Distributed Control Concept for a 6-DOF Reconfigurable Robot Arm

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Abstract

Current trends such as shorter product lifecycles, reduced time-to-market and mass-customization require new paradigms and approaches for production lines and machines. In the long term, production and manufacturing companies will only be able to survive in the face of increasing globalisation if they can react flexibly and quickly to changing customer and market demands. New paradigms and approaches are waiting to fulfil these requirements, but their implementation requires completely new technologies.

Reconfiguration, both at machine (physical) and control technology (logical) level is a promising candidate to achieve the flexibility required by these paradigms by technical means. This makes a shift from centrally controlled, highly interlinked, and often tightly interlocked production systems to distributed, modular, collaborative components essential. This paper describes the distributed control concept for a 6-DOF reconfigurable robot arm as a demonstration platform for reconfigurable approaches at PROFACTOR.

Keywords: Production Automation and Control, Distributed Control, Reconfigurable Robots

1. Introduction

Today's markets and economies are becoming increasingly volatile, unpredictable, and change radically/abrupt. The accelerating speed of innovation with reduced model life cycles & increased product variety induces ever more frequent changes. Manufacturing companies in the 21st century will face frequent and unpredictable market changes. Economic viably production of small lot-sizes is required especially in Europe. Manufacturing technology and systems and therefore their ICT-infrastructure must undergo radical improvements to keep pace with this trend: New, more flexible technologies and embedded agile components which support the possibility to flexibly compose systems from machines to entire plants are required.

Today's manufacturing systems based on state-of-the-art technology are inadequate to meet the above requirements for more flexible manufacturing technologies. The manufacturing industry mainly uses a portfolio of Dedicated Manufacturing Systems (DMS) and Flexible Manufacturing Systems (FMS) in production. DMS are characterised by high throughput, but poor flexibility. This manufacturing system is tailored towards a specific product and adoption to new products is almost impossible. Thus a DMS represents in many cases a problem when the production life cycle of the corresponding product reaches its end. A FMS is characterised by high flexibility, but also by high costs due to expensive machinery, preventing it from extensive deployment [1]. Both manufacturing concepts are mainly controlled using centralised approaches based on Programmable Logic Controller (PLC) and Computerised Numerical Control (CNC) technology.

On the other hand an adaptable system incorporates a production capacity that is adjustable to fluctuations in product demand, is adaptable to new product functions, and is designed to be upgradeable with new process technology to accommodate evolving product specifications and government regulations. Current systems, even so-called flexible manufacturing systems, do not have these characteristics. A new manufacturing paradigm—called Reconfigurable Manufacturing Systems (RMS)—will position manufacturing companies for the 21st century and in the future. The aim of RMS is to design systems, machines, and controls that are cost-effective and can respond rapidly to changes in market and product demands. Methodologies for the systematic design and rapid ramp-up of RMS are the cornerstones of this new manufacturing paradigm. The new reconfigurable manufacturing paradigm provides exactly the needed functionality and capacity.

One of the key enablers of RMS are Intelligent Mechatronical Components (IMC) which can be considered as basic building elements/blocks [2] of RMS because they can easily be replaced. IMC are a combination of mechanics, electrics and an embedded ICT infrastructure for a certain manufacturing task. Most of the current approaches utilise a distribution set up on the granularity of PLCs and do not support the flexibility at actor/sensor levels although it is fundamentally necessary [3] for composable, reconfigurable components of automation and control systems. The major problem for the industrial usability that does not allow turning such agile systems into reality is that state-of-the-art ICT infrastructure (PLCs and CNC Controller) does not sufficiently support distribution, reconfiguration, modularization and scalability [2],[3]. More than that, up to now reconfiguration is expensive and time consuming as production lines must be stopped during reconfiguration processes and the setup of the new ICT infrastructure is very complex and not prepared for online reconfiguration [3] (i.e. reconfiguration during operation is hardly to achieve at these levels at the moment). To facilitate online reconfiguration of RMS in an economical way, an innovative ICT-infrastructure together with innovative, distributed and embedded software control modules that are dynamically reconfigurable are necessary.

The aim of this paper is to present a demonstration platform for a reconfigurable machine (i.e. reconfigurable robot arm) based on IMC in order to demonstrate the possibilities and features of such an approach. The main focus of this publication lies on the distributed control architecture. The paper is organised as follows: chapter 2 introduces the mechanical and electrical layout of the reconfigurable robot arm. The robot model and the control architecture are explained in chapter 3. The distributed control concept and its implementation are explained in chapter 4. The summary and conclusions are given in chapter 5 of this paper.

2. Reconfigurable Robot Arm

2.1. Mechanical Setup

The robot arm that will be used in this demonstration is a modular 6-DOF reconfigurable robot arm that is composed out of IMC, as depictured in Fig. 1. The robot consists out of six separate joints (i.e. IMC), which are PowerCube modules from Schunk company [6]. They are connected with each other via special connector elements (i.e. golden parts in Fig. 1).

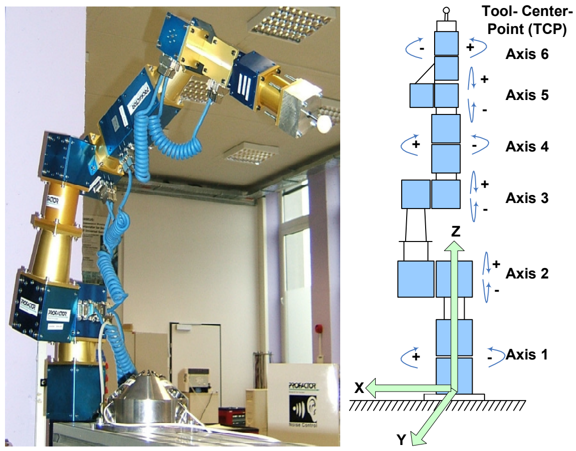

Fig. 1. Mechanical Setup of the Reconfigurable Robot Arm.

2.2. PowerCube Mechatronical Components

The PowerCubes are IMC that can be easily applied for manufacturing and assembly tasks which require fast and flexible adaptation of processes. Fig. 1 shows a PowerCube joint axis. For further information and technical documentation, for example the communication protocol, we refer to the homepage [6] of Schunk company.

Fig. 2. PowerCube Mechatronical Components.

The following list gives a brief description of the PowerCube functionalities:

- Brushless servo motor with Harmonic Drive gear head
- allows its usage for robotic based tasks,
- Incremental encoder for positioning and velocity control,
- Limit switches-, voltage-, current- and temperature monitoring,
- Integrated reference- and limit switches,
- Magnetic brake,
- Output of internal encoder signal,
- Input of external encoder signal.

Furthermore Fig. 2 shows also the internals of the PowerCube which are:

1) Electronics with integrated control and amplifier part,
2) Encoder for measuring the actual position,
3) Electro motor for high torques,
4) Harmonic Drive gear with gear ratio of 161:1,
5) Break for holding the actual position in case of a halt or in case of losing power, and
6) Covering.

The robot used for the demonstration consists out of three different PowerCube modules. Axes 1 and 2 are of type PR-110, axes 3 and 4 of type PR-90 and axes 5 and 6 are of type PR-70. Furthermore, Table 1 gives an overview of specific parameters that are set for the different PowerCubes in the reconfigurable Robot arm.

Table 1
Specific PowerCube parameters used for the robot arm

Parameters	PR-70	PR-90	PR-110
Nominal Torque	0.181 Nm	0.558 Nm	1.1 Nm
Maximal Torque	0.568 Nm	1.6 Nm	3.3 Nm
Voltage	24 ± 1 V	24 ± 1 V	24 ± 1 V
Max. current	15 A	30 A	30 A
Nom. work torque	23 Nm	72 Nm	142 Nm
Max. work torque	73 Nm	206 Nm	425 Nm
rpm	5000 min^{-1}	4300 min^{-1}	4500 min^{-1}

The embedded micro-controller provides different functionalities in order to operate the PowerCube (e.g. halt, turn, stop etc.). Furthermore each PowerCube has its own axis controller included. The embedded axis controller is responsible for the position and velocity control of each module. In order to communicate with a PowerCube the following fieldbus interfaces are provided:

- Control Area Network (CAN)
- Profibus
- RS 232

3. Robot Model and Control Architecture

3.1. Dynamic Robot Model

In order to derive the control concept for the robot, a robot model is calculated. Therefore, the kinematic model is based on a kinematic chain as depicted in Fig. 1. The robot consists of a serial kinematic chain with 6-DOF through its modular assembly based on the PowerCube.

In order to calculate the position and orientation of the endpoint of the robot (Tool Centre Point - TCP) in the Cartesian and in the Joint Coordinate system of the PowerCubes, the forward and inverse kinematics were calculated. For a 6-DOF robot and with a central gripper on the last joint, the solution for the inverse kinematics can be calculated analytically.

Without a central gripper or with more than 6-DOF, a solution for the inverse kinematics can only be calculated using an approximation algorithm. For comparison, the Newton approximation algorithm was also used for calculating the inverse kinematics. It turned out that the analytic way can be calculated faster than the approximation one. Therefore the first was used in this demonstration. For the calculation of the equation of motion

$$M(q)\ddot{q} + G(q,\dot{q}) - Q = 0 \qquad (1)$$

with the vector of generalised module coordinates q, the robot mass matrix M, the gyroscopic matrix G and the vector of generalised forces Q, the projection equations according to [11] were used.

3.2. Motor Model

The torque produced for each robot axis is generated by the DC motor of the PowerCube. For the calculation of the motor model an equivalent circuit diagram of a permanent excited DC motor was used. Fig. 3 shows the electrical equivalent of the DC motor.

The resulting PowerCube torque including the gear ratio of the Harmonic Drive gear can be calculated according the following equation (by negligence the motor impedance L_A):

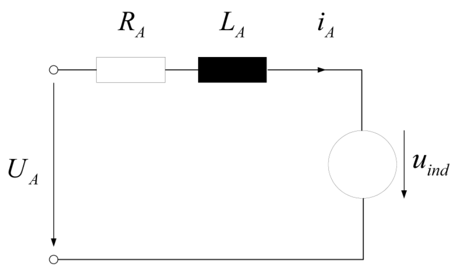

Fig. 3. Equivalent circuit diagram for the permanent excited DC motor.

$$M_{PC} = \frac{k_m}{R_A}\left(U_A - k_m i_G \dot{q}\right) \qquad (2)$$

with

M_{PC} … PowerCube torque (at motor axis incl. gear),
k_m … Proportional factor motor torque and motor current (i.e. $M = k_m i_A$),
U_A … Motor voltage, and
i_G … Gear ratio.

3.2. Control Concept

The control concept of the modular, reconfigurable 6-DOF robot is depicted in Fig. 4.

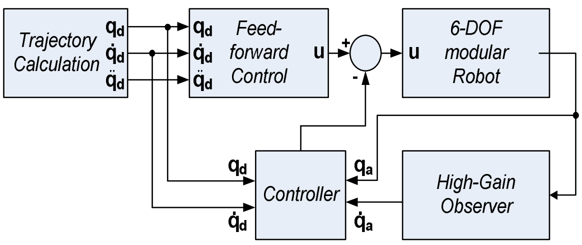

Fig. 4. Control Concept.

The goal of the control concept is to move the TCP of the robot along an interpolated path from a chosen point A to point B. The robot motion should be smooth. For the trajectory generation a *sin²*-based acceleration profile was applied (see Fig. 5). The Trajectory Calculation block in Fig. 4 calculates the desired angular position *q*, the desired speed $\dot{q}$ and the desired acceleration $\ddot{q}$ for each PowerCube module.

In order to get better control quality, a feed-forward term (Feedforward Control) was introduced into the control concept [12]. It is calculated based on the robot equation of motion (see above) and the force term (i.e. motor torque) generated by the PowerCubes:

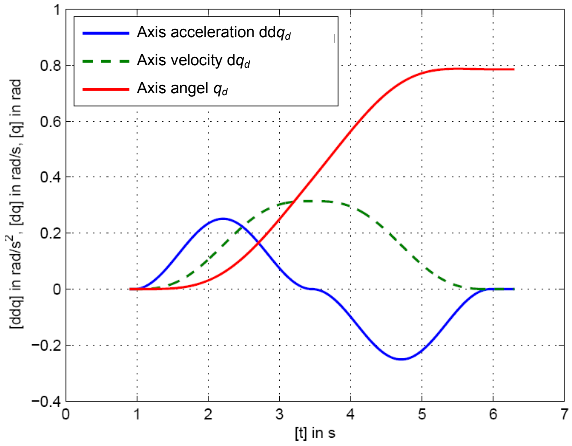

Fig. 5. Trajectory with sin²-based acceleration profile.

$$Q = Bu \qquad (3)$$

This leads to the feed-forward term *u* of the control concept:

$$u = B^{-1}\left[M(q)\ddot{q} + G(q,\dot{q})\right] \qquad (4)$$

For the feedback control term (i.e. robot controller) a PD control approach is used. The trajectory in the used control law includes the angular position and the angular speed of the joints (PowerCube modules). This results in the following PD controller (controller parameters K_P and K_D):

$$u = K_P\left(q_d - q_a\right) + K_D\left(\dot{q}_d - \dot{q}_a\right) \qquad (5)$$

with q_d the desired position and q_a the actual position of the joints.

Since each PowerCube has only an encoder for the measurement of its angular position, a direct measurement of the angular speed is not possible. But for the used control concept it is necessary to know the angular speed of each PowerCube.

In order to calculate the angular speed, a High-Gain Observer is used. This approach is common for mechanical structure since it uses the equation of motion. Fig. 4 shows the control concept including the High-Gain Observer for calculating the angular speed of each PowerCube based on the angular position.

4. Distributed Control Concept

4.1. Embedded Hardware and Software Setup

Fig. 6 shows the hardware (embedded control) setup of the reconfigurable robotic system. Respectively two robot axes are controlled by PC/104 embedded PCs [7] equipped with a Debian Linux [8] and an OSADL real-time kernel patch [9].

The whole robot control concept explained in chapter 3 is implemented in IEC 61499 Function Blocks [15] in order to support reuse and reconfiguration on the Function Block level. The FORTE [5] IEC 61499 compliant runtime environment is installed on each of the PC/104 controllers and used for the execution of the IEC 61499 Function Block control application.

The data exchange between the PC/104 and the PowerCubes is done via CAN [10]. The engineering and visualisation PC is connected via standard Ethernet to the PC/104 controllers.

The engineering of the IEC 61499 robot control program is carried out via the 4DIAC-IDE [5]. The visualisation and HMI are also modelled with IEC 61499 Function Blocks. Therefore the Java-based FBDK [4] is used as runtime environment for the execution of the visualisation program.

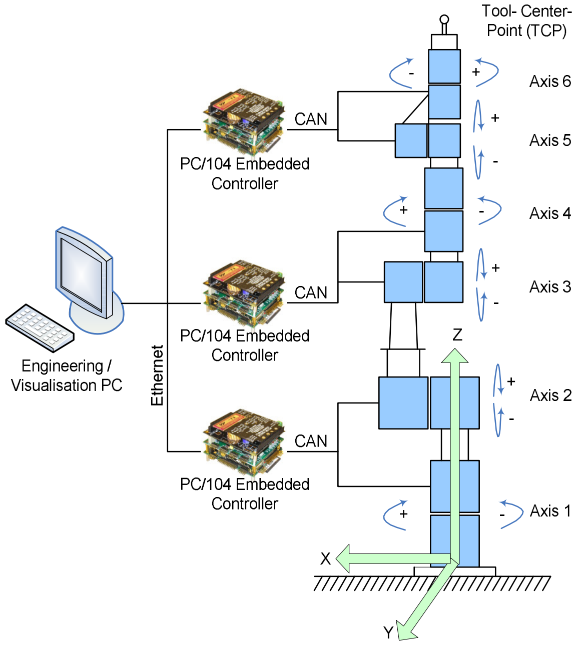

Fig. 6. Embedded Hardware Setup.

4.2. Distributed Control Implementation

The above introduced control concept (see Fig. 4) and the chosen hardware structure of the modular 6-DOF robot (as depicted in Fig. 6) leads to the IEC 61499 system configuration as presented in Fig. 7 [13].

The following two separate IEC 61499 applications have been developed:

- Robot Control Application (RCA)
- Robot HMI Application (RHA)

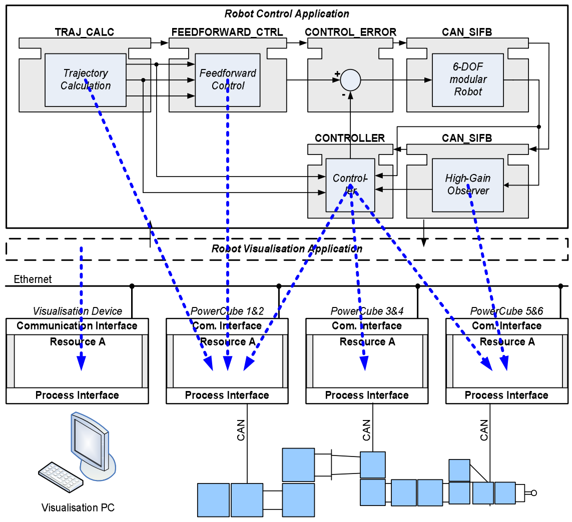

Fig. 7. IEC 61499 System Configuration for the 6-DOF reconfigurable robot arm.

The RCA contains the implemented control concept (see above) as IEC 61499 application. Each component of the control concept has its own IEC 61499 FB representative (i.e. TRAJ CALC, FEEDFORWARD CTRL etc.).

For visualisation and parameterisation issues, an own RHA was developed. The RHA is also built out of special IEC 61499 HMI Service Interface Function Blocks (SIFBs). The two applications communicate with each other via Publish/Subscribe Function Blocks. The IEC 61499 system model for the robot controller consists of four different remote devices. One remote device is executed on the Visualisation PC (equipped with the FBDK), the other three devices are executed on the PC/104 embedded hardware (equipped with the FORTE). The communication between all devices is done via Ethernet. The whole RHA is mapped to the visualisation device while the trajectory calculation and the feedforward control Composite Function Block (CFB) are mapped to the PowerCube 1&2 Device.

The High-Gain Observer CFB is mapped to the PowerCube 5&6 Device. The other control modules (CAN SIFB and CONTROLLER) are represented as sub-applications in the RCA and are distributed to the three PowerCube devices.

4.3 Motion Control Library

For the interaction of the PC/104 embedded controllers and the PowerCube modules an IEC 61499-based motion control library was developed (example see Fig. 8). The interface specification of the motion control function blocks is based on the Motion Control Specification of the PLCopen association [14].

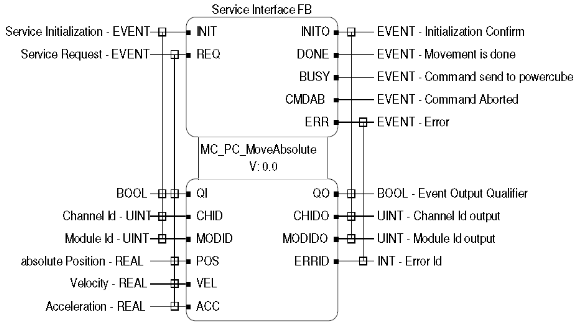

Fig. 8. IEC 61499 Move Absolute Motion Control Block.

5. Summary and Conclusions

In this paper the need for reconfigurable approaches in manufacturing was discussed. In order to demonstrate the advantages of such systems and machines a demonstration platform (i.e. reconfigurable robot arm) was introduced. The reconfigurable robot consists of PowerCube IMC.

Furthermore a robot control concept was presented which can be distributed to different embedded hardware. For the implementation of the distributed control concept the IEC 61499 standard was used. The distributed control hardware consists of PC/104 embedded controllers equipped with a real-time Linux.

Together with the modular hardware of the robot arm and the IEC 61499 based control concept it is relatively easy to make modifications to the configuration of the reconfigurable robotics system (i.e. hardware as well as software reconfiguration becomes possible).

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