Production assistants: The rob@work family

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Abstract—Mobile robots offer a high potential for future manufacturing and assembly. To this day the co-operation and co-action is in these fields hardly applicable, because of safety regulations, insufficient technology and its missing integration. In order to fill the gap this paper presents the hard- and software design of the mobile assistant rob@work 2. This system is the second iteration of the rob@work system. As an exemplary work the conditions of a prototypic industrial application are analyzed and divided into modes of operation which are portable to generic assembly processes. For each mode of operation the safety requirements for human-robot interaction are surveyed taking into account recent regulations. In order to evaluate the performance of the robotic system, repeatability benchmarks and respective measurements are presented.

I. INTRODUCTION

There is the need to quickly react to changing requirements in industrial productions. Assisting qualified workers has an enormous potential to increase the production quality and productivity, to reduce costs, and to react faster on the market especially by means of assembly by request [2], [6]. However, to this day the effective co-operation and co-action between human and robot are limited because of insufficient integration and missing safety features [5]. To enable assisted assembly and machining a novel flexible robot system called rob@work 2 was developed at Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) [3]. On the contrary to Cobot systems which are highly collaborative systems, the rob@work 2 is largely independent from workplaces or operating distances [4], [13].

In this contribution the realized prototype is shown, consisting of a real-time robot controller, a mobile platform, and a seven degree-of-freedom lightweight robot (Fig. 1). The development’s purpose is to design a flexible robotic system thinkable as real moving robot cell that copes with tough industrial environments and is operated by mostly untrained workers. To encounter those challenges a robust hardware frame and at its best off-the-shelf components were used and embedded into a system architecture. For interaction with the environment and the workers, sensors and a human-machine-interface are integrated and presented. In consideration of operating the robot in relevant applications such as assembly tasks, charging and discharging the co-operation and -action between human and robot are analyzed and embedded into modes of operation (Sec. IV). In doing so, this results in different safety levels that prescribe the requirements for the safety system including the risks for the operator and machine and the required component features. Recently published regulations concerning the safety of human-machine interaction became effective [1]. It is a major challenge for new industrial robotic systems to comply with these standards. The potentials for industrial applications and for close interactions with humans are shown and exemplary repeatability benchmarks are validated on a prototypic setup.

The paper is organized as follows: In Sec. II the focus of related robotic systems is presented. Sec. III outlines the system architecture and gives details on the integrated components. In Sec. IV modes of operations are introduced to distinguish between different working conditions. The requirements and subsystems for the safe operation of the rob@work 2 system are detailed in Sec. V. Results from the experimental evaluation of the repeatability are presented in Sec. VI. The paper closes with the conclusions and future works (Sec. VII).

II. RELATED WORK

Currently, there are autonomous robotic systems under development. But all of those robotic systems have in common that they are pure development platforms with little emphasis on industrial everyday tasks. In particular, main interests of research among others are autonomous navigation, mobile manipulation, bi-manipulation, sensing, locomotion, and perception. At the moment it is exhausting even up to impossible to achieve a fully integrated system. In general research institutes address therefore just a range of robot capabilities for unstructured human-centric environments.

On the one hand systems feature capabilities of human-like tasks. One example of bi-manual dexterous manipulation including hands/fingers is Justin at the DLR in Germany [12].
Similar work was done with the Centaur system of NASA [10]. Both systems are capable to perform complex sensed manipulation tasks like the cooperation of two arms using redundant degrees-of-freedom. The humanoid robot ARMAR-III at the University of Karlsruhe incorporates furthermore mobility [11]. This robot is equipped beside two arms and hands with a holonomic platform with three wheels. Another humanoid example is Honda’s bipedal robotic system ASIMO [9] whereas the focus is the bipedal locomotion according to human behavior in flexible movement.

On the other hand in order to establish sophisticated mobile manipulation and human-machine interaction human-like tasks are not essential. To that effect the following two systems use a single arm and a wheeled platform. Firstly, the University of Massachusetts Amherst realized such mobile manipulation system with the goal of implementing and testing new algorithms. Secondly, the Care-O-bot3 from Fraunhofer IPA prescribe a service robot product that interacts with the human in real households [7].

III. SYSTEM ARCHITECTURE

The development, selection, and integration of components is crucial for such a complex mechatronic system. The goal for creating the rob@work 2 system was to integrate all necessary equipment into a mobile platform in order to quickly install the robot in industrial environments where it is needed and to allow collaborative appliance for instance by sharing the same workspace. The prototypic system setup is depicted in Fig. 1. Subdividing the robot into the main functionalities one maintain the following parts:

- an autonomous mobile platform consisting of a differential drive and energy supply through batteries;
- two laser scanners for safety and navigation;
- a seven degree-of-freedom lightweight arm equipped with an end-effector depending on the industrial application;
- an industrial PC for the control of the mobile platform including autonomous navigation;
- an industrial PC with real-time operating system running the robot controller, a PLC, and task specific application modules;
- a touch-screen as intuitive human-machine interface.

The mobile and flexible concept puts strong requirements on the components and interfaces in terms of energy consumption, lightweight, installation space and accuracy. As a result the hardware was carefully chosen with respect to the control system architecture. For the sake of a compact design, different functionalities have to be integrated, see Fig. 2.

A. Hardware

Due to the requirements the robot arm consists of seven modular lightweight rotary units which are standardized in four different sizes. The rotary units possess center bores for a covered cable feed through. Additionally, a magnetic brake, which saves the position in power outage as well as the module control (electricity, number of revolutions and position) with power electronics, is fully included in each module. The actuation takes place by using a brushless DC servo-motor combined with a harmonic drive gear, which allows a turning range exceeding 360°. The combination of seven units allows the nominal load of 5 kg. The set-values for the servo-controller are cyclic transferred via CAN bus.

The platform has an overall size of 856 × 783 × 415 mm³. Despite the small size the platform offers a robust interior structure that is cased with aluminium plates. Eight leakage-free batteries, situated in the interior of the platform allow a suitable uptime of approximately eight hours, depending on use scenarios. As a result of the persistent robust design the maximal payload is 150 kg. The mobility of the platform is achieved by five wheels, where the two outer wheels are differentially actuated. The movement of the platform is controlled by a PC-based navigation system.

For navigation and further for safety around the robot it is equipped with two laser scanners. The laser scanners are operated in master-slave mode, i.e. the data measured by both laser scanners is first consolidated in the master laser scanner before being transmitted to the robot system. It is of great benefit to mount the scanners on opposite corners of the robot system as depicted in Fig. 1. This design offers a view all around the system. For safety aspects the laser scanner devices are able to monitor at the same time two different fields around the robot system. The first one is the so-called warning field. Presence of objects inside of this field is indicated to the control system. No action is taken by the laser scanner. But, for some reasons may be conceivable. Further on, the scanners are supervising the so-called protective field. If objects are detected in this field the laser scanner trigger an emergency stop of the whole system. In those cases the laser scanner system cuts immediately the power supply for the servo-motors of the arm just as platform and activates the brakes. This means that any movement of the arm and platform are inhibited and hence the risks of injury for humans such as impact, shearing, coiling, penetration, and crushing are mitigated. More details on the safety are given in Sec. V.
B. Real-time Control System

The real-time PC contains a CoDeSys soft-PLC, a machine tool NC kernel for Cartesian control of the robot, and application specific programs for human-machine interfaces. The integrated soft-PLC reduces the necessary hardware and offers the possibility to use it with any processor just as PC. For the controller an IPC, an embedded PC or a box-PC was considered. In order to reduce the space, an industrial box-PC combined with a touch-screen is selected. For deterministic and reliable operation a real-time operating system is needed for the soft-PLC and the NC-kernel. This is achieved through the RTX real-time extension for Windows. This allows to integrate all software component into a single PC (Fig. 2). An industrial real-time NC-kernel is adopted from a machine tool. The integrated motion control functionality makes available six axis Cartesian controls with smooth trajectory generation (jerk limited spline interpolation). On the contrary, axes control manages each axis individually. The communication between the NC-kernel and soft-PLC is realized with a shared memory which holds all relevant process data. The shared memory is organized as a complex data structure that contains the axes, the commands, the confirmations, and the status information. In order to access the interface the alignment and view of the memory must be the same for both. Therefore, monitoring mechanisms are necessary to control the exchange and to create the data consistency. Programs running in Windows user mode can access the real-time states in the shared memory making application development straight forward. Additionally, the cyclic set values are transferred to the motors of the robot arm via CAN-bus interface with a cycle time of 4 ms for each module.

In terms of human interaction with the robot the human machine interface (HMI) is divided into two segments. On the one hand the graphical user interface (GUI) and on the other hand the operation part. The communication is carried out either through the shared memory by using the PLC or through a special API. The latter comprises the robot programming with numerical control implementations according to DIN 66025 (G-code). Nevertheless this offers a standardized interface for task level programs that can be compiled in G-code.

C. Safety Architecture

Fig. 3 depicts the safety architecture of rob@work 2. The rob@work 2 safety system consists of a software and a hardware safety path. The idea behind this separation is to avoid the implementation of safe control software and hardware that encompasses following very strict development and validation processes. For rob@work 2 the safety of the system is always ensured by the hardware, i.e. the hard-wired safety path. This is done by limiting the energy of the robot or cutting the energy in case a hazard for humans is detected. Thus, the software functions are not safety critical. They merely ensure that the hardware safety functions are not triggered since reactivation of the hardware safety functions might be cumbersome, e.g. replacing a fuse. Hence software development for rob@work 2 is much easier compared to software development for safety related programmable systems without hard-wired protection.

The hardware safety path consists of the laser scanners and a safety relay board. In case the safety scanner detects intrusion of objects into its protective field the relay board is triggered and cuts the power supply to the drives of robot arm and platform. This triggers the brake systems of robot and platform causing all motion to halt. The shape of the active safety field can be adjusted using fail-safe input signals to the scanner system. Further activation of the safety relays by the power monitoring of the arm is included in the design.

The software safety path is integrated into the controller of the robot arm. It relies on data from laser scanner and in particular position data of the robot arm for safe speed limitation. This path is used for situations where hard wired safety features do not offer an appropriate level of flexibility and complexity of behavior. For the prototype of rob@work 2 the software path is currently not safe. However, applications in the field of industrial robotics [14] show that implementation of safe speed monitoring is possible in case this functionality is needed for future applications.

IV. OPERATION CONCEPT

As a result of the system architecture this robot is designed to be used as a highly flexible tool with two focuses. On the one hand the robot assists the human and releases him from monotonous tasks. And on the other hand due to the mobility and lightweight structure the presented robot is adjustable to workplaces that are conceived for humans.

Fig. 4 shows the assembly of a gear. This application was chosen to study the behavior of the robot and the complete operation procedure. The essential tasks are outlined in the following enumeration.

1) the human worker guides the mobile robot towards the workplace;
2) the operator performs a localization procedure to establish the position of the task with respect to the robot’s position; the robot verifies with its sensors that the position is feasible;
3) the operator starts the automatic assembly process; the operator leaves the supervised workspace of the mobile
robot; the robot carries out the assembly process; the safety sensors are used to verify that no worker enters the workspace;
4) after completing the assembly process that robot settles to a safe state; either the robot awaits the worker to guide it to a new position or the worker admits a repetitive task execution.

A G-code programm was therefore implemented and run on the robot. Since resulting working sequences in industrial applications are almost similar the identified procedure is transferable to other relevant applications such as processing. Those production steps represent the working behavior of the robotic system as well as actual working conditions and define a combination of modes of operation.

A. Modes of operation

Each mode of operation affects the human-robot interaction and likewise safety aspects which are discussed in-depth in Sec. V.

1) Idle Mode: In Idle Mode the robot is inactive and awaits new orders from the human worker. An order corresponds hereby the selection of a mode or its combination. After finishing the order the robot returns to the idle mode. So the idle mode defines the starting and end position and can only be changed manually.

2) Guiding Mode: During Guiding Mode the arm is in a safe position and in any module the brake is active. However, the moving of the platform towards the workplace is allowed. Different options for platform navigation are available. Firstly, navigating the platform via manual input unit or gamepad and secondly, via autonomous navigation as a result of specifying on a map. Thirdly, it is planned to integrate a force-torque sensor that allows touching and directly guiding at the TCP (Fig. 4).

3) Localization Mode: The goal of the Localization Mode is to adjust the tool to some kind of local features and compensate possible errors. Typical errors are compliance and temperature. At this time the worker has to enter the robot’s reachable workspace and position the arm manually, for instance automatic support like visual servoing is also conceivable. Contrary to the arm the platform is inactive.

4) Automatic Mode: In order to realize the Automatic Mode the system has to monitor the workspace around the robot plus an offset for stop time and arm reach. Consequently the human cannot enter the workspace without interrupting the robot. Violating the workspace of the robot will stop it. If no safety issues occur the robot executes a predefined assembly program.

V. SAFETY CONCEPT

The operation concept of rob@work 2 as outlined in section IV comprises different operation modes that include close interaction of robot and human worker. This section outlines the safety related aspects of the control system arising from this close interaction.

To allow for interaction between robot and human worker hazards resulting from the movement of the arm have to be eliminated. This feature is certainly required during Localization Mode and also helpful during Automatic Mode in narrow workspaces.

Elimination of hazards due to the robot is accomplished in accordance to part 1 of DIN EN ISO 10218-1 [1] by limiting the dynamic energy of the robot. This can be achieved using one of the following approaches:

- Limitation of input power to the robot to a maximum of 80 W [section 5.10.3]. This is done using redundant monitoring of the power supplied to the robot in the hardware safety path. In case an exceedance of the 80 W power limit is detected the power supply to the arm is cut. The software safety path limits the speed of movement of the robot using a model of the robotic manipulator to ensure the power limitation function of the hardware path is not tripped.

- Implementation of controller hardware and software capable of safe speed limitation [section 5.10.3] with Category 3 according to DIN EN ISO 13849. This requires safe hardware and software for the computations required for the speed monitoring. Since computations for speed monitoring of the robot are more complex and rely on sensor data from the encoders of the robot the development effort for this safeguarding approach is significantly higher compared to input power limitation.

In case of co-operative work any movement of the robot needs to be enabled by the human by pressing a three-position switch to further improve safety. Additional to the analysis of the hazard due to the robot the validation of the safety concept for the particular application presented above also has to include the safety assessment of the tool used by the robot.

For Automatic Mode hazard mitigation by using the laser scanner system as presence detecting device to monitor a safety zone around the robot is an alternative. DIN EN 999 as the applicable standard for this approach requires monitoring of a safety distance $S$ defined by:

$$
S = (1600\text{mm/s} (T_{\text{M}} + T_{\text{C}})) + (1200\text{mm} - 0.4H) + Z_G \quad (1)
$$

where the applicable data for rob@work 2 is listed in Tab. I.

The resulting safety distance for rob@work 2 is $S = 3060\text{mm}$. The mayor contribution to this safety margin comes from the stop time of the robot arm. This margin also has to include the stop time of the robot tool in case
the tool exhibits a hazard to workers. The required safety margin reduces the flexibility of use of the robot since obstacles within the safety margin need to be learned for the application. The workplace of the robot inside the safety zone may not alter since this would cause the robot to erroneously detect intrusion into the safety zone. Further access of workers into the safety zone for tasks not related to the robot operation is not possible. This poses a critical disadvantage in particular for narrow workspaces like for example in shipbuilding. Therefore the limitation of the energy supplied to the robot appears to be the superior approach for this kind of application.

**VI. EXPERIMENTAL DETERMINATION OF REPEATABILITY**

In order to evaluate the capabilities of the robot system with respect to handling tasks test benches have to be defined and measurements must be taken. Therefore, the main area of the experiment is the robot arm and the linked control system. The most significant assembly applications is exact part to part positioning. Concerning relevant robot test benches the norm DIN EN ISO 9283 is applied. This norm defines both main system characteristics, and measuring setups. For part to part positioning the static characteristic pose repeatability is significant. The experimental results are determined with the presented system as well as selected measuring setup and may not reflect the general system performance of the robot arm.

Due to the relevance of the application the measurements were carried out in the suspected main working area. Hereby DIN EN ISO 9283 suggests constructing a cuboid, fitted into the main working area, that yields five points on a plane where the measurements take place. See Fig. 5 for more details.

![Fig. 5. Visualization of applied measuring points and measurement setup](image)

To allow for repositioning of the system in **Guiding Mode** appropriate safety measures are required to avoid hazards due to collision of the robot. DIN EN 1726 is used to derive safety requirements for the case that the system is relocated by hand-guiding or remote control. The most important safety requirements implied by this standard are:

- speed limitation to a maximum speed of 6 km/h;
- stop of movement upon release of control device;
- protection against unauthorized use.

These safety requirements are fulfilled by rob@work 2 due to its hardware.

In case of autonomous navigation the system is designed according to DIN EN 1525 For this case the required safety distance is computed as the sum of the stop distance of the platform, an additional safety margin for erroneous readings of the laser scanner system required by the manufacturer and a safety margin for the low ground clearance of the platform due to its front wheels. The related parameter values can be found in Tab. II. Experiments for determination of the platform stop distance were carried out under different operating conditions and already contain alteration of brake efficiency due to wear and repeated braking. The safety distance of the platform resulting from the data of Tab. II is 750 mm. This safety margin in front of the platform is monitored by the laser scanner system.

**TABLE I**

**DATA FOR COMPUTATION OF SAFETY MARGIN IN AUTOMONOUS NAVIGATION IN GUIDING MODE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_M$</td>
<td>Stop time of robot</td>
<td>1 s</td>
</tr>
<tr>
<td>$T_R$</td>
<td>Reaction time of safety system</td>
<td>140 ms</td>
</tr>
<tr>
<td>$H$</td>
<td>Height of the laser scanner systems above ground required for protection against reach-over with upper limbs</td>
<td>160 mm</td>
</tr>
<tr>
<td>$Z_G$</td>
<td>Safety margin for evaluation errors of the laser scanner system</td>
<td>100 mm</td>
</tr>
</tbody>
</table>

**TABLE III**

**REPEATABILITY RESULTS AT POINT P1 (50 % OR, 102 % NL)**

<table>
<thead>
<tr>
<th>Type</th>
<th>Experimental result</th>
</tr>
</thead>
<tbody>
<tr>
<td>position repeatability</td>
<td>0.1555 mm</td>
</tr>
<tr>
<td>orientation repeatability x-axis</td>
<td>±0.0156°</td>
</tr>
<tr>
<td>orientation repeatability y-axis</td>
<td>±0.0352°</td>
</tr>
<tr>
<td>orientation repeatability z-axis</td>
<td>±0.0196°</td>
</tr>
</tbody>
</table>
to the measurements presented in Tab. III all other results have less deviations. Generally, it is comprehensible, that the farther the points are the pose repeatability increases. As anticipated the equidistant points of the cuboid have similar repeatabilities for the pose. Above all the measured pose variations are less than 0.2 mm or apart from measurements that have to be discussed in detail less than 0.1 mm, (Tab. IV). As can be seen in Fig. 6 most values are even in a smaller range than 0.1 mm.

However, especially the results belonging to the spreading of position data along the y-axis show that points exist which differ more and do not reflect the majority of the measurements. Compared to the measurements that were accomplished at point P4 with an OR of 50 % and a load of 44 % NL one can observe such an effect, too. As it is depicted in Fig. 7 it is more significant. Only one measurement declines the achievable value.

VII. CONCLUSIONS AND FUTURE WORKS

This paper presents the assistant robot system rob@work 2 for industrial applications. The system architecture is discussed and the final integration is introduced according to the needs in industrial applications. Regarding the workplace conditions and safety issues modes of operation are proposed to simplify the use of the robot and thus the safe co-operation between human and machine. The safety requirements are discussed in detail and techniques are proposed to comply with recent norms and standards. Furthermore, it is shown by experimental verification that the realized robotic system is able to achieve a pose repeatability smaller than 0.2 mm. Since flexibility and accuracy has been pointed out as the optimal solution towards effective collaborative automation the proposed robot system is able to produce relief. Based on the experience with the rob@work 2 system the third generation of the rob@work family has just been released offering omnidirectional motion and integration with ROS.

VIII. ACKNOWLEDGMENTS

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