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A Laboratory Platform for Project Based Training Concerning the Development of Complex Networked Control Systems

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Abstract: Due to modern trends in the development of mechatronic systems, requirements on developers are changing. Beside the classical approaches to control design, engineers need competence in fields like integration of heterogeneous systems, communication between different components, interoperation between various software components, and simulation of complex systems. Further, development is carried out by teams of specialists. Teaching in the field of automatic control needs to be adapted to these new trends. A new laboratory platform has been developed and installed to offer laboratory projects tailored to these requirements. A robot arm and corresponding control hardware is composed of carefully selected components used in industrial equipment. The robot is complemented by auxiliary systems which allow the accomplishment of a range of laboratory projects by groups of students. After acquiring particular skills in workshops during an advanced study phase, students form teams to complete a given team project. Project steps from analysis of requirements to test and presentation are planned and accomplished by the team. This process is very similar to industrial development processes and allows students to acquire valuable skills in mechatronic system design.

Keywords: Control education; Robot control; System architectures; Training; Control system networks.

1. INTRODUCTION

The essential objective of the project described in this paper is the orientation of teaching in the field of control science towards new challenges in mechanical engineering. Automatic control in mechanical engineering means the quick and accurate control of motion of mechanical parts. By observing the development in this field in the past years, some significant trends can be identified:

- Formerly pure mechanical functions are replaced or complemented by electronic functionality resp. automatic control.
- Thus, simple control loops increasingly are replaced by complex control structures demanding comprehensive algorithms for information acquisition and processing, modeling, optimization etc.
- Interconnection and interoperation of several heterogeneous information processing components plays a decisive role in the composition of systems.
- Multiple control components of one product are interconnected, influencing each other, and operating cooperatively.

These trends have to be addressed in teaching of automatic control – especially in mechanical engineering. Accordingly, the classical approach of controller design needs to be complemented by the development of control systems consisting of heterogeneous components under practical conditions.

Resulting from the trends mentioned above, the intention has been developed to create a laboratory platform where students of mechanical engineering are able to design, program and test parts of a networked control system. The purpose of this laboratory work is not the design of controllers under predetermined laboratory conditions. Rather, students are supposed to experience critical constraints like real time behavior, data transfer across different channels, interactions between control components and priorities themselves. They are supposed to develop strategies and solutions to resolve the constraints.

To keep the laboratory equipment in step with actual practice, the following requirements have been defined for the laboratory platform:

- The platform is based on a technology well-known to the students from courses as well as common in industrial applications.

- The technology is sufficiently complex to allow a range of complex, extensive applications as well as further advancements in the next years.
- The platform consists of heterogeneous hard- and software with practical demands regarding interconnection of several components,
- The platform comprises diverse networking technologies like industrial bus technology and Ethernet.
- Last but not least, the technology used is supposed to have a certain fun and game factor.

A laboratory platform developed for these purposes is introduced in the following section. First, the approach is described (Sec. 2). Subsequently, the system configuration is given in Section 3. Then, the organization of the laboratory projects is explained (Sec. 4). In Section 5, a sample laboratory project is described. Finally, results are given in the conclusion (Sec. 6).

2. APPROACH

Because of the requirements a robot arm has been chosen to provide a basis for laboratory work. The robot arm consists of one longitudinal axis, several rotary joints and a gripper as end effector. Advisedly no commercial or standard robot arm has been used. Rather, the robot is composed of individually selected and obtained hardware components and is controlled by a software system arranged accordingly. This approach allows students using the equipment full access to all components, interfaces and source codes. Moreover, improvements and updates can be easily incorporated over the years.

The robot arm provides a basis for the coupling of auxiliary components in order to develop a wide range of applications.

The system configuration of the laboratory robot – mechanical and from a information processing point of view – is described in the following section.

3. SYSTEM CONFIGURATION

In Figure 1 the arrangement of the equipment is displayed. The central element is the robot portal. Beside the portal the control cabinet is arranged. The cabinet contains the complete control hardware including axis processors and robot control computer.

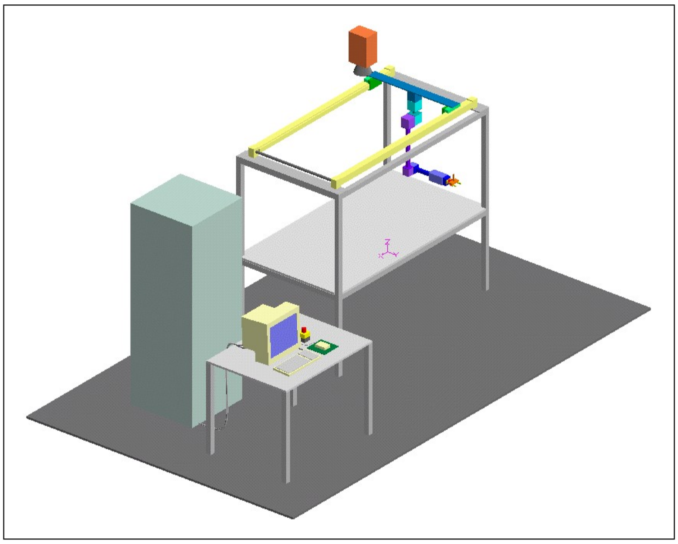

Fig. 1. System configuration

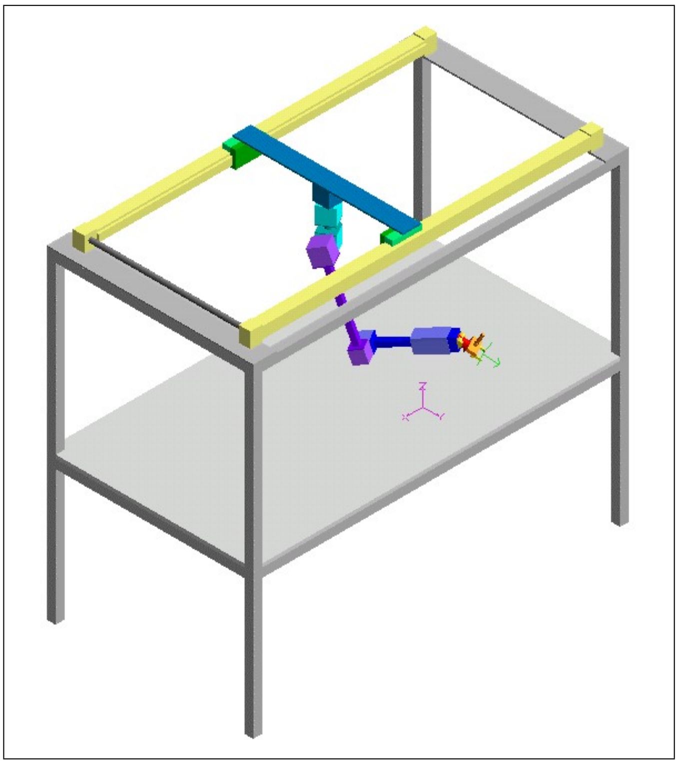

Fig. 2. Mechanical composition of the robot

3.1 Mechanical composition

The mechanical resp. kinematical composition is displayed in Figure 2. The axle drives constitute the link between robot control and mechanical components. They are connected via analog or digital interfaces resp. the implemented Controller Area Network (CAN) bus to the axis processors of the lower control level. The axis processors communicate among themselves or with the robot control processor via CAN bus.

The robot used in the laboratory platform is a folding arm robot with five axes (serial kinematics). The folding arm is attached suspending to a carrier moving on two parallel longitudinal axes. A picture of the robot arm is given in Figure 3. Hence, the robot consists of six independently controllable axes. Due to the kinematic configuration of the six axes the robot arm is restricted in reaching arbitrary orientations. But, the gripper is able to reach any point in the workspace. From an engineering mechanics point of view the robot is a typical multi-body system. Due to the complexity of robot systems and according to common practice one degree of freedom per axis is implemented. The robot arm consists of several links attached by joints. The robot arm is modularly arranged from standard rotary drives. Electronic control components are integrated, only one cable for power supply and CAN bus communication is connected to each drive. The links and connectors are quickly exchangeable and easy to assemble, thus, varying configurations are easy implemented if required. (Schweiger and Kaufmann (2006))

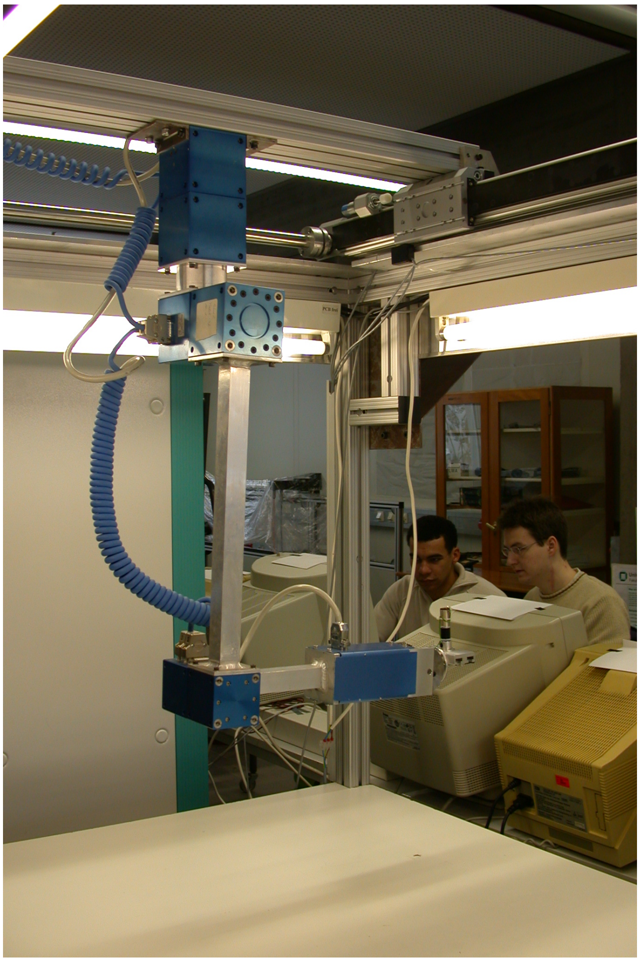

Fig. 3. Robot arm

3.2 Information Processing Approach

In Figure 4 the modular structure of the control hardware of the robot is displayed. On the left hand side, the components of the robot itself are represented. Auxiliary components for the development of certain applications are shown on the right side (see further explanation in Section 3.3).

As shown in Figure 4 the robot control consists of the following components:

(1) an operating terminal,
(2) a programming terminal
(3) a robot control computer,
(4) one axis processor for each rotary axle drive, the longitudinal axle and the gripper,
(5) auxiliary equipment for special purposes.

The robot control computer and axis processors are running on Windows operating systems. The robot control computer is an industrial PC equipped with Non Maskable Interrupt (NMI) timer and interrupt mapping for real time operation. Accordingly, real time operation with the Windows operating system is an issue in laboratory work. The robot control computer (3) calculates reference path curves and transfers reference motion and velocity values via CAN bus to the axis processors. Beside the superordinate robot control computer, the axis processors (4) are an important part of the control concept. Axis processors are embedded computers with A/D converter (8 channels, 12 bit), D/A converter (4 channels, 12 bit) as well as CAN bus interface. The control of the axis drives is possible both by analog standard signal ($\pm 10\ V$) and CAN-Bus. The CAN bus has been chosen because of it's relevance in applications of mechanical engineering, see Pfeiffer et al. (2003); Lawrenz (2000).

Ethernet is used for communication in the upper level (Fig. 4). This network access technology, which is a de facto standard in office communication, is increasingly used in automation, (Furrer (2003)). The network composed of office communication components is connecting the robot control computer, the operating terminal and auxiliary component. Communication is conducted using TCP/IP.

The modular structure of the control hardware assures the transparency and maintainability necessary for the laboratory projects. Further, all components are scalable and upgradable to allow a wide range of projects.

The same principles applies for the control software. The core is the software package NoVAL+ running on the robot control computer. NoVAL+ is a planning and control system for industrial robots which has been developed at the University of Karlsruhe (Wurll et al. (1998)). NoVAL+ provides the necessary functionality for control of robot elements and communication to lower and higher control levels. Adaptation and expansion of the software is carried out using an API (Application Programmer Interface) (IRA (1999)).

The control approach used in the laboratory platform adequately demonstrates modern methods of automatic control. This comprises decentralized control including field bus communication, automation approaches based on Windows operating systems, application of simulation tools for design and development of programs using C++.

3.3 Extensions

The laboratory robot is complemented by auxiliary equipment used in several laboratory projects (Fig. 4). To create new projects additional equipment can be connected to the core robot system.

Machine Vision An image processing system is connected to the robot to allow applications of machine vision. The vision system consists of a digital camera attached to the ceiling and connected to an image processing computer by firewire interface (IEEE 1394). The software system Khoros is used to acquire, visualize and process camera images (Dreer (2002)).

Simulation A simulation terminal is connected via Ethernet to the robot system. Currently, the software package WORKSPACE (Flow Software Technologies) is used for off-line programming and simulation (WOR (2007)). This system has been chosen for the laboratory projects for the following reasons:

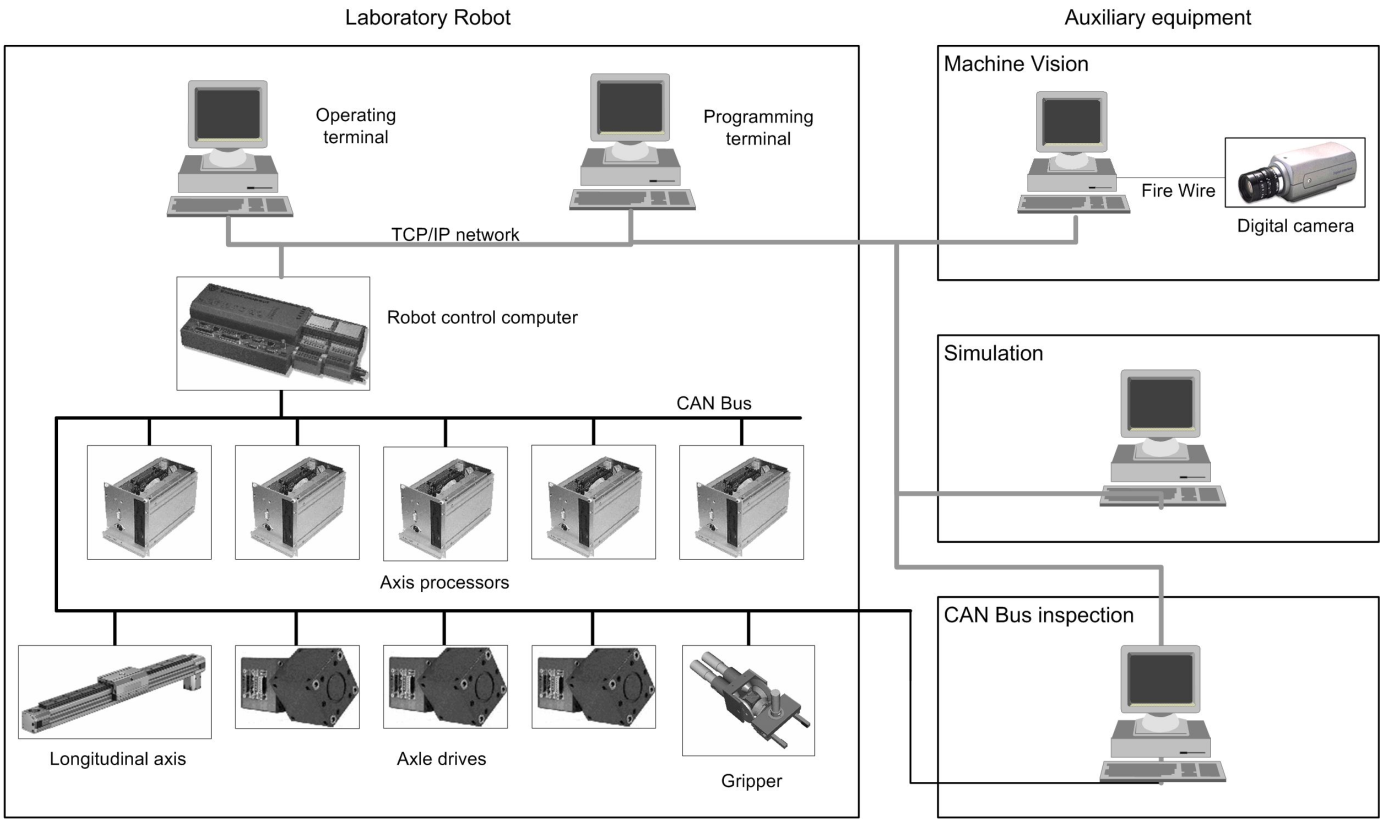

Fig. 4. Information processing structure of the laboratory robot

- WORKSPACE allows rapid test of kinematic designs (rapid prototyping).
- The graphic representation of work results is powerful.
- The system permits riskless test of control and collision avoidance algorithms.
- Off-line generation and test of robot programs is possible.

Furthermore, the system is used to teach basics of robot programming. The robot programming language implemented in WORKSPACE is suitable for this purpose. Using a specific API the programming and simulation environment can be adapted to the real robot. This includes the preparation and integration of application specific kinematic and dynamic models. Via TCP/IP communication it is possible to control the robot from the WORKSPACE environment as well as to visualize the real movements of the robot.

CAN Bus Inspection One Workstation is designated to the examination and inspection of the CAN bus communication. According tools are installed. A programming interface allows the direct interaction with CAN bus clients.

4. ORGANIZATION OF LABORATORY PROJECTS

According to the curriculum at the University of Karlsruhe it takes approximately four months (one semester) to complete the required laboratory project. This includes at least three hours of work in the laboratory per week. The laboratory project is organized in two subsequent phases:

(1) the 'Advanced Study Phase' (see Section 4.1) – to allow the students to acquire specific know-how and to get familiar with the tools necessary for the laboratory project – and
(2) the 'Team Work Phase' (see Section 4.2) – to accomplish a given project using the acquired skills.

Both phases are accompanied by teaching personal and/or tutors. Their main focus is to help students getting the entry to the subject, to discuss problems and to help if necessary. In many cases tutors themselves have accomplished one of the laboratory projects before.

4.1 Advanced study phase

During phase (1) participants of the laboratory project meet in workshops to acquire skills necessary to work with the robot. Topics of the workshops include the acquisition of knowledge and skills regarding:

- WORKSPACE software for kinematic modeling and simulation of robots,
- C++ program development tool,
- image processing and machine vision,
- network specifications, protocols and network configuration for CAN bus communication,
- programming for Ethernet and TCP/IP communication.
- modeling and simulation of multi body systems,
- mathematical description of robot kinematics (e.g. DH notation).

These topics are organized into four 'Advanced Study Workshops':

(1) *CAN-communication and robot motion programming*
In this workshop, design and functionality of the CAN bus is acquired. Additional programming interfaces and software drivers are examined. Message administration in a CAN bus environment is especially important for robot projects. The utilized CAN bus protocol is investigated. Protocols for communication between axle processors and robot control computer are examined.
Another important topic in this workshop is the control of single axes. The axle types of the robot are examined from a control point of view.
(2) *Machine Vision and Image Processing*
Connected to the machine vision system, the robot is able to locate objects deposited on the worktable. Different objects are distinguished and grasped accordingly. The robot moves the objects to a defined position. The basis for these robot skills is the machine vision system. In this workshop tools and techniques of machine vision are examined by the students. Illumination, image recording, image digitalization, image processing operations – e.g filtering, smoothing, straight line detection, binary operations – are especially addressed. Finally, students become acquainted with the image processing software system Khoros mentioned above.
(3) *Kinematic Robot Simulation and TCP/IP Network Communication*
An insight into Ethernet-TCP/IP communication is a substantial part of this workshop. TCP/IP communication is especially important for the communication between operator station and the robot control computer. Participants of the laboratory project are coding their own data transfer programs using C++ programming language.
Geometrical and kinematical models of robot parts are prepared using the WORKSPACE tool mentioned above. Off-line programming and simulation of robot motion are practiced.
(4) *Dynamic Multi-Body Simulation and Control of Robot Motion*
The multi-body system of the robot is modeled using ADAMS (MSC Software Corp.) software. Robot motions are simulated and the dynamics are investigated. Further, problems of robot control are analyzed using MATLAB/Simulink (The MathWorks, Inc.) software.

4.2 Team Work Phase.

The knowledge acquired during the 'Advanced Study Phase' is applied in phase (2). During this 'Team Work Phase' groups of up to eight students are formed. Each group consists of students which have attended different workshops. During different time slots each group is able to work on a given team work job (Fig. 5. For better understanding a sample team work job is described.

4.3 Participation

Typically, twenty-four students take part in one laboratory project. Participants are divided a follows:

- Four groups of six students attend the workshops during phase (1). Each student chooses two from the four topics offered according to his/her interests.
- Three groups of eight students are competing during phase (2). Each group is assigned a weekly time slot for work in the laboratory.

The participants have usually finished their third academic year. A prerequisite for attendance is the successful completion of the course "Introduction to Mechatronics".

5. SAMPLE TEAM WORK JOB

The configuration of the laboratory platform allows different demanding team work jobs. In the following one job is explained in detail:

Team work job: Recognition and Relocation of Objects
As a result of this laboratory job the robot system is supposed to locate, distinguish, grasp and relocate objects on the worktable. Position and orientation of the objects are determined by the image processing system and transmitted to the robot control in the form of gripper positions. This requires sophisticated calculation robot geometry and movements. The robot subsequently grasps and moves the objects to a given position. The general task is divided into the following steps:

(1) Analysis of the global task and determination of the necessary subtasks by the group. Result of this analysis is usually an operation chart used to in further steps.
(2) Determination and assignment of subtasks to group members. Useful subtasks are for example
    - configuration of CAN bus communication,
    - configuration and programming of machine vision,
    - calculation and simulation of robot movements and,
    - programming of the robot control,
    - creation of an user interface for activation and control of the robot.
(3) Subtasks are carried out by team members who have acquired the corresponding know-how.
(4) The integrated system is examined and tested for consistent interoperation and communication.
(5) In the final step the group presents the accomplished results. A test run is conducted check the operational capability.

During the project work all team members have to discuss issues like interfaces, data transfer and integration of components continuously. After the successful test all results are carefully documented to serve eventually as basis for other projects.

6. CONCLUSION

To see the robot finally moving and doing the intended task is an invaluable incentive for many participants of the laboratory projects. This game factor cannot be overestimated. Many students spent hours and days of extra time to get the robot moving.

Regardless of the enthusiasm for moving objects, the following results can be stated:

Fig. 5. Students working at a robot laboratory project

- During the 'Advanced Study Phase' students acquire deep insight into specific know-how necessary to develop a robot application.
- During the 'Team Work Phase', a team of students who have acquired different know-how is able to accomplish a complex and demanding laboratory project successfully.
- Beside the classical approaches of teaching in the field of automatic control the laboratory platform allows to align training according to new requirements.

Former participants report a strong relevance of the laboratory work to their current jobs. This is a reassurance to further develop and extend the laboratory platform.

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