unit, a high priority smart infrared barriers unit, a low priority smart magnetic field sensing unit and a human–machine interface. All smart devices are connected to the master unit by means of a serial communication protocol. Applying power to the test bench, the initialization sequence of the smart equipments starts. After the initialization sequence, the master unit starts searching periodically for newly connected smart equipments. Configuration of the smart equipments is done via software algorithms.

For example, the configuration of the smart electro-mechanical axis consists of monitoring the electric parameters, tracking of the operation time, selecting the stepping mode of the actuator, selecting the speed, allowing remote control (off/on), learning the moves and working sequences, allowing independent decisions based on data received from the smart sensors in the network, selecting the smart sensors to be used from a library of identified connected sensors (e.g. IR or magnetic), alerting operators about preventive maintenance and periodic maintenance requirements, recording the status of the whole network (e.g. what new units are connected and how to collaborate with it in case of necessity), etc. Using the additional hot swappable communication buffer to the hardware design of equipments, no data was lost, even at high speeds of communication (e.g. speeds of 200 kbits/s). All data packets sent by the master unit were received by the smart equipments in the distributed network, regardless the frequency of adding or removing equipments to the communication protocol. An average of 3 s is

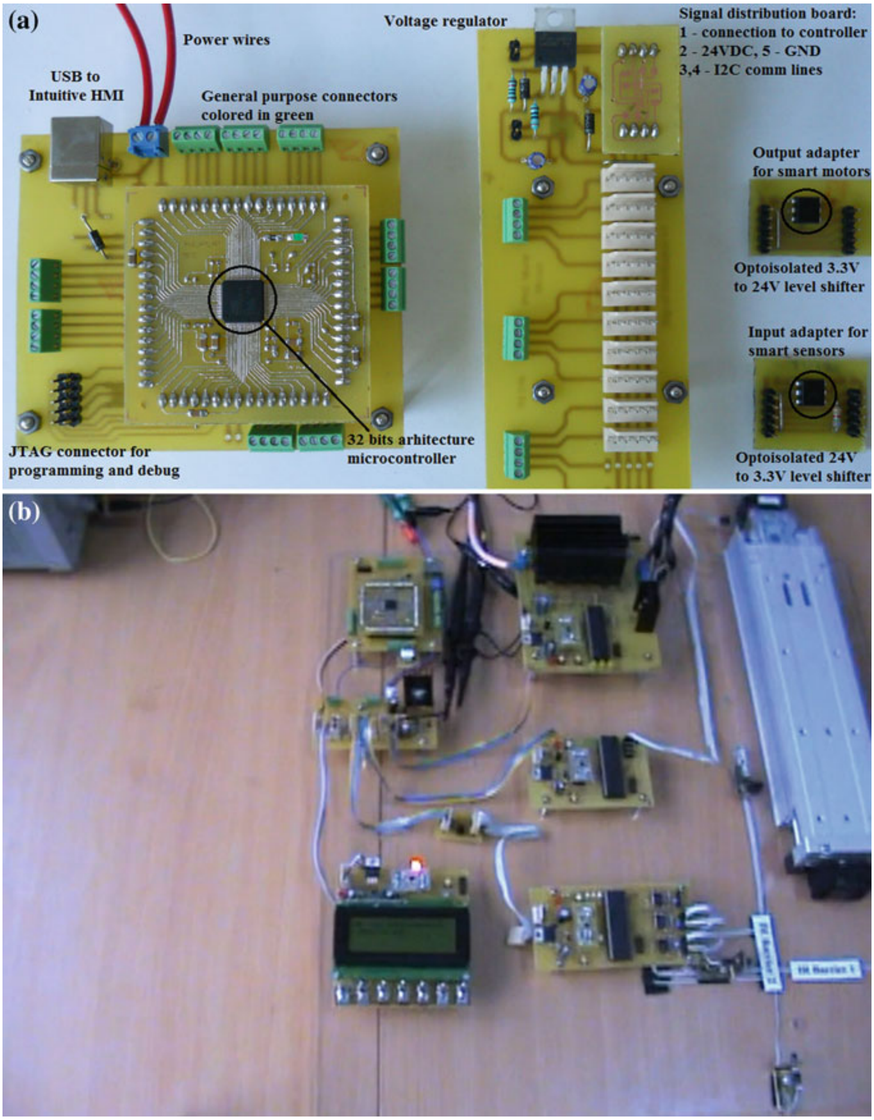

Fig. 6 Experimental bench. **a** The master control unit and examples of interfacing boards for the slave units. **b** Integrated intelligent units into an intelligent kinematic translational axis

necessary to reconfigure the system if the speed of the communication protocol is from 10 upto 50 kbit/s, 1.5 s for speeds from 100 up to 200 kbit/s, and less than 1 s for 400 kbit/s speed. The average time required to configure intelligent equipments is about 5 min. for a dummy operator. Tests on the experimental prototype have shown that better communication performances between the master and the low priority slave unit require speeds of 400 kbit/s of the communication protocol. Another option is to employ a better communication protocol.

7 Conclusions

This research proposes a new architecture for integrating smart units in distributed networks with proven advantages in terms of fast reconfiguration of the control system. Thus, it is suitable to support design engineers in cost effective and rapid building of various prototypes of complex robot structures that require enhanced intelligence, as it is the case of surgical robots. Smart sensors, smart mechanical interfaces and smart actuators can replace traditional units for enhancing safety and interaction capabilities of surgical robots. Despite the strengths of the new concept in terms of reconfiguration and enhanced intelligence, communication speed still remains strongly dependent by technology; that is by the performances of the communication protocol. Based on the promising results obtained during tests, additional applied research directions are defined in order to increase the potential of this concept. Thus, a PC-based intuitive user centered interface will be designed in order to define the configuration of the system. USB and wireless communication protocols of the master unit will be explored to get an even simpler interaction between the process and the operator. A new and more powerful communication protocol, like CAN or FlexRay, will be also investigated.

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http://www.springer.com/978-3-319-01591-0

New Trends in Medical and Service Robots
Theory and Integrated Applications
Pisla, D.; Bleuler, H.; Rodić, A.; Vaida, C.; Pisla, A. (Eds.)
2014, VIII, 238 p. 167 illus., 127 illus. in color.,
Hardcover
ISBN: 978-3-319-01591-0