An Integration Challenge to Bridge the Gap among Industry-inspired RoboCup Leagues

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Abstract. Manufacturing industries are changing rapidly towards more flexibility and autonomy. The RoboCup Logistics League (RCLL) and RoboCup@Work tackle research questions in this domain focusing on automated reasoning and planning, and mobile manipulation respectively. However, future scenarios will require both aspects (and more) and will most likely operate with more heterogeneous systems.
In this paper, we propose a cross-over challenge to foster closer cooperation among the two leagues to address these challenges. We outline four integration milestones and propose a specific scenario and task for the first milestone. The effort is driven by stakeholders of both leagues.

1 Motivation

In industry, cyber-physical systems (CPS) in the context of Industry 4.0 [1] have received a lot of attention recently. They strive to combine computation with sensing and actuation. The canonical meaning in industry are embedded computers and networks which monitor and control the physical processes and have a wide range of applications in assisted living, advanced automotive systems, energy conservation, environmental and critical infrastructure control, or manufacturing. Robots are one, if not the, most complex form of CPS.

Competitions, on the other hand, represent an important keystone in engineering education and research [2]. The combination of challenging tasks and motivating team work attracts students to work hard for a good performance and ranking. In order to reach this goal the students have to coordinate their interdisciplinary team similar to a "realistic" development process. This involves topics such as software engineering, methods research, project management and interface definition among others.

RoboCup [3] is the best-known international initiative to foster research in the field of robotics and artificial intelligence through such competitions. It is particularly well-known for its soccer leagues, but application-driven leagues such as RoboCup Rescue or RoboCup@Home [4] become more prominent every year. In this context, RoboCup@Work (@Work) [5] and the RoboCup Logistics League (RCLL) [6] are industry-inspired leagues based on scenarios known as Factory of the Future (FoF) or Smart Factory. These are context-aware production facilities that consider, for instance, object positions or machine status to assist in the execution of manufacturing tasks [7]. It can draw information from the physical environment or from a virtual model, for example, from a process simulation, an order, or a product specification. It is designed to cope with the challenges that arise from the desire to produce highly customized goods which result in the proliferation of variants [7] and therefore smaller lot sizes.

While both leagues share the same basic problems such as navigation, object handling, or device interaction, there are also significant differences. @Work tasks are focused on grasping and mobile manipulation operations, while the RCLL concentrates on research questions about task-level planning and scheduling, automation in an industrial production workflow, and multi-robot system integration process. However, in an industrial scenario implementing a realistic production process both aspects – complex manipulation *and* optimized resource planning have to be considered.

In this paper, we propose a *cross-over challenge* that requires involvement of teams of both leagues to cooperate on a common task. As we will outline, the aim is to foster cooperation of the two leagues; it is not intended that one leagues will be subsumed by the other. Since both individual leagues' tasks are already complex by themselves, we intend to start with simple cooperation of the robots that essentially involves cross-league communication through their respective refboxes in 2016. We will also outline, how we intend to increase and strengthen cooperation and allow for more integration in future competitions.

In the remainder of the paper we briefly introduce the two leagues in Sect. 2 and review a proposal for an industrial umbrella league (Sect. 3). We then outline how the cooperation and integration may be developed in Sect. 4. We then describe the proposed cross-over challenge in Sect. 5 before we conclude in Sect. 6.

2 League Descriptions

In this section, we describe the RoboCup Logistics League and RoboCup@Work, and give a brief overview of similarities and differences.

2.1 RoboCup Logistics League (RCLL)

The industry-oriented RoboCup Logistics League[7] (RCLL) tackles the problem of production logistics in a smart factory. Groups of three robots have to plan, execute, and optimize the material flow and deliver products according to dynamic orders in a simplified factory. The challenge consists of creating and adjusting a production plan and coordinate the group [6].

A game is split into two major phases. In the *exploration phase*, the robots must determine the positions of machines assigned to their team and recognize and report a combination of marker and light signal state. During the *production phase*, the robots must transport workpieces to create final products according to dynamic order schedules which are announced to the robots only at run-time.

Fig. 1. Teams Carologistics (robots with additional laptop) and Solidus (pink parts) during the RCLL finals at RoboCup 2015.

The RCLL focuses on the topics of automated planning and scheduling, reasoning under uncertainty, and multi-robot cooperation. Other robotics aspects are intentionally kept simpler, e.g., handling of the machines or perception. The planning is open to a variety of approaches, from local-scope (single robot) to global-scope (overall fleet) planning, to distributed and centralized approaches [8]. A capable simulation of the environment is available as open source software to further corroborate this focus [9]. The RCLL task and its simulation also form the foundation for a Robot Planning Competition Tutorial at ICAPS 2016[8] [10].

2.2 RoboCup@Work League

The RoboCup@Work league[9] (short @Work) is the latest within the family of RoboCup challenges. It is inspired by industrial mobile manipulation scenarios and accordingly covers a large spectrum of current research topics related to the Factory of the Future (FoF).

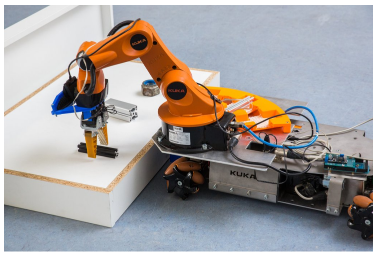

Fig. 2. @Work robot of the robOTTO team in front of a rack grasping an object.

The competition combines a number of separate runs addressing navigation, grasping and handling tasks of different complexity. The manipulation objects are motivated by industrial scenarios (profiles, nuts, screws). In one of the tasks during a competition the robot has to recognize the correct objects, transport them from one shelf to

[7] RoboCup Logistics website: http://www.robocup-logistics.org
[8] ICAPS tutorials: http://icaps16.icaps-conference.org/tutorials.html
[9] RoboCup@Work website: http://www.robocupatwork.org/

another and place them into object-specific cavities, thus benchmarking object perception, navigation and precision placement capabilities of the robot. For all the tasks different instances allow for different levels of complexity and therefore new teams as well as experienced teams are provided with a challenging environment setting. The referees evaluate the correct execution of tasks, collisions with the environment and score the fastest run according to specifications set in the rulebook.

2.3 Comparison of the Main Objectives

Table 1 compares some of the similarities and differences between the two leagues. The focus lies in organizational, environmental and hardware topics. The most prominent difference is the common robot platform. The RCLL requires the Festo Robotino as base platform, while @Work is open to different robots. However, since the beginning of the @Work competition, the KUKA youBot emerged as de-facto standard platform for this league. Both, the Robotino as well as the KUKA youBot can be extended and modified with different sensor configurations. This gives teams flexibility in designing their robot to suit their research needs. The arenas of both leagues are of comparable size and includes networked devices to be used for various league specific tasks. For example, a conveyor belt is employed in @Work for the conveyor belt test whereas the Festo Modular Production System (MPS) is employed for the whole competition. A key difference of the leagues is the mode of competition, whereas RCLL performs parallel runs in a shared environment whereas in @Work the environment is not (yet) shared. This can be explained with the different scientific objectives of the leagues. In RCLL the focus is on multi-agent planning and scheduling whereas in @Work the focus is on mobile manipulation including the required capabilities such as perception, control and motion planning. The different objectives yields also in a heterogenous design of the competition objects – @Work includes a breadth of different object instances (variants in shapes and colors) whereas RCLL covers the depth of the variants of one object.

2.4 Other industry motivated robotic leagues

Outside of RoboCup there are further competitions with an industrial background. The Amazon Picking Challenge addresses the manipulation process of daily objects. The scenario reflects the commissioning process in a warehouse. Different goods have to be localized, grasped and placed to a box [11]. The second version of the challenge is held in Leipzig during the RoboCup 2016.

In contrast, the Airbus Shopfloor Challenge is focused on the simulation of the production process [12]. During the first performance at the ICRA 2016 the teams had to present a robot that could drill holes in a metal plate. The number of holes and their quality define the evaluation criterion.

Another competition targeting the industrial domain is the RoCKIn@Work competition [13] which is part of the recently finished EU-funded project RoCKIn. In RoCKIn@Work several task and functionality benchmarks related to mobile

Table 1. Comparison RoboCup Logistics League and RoboCup@Work

	Criteria	RoboCup Logistics League	RoboCup@Work
League	Established	2010 (Demo) 2012 (Competition)	2012 (Demo) 2014 (Competition)
	Teams (RC 2016)	10+	10+
	Competition Mode	parallel runs in shared arena	individual runs
	Disciplines	1 + 3 challenges	9+2 challenges
Referee box	Communication	Broadcast/Multicast with Protocol Buffer encoding	Broadcast/Multicast with Protocol Buffer encoding
	Task generation	Randomized order combination and machine placement	Distribution of the objects and their destination
	Visualization	Arena/Map w/robots, Task, Time, Score	Arena, Current task, Time
	Scoring	Production steps, Delivery, Exploration Reports	-
Common Platform	Robot	Festo Robotino	KUKA youBot
	Locomotion	holonomic (3 Wheel)	holonomic (4 Wheel)
	Manipulator	Typically Gripper	5 DoF Arm w/ gripper
	Connectivity	Wifi and LAN	LAN
	Embedded PC	Intel i5, 2.4 GHz, 8 GB RAM, 64 GB SSD	Intel Atom 510, 1.66 GHz, 2 GB RAM, 32 GB SSD Flash
	Circuit Boards	Motor, Power, I/O	Motor, Gripper, Power
	Power Supply	2x lead acid batteries	lead acid battery
Adaptations	Common Hardware Modifications	Gripper, Extra Computer, Sensor Mounts	Gripper, Kill switch, Elevated sensor platform, Wifi, CPU
	Common Sensors	Laser Range Finder, Odometry, Bumper, Cameras, IR-sensors, RGB-D camera	Laser Range Finder, Odometry, Cameras, RGB-D camera
Arena	Maximum size	$14\,\text{m} \times 8\,\text{m}$	$10\,\text{m} \times 12\,\text{m}$
	Operating Level	90 cm	0 - 15 cm
	Devices	Festo Modular Production Systems (MPS)	Round table, Conveyor belt
	Obstacles	Opposing robots, MPS stations	Barrier tape, Variable obstacles
Obj.	Number	1 ($\sim$ 250 variants)	13
	Motivation	Industrial workpieces	Industrial components
	Heterogeneity	Single shape, various colors	different shapes and colors

manipulation scenarios in small and medium sized factories are performed. A focus of RoCKIn@Work and RoCKIn in general was on developing experimental methodologies, benchmarking procedures and competition infrastructure and testbeds. The RoCKIn project significantly contributed to RoboCup@Work and vice versa as several elements from RoCKIn (e.g. testbed [14]) are in the meanwhile employed in RoboCup@Work.

3 RoboCup Industrial Umbrella League

Movements like *Industry 4.0* document an increased interest in industry towards more autonomy in manufacturing processes. These are based on cyber-physical systems that combine computing processes and physical interaction in heavily networked systems. In our context, we assume *autonomous mobile robots* as one of the most complex classes of such systems [15]. As such, testbeds are required for benchmarking methods and systems for smart factories. In 2016, the *RoboCup Industrial* umbrella league [16] has been established with the mission to combine the efforts in the context of RoboCup towards this goal. Given the key differences (single- vs. multi-robot, scenario vs. solution design, multiple short-term tests vs. single long-term test, focus on manipulation vs. planning and scheduling) that we have outlined in Sect. 2, we strongly believe that merging the leagues is in neither league's best interest in the near future. However, we do see a high potential for cooperation on the technical level. *Long-term alignment of the research agenda* could keep diversity and cooperation alive through the common cross-over tasks. This would, at the same time, allow for the individual development and focus of the leagues. This would be akin to the organization of RoboCup soccer leagues. While the leagues have an overall common scheme of multi-robot systems playing soccer, the organization stays decentralized to a certain degree. The benefit is that ideas, methods, and sometimes software or even hardware components are shared across the different sub-leagues without forcing them to merge or otherwise one being subsumed by the other.

As a first endeavor in this context, several major stakeholders of both leagues are cooperating towards the creation of a single common autonomous referee box (refbox).[10] This project is based on the RCLL refbox efforts started in 2013. It had been adopted for the RoCKIn@Work competition [14] and from there adopted in RoboCup@Work. With the recent effort, the idea is to create one common infrastructure (reasoning engine, communication, code base) and then model the specific scenarios. This would also greatly simplify the crossover challenge presented in this paper, as both sides would use the same executing machinery for the refbox.

4 RCLL/@Work Cross-Over Challenge Development

Besides the will and effort of stakeholders of both leagues to drive the overall integration as described above, also needed is a technical integration effort to pave the way for cooperating robots. Based on our observation of the RCLL and @Work, we expect there to be four major milestones on the way to full integration as depicted in Fig. 3: the transition from different to commonly used object to handle (A), the operation in a common arena or space (B), the operation of each other's on-field devices (C), and finally direct robot interaction (D). These levels of integration configure four component classes (manipulation objects, arena, devices and robot interaction) in different ways.

[10] Code available at https://github.com/robocup-industrial/rci-refbox

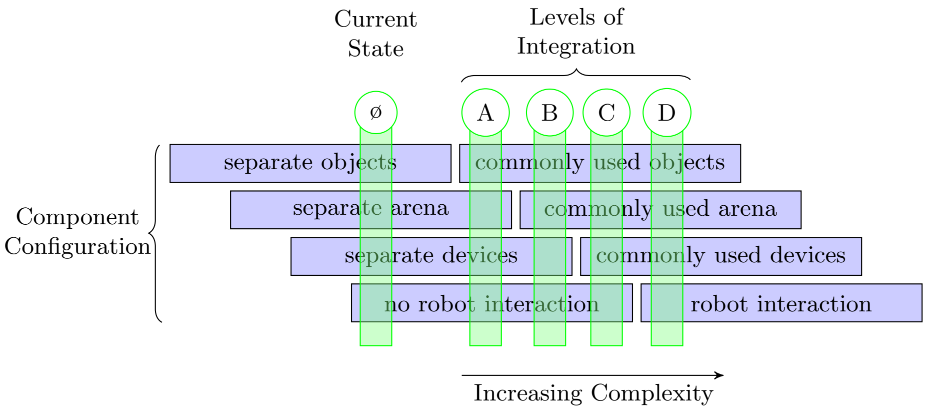

Fig. 3. Levels of interactions between both leagues

Each of these levels requires considerable effort. For (A), the gap in the operational height of the robots must be overcome. For (B), a certain level of acceptance is required in both leagues as some "field-time" will have to be devoted to the testing of a common task. For (C), the operational height becomes an even more pressing issue, since now the interaction must be two-way. In (A), it is sufficient to move objects from the higher to the lower level. And for (D), an extensive communication infrastructure and robot-to-robot handling must be implemented. In the following, we analyze the levels and evaluate challenges.

The separate objects configuration ø reflects the current situation with different types of objects (as listed in Tab. 1) where both leagues operate completely separated.

The use of common objects (A) can be achieved in multiple ways, ranging from using the superset of both leagues and expecting robots of either league to be able to handle all of them – a goal that probably @Work teams can accomplish more easily. More likely, however, is to use a subset with only some objects from both leagues.

Using separate workspaces (B) is possible via manipulation objects transferred from one area to another. Objects have then to be transferred by external means like a conveyor belt. Intersecting arenas with commonly used parts increase the complexity of the scenario significantly where collision-free operation and an effective trajectory planning for a heterogeneous multi-robot application has to be performed – a task that is currently performed only in the RCLL.

Shared devices (C) would exist only in commonly used areas. This component class involves all electrical elements of the arena beside the robots such as production units, transport systems, or storage elements. Common use of the same resources requires communication among the robot and teams to avoid conflicts – something that RCLL at the moment implements only at the team-level and @Work not at all. As outlined in Tab. 1 this is not yet the case.

Intermediate robot interaction (D) can require direct hand-overs among robots, or operating a machine at the same time (e.g., one robot feeds a work item that another operates the machine or needs to collect the object on the other side). Members of the @Work league will be able to adapt more easily due to their focus on manipulation and handling. A balance could be achieved by an @Work robot handing an object to an RCLL robot, combining both handling capabilities, which is nonetheless a challenging problem [17]. Additionally, this also requires combined or cooperative task-level planning – which is a focus area in the RCLL. This would require an even extended common communication infrastructure. Here, efforts of the RCLL to engage the planning community could prove helpful to create common plans and suggest tasks to @Work robots.

5 Cross-over Challenge Proposal

To foster the close cooperation of the RCLL and @Work, as a start we propose a scenario to achieve the first milestone (A) (cf. Fig. 3). To be able to conduct the challenge, we assume co-located RCLL and @Work arenas and a shared zone reachable from both. The task (represented in Fig. 4) is to dispatch an order from a human, produce or retrieve the product from the RCLL side, hand the product over to the @Work robot, which then packages and delivers it. The integration aspect in this first step is handled through the leagues' respective referee boxes that will be extended to directly communicate with each other.

In the following, we outline the task in more detail, before stating requirements and challenges.

5.1 Scenario and Task

We emulate an industrial process in a multi-stage production and packaging scenario with human-robot interaction and cross-vendor robot cooperation depicted in Fig. 4. It clearly distinguishes the task to be performed by the robots of the respective leagues and roughly follows the following steps. A human worker initiates production by requesting a specific product ①. The request is processed by the @Work referee box (refbox) and immediately communicated to the RCLL refbox ②. It generates an order and sends it to an RCLL robot for completion ③. Once production is completed, the product is supplied to a shelf or similar in the shared zone and informs the RCLL refbox, which in turn informs the @Work refbox of the availability of the product ④. This informs an @Work robot which picks up the object and puts it into a box, that is then delivered to the human worker ⑤.

A basic requirement for multi-robot cooperation is the capability to communicate with each other. In this scenario, this is handled through the respective refboxes. Robots communicate with their respective refbox and the refboxes with each other. We chose this approach to minimize the teams' efforts. They can keep using the same communication channels as in their respective leagues. While we encourage a common communication infrastructure in the future, enforcing this

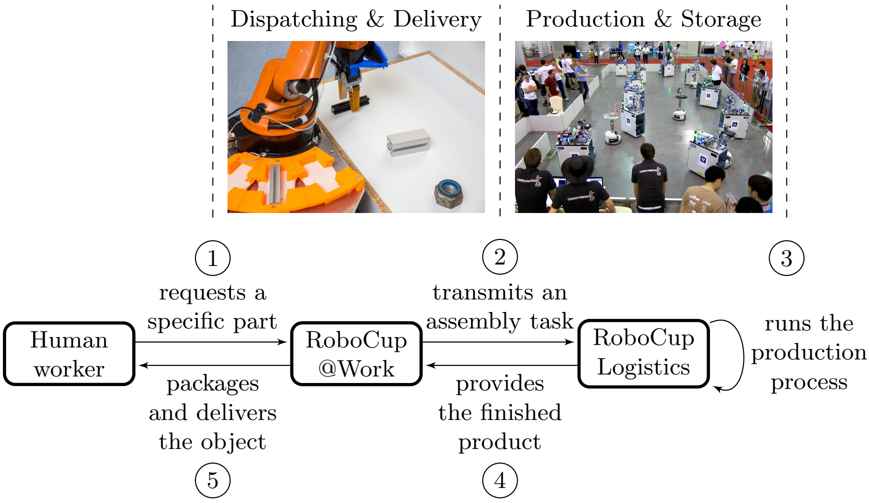

Fig. 4. Workflow of the scenario and the interaction between @Work and the RCLL.

in the very first cross-over challenge would most likely be a roadblock for some teams. A number of speech acts are required between robots and the refboxes, which are depicted in Fig. 5.

After generating the corresponding task related to the workers request, the @Work refbox transmits the requiered information – Request ID, Object ID and the expected delivery point – to the RCLL refbox. In case of a successful task generation the RCLL refbox acknowledges the request and starts the run. The RCLL refbox will announce the completion if the object is available at the delivery point. At the end, the @Work task is executed, the robot grasps the object and delivers it.

5.2 Challenges and Requirements

A key feature for a successful initiation of a new challenge is a careful balance of its complexity. If we would aim for more integration right away, teams would be overstrained and could be demotivated from further participation. This could also influence the respective leagues themselves, as too many of the scarce development resources would be bound for the cross-over challenge. Therefore, we focus on communication integration through the refboxes providing goals to accomplish for teams within their own respective scenario. Entering and navigating in the shared zone – outside of their arenas – poses a slightly extended task. The execution of the requests by the robots combines already implemented robot capabilities with slight adaptations in order to minimize the needed adjustments.

The scenario addresses several challenges which are characteristic for the smart factory of the future: (a) connect mobile robots and external sensors, (b) integrate different specialized robot systems, and (c) apply an intermediate

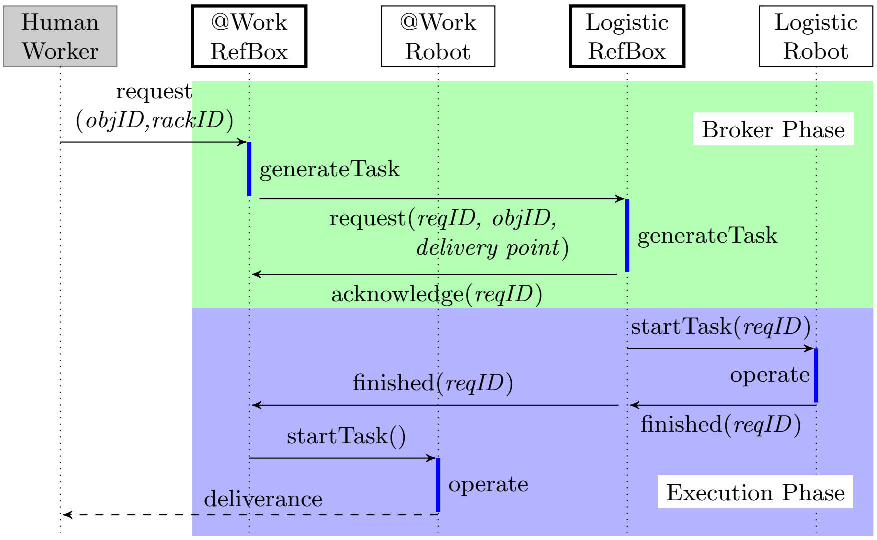

Fig. 5. The sequence diagram depicts the interaction between the @Work and RCLL referee boxes related to an object request. The green part illustrates the generation of the two separate tasks, the blue one their execution.

interaction with human workers. Hence, based on this scenario the intended cross-over challenge is a first step to bridge the gap between the two leagues. It also emphasizes research topics not on the agenda of any of the two leagues, like handling heterogeneity of systems.

The object that can be handled is constrained by the handling capabilities of the RCLL robots and MPS stations. Therefore, the common object used will be of cylindrical shape similar or even the same as in the RCLL. This is intentional in the RCLL to keep the focus on planning and scheduling, rather than mobile manipulation, since this is the very focus of @Work.

The transfer of the object from the RCLL to the @Work robot is a major challenge as the gap in the operational height must be bridged. While RCLL robot operate roughly at table height, the robots in @Work handle objects roughly at the ground level and small shelves. Several options were discussed from active elevators to passive slides. An alternative considered is to use a robot arm to bridge the distance.

An additional node for human input has to be added to the @Work arena. It is required to recognize and interpret the incoming request.

6 Conclusion

Future manufacturing industries that strive to offer production for more individualized goods and generally smaller lot sizes will require more flexibility and a number of new technologies. Such systems will most likely be heterogenous (either due to incremental upgrades to existing production facilities or to avoid vendor lock-in) and at least partially autonomous. Both, the RoboCup Logistics League (RCLL) and RoboCup@Work operate under the premise that autonomous mobile robots will play a role to achieve this goal. They each focus on distinct areas, in particular mobile manipulation in RoboCup@Work and automated multi-robot reasoning, planning, and scheduling in the RCLL.

As a *first step* towards a more heterogenous scenario we propose a *cross-over challenge* that involves robots from both, @Work and the RCLL, each bringing in their particular strengths. The cross-over task has to balance required effort and challenges posed to motivate teams to participate. We propose to base the *first challenge* on the already available referee box used in the two leagues and *focus on communication* to coordinate the robots and devices in both arenas. The interaction is then done through the refbox, such that the teams from the respective leagues do not need to adjust to a new infrastructure initially.

At the moment the *complexity level* of the scenario is *limited intentionally.* We have outlined *four milestones for future development* and closer cooperation and argued that we need to start with a simple motivating scenario. Eventually, the cross-over challenge will cover a larger variety of topics relevant to smart factories than the individual leagues alone. Yet, keeping the two leagues separate allows to foster development on their respective focus areas, automated task planning and mobile manipulation, respectively. The highest level of integration would benefit from the common referee box that is currently being worked on.

The cross-over task does not only pose challenges to participating teams. It requires a major effort by organizing teams and event organizers to create the necessary infrastructure, from aligning the competition arenas, over a handover device, to the refbox communication. This effort is one of the first cooperative projects within the recently established *RoboCup Industrial* umbrella league.

As to the best of our knowledge, such a common challenge and the explicit structure overarching several (comparable) leagues is a novelty in RoboCup. For example, we are not aware of any cross-over game or common organizational structure in robot soccer. Therefore, this project explores new ways of inter-league cooperation, and research and development alignment.

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