The European Co-ordination Hub for
Open Robotics Development

CoHRoS – Cooperate Programming of Highly Redundant Robot Systems

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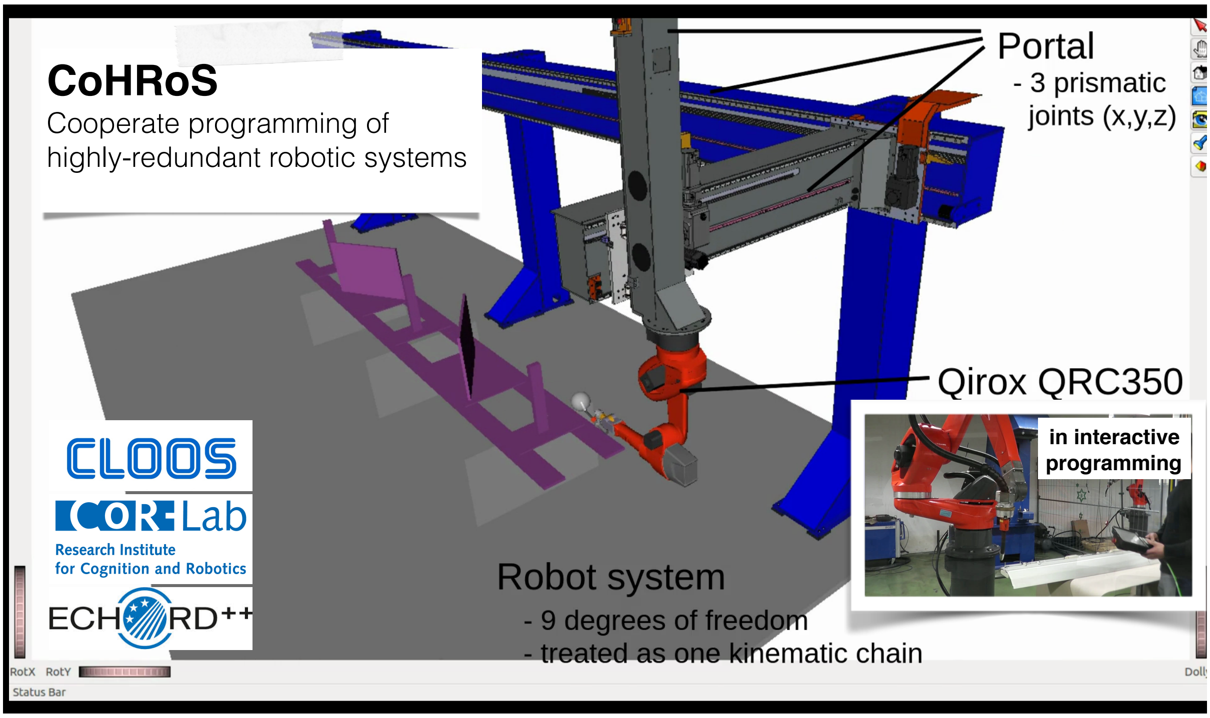
Section 1: Executive summary

Highly redundant robots with up to ten or more degrees of freedom are commonplace for welding, grinding, or varnishing of large in sectors like earthmoving equipment, agricultural machines or automotive engineering. Programming these systems is tedious, costly and needs highly specialized expertise, which is an important factor to achieve a reasonable return-of investment for automation. Current programming is mostly based on manual recording of up to thousands of key-frames, typically done by domain experts in a tedious step-by-step procedure.

The project CoHRoS aimed at redefining and advancing the state-of-the-art in programming for such highly redundant robot systems through developing a practical and robust method for assistive teaching. It developed a structured user interaction to transfer their contextual knowledge about the application step by step to the robot. The project employed machine learning for generalizing this knowledge from examples. The method was implemented and tested by application programmers as a prototype on a redundant welding robot manufactured by Cloos. The results showed that programming of complex applications for highly redundant robots can be significantly facilited.



Section 1.1: Milestone overview

#	Description	status
M1	Requirements and TRL levels available	Timely achieved
M2	Working proof-of-concept in simulation	Achieved
M3	Working prototype in real-world scenario	Deviated

Note on M3: Given the unfortunate situation that Cloos, due to changes in the personnel, could not work with the foreseen resources and support on the project, the transfer of the developed methods into practical application was delayed. Nevertheless, with high effort of the remaining personnel, a real-wold working prototype was created and evaluated qualitatively by Cloos developers. The planned more in-depth user-study could not be performed in the lifetime of the project.

Section 1.2: Deliverable overview

#	Description	status
SB	Story Board	submitted
MMR	Multi-Media Report	submitted
D1	Requirements for reference application	submitted
D2	Simulation of high-DOF welding robot teaching	submitted
D3	Video: Teaching redundancy resolutions and welding tasks in simulation using shared human-machine control	submitted
D4	Design of user study in real-world welding tasks	deviated

Note on D4: see explanation above.

Section 1.3: Technical KPIs

#	Description	status
1	Speed up in development/ programming/ setup	Achieved
2	Number of trajectory key points	Not evaluated
3	Quality of the trajectory	Not evaluated
4	Speed up in execution	Not evaluated
5	Scalability of the learning algorithm for different platforms	Achieved
6	Human robot interaction strategies	Achieved
7	Safety consideration for certification purposes	discussed

Note on tKPI 2-4: Given the unfortunate situation that Cloos, due to changes in the personnel, could not work with the foreseen resources and support on the project, the transfer of the developed methods into practical application was delayed. Therefore, quantitative data from a user-study that would allow to verify tKPI 2-4 is lacking. The qualitative evaluation perfomed by Cloos programming experts nevertheless suggests that these tKPIs could be reachable. Therefore the correct status is "not evaluated", rather than "not achieved". tKPI 7 was discussed between the partners in the final meetings, with the conclusion that a safe implementation into the controller still requires significant development and testing work, which however is beyond a fundable research project.

Section 1.4: Impact KPIs

#	Description	Status
1	Impact on Cloos: reduction of development costs by estimated up to 25%	Not achieved/ evalutated
2	Impact on Cloos: Reduction of production costs for end consumer	Not evaluated
3	Impact on Cloos: programming will be made easier - less application support from Cloos will be necessary	Not evaluated
4	Impact on Cloos: secure and possibly increase market share. Support work places in Europe	Not evaluated
5	Competitors	Not evaluated
6	Scalability (general) New, for Cloos non-competitive applications can potentially be reached by reusing the functionality	Achieved
7	Scalability (general) The methods to be developed could be used in other applications and domains	Achieved
8	Scalability (general): The methods to be developed can also be used on only mildly redundant robots	Achieved

Note: this list of impact KPIs was not part of the original proposal and was included only after acceptance of the project upon further negotiation and some pressure from the project management. Naturally, in particular the points 2-4 are unrealistic to achieve within the lifetime of a short project like an ECHORD++ experiment, regardless problems in the project execution. Given the unfortunate situation that Cloos, due to changes in the personnel, could not work with the foreseen resources and support on the project, it is currently basically impossible to evaluate these iKPIs.

For reference, the original KPIs proposed by the project together with the status at the end of the project are reproduced below. Note that there are currently no follow-up activities after end of the project due to the changes in personnel and policy of both partners.

No.	Description of indicator	Intended impact of the experiment	Way to measure the impact achieved	Impact achieved at the end of the runtime of the experiment	Impact achieved one year after the end of the runtime of the experiment	status
1	Expected reduction of application development costs by 25%	Economic	Direct measurement on comparable applications	Benchmarked and verified reduction for typical real application with Cloos expert developers	Reduction of cost for most applications developed at Cloos	Not achieved due to delays in the project execution
2	Creation of new products	Economic	Product available	Prototype ready for final industrialization	Included in new programming tools by Cloos	deviated/ achieved
3	Boost of robotic market	Economic	Take-up of method in other domains for highly-redundant robots	Documented interest (e.g. contacts through fair) from other customers	Negotiations on transfer to other domain ongoing	not evaluated
4	High level publications	Scientific	Publications accepted	At least one ICRA/IROS publication accepted	Three publications accepted	Not yet achieved, submitted
5	Reuse of knowledge	Scientific	Proposals/Projects Submitted/accepted	One follow-up project defined	One follow-up project submitted	Ongoing, confidential information

NOTES: congruent to the delay in the project on the transfer into real application at partner Cloos, the respective PR and dissemination could not all be instantiated.

Section 1.5: Dissemination KPIs

Events/Media	description	status
Newsletter	CLOOS customer information newsletter	Not achieved
Fairs	Automatica 2016	Not achieved
Magazines, newspapers, journals, etc.	High-impact journals, Automatisierungstechnik	Paper submitted
Conferences	ICRA/IROS	To be submitted

Multi-media	CoR-Lab Video channel, Echord Website	achieved
Workshop	Robotics workshop organized by CoR-Lab in collaboration with production technology association (as part of a serious on robotic technology scouting)	Not achieved
Demonstrations in Bielefeld Transfer Lab	Frequent demonstrations to external visitors, on average 2/week	Achieved, ongoing
Echord++ workshops	Echord++ workshops	Invited to E++ review
Concertation meetings	euRobotics Forum, both CoR-Lab and Cloos are members, Cloos even founding member	partially achieved

It was an agreed policy of both partners not to advertise planned work and rather only results.

Section 1.6: Additional (unplanned) achievements

#	Description	status
(invited) talks	The project and respected technical progress was presented at a larger number of (invited) talks and workshops by the coordinator Prof. Steil.	Achieved
Collaboration with SME network(s)	Prof. Steil collaborates with the newly founded “Zukunftsallianz Maschinenbau Norddeutschland”, an association to promote future technology in particular for SME in production engineering.	Achieved
Master/PhD Thesis	The main researcher Dr. Emmerich, Uni Bielefeld, sucessfully submitted and defended his PhD thesis at the end of the year 2015. One master thesis on automatic training data generation was completed in 2015.	Achieved.

Section 2: Detailed description

Section 2.1: Scientific and technological progress

Section 2.1.1 - Task 1: Requirement analysis

Requirements were jointly analysed during a kick-off meeting and based on interviews with several Cloos programmers. These reported that in practice (i) collisions of the robot body with the environment, (ii) lack of awareness about singular robot configurations and joint limits, and (iii) suboptimal use of additional axes (e.g. 7th axis in the Qirox robot) are relevant problems. Respective target scenarios based on the 7-DOF Qirox were chosen (see. Fig.1) and simulation models exchanged. Additionally, UniBi defined requirements on the software architecture and integration in order to enable re-use of background knowledge. The requirements were submitted as D.1.

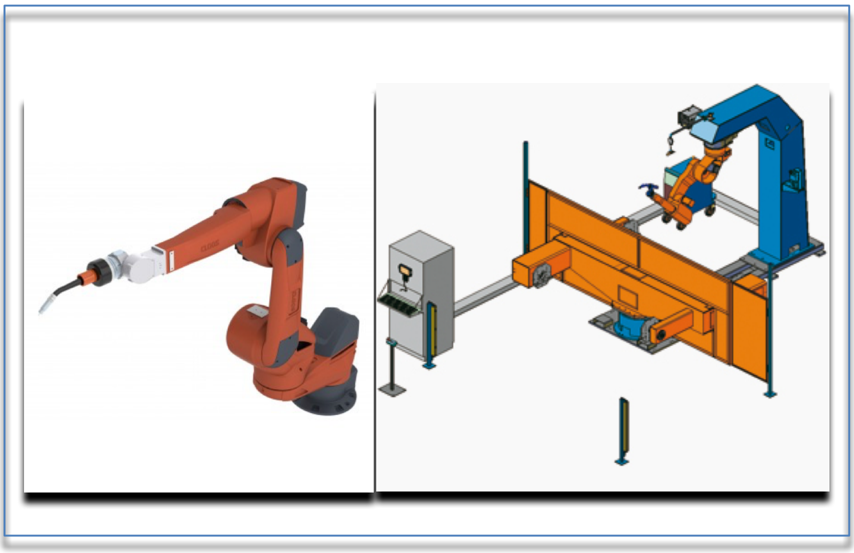


Figure 1: Left: CLOOS robot with 7-DoF axes (Qirox) for increased workspace reachability. Right: Sketch of second application with a 6/7-DoF robot mounted on a C-shaped rack.

Section 2.1.2 - Task 2: Software integration and data assessment

An integrated interactive simulation environment for further testing of algorithms was set up based on kinematic descriptions of Cloos robots and applications and with interfaces for utilizing background knowledge of UniBi. The software concepts, components and their integration were defined and realized. Furthermore, the interfaces for later hardware integration were defined, however, their implementation was interrupted by the personal change at Cloos. Methodically, UniBi suceeded on adapting the previously developed method for teching the redundancy resolution preference for Kuka-LWR, which previously was based on kinesthetic teaching, to a more standard panel interface and to scale it up to more DoF (see Fig. 2, Right). These results are documented in detail in the PhD thesis of Dr. C. Emmerich (open access available at https://pub.uni-bielefeld.de/publication/2900019) .

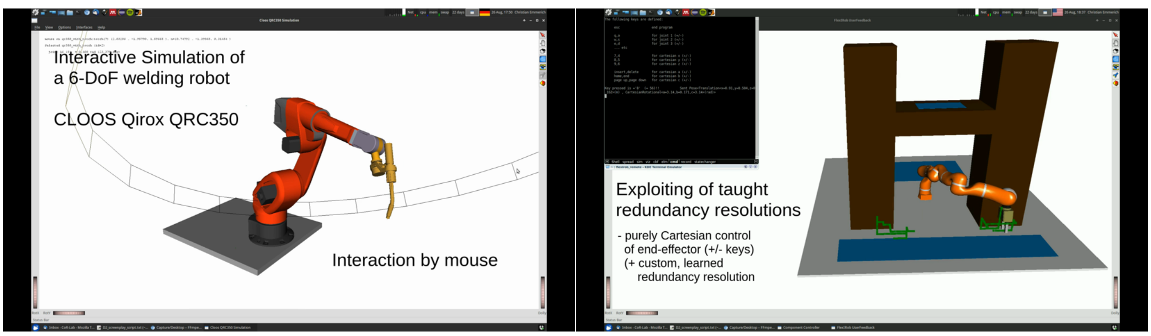


Figure 2: Left: CLOOS Qirox in interactive simluation environment. Right: Scale-up of teaching for standard control panel and more DoF with a 9-DOF robot. Both images are screenshots of video Deliverable 2.

Section 2.1.3 - Task 3: Design and development of shared human-machine control mode

This was the core technological task aiming at the development of the new interactive teaching method and implementing it in simulation first (M2, deliverable D3) and then in the final real-world prototype (deliverable final MMR). Key issues to solve were the integration of inhomogenous DoFs (robot, portal) in one kinematic chain, the implementation and configuration of a complete redundancy resolution for this chain and to devise efficient user-interfaces and methods to interact with this high-DoF system including the automatic generation of extendd training data from relative sparse teaching information. The latter was also investigated in a master thesis and finally included in the system. Methodologically, the results were fully satisfactory and all devised simulation, training and teaching methods scaled well. The respective summarizing figure in Section 1 and Figs. 3 below show the full scenario. It was, however, apparent that due to the lack of resources and the project delay at Cloos this full scenario could not be tested in the real implementation, as this would have required a lot of implementation work on the lower-level control framework. Therefore, the partners finally focused on the simpler 7-DOF scenario for teaching redundancy resolution for the 7-DOF Qirox in the real world. Many technical details can be found in the PhD thesis of Dr. C. Emmerich.

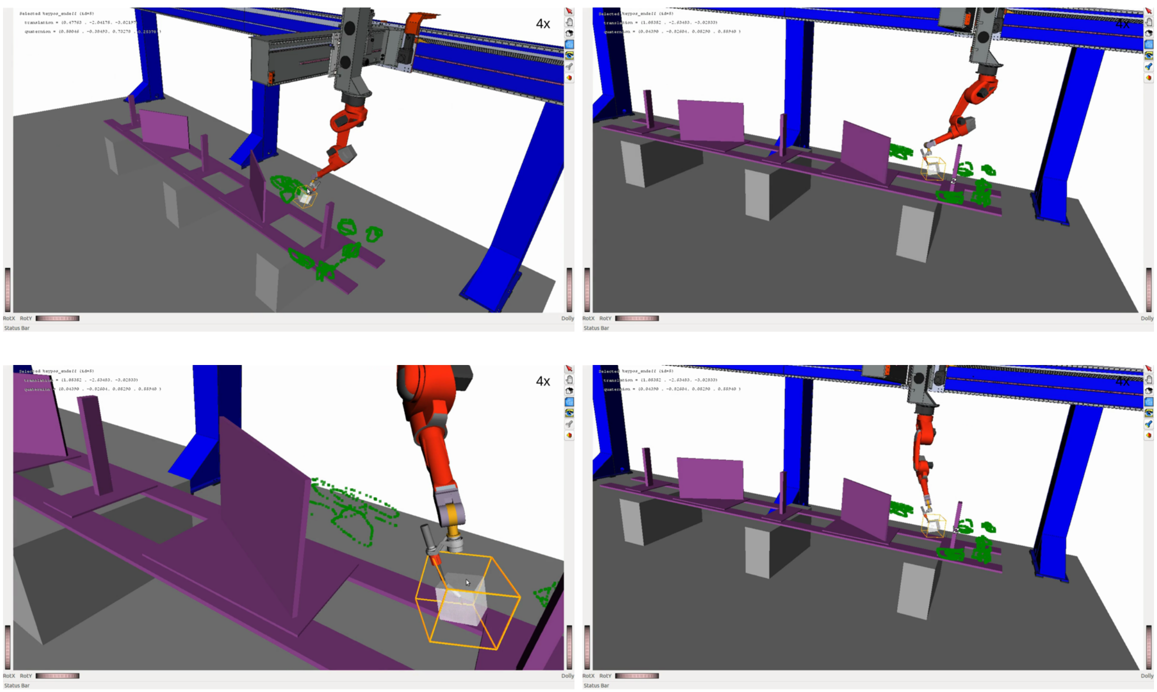


Figure 3: Full scenario of teaching task and redundancy resolution in 9-DOF. Recorded teaching data are in green, users can both manipulate the EE (lower right), but as well the redundancy resolution for fixed EE, e.g. from “portal right” to “portal left” from upper to lower pictures. All images are screenshots from video deliverable D3.

Section 2.1.4 - Task 4: Evaluation in real-world scenario

As discussed above the real-world evaluation could not fully be conducted, due to the lack of resources and the respective delay at Cloos (see also below: Sec. 3 use of resources). The task finally focused on a proof-of-principle real world implementation with a 7-DoF Qirox (standard Qirox with addition rotary joint at the base), which is a very common configuration on the market for Cloos customers. A respective user-interface was implemented on the native Cloos control panel, while the computation of redundancy resolution and the machine learning for generalization from examples was realize on an external Laptop provided by UniBi and interfaced via TCP-based message passing. Two experienced Cloos developers tested the interface and teaching method at the Cloos premises and easily succeeded in programming a standard task with the new approach. Fig. 4 below shows the real-world interactive scenario that also included automatic bootstrapping of training data from only few examples (see also the multi-media report).

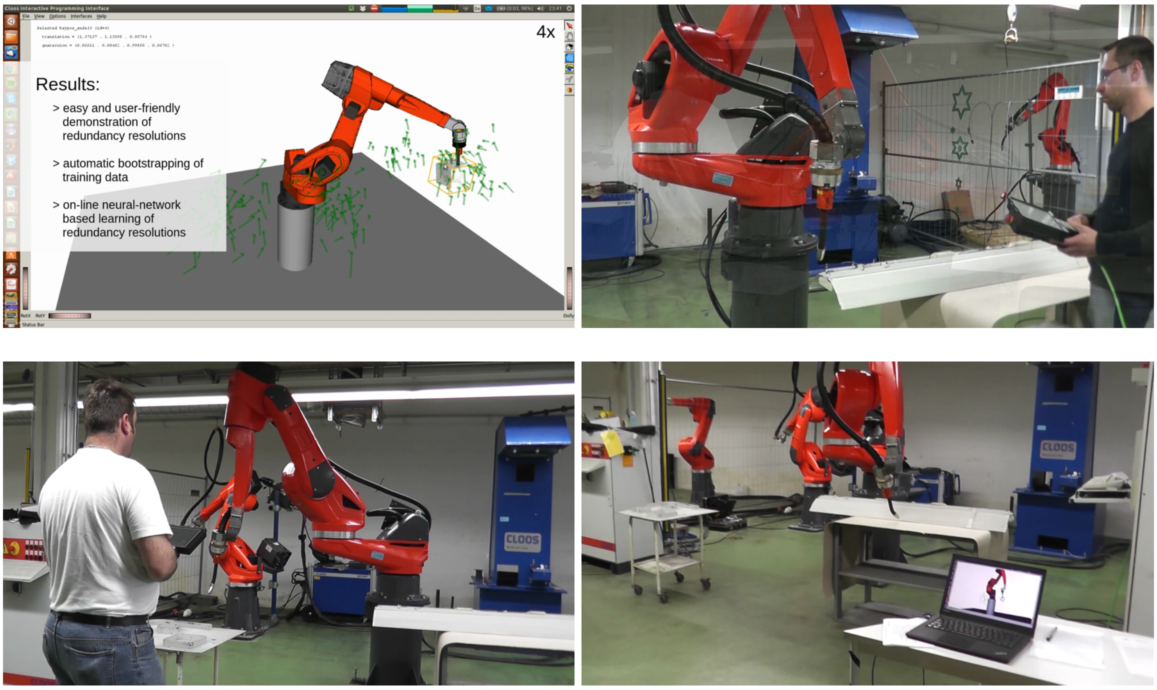


Figure 4: Real-world prototype evaluated by Cloos developers. Upper left: Upon button press, training data is recorded at the current posture and bootstrapped automatically around it to enrich training data set. Upper right, lower left: Developers adjusting the 7-th Axis for better redundancy resolution to enhance reachable workspace for a straight line welding. Lower right: integrated visualization in the simulation environment running on the external computer.

Section 2.2: Scientific and technological achievements

The main technological goals were:

- to scale up the “redundancy learning method” (background of UniBi) from 7-DoF to higher-DoF in realistic scenarios
- to replace the previsous teaching method based on kinesthetic teaching with a more standard interface (panel)
- to verify that enough and reasonable training data for practical application can be collected with such interface in a standard development process.

These technological achievements have clearly been reached and documented through videos, the PhD thesis of Dr. Emmerich and research papers (submitted). Based on these results, we are convinced that the basic methodology could be applied in other application areas and with various interfaces as well. A further technological goal was to prove that

- such teaching method can be implemented in practical standard robot hardware and control

for the Cloos products. While this goal has been partially reached through implementation of the method based on the Cloos panel, it is apparent that the full integration of the algorithmic core, which was run on the external computer for the project, would require a further development project and more consideration of safety layers. This was beyond reach of the project.

Section 2.3: Socio-economic achievements

n.a.

Section 2.4: Dissemination activities

It was an agreed policy of both partners not to advertise planned work and rather only results. Consequently, the outset of the project and technical progress were presented in a larger number of workshops and talks by Prof. Steil, while the impact on Cloos and dissemination activities of Cloos have been stalled according to the delay in the project. Below see a non-exhaustive list of presentations/workshops, where the project and/or the results/methods were presented:

- 13.01.2015 Kickoff E++
- 20.01.2015 Workshop “Future of work” with practicioners from regional industry, together with the IG Metall (workers union in metal engineering)
- 03.03.2015 invited talk computer science/engineering colloquium at TU Braunschweig
- 11.03.2015 ERF, Vienna
- 23.04.2015 Invited talk at annual BMBF Project coordinator’s meeting
- 11.05.2015 Workshop “Industrie 4.0/Interactive robotics” for project leaders and students of graduate school “Arbeit 4.0”, funded by state Nordrhein-Westfalen
- 17.07.2015 Lab-demo to NRW-MP Ms. H. Kraft
- 14.10.2015 open lab demo to members of German “Wissenschaftsrat”
- 19.11.2015 2. Innovationsdialog “Automatisierung, Robotik und Arbeitsorganisation im Kontext von Industrie 4.0” organized by Zukunftsallianz Maschinenbau (http://www.zukunftsallianz-maschinenbau.de/)

- 08.12.2015 Workshop "Human-Machine Interaction" at the yearly summit of the BMBF-funded leading edge cluster in Intelligent Technical Systems (it's OWL)
- 22.01.2016 Workshop for regional practitioners on "Industrie 4.0 und Robotik", organized in collaboration with the Technologieberatungsstelle NRW (www.tbs-nrw.de)
- 15.02.2016 short course on robotics, Padua University, Italy
- 07.03.2016 short course on robotics, Brookes University, UK+
- 29.06.2016 keynote lecture at the DGR-days, Leipzig
- 30.09.2016 keynote lecture at 9th conf. Human-Friendly Robotics, Genua, Italy
- numerous lab-demos for visitors, potential partners, and policy makers

For further activies see also Sec. 1.6.

Section 3: Resource usage summary

The use of resources was adjusted according to the delay and the problems in the project.

UniBi claimed (first period) and used (second reporting period, not yet claimed) the foreseen resources.

Cloos claimed only about 6.000 EUR in the first reporting period and will claim only about 2 PM in the second period, that is about 20% of the foreseen resources.

Section 4: Deviations and mitigation

The responsible person and LEAR, Mr. Ruskowski, has left the company Cloos during the first report period. This created a major delay in the project execution at partner Cloos, because neither Mr. Ruskowski's expertise nor his work-power could be substituted on short notice. Consequently, Mr. Löhr, who was involved at Cloos from the beginning had to take over the project leadership, among many other duties of Mr. Ruskowski, which created a further bottleneck also for concrete implementation. While Cloos made the best possible effort to achieve project results, it quickly became apparent that not all planned targets could be reached.

Additionally, the integration of the learning framework into the standard control panel of Cloos turned out not easy, which was already foreseen as risk in the propsal, see below.

	Risk	Likelihood/ Impact	Contingency Plan
R3	System integration with Cloos programming tools and controllers more difficult than expected.	Medium/Low	Resort to shortcut, where Bielefeld programming system communicates via message passing. Delays industrialization, however, still allows for quantifying progress in terms of efficiency, number of points etc. Will have less impact on the direct outcome of the experiment than on the mid-term impact.

Technically, we exactly resorted to this contingency plan, because the originally planned integration with a prototype of the B&R control system could not further be pursued at Cloos. Still, the respective integration with the existing Cloos controller and control panel prooved a significant technical challenge, which only Mr. Löhr could and did solve.

As qualified work-force can not easily be created for an SME like Cloos, a respective delay in the project execution was inevitable and the goals had to be adjusted accordingly. It turned out that nevertheless most of the technical goals of the project could be achieved, including the realization and testing of a real-world prototype with a standard Cloos Qirox 7-DOF welding robot. However, the originally planned more in-depth user study in a real application could not be performed.

Section 5: Future work

Methododically, the work is mature and a respective teaching and planning system could be implemented on any standard robot controller and application, provided the low level controllers allow a respective level of access. Currently, the coordinator Prof. Steil pursues (partially confidential) negotiations with partners in other application domains, e.g. automotive. The major obstacle for implemantion, however, is that the advanced methods to treat a whole kinematic chain composed of different hardware in a single controller typically needs low level access to the robot and device control, which is not provided by standard proprietary robot controllers. Therefore, follow-up projects need to include respective controller manufacturers to get closer to the actual market.

Section 6: Lessons learned

There are several lessons and remarks:

- Small projects are generally risky. Be prepared that a short-term, small size project can very easily fail due to all kinds of unfortunate, but uncontrollable issues. It is sufficient that one (!) person leaves unexpectedly.
- SMEs do not have many human resources – overload of one (!) person can cause serious delays.
- Universities are slow in personnel matters and can not easily and quickly change assignment of people to projects (any more). Thus small projects and delays delays are not easy to deal with.
- Don’t count too much on continuity at either of the partners, company policies change, researchers move.
- Keep expectations on level with resources to spend:
    - Don’t expect PIs and company management staff to spend disproportionally much time on a small projects.
    - Don’t force projects to make big PR before they have results. (This is very prominent in ECHORD/ECHORD++ and was also already discussed controversially at the start of the project).
    - Don’t force projects to formulate KPIs that nobody believes in (this was already controversially discussed in the outset of the project between the ECHORD++ team and the coordinator Prof. Steil, with backing from Dr. Ruskowski).

  - Keep reviewing/reporting overhead small. On-site reviews are too much effort for both, reviewers and project partners.
- NEVER change the (reporting) rules after the instantiation of the project. (Should not need mentioning, but it happened in E++).
- Be more aware of the thin line between research funding and forbidden subsidy (again: controversially discussed already in the negotiation, some of the (desired by E++) impact KPIs for the industrial partner give strong reason to suspect subsidies).