The KUKA-DLR Lightweight Robot arm – a new reference platform for robotics research and manufacturing

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Summary / Abstract

Transforming research results into marketable products requires considerable endurance and a strong sense of entrepreneurship. The KUKA Lightweight Robot (LWR) is the latest outcome of a bilateral research collaboration between KUKA Roboter, Augsburg, and the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR), Wessling. The LWR has unique characteristics including a low mass-payload ratio and a programmable, active compliance which enables researchers and engineers to develop new industrial and service robotics applications with unprecedented performance, making it a unique reference platform for robotics research and future manufacturing. The stages of product genesis, the most innovative features and first application examples are presented.

1 Introduction

Innovation at KUKA Roboter is seen as a core component of the company's business strategy. Innovation becomes a reality when research results are transformed into products, so that these products can be bought and people gain employment. KUKA has a track record of successful collaboration with academia and has managed very often to turn the outcome of collaborative research projects into successful products [9].

The latest innovation in this sense is the KUKA-DLR Lightweight Robot (LWR). After many innovative steps, first at DLR, later at DLR and KUKA, both partners managed to successfully go the strenuous road from the original invention, an idea made manifest in 1991, to prototypes produced in a small series starting in December 2008.

The main motivating force behind the lightweight robot development is to revolutionize the applicability of robotics in our society. Robots should become available not only on the shop floor, but also at our homes, offices, in the public and in space. Looking at the future of automation, robots will not only be stupid machines carrying out dull and dangerous work and being caged behind fences, but work as robot assistants in close proximity of, and in cooperation with, humans. These robot assistants will require the characteristics presented in Table 1 in comparison to today's industrial robots.

Future robot assistants may be realized by integrating lightweight robot arms because they are in principle less dangerous for tasks which require closer human-robot interaction without fences and are much more portable, and thus suitable for mobile robot applications.

In the following, we present the LWR product genesis starting from the first research demonstrators (Section 2). Key characteristics of the LWR will be explained in Section 3. First applications in research and industry are outlined in Section 4. The summary and strategic conclusions will be presented in Section 5.

"Classical" industrial robot	Future production assistant
fixed installation	flexibly relocatable (manually or on mobile robots)
periodic, repeatable tasks; seldom changes	frequent task changes; tasks seldom repeated
programmed online / offline by a robot specialist	instructed online by a process expert supported by offline methods
infrequent interaction with the worker only during programming	frequent interaction with the worker, even force / precision assistance
worker and robot separated by fences	workspace sharing with the worker
profitable only with medium to large lot sizes	profitable even with small lot sizes

Table 1: Comparing classical industrial robots with future production assistants.

2 Stages of research and product development

The development of the lightweight robot has its roots in the 1993 ROTEX space shuttle mission, which demonstrated for the first time a robot arm in space that could work both by tele-operation from the ground and autonomously in space, e.g., to catch small flying objects.

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To enable the astronauts to train for the mission they needed a comparable robot on Earth. However, the standard robots at that time were too heavy (and not powerful enough) to sustain on ground against gravity. Thus, the need for a small lightweight robot was born, which was supposed to be based on the human model of an arm aiming at a weight-to-payload ratio of 1:1 and similar performance. To achieve these design goals it soon became apparent that the weight-to-payload ratio of existing robots had to be reduced by an order of magnitude which could only be achieved by an extremely lightweight construction and unifying mechatronic design approach. In the following, the three development phases research, technology transfer and product development are described in more detail.

2.1 Stage 1: Research at DLR

The intensive research and development phase at DLR led to three generations of lightweight robots: LWR I, LWR II, and LWR III (Figure 1).

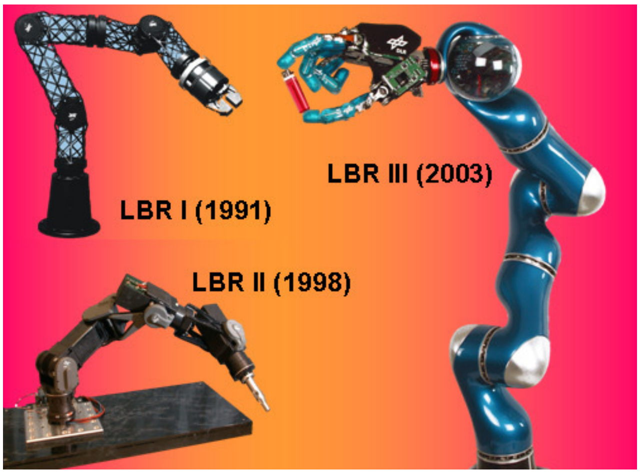

Figure 1: Three generations of lightweight robots at DLR.

All three generations had two major characteristics in common from the very beginning:

- kinematic redundancy, i.e., seven degrees of freedom, similar to the human arm, which made possible, e.g., an elbow motion while maintaining the pose of the hand,
- joint-integrated power and signal processing electronics including torque measurements in all joints by means of torque sensors mounted on the gear box output side.

To achieve these characteristics, significant advances in drive technology, a unifying mechatronic lightweight design and new control concepts were required. These new control concepts are based on precise torque measurements in each joint, on the link side, i.e., after the gear. Special high-resolution torque sensors were developed which were based on linear variable differential transformers (LVDT) for the LWR I and on strain gauges for the LWR II and III. These sensors enable:

- active vibration damping and sagging compensation of the very slim, and therefore, elastic joints and structures, resulting in high precision and settling times comparable to much heavier and stiffer industrial robots;
- actively controllable, programmable compliance at joint and Cartesian levels. Joint and Cartesian stiffness and damping parameters can be adjusted between zero and the maximum value corresponding to position control. This allows for fine-tuning the robot characteristics to a particular task or environment. Also, the robot may be intuitively programmed by manually guiding it;
- sensitive detection of contacts and collisions to allow for a safer interaction with humans and compliant reaction to slightest touch.

The second lightweight robot generation demonstrated successfully the main performance and control characteristics. The third generation (LWR III) excelled by employing motors and encoders developed by DLR, by reworking and largely renewing the joint electronics, rigorously applying lightweight construction principles, and further developing and augmenting control concepts. The performance improvement could be seen in the achievable dynamics, controllability during contact and in detecting collisions. At the same time the power consumption could be cut by 50%. The kinematics was changed to an anthropomorphic joint order with shoulder, elbow and short wrist axes to allow for a more intuitive operation and manipulation. The wrist axes can be easily reconfigured to carry artificial hands in an ideal way. The newly introduced carbon fiber reinforced plastics with round contours both improve the robot's appearance and reduce the reluctance of users to touch the robot, and thus promote the goals of "soft robotics". Last but not least, the LWR's third generation was optimized with respect to commercialization regarding manufacturability and cost by designing the joint modules with a large number of economically producible common parts.

2.2 Stage 2: Technology transfer

Towards the end of the research stage both KUKA and DLR thought about how to transfer the developed technology. Although quite mature the advanced control concepts were not yet available with an industry-proven controller that could provide a programming and operation environment and sequence control. To be able to combine the best of both worlds the PAPAS project – sponsored by the German Federal Ministry of Education and Research (BMBF) – was initiated in 2003.
Besides the development of plug-and-play drive and control technologies (see [18]) and a mechatronic development environment (see [11]) the DLR basic controller and the KUKA controller were for the first time connected with each other [2]. The KUKA teach pendant provided the already established programming and operation environment and look & feel for the industrial user and at the same time enabled the access to the new lightweight robot technology with its unique performance characteristics.

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The DLR controller was used as the external clock for the KUKA controller which could adjust to this external timing. Both controllers communicated asynchronously and synchronously at the interpolation rate of the KUKA controller. Asynchronous commands were used to convey impedance and redundancy parameters, while interpolated joint angles and the Cartesian position of the flange were synchronously communicated (Figure 2). Thus, the KUKA controller could provide sequence control and offer the user an industry-proven interface for programming and operation, and for the first time, the DLR compliance control could be made available for application programming.

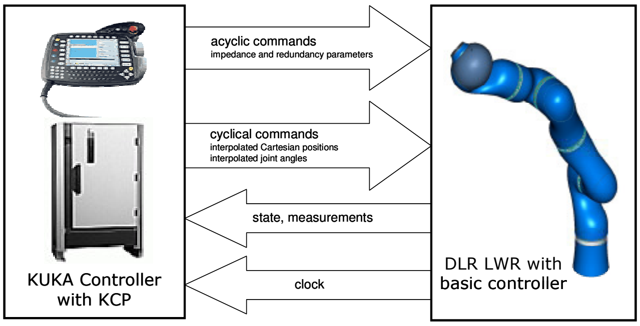

Figure 2: Coupling of KUKA robot controller (KRC) and operator interface (teach pendant KCP) with DLR basic lightweight robot controller.

On the occasion of “Automatica 2004” (the world’s largest robot exhibition) the “RoboAssistant” – this is how the combination of DLR LWR and KUKA controller was called – was presented to the expert visitors for the first time (Figure 3). Programming by demonstration and joining various bolts were successfully demonstrated. The visitors were allowed to manually move and program the robot as described in [7]. The vision of a robot assisting a worker during production processes was thus becoming obvious for the visitors. Some visitors rated the different characteristics of the lightweight robot in a questionnaire (see also Section 4.1).

Figure 3: First public presentation of the “RoboAssistant” (DLR lightweight robot controlled by KUKA KRC) at Automatica 2004.

The results of the PAPAS project and the public presentation were very encouraging for KUKA and DLR and led to increased efforts in the technology transfer. Once again the BMBF supported this technology transfer through the project DESIRE [5], of which one part was designed as a PAPAS follow-up technology transfer project between DLR and KUKA. Although largely financed by KUKA alone, DESIRE nevertheless financially supported the development of a one-PC controller solution (based on the KUKA KRC) as opposed to the former two-PC controller solution resulting from the PAPAS project. A data buffer could thus be eliminated that was needed for the PAPAS communication, but led to dead times that were thus limiting the performance of the whole system. Moreover, the impedance control was further improved– all important factors on the way to a product.

2.3 Stage 3: KUKA product development

In parallel with the DESIRE project, work was started without funding on finding ways toward series development. Intensive cooperation therefore took place between KUKA and DLR in order to communicate to the KUKA developers the know-how and understanding required for the development of lightweight arms, sensor components and integrated electronics. The mechanical and electronic components of the robot, as well as the drive technology and the controller, were jointly subjected to a critical revision. The decision was taken to produce a first small series of the lightweight robot, which would be closely related to the LWR III of the DLR. 18 robots of this type (KUKA LWR3) were built. Some of these were used to carry out load tests at KUKA, in order to allow further development of the software and servo control at DLR and at KUKA, and to enable the LWR to be adapted to the applicable EMC directives. The remainder was assigned to selected research and development partners for development of applications to be able to demonstrate the potential and limitations of the specific control technology of the LWR.
The LWR3 was presented in various applications on the KUKA booth at Automatica 2006 (Figure 4). The advantages of the compliance control were demonstrated in the tracing of an unknown wavy surface which could be pushed into different orientations by the visitors. Rotation of a crank on an inclined plane of unknown gradient could also be shown here. A further exhibit showcased programming by demonstration, in which the robot mimicked

Figure 4: Two example applications of the lightweight robot at Automatica 2006: compliant surface following (left); programming by demonstration through manual guidance (right).

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the assembly of Lego bricks as shown by the visitor. Once demonstrated, the robot was able to reproduce the assembly steps; this was done not by recording and playing back the trajectory used by the visitor, but by calling different pre-programmed skills for gripping and joining the bricks at the target positions.
A further robot was presented on the neighboring DLR booth. Here, image-controlled and compliance-controlled assembly processes were shown for the first time, together with new methods for collision detection and reaction.
After the successful trade fair presentation, it quickly became apparent that 18 robots were not enough to be able to meet the demand for the LWR. Experience from the load tests and the first applications were therefore used to design an improved version – the LWR4. Certain components, such as the gear units and cable routing, were modified to make the robot easier and more cost-effective to produce and to ensure greater reliability. The power section was expanded for the control of the joint sensors, the cables to the torque sensor were changed and the cable inlet from the controller to the LWR on the robot base was made pluggable. For the LWR4, DLR completely revised the servo-control section of the controller software as well as the joint software, in order to achieve a streamlined and easy-to-service structure with significantly reduced latencies, with the result that a servo-control switchover (for example, in the event of contact) can be performed smoothly at full speed within 1 ms.
The user-friendliness was further improved, and a wide range of new software functions were implemented, such as contact detection, virtual walls or the superimposition of impulses. These new functions, utilizable under KRL, allow simplified programming of assembly processes. For example, the parameters of Cartesian impedance control can be freely programmed in a system variable. Moreover, it is possible to switch to Cartesian impedance control, i.e., from stiff position control to compliance control, within 1 ms in the event of contact ("TRIG_BY_CONTACT"). During joining itself, force oscillations can be superimposed ("DESIRED_FORCE") in order to prevent the parts from getting jammed.
Since December 2008, production has been ongoing for a planned total of 60 robots of this fourth LWR generation, which are being sold to customers throughout Europe (Figure 5). The robot is not yet released for use in production, so that the purchasers largely come from the research sector and from the advance engineering departments of companies which are looking to create new, more efficient production methods through the use of the LWR.

Figure 5: The KUKA lightweight robot with controller (2006).

3 Innovative characteristics of the KUKA Lightweight Robot

The characteristics of the LWR3 and LWR4 are comparable and are based on concepts which are generally regarded as decisive for the next generation of robots that are to be capable of working together with humans. The weight was reduced to the limits of what is technically possible, which decisively improves the robot's dynamic performance. The lightweight robot LWR4 is designed for a rated payload of 7 kg, and itself has a mass of 15 kg. Its low mass helps reduce the power consumption and additionally allows a hitherto unknown degree of mobility for robot arms. In the first place, the robot can be carried manually to its place of use, and secondly, battery-powered operation is possible in mobile robot systems, for example.
With its seven axes, the robot has one redundant degree of freedom, which gives the programmer more flexibility in cluttered workspaces. The seven axes also help to avoid typical singularities of 6-axis kinematic systems. The rounded design, which rules out any risk of crushing between structural components, contributes to the overall safety.
Torque sensors in each of the seven joints, a detailed dynamic model of the robot, state control and a high servo-control cycle rate (3 kHz locally in the joints, 1 kHz overall), combined with powerful drives and the lightweight construction, enable active damping of vibrations to achieve excellent motion performance (path accuracy, repeatability) [1]. Furthermore, this also makes it possible to achieve a programmable compliance, both axis-specific and Cartesian [12]. This allows the robot to act like a spring-damper system in which the parameters can be set within wide limits. This compliance control enables the robot to be manually guided, thereby opening up a totally new experience in human-robot interaction. A programmer or user can thus move the robot intuitively and quickly to the desired position. A further advantage is to enable the programming of assembly procedures that could previously be implemented only with great difficulty. Moreover, it is no longer necessary to use compliant grippers or other equipment, as the arm already provides the required compliance.

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Control parameters can be switched over within one control cycle (1 ms). In this way, it is possible to switch extremely quickly from a stiff, position-controlled mode to a compliant behavior. The high sensitivity of the lightweight arm and the detailed knowledge of the model allow detection of collisions. This sensitivity, coupled with the advanced servo control, enables faster joining of components since it is possible to move on the programmed path right up to a planned collision with the component, and then search for an edge or hole in compliant mode. In this way, the time taken to execute an assembly task can be significantly reduced.

4 Application examples

In the following a number of application examples of the lightweight robot technology are given.

4.1 PAPAS: First application development and results of a user survey

In the BMBF-sponsored project PAPAS described in detail in Section 2.2, prototype applications were already implemented which clearly demonstrated the outstanding performance and potential of the LWR technology for the industrial sector. These include programming by demonstration, and repeated execution of these programs for different mating and peg-in-hole tasks (see Figure 3).

At Automatica 2004 the users were asked for the first time what features they liked best about the new robot system. The answers are shown in Figure 6. Programming by demonstration, compliance, and the internal cable routing were named as the three most outstanding features.

The potential offered by the robot system's compliance was shown in the extreme example of turning a crank. What was programmed in KRL was a square path. What was executed, due to the enforced guidance of the crank, was a circular motion. It is the compliance of the LWR that permits this automatic adaptation of a program created before runtime to the physical conditions of actual execution. These and other applications were shown to the general public at Automatica in 2004 (Figure 3), 2006 (Figure 4) and 2008 (Figure 8 and 9).

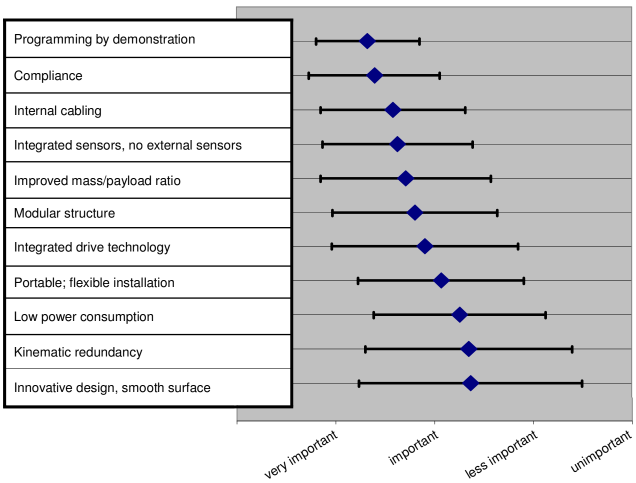

Figure 6: Results of the first LWR user survey, conducted at Automatica 2004 (standard deviation calculated from the assignment of the ranking 1 = "very important" to 4 = "unimportant").

4.2 DESIRE: Mobile dual arm robot with 4-finger hands

The DESIRE project [5] was a BMBF-sponsored project which had the overall objective of maintaining and extending the leading role of German industry and research in the field of service robotics. Alongside the activities already described in Section 2.2 in connection with the technology transfer from DLR to KUKA, one major aim of the project was to increase the everyday applicability of perception and manipulation and to integrate the majority of the components developed in the project to a common technology platform (Figure 7).

In the area of perception, the recognition of everyday objects was successfully increased to a total of 100 different objects. These objects could also be manipulated by the DESIRE technology platform. Its two lightweight robots were connected via an easy-to-use programming interface ("Manipulation API") to next higher-level controller responsible for manipulation and grasping [17]. The data were exchanged at the interpolation cycle rate of the controller (12 ms). The two LWR models were equipped in the course of the project both with the 4-finger hands from DLR and SCHUNK and with the 3-finger hands from SCHUNK. This was easily accomplished thanks to the quick-change adapter on the flange on the LWR, which was also developed as part of the project. A particular advantage here was that the data cables and energy supply system to the hand could be routed inside the LWR, thereby preserving the interference contour of the system. This could also be put to advantage for collision avoidance. It was possible to detect, before they occurred, possible collisions of the arms with each other, with the body and head of the technology platform, and with surrounding objects [10] – though not in safe technology, however.

Figure 7: Mobile DESIRE technology platform with two lightweight arms and two 3-finger hands.

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4.3 SMErobot: The worker's third hand

The aim of the EU-funded project SMErobot [15] was the development of robot systems that would be particularly suitable for use in small and medium-sized enterprises which require the characteristics of future robotic assistants listed in Table 1. These companies are still reluctant to invest in robot systems because they are too difficult to program and operate and thus only partially suitable for manufacturing small batch sizes.

One of the project's technology demonstration cells, contributed by KUKA with the support of the DLR, was designed to facilitate assembly tasks by acting as the worker's "third hand". The robot's task is to fetch the components and position them while the worker carries out the actual joining process (Figure 8).

Tack welding was chosen to demonstrate the technology, because this involves highly repetitive and time-consuming positioning tasks before the tack welds can be made. The demonstration cell constructed during this project allows the robot first to be programmed by demonstration and then to execute the learned production steps repeatedly as often as required.

Both at the demonstration phase and during actual production, the worker is guided by a predefined work sequence. Interaction with the sequence controller is carried out via a touchscreen. The robot memorizes the demonstrated sequence, consisting of the start and end positions, robot motions and tool commands. The sequences can be changed via the user interface.

The robot itself can be quickly guided through the workspace thanks to its highly responsive sensors and servo control technology. Fine positioning is carried out in the so-called step mode, where simply tapping on the structure of the robot causes the system to move in steps of a fixed size. The less accurate positioning by free-hand guidance is thus supplemented by an intuitive means of fine positioning.

During task demonstration, a model of the robot's surroundings is built up automatically. This enables collision-free path planning during positioning operations, which is carried out autonomously by the system to support the worker and ultimately to contribute to greater productivity.

The quality of the components can be inspected using a 3D scanner [16]. Further automated processes can be prepared.

The technology demonstration cell "The worker's third hand" was shown in action at Automatica 2008 and at the final project presentation in May 2009. The visitors could observe the robot acting as the worker's third hand, fetching the parts for assembly, precisely positioning them and holding them so that a worker could easily perform the required processes.

Figure 8: Welding of workpieces in small batches without fixtures – The robot as the worker's third hand.

4.4 PHRIENDS: Safe human-robot interaction

Safe human-robot interaction is a basic requirement for the coexistence of humans and robots in industrial environments and public and private domains. In the EU-sponsored project PHRIENDS [13], the potential risks of physical contact were investigated and scientifically evaluated on the basis of the results from the SMErobot project. First solutions were developed with the aim of allowing people and robots to share the same workspace in the future (Figure 9).

First, a sound scientific basis for safe human-robot interaction was created by analyzing biomechanical and forensic injury criteria. Simulations and real crash tests between dummies and different robot arms with payloads ranging between 3 - 500 kg were carried out and the robotic risks evaluated to standards equivalent to Euro NCAP. It was shown that none of the investigated robots could inflict life-threatening injuries on humans as a result of a blunt impact, provided that the person does not become trapped in the process [8]. From the knowledge gained about the potential degrees of human injury involved, design recommendations could be made for safe robot systems.

Further development work is necessary, however, before *certified safe* human-robot cooperation is achieved. Even though the LWR has powerful features which detect collisions very quickly and react appropriately, these functions cannot yet be guaranteed under sensor failure. The next step on the road to robotic applications without external safeguards is thus the implementation of the detection of collisions and the reaction to collisions in *safe technology*. The PHRIENDS project has, however, produced confirmation that the accurate dynamic model of the robot and the integrated torque sensing engender a high degree of sensitivity along the entire structure of the robot, and that new reaction strategies, including virtual walls, significantly improve the human friendliness of the robot.

4.5 BRICS: Fast interface for research

One goal of the EU-funded research project BRICS [3] is to establish the KUKA LWR as a reference platform for research, in order to make results easier to compare and to transfer to industry. A further goal is the creation of a

Figure 9: Safety exhibits at Automatica 2008: Crashtest with ADAC dummy (left), clamping test set-up (right).

small-scale controller in order to make it easier for users and system integrators to integrate the lightweight robot as a component in their own (higher-level) (control) system – for example as a manipulator for a mobile platform.
As a first step toward reaching this goal, a software interface was created (building on work from the PHRIENDS project) to enable the robot behavior to be very precisely monitored (e.g., position and torque measurement data). Additionally, the robot can be remote-controlled in selectable autonomy levels (ranging from discrete events in KRL to quasi-continuous motion at millisecond intervals). The existing control processes of the robot can be utilized for this purpose; the parameters (e.g., stiffness and damping) can be set via the interface (Figure 10).
In a second step, this interface was completely integrated into the KUKA LWR controller, and is now available to research partners as the "Fast Research Interface" (FRI) [14]. Based on a simple UDP protocol, the interface allows the user to control the robot and monitor its status from an external PC. When establishing a connection, the sampling rate of the interface can be freely selected between 1 and 100 ms. Motion commands which are issued more slowly than at millisecond intervals are preprocessed and fine-interpolated by the KUKA controller. As Ethernet UDP is used as the connection technology, the interface can be ported to a wide variety of operating systems and computers.

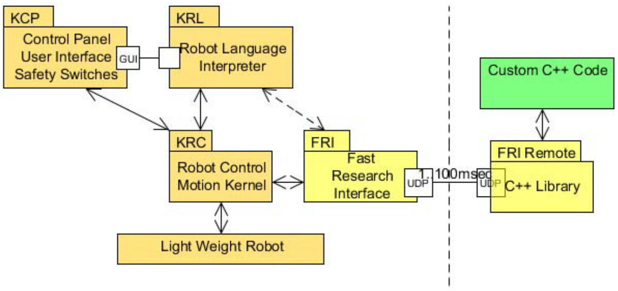

Figure 10: Overview of the Fast Research Interface (FRI) control system architecture (for details see [14]).

4.6 First industrial applications

On account of its high-performance force control, the KUKA lightweight robot is particularly well-suited to assembly tasks. Parts are mated using a human-like tactile sense with the aid of the compliance control. A paradigm shift is thus taking place. The joining tasks are solved by tactile position detection rather than on the basis of position accuracy, as previously. This makes it easy to compensate for inaccurate component positions.
The effectiveness of this approach has been demonstrated in a number of prototype applications. These include the insertion of rubber plugs in manufacturing application (Figure 11, left), for example, and the automated clipping of cables into cable clamps. With the torque monitoring, screws can be tightened to a specified torque directly by the LWR using a tool consisting only of a simple holder with a driver bit. The screw head can be reliably located by the LWR performing a search motion. A major car manufacturer has implemented a pilot system in which two KUKA LWRs assemble a transmission in an operation making multiple use of the special properties of the LWR [4].
The vision of easily programmable and temporarily implementable automation of machine tool loading and unloading was demonstrated at EMO 2007 (Figure 11, right). Together with its controller and an operator panel, the KUKA lightweight robot is mounted on a trolley, which is brought into position in front of the machine tools. The capability of manually guiding the robot means that it can be quickly and easily instructed by the operator. Even complex movements, like opening a door along a circular path, are very simple to perform by means of the compliance control, with the robot being stiff in the main direction of motion and compliant at orthogonal directions.

Figure 11: LWR inserting rubber plugs in a manufacturing scenario (left) and loading/unloading machine tools (EMO trade fair 2007).

5 Summary and strategic conclusions

We presented the development history of the KUKA Lightweight Robot (LWR), from its early stages of research at DLR beginning in the 1990s through the technology transfer stages (since 2004) and product development. The LWR is a complex mechatronic product with unique characteristics. Of utmost importance are its sensitivity along the arm structure and its active compliance using joint torque sensors and control. The robot is available to researchers and advance engineering departments of manufacturers which are looking to create new, more efficient production methods through the use of the LWR.
A key factor for this innovation to happen was the transfer of knowledge through people coming from the research partner DLR and hiring at KUKA. These people pushed the technology transfer and proved an entrepreneurial spirit. They made KUKA believe in the lightweight robot technology and advanced its development.
Important development milestones were reached in public funded research projects such as PAPAS, DESIRE, SMErobot, PHRIENDS and BRICS. Here, the merge of the DLR controller and the KUKA controller and initial application developments helped to gain visibility within the company, but also externally. Public presentations of the LWR system at exhibitions and project meetings increased the demand for this technology and had a very positive marketing effect positioning KUKA Roboter as technology leader.
This position is amplified by the recently developed Fast Research Interface (FRI) which turns the KUKA LWR

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into a unique reference platform for robotics research with a 1 ms access to core controller functions. The authors hope that the LWR will become a central element in robotics research world-wide.

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