10

A Concept for Isles of Automation

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1. Introduction

1.1 Approach to the topic

There has been a major change in the manufacturing after year 2000. At the same time when production is struggling with tougher price competition, the requirements for flexibility are increasing. Life cycles of the products are getting shorter, the variety of products is increasing, and production costs should be decreased at the same time when there is no good technical solution on the market to answer to this. Customer assumes to get a tailored solution with the same price and delivery as a mass product previously.

Using the current manufacturing technologies response to the needs of the market is getting increasingly difficult. Even if the modern manufacturing systems include a remarkable amount of ICT technologies, the flexibility of a human worker is very challenging to reach. Although robotic systems are classified as a flexible production technology, in practice the current robotic implementations are concentrated to high volume production (Naumann et. al 2006). Only a few industrial solutions have been installed for short and single series production. The main obstacle in installing robots for short series production is the amount of product-specific costs caused by the manual work still required for using the robot system (Sallinen et. al 2004). In most of the cases each work phase and process for each product has to be programmed, and the function of auxiliary equipment is usually based on part-specific geometry e.g. no exceptions beyond the designed parts are allowed. If the volumes of the product are low, the effective utilization of a robot assumes that it is applied to a large variety of parts, or to a large amount of different work phases, to bring the robot utilization rate to a decent level typical of the SME industry. In addition, parts to be processed in the production environment very often have complicated forms which make manipulation more challenging. This is the case especially in the short series production when most of the manufacturing processes are solved relatively well at the moment.

1.2 State-of-the-art

The development of manufacturing systems has had two main approaches (Maraghy 2006): Flexible Manufacturing Systems (FMS) and Reconfigurable Manufacturing Systems (RMS). The concept presented here has adapted features from both. Our approach is that the basic element of the automation island is an industrial robot equipped with different kinds of external sensors and auxiliary devices combining mechanics, sensor technology, tools and

software. This gives high level flexibility in terms of programmability, reconfigurability, reusability and price.
A lot of studies from different areas related to flexible robot automation can be found such as off-line programming (Brock 2000)(Burns & Brock 2005)(Sanchez & Latombe 2002). There are solutions for off-line programming where the first area has been welding (Dai & Kampker 2000). Another approach is on-line programming which modern version is called programming by demonstration (PbD) (Dillman et. al 1999)(Chen & McGarragher 2000)(Rogalla et. al 2002). Typical example of PbD is where human with ordinary tools shows the task by guiding the robot by hand (physical interaction) or human shows some task and the robot recognizes that by a vision system. System even try to learn tasks from the demonstation (Kang & Ikeuchi 1995). Learning can be divided to task- skill and body recognition which have been studied in (Nakaoka et. al 2006).
Studies about flexible robot system architectures can be found from mobile robotics. In the studies the task level control is common topic (Camargo et. al 1992)(Parker 1998). Compared with the architectures presented in the literature we present a solution called "Isle of Automation" which enables multiplying the workcell while the whole structure defines the overall architecture. Architecture of a holonic manufacturing system (Takamura et. al 2003) is close the approach presented in this chapter. The principle of operation of an automation island is that it is working autonomously but is not cooperative by default as holons are.
In this chapter, we present a concept for short series production based on backround system called *Engineering resources* and executive robot cell called *Production cell* consisting of industrial robots equipped with assistive manipulation systems, sensors and a control system. We call this complete system as an *Isle of automation*. The new concept is beyond the current robot workcells by the properties of flexibility, reconfigurability, context awareness and programmability. In the concept, there are modules for programming, sensing, material handling and flow as well as communication. The overall architecture defines how these modules are working together. In this chapter, we present these modules and illustrate the operation in pilot case.
This chapter has been organized as follows. In chapter 2 we introduce and define the overall concept of the isle of automation, in chapter 3 we introduce the architecture of production cells, in chapter 4 components of the isles of automation. Communication between the structures are explained in paragraph 5. Feasibility of our approach is shown in chapter 6 by a pilot case, discussion is given in chapter 7 and finally conclusions are drawn in chapter 8.

2. The Overall Concept for Isles of Automation

The concept of isles of automation for short series production consists of two main parts: Engineering Resources and Production cells. The overall system follows a modular structure and realizes highly flexible and controllable robotized system. It exploits the features of ubiquitous technology including flexibility, adaptivity, context awareness and reactivity, which are beyond the current automation solutions. The production system easily adapts to new products or product variants and to deviations in work pieces. In addition, data acquisition presents new possibilities, when open interfaces are offered down to the sensor level (e.g. measurement signals can be monitored). This means sensors offer services and are visible to the whole control system including user. Sensors can be used for on-line purposes such as control but also off-line monitoring such as quality control and prognosis of the

maintenance of the machines. This kind of features can not be found in the current systems such as presented in (Bloomenthal et. al 2002).
The operation of the automation island is managed by control software locating in Engineering Resources, called *Isle Manager*, which is controlling the execution of tasks in a high level. It also manages the sensing and reactions to non-expected situations in the robot cell. The work is carried out by communicating with distributed modules and providing the ways to carry out the tasks.
Figure 1 illustrates the concept of Isles of Automation. In the top there is the Engineering Resources and below that Production cells. More detailed description is given in next paragraphs.

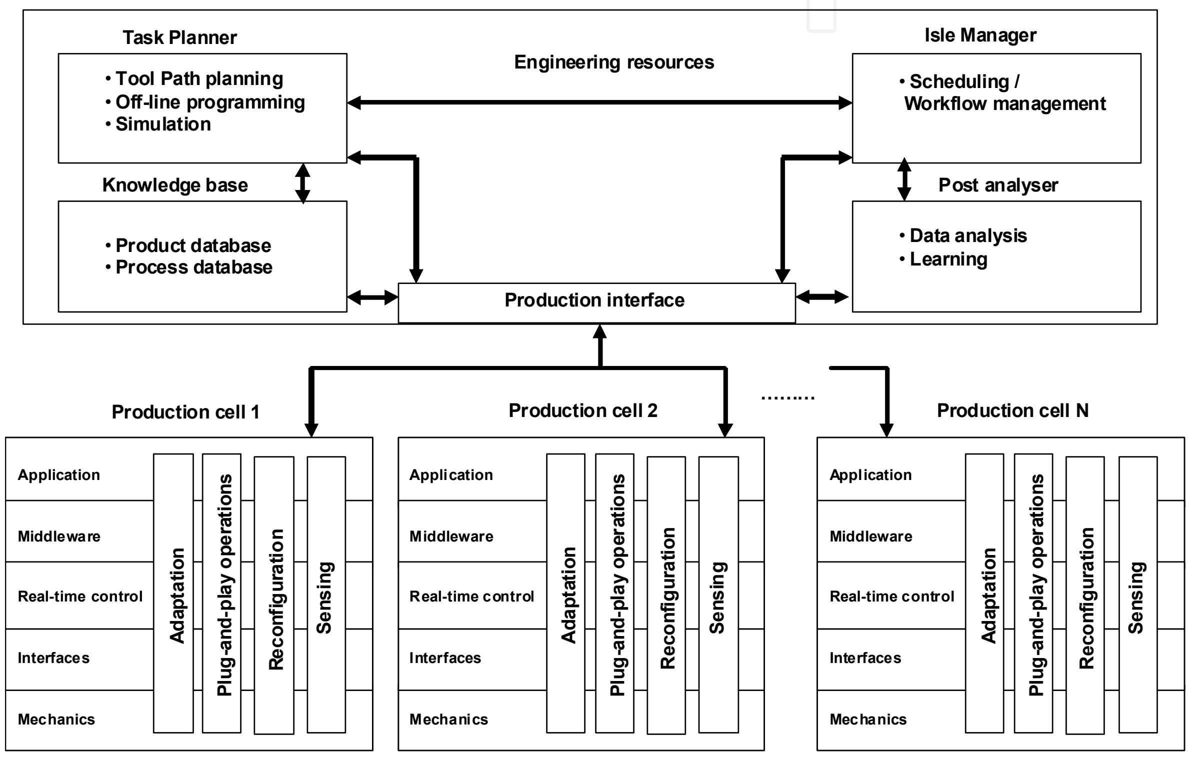

Fig. 1 The conceptual structure of isles of automation

The concept of the automation island is described in the figure 1. The main parts of the system are *Engineering Resources* and *Production Cells*. Interaction between these parts is described in paragraph 5.

2.1 Description of the concept: Engineering resources

The Engineering Resource is working as an autonomous backround system and operating mainly off-line. It consists of pre-processing and post-prosessing functions depending on the time of operation. Operation of the robot and auxiliary device is supported by pre-processing functions for which there are planning, off-line programming and simulation, see box in top left in the figure 1. To support the process, there is a knowledge base for product and process information. Knowledge base may locate in local engineering computer or the information can be obtained from enterprise factory database. For overall feedback and analysis, there are data analysis and learning modules, see boxes in right down in figure 1.

Isle manager takes care of the overall management and workflow in the whole system, see box right up in the figure 1.
If the factory contains a large number of production cells in many departments, there can be a pool of Engineering Resources which gives services for productions cells. Another option is that each cell has its own Engineering Resource which means they are operating autonomously like separate islands. This is a typical case when there are one or two production cells in the factory and they are operating in very different applications. In that case engineering resources are embedded in the Production Cell. In principle, an engineering resource of one production cell can offer services to other production cells as well.
The decision making is distributed in the Isle of Automation. There is a high level controller, which takes care of the high level production management. Flexibility in production also sets requirements to the managing and controlling of the island. To use hardware efficiently, flexible, modular and reconfigurable software must be used at every level to manage the whole system. Modular structure and re-programmable software means that operations and functions of the production cells can easily be configured and used on-line. This approach has several features of Service Oriented Architecture approach in production environment, see e.g. (Veiga et. al 2007).

2.2 Production cell

The concept of the Production cell has a layered structure for different response levels. These layers include hardware, interfaces, real-time control, middleware and application layers. The key-functions in the island are adaptation, reconfiguration, sensing and plug-and-play operations. These functions are operating vertically in the cell, see figure 1. Depending on the requirements of the applications, the properties, operation and status level of these key-functions are defined. They are explained more detailed in chapter 3.2.

2.3 Interaction between Engineering Resources and Production Cell

Communication between the cells and engineering resources is carried out through a production interface between the application layer and modules of the engineering resources system, see figure 1. Data exchange is not time critical and common formats are defined.
There can be several production cells in the system as illustrated in the figure 1. Each cell may have it's own function such as the first cell is making the cutting, the second cell is doing the welding and the third cell is doing the deburring. They can exchange and share information (e.g. updated product status data and geometrical information) and resources (e.g. sensors, devices, tools). Flexibility of production means that a product can be manufactured in any of the cells if the cells change the required tools and sensors guided by the Isle Manager.

3. Architecture of the production cells

The architecture of production cells. It is built based on layered structure consisting horizontal layers for required operations. In addition to horizontal layers, there are vertical functions called Key functions which use properties of different horizontal layers.

Architecture described in this chapter gives rules and methods for cross-operation of these layers and functions.

3.1 5-Layered structure

Layers of the production cell are described in the figure 2. All the units of the cell (e.g. robot manipulator, controller and device controller) will contain the same layered structure: application layer, middleware, real-time control, interface (API) and physical layer (e.g. mechanics). Each layer consists of operations to operate with other layers. Also if a new unit or device is connected and the operation should be transparent to the user, the layer structure should be the same. Depending on the functional requirements of each unit, different layers will have respective operations.

Communication between the vertical layers is carried out using interfaces suitable for each device (e.g. sockets, buffers or ethernet). Communication is recommended to be carried out between same layers to enable reliable and secure synchronization of the communication, especially in the real-time control layer. In the upper layers (application, middleware and real-time control) communication is carried out using textual structures, e.g. XML. In a time critical layer such as real-time control, interfaces and communication can be carried out using special real-time standards such as industrial Ethernet or digital or analog I/O or industrial field buses if very fast communication is required.

An exemplary content of each layer is described in table 1. In the application layer, there can be application or robot application program running in the cell computer or in a robot controller. The common property is that programs are not time-critical compared with programs in real-time control layer. In the case when programs run in cell computer, they may operate on Windows or Linux operating systems. In the middleware layer, there are services for application layer. Most of the services are built such that they are invisible to user.

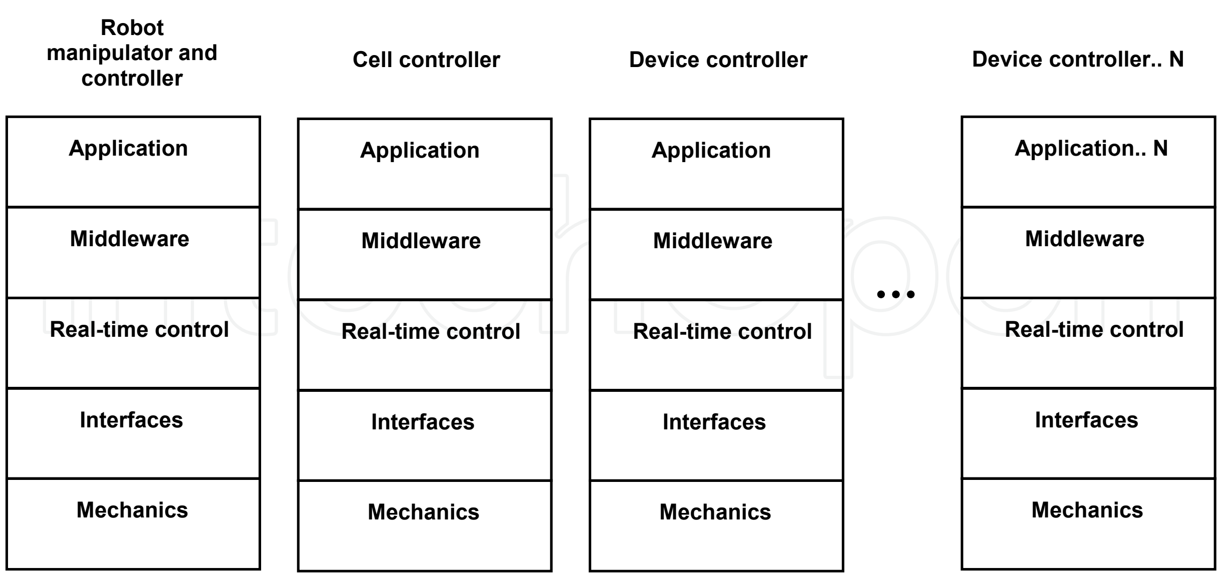

Fig. 2. Layer structure of the units of the production cell

The basis for key functions are in the middleware layer. Real-time control layer is established with user functions, upon the services of real-time operating system. In the robot controller, all the kinematic calculation and motion control is carried out in this layer. In this layer, there are often real-time operating systems such as real-time linux or embedded windows or KUKA's RT kernel. Interface layer has interfaces to external devices and communication networks using digital or analog lines or standard ethernet or industrial Ethernet. At the bottom, there are Mechanics layer which has physical devices, interface cards and tools, see table 1.

3.2 Key functions

Key functions are services available in the production island going through the layers as described in figure 3. Multi-layer operation means that they utilize each layer depending on the requirements. The purpose of the key functions is to carry out ubiquitous operations of automation island. It consist of intelligent, interactive and reactive operations of a cell can consist of one or several key functions.

There are four key functions which are adaptation, plug-and-play operations, reconfiguration and sensing. As layers described above, there do not have be fully operating key functions in every unit. Also, the architecture supports the operating principle where different units or devices can or do utilize key functions from each other. Example of this can be e.g. that operation of force sensor is utilized by both programming-by-demonstration and reactive execution. Operation for requirement of application of force sensor is provided by the co-operation of both Key-functions adaptation and sensing where adaptation includes operations for changing the robot motion paths and sensing includes properties for signal processing of low-level force sensor.

The operation principle of key functions are as follows: Adaptation function is on-line or off-line reaction to changes of product or production. It utilizes sensing –key-function to achieve the measurement data for the basis of the operation. Plug-and-play function enables easy connectivity of new sensors which can be used in the adaptation of the production system to new, different size of workobjects. In general, plug-and-play functions enable an easy way to connect and disconnect components such as sensors, actuators, tools and devices between production islands. Reconfiguration function enables making of structural changes in the production cell automatically or by physical assistance of operator.

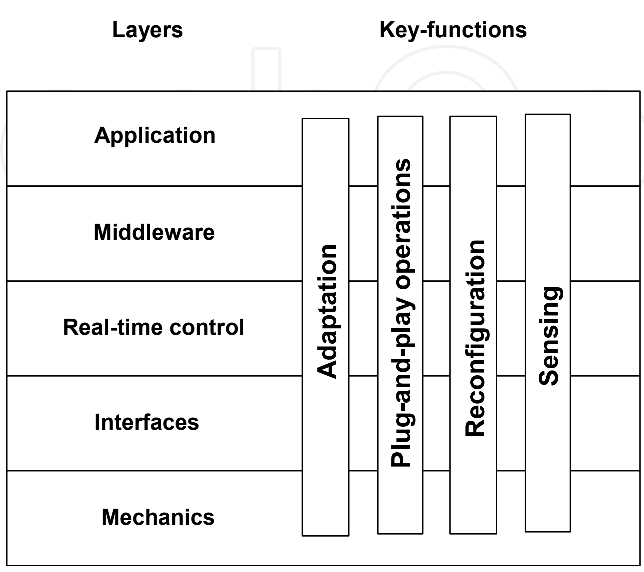

Fig. 3. Key functions going through the layered structure.

The changes are carried out such that all the required properties of the island will be achieved. Reconfiguration is also supported by plug-and-play operations. Sensing includes low-level signal processing properties and it also provides different kind of upper level sensing / measurement services for other functions and layers. It will utilize plug-and-play operations to easily change sensors between production cells.

Layer	Example of operation
Application	Application program, robot program
Middleware	Services for upper and lower layers including key functions
Real-time control / OS	RTOS: RTLinux, linux, embedded windows
Interfaces	Analog, digital, ethernet, device drivers
Mechanics	Manipulators, grippers, feeders, tools, sensors

Table 1. The content of the layers

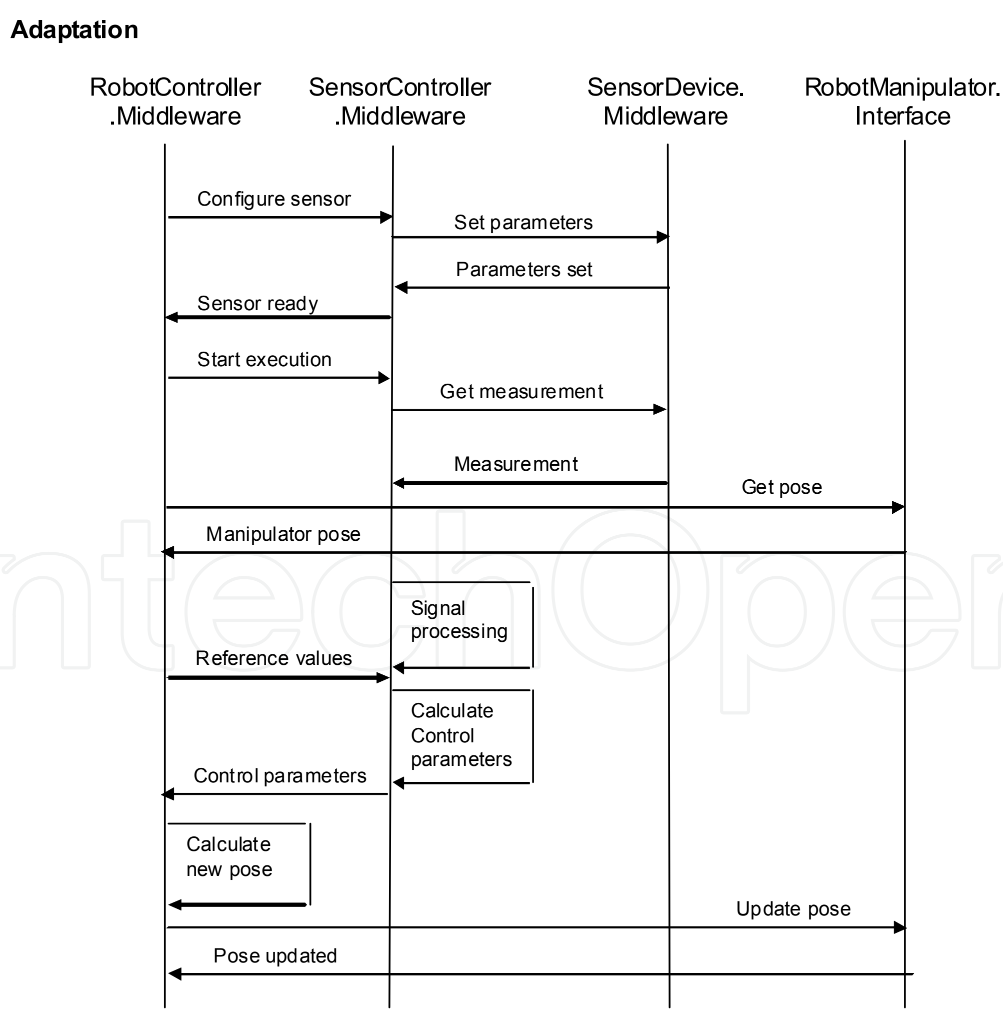

Fig. 4. Message sequence for adaptation –key function

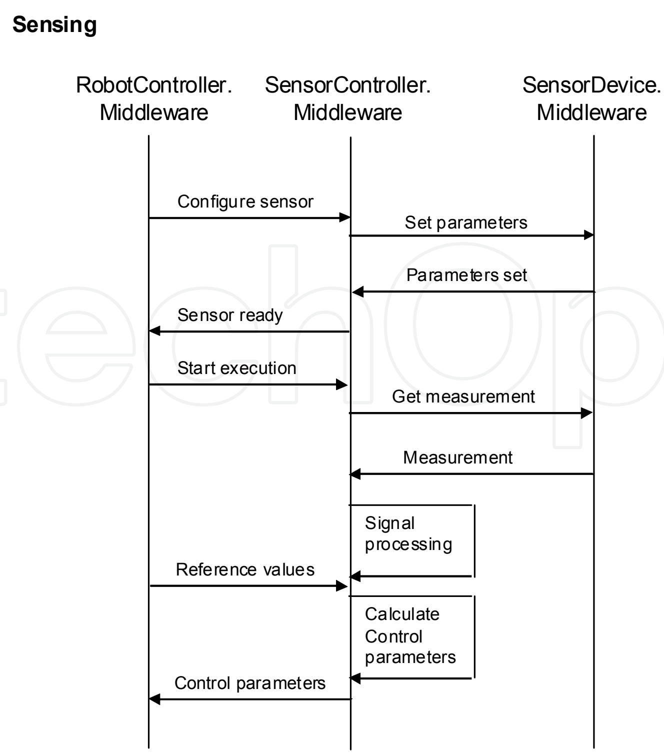

Fig. 5. Message sequence for sensing –key function

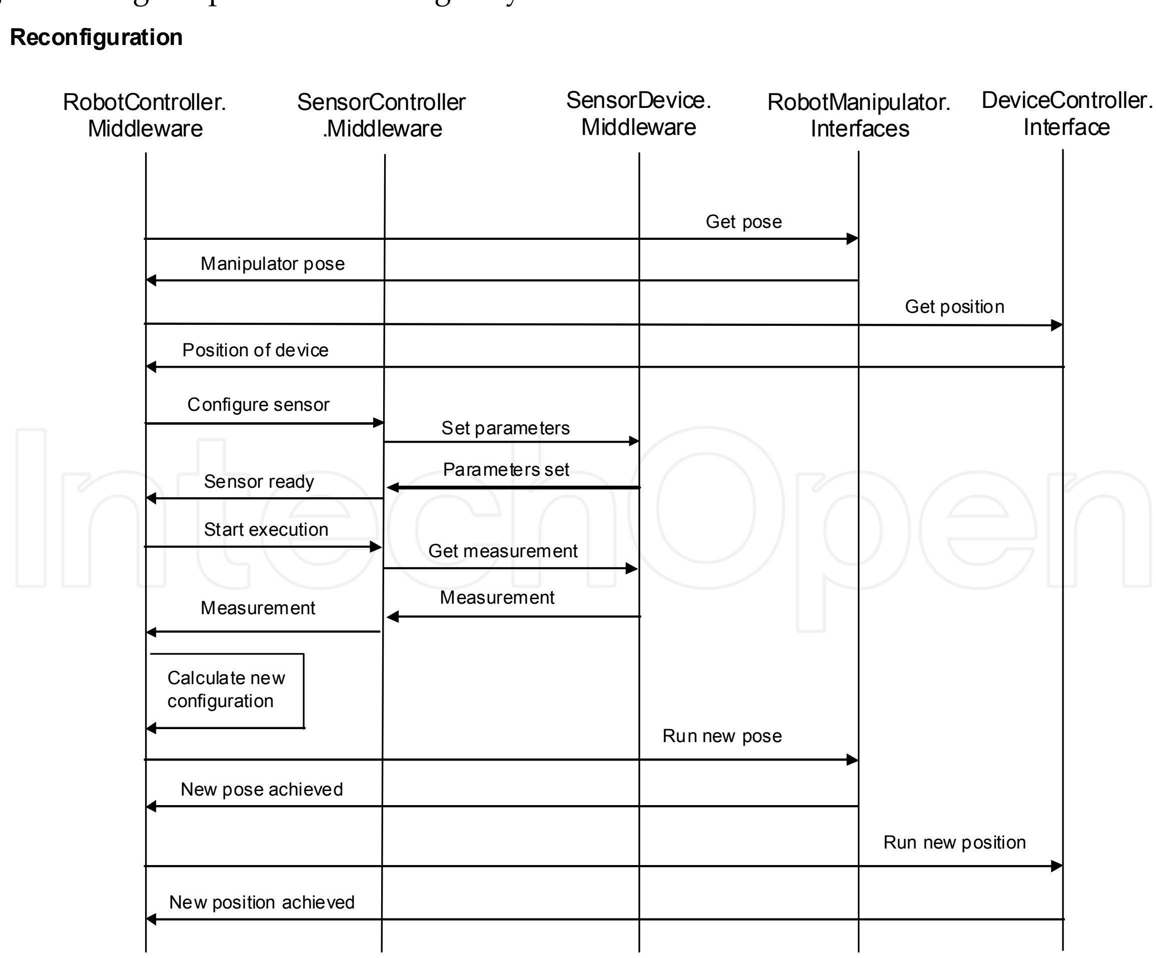

Fig. 6. Message sequence for reconfiguration –key function

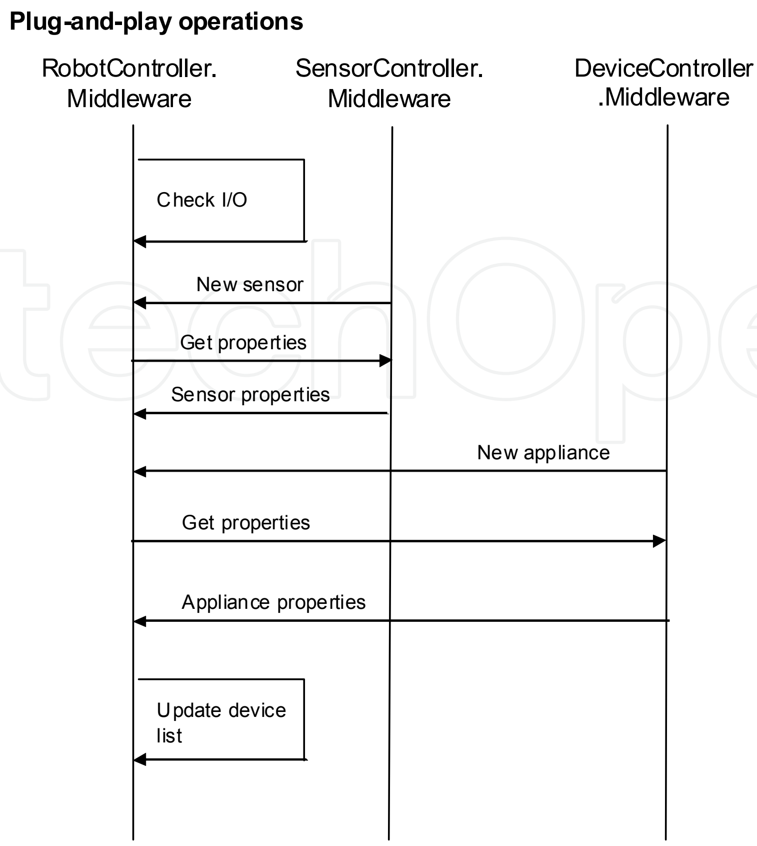

Fig. 7. Message sequence for plug-and-play –key function

4. Components Isles of Automation

Here we introduce components used in the Isles of Automation. The work operations of the Isles of Automation can be grouped and named as components and they are working in the layers and key functions described above. For this component-based approach for the Isles of Automation is given. Components are also in line with the architectural description given in chapters 2 and 3. Based on analyses of the current stage of the technology, technologies and methods are selected for the concept (Sallinen et. al 2006)(Salmi et. al 2007).

4.1 Description of the components

The main components of the automation island are 1) programming subsystem, 2) robot and external sensors, 3) material handling devices (e.g., grippers, feeders), 4) control system and 5) communication system. Simplified information flow of these is also described in figure 4. Programming tools include both off-line programming tools and on-line programming which is required in on-line reactivity. Robot and external sensors include robot manipulator and sensors like force, vision and laser rangefinders to observe the environment. The selection of these sensors depends on the requirements of the application. Material handling devices will make sure that the robot has pieces in the right position to be manipulated. Grippers and manipulators are specially designed or selected from the existing ones to manage flexible operations. Requirement of those is at least a low level

programming to behave actively in the Automation Island. In that way they can support also reconfigurable operations such as modification to very different size of workobjects.
Workflow management software in Engineering Resources is above all and controls operations in the task level, e.g. how different phases of the workobject are carried out in the work flow. New tools and devices can be connected in a plug-and-play manner without parameter configuration. They utilize plug-and-play key functions. Communication and control system defines the information flow in the Isle of the Automation, where communication defines the protocols of the communication. All these components are designed to be built up using both commercial components available from the market as well as components built by ourselves. If the component available in the market fills the system requirement, it is the best selection for the use.
Component-based approach is a key element in achieving the desired flexibility and reconfigurability features. The components are spread out from the factory level down to the smallest functional units of devices such as sensors. It affects the physical structure, control devices, data transfer solutions and sensor utilization. The concept includes necessary modules for various purposes. The modularization also serves the aims of standardization and quality.

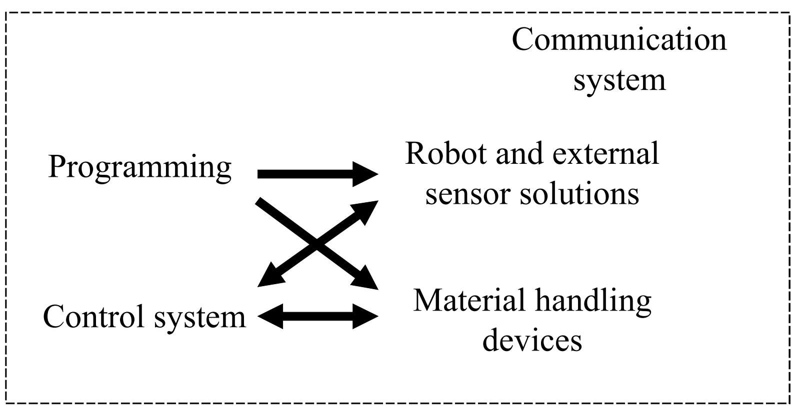

Fig. 8. The connectivity flow between the main components of the isles of automation.

5. Communication in the Isles of Automation

Here we explain the communication between the units in Isles of Automation. In the figures 5 and 6 there is a description of signal flows of in the case of task planning and task execution.
Task planning is operating in Engineering resources and is starting by order request from scheduler, see figure 5. It is requested from the task planner. Task planner is requesting a program from CAD tool. CAD tool will collect data from product database and process database. It has also information about the workcell environment including robots and all additional peripherals such as tools and sensors. Whet it receives this information it plans, simulates and makes a program ready-to-run in the robot. When program is ready, it's timing in the work line will be requested from the workflow manager and returned to schedule that task is in organized.
Task execution is operating in production cells, see figure 6. Task planner is sending the program to robot controller using ethernet or serial line. This can be done off-line. Scheduler will be responsible to start the execution of the program in the robot controller.

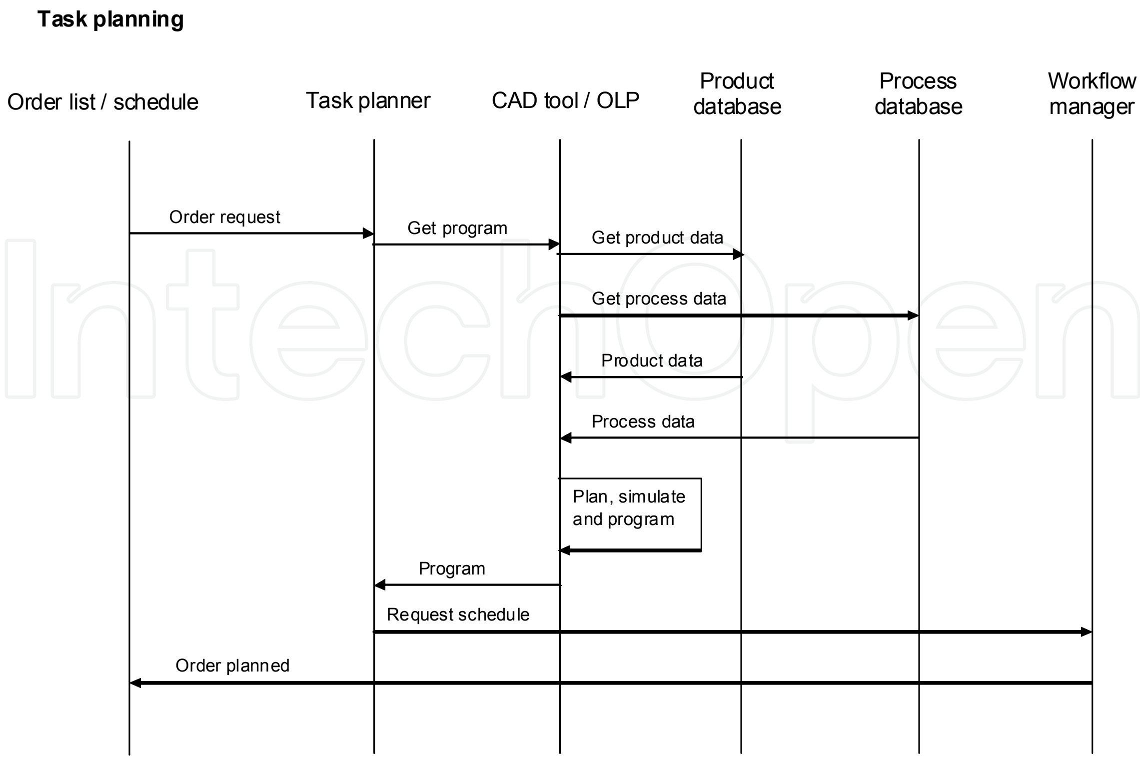

Fig. 9. Message sequence for the task planning

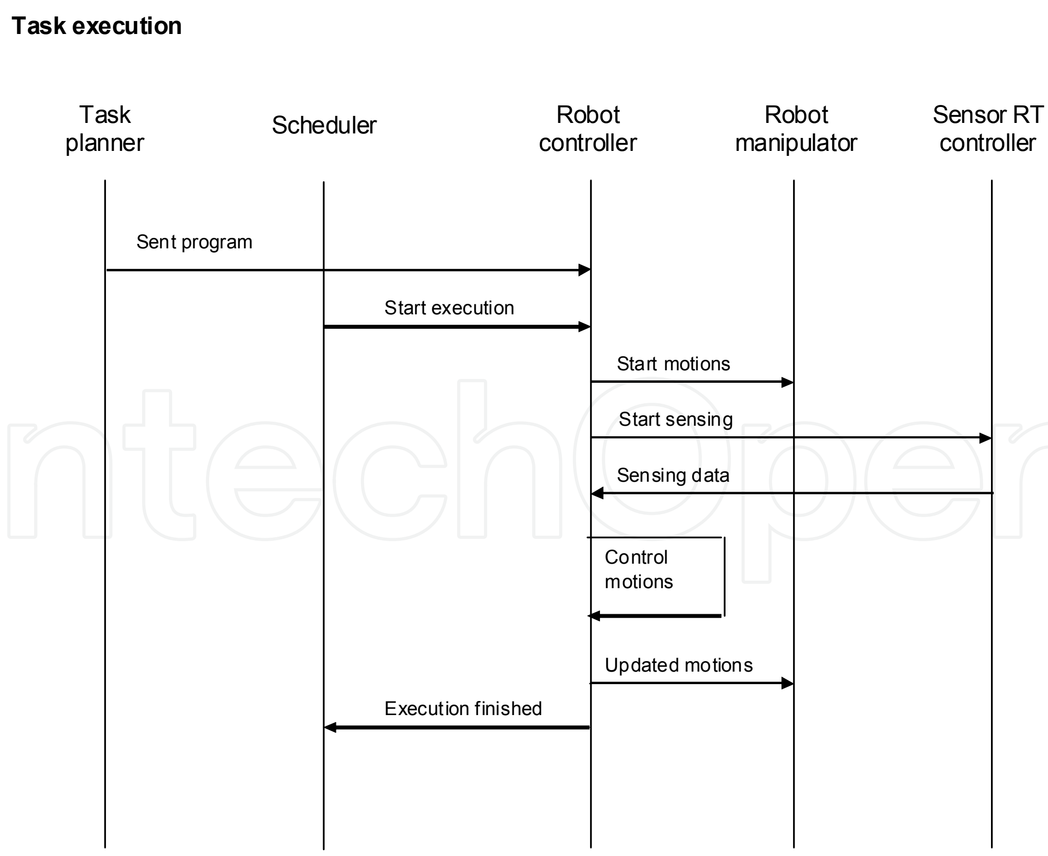

Fig. 10. Message sequence for the task execution.

Execution is carried out by first starting the motions in the robot manipulator and starting also the sensing of the external sensors by communicating with the sensor real-time controller. This sensor is typically force-torque sensor. During the execution, sensor returns the sensing data back to the robot controller. Based on the motions and pose of the robot and sensor measurements, motions for the robot manipulator will be calculated. Afterwards these updated motions will be sent to robot manipulator. When the execution is finished, information to the scheduler will be sent.

6. Demonstration

In this chapter, we give an example of applying the concept for Isles of Automation in a pilot case. The task of the demonstration was to deburr bevels of a sheet metal plate which was bent into 3D form. Input data for the system was a 2D-CAD drawing of the workobject and manufacturing data. The properties of the robot workcell (such as dimensions between the objects and reachability of the robot) was known.
In the engineering resources, off-line programming of the robot motion paths is based on 2D-CAD drawings made in Nestix2 (Nestix 2009) software. The software itself is designed for nesting 2D workobjects such as sheet metal plates and bewelling or deburring paths in 2D space. The drawings included both geometrical information and 2,5D milling paths for the deburring of the bevels. The 2,5D information of the paths included location in the 2D plane and angle of the bevel.

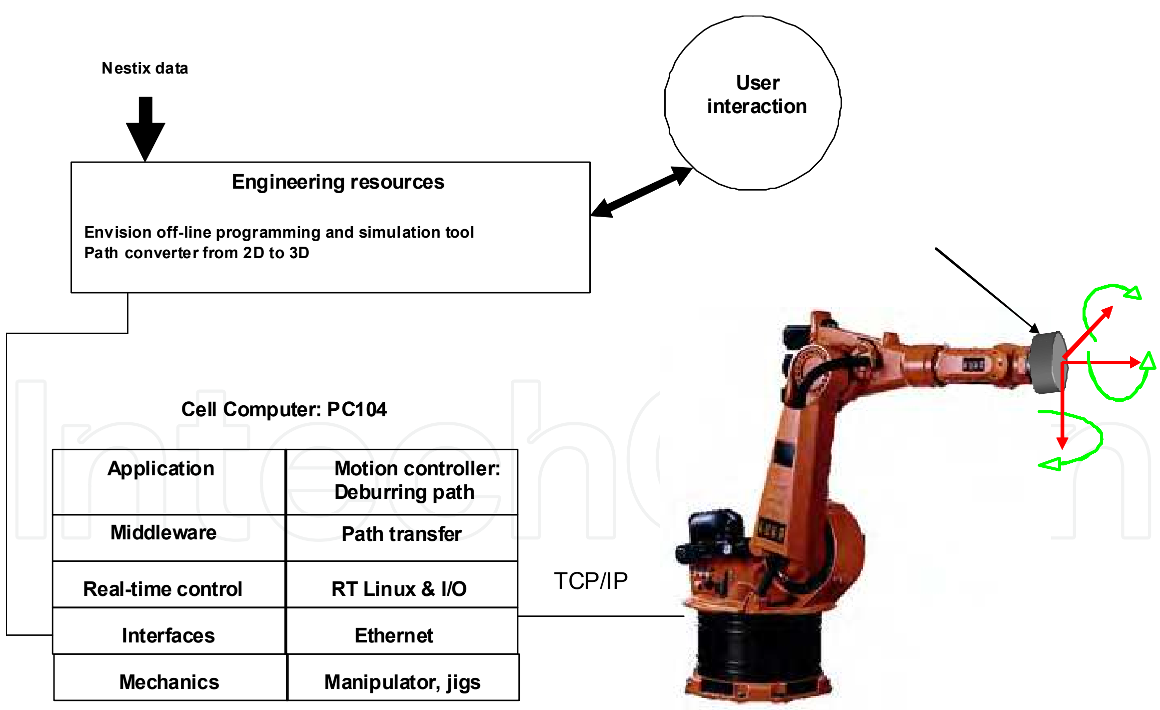

Fig. 11. Case implemented into Automation Island framework.

To fasten the programming of the robot, a converter to transform paths from 2D plane into 3D space based on the part 3D bending information was developed. After the transformation, there was a 3D model of the workobject and a 3D deburring paths (tags in the surface of the workobject). The robot motion paths were generated based on the 3D tags

in the surface of the workobject. This phase was supported by a robot motion path planner which calculated the paths for robot motion such that all points are reachable in a same joint configuration (for more information, see (Sallinen et. al 2006)).
The workflow of the demonstration task is illustrated in figure 8. In the workflow, first three operations are carried out by the engineering resources and the last one by the production cell. Scheduling / Workflow management is carried out manually by the shop floor operators. Engineering resources will generate programs to application layer in the production cell.
The robot programming was carried out using the ENVISION off-line programming tool by Delmia (Delmia 2009) for visualizing the virtual robot cell and transformation of workobject from 2D to 3D data. In the actual demonstration we used KUKA KR150-L110 industrial robot with KRC2 controller and deburring of the bevelling were done by a simple tool protype. Localization of the workobject was carried out using robot's own touching method where user shows axis in the workobject. In the demonstration, the purpose was to show the interfaces between the different parts of the system could be done easily. Generation of 3D model and paths from workobject 2D data succeed. In the demonstration, we did not consider any further process related issues such as tools and quality of the bevelling.
The implementation of the architecture into proposed framework is illustrated in figure 7. It also described the communication between cell computer and robot controller. Lines where data is transferred. Cell computer is PC104 –based solution with real-time linux which enables easy-to-integrate interfaces for sensors and actuators. There is not so much attention paid to workflow management because demonstration is not an industrial case or the productivity in the sense of workflow is not that important.
In the demonstration case there was no external sensors, especially which would need real-time communication and control. Therefore Ethernet communication was a proper solution for the communication.

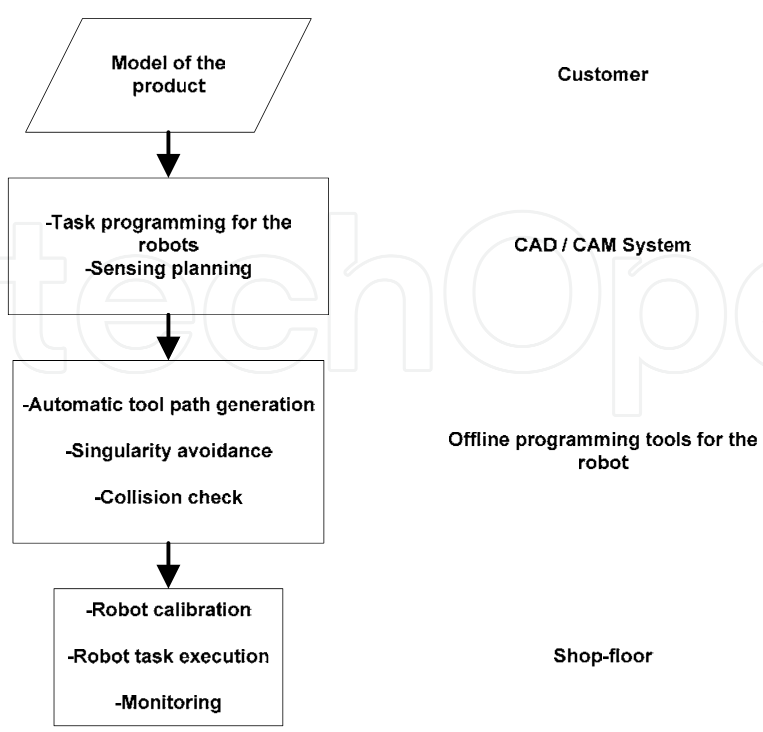

Fig. 12. Workflow in demonstration case.

7. Discussion

The proposed concept gives a framework for design of the robot workcells and different types of production units. The purpose has also been to give a design tool or guideline for making an efficient production unit. The proposed system do not necessary have to be completely implemented, there is possibility to also take part of the concept for the system.
The demonstration gave very promising results about the usability of the concept. From 2D to 3D converter operated well and it fasten the programming. Off-line programming in short series production is cost effective when it is done half- or fully automatically. If the user have to make a lot of manual work, it may even take more time and is more expensive than on-line programming. Unfortunately that is the case in many real production cell. One solution for this is fully automatic off-line programming tool which optimises robot motion paths using tag point information (Simtech 2010).

8. Conclusions

In this chapter, we presented a novel concept for short series manufacturing. The concept is called Isles of Automation and it defines a system structure composed of engineering resources and production cells. System consists of key functions whose content we defined. Also communication between the functions and different tasks was described. System is scalable and can be implemented into several applications. We described the content of these parts in detail and how the whole system operates. In the chapter, we illustrated a demonstration case in laboratory where selected parts of the concept were implemented into a robot cell in the deburring application. The proposed concept showed to be efficient and easy-to-integrate into the different applications.

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Robot Manipulators New Achievements

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Robot manipulators are developing more in the direction of industrial robots than of human workers. Recently, the applications of robot manipulators are spreading their focus, for example Da Vinci as a medical robot, ASIMO as a humanoid robot and so on. There are many research topics within the field of robot manipulators, e.g. motion planning, cooperation with a human, and fusion with external sensors like vision, haptic and force, etc. Moreover, these include both technical problems in the industry and theoretical problems in the academic fields. This book is a collection of papers presenting the latest research issues from around the world.