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Humanoid Robots in Soccer – Robots Versus Humans in RoboCup 2050

Reinhard Gerndt[1], Daniel Seifert[2], Jacky Baltes[3], Soroush Sadeghnejad[4], and Sven Behnke[5]

[1] Ostfalia University of Applied Sciences, 38304 Wolfenbüttel, Germany
r.gerndt@ostfalia.de, http://www.wfwolves.de
[2] Freie Universität Berlin, Intelligent Systems and Robotics, 14195 Berlin, Germany
daniel.seifert@fu-berlin.de, http://www.fumanoids.de
[3] University of Manitoba, Winnipeg, MB, R3T 2N2, Canada,
jacky@cs.umanitoba.ca, http://www.cs.umanitoba.ca/~jacky
[4] Amirkabir University of Technology, No. 424, Hafez Ave., Tehran, Iran,
s.sadeghnejad@aut.ac.ir, http://autman.aut.ac.ir
[5] University of Bonn, Autonomous Intelligent Systems, 53113 Bonn, Germany
behnke@cs.uni-bonn.de, http://www.ais.uni-bonn.de/behnke

Abstract. This paper describes the history and major achievements of the RoboCup Humanoid League from its start in 2002 to today. Furthermore it gives an indication on how the league may evolve over the coming years until 2050, when a team of autonomous humanoid robots shall play soccer against the human world champion. We show how the competition drives humanoid robot research and serves as a benchmark to measure progress.

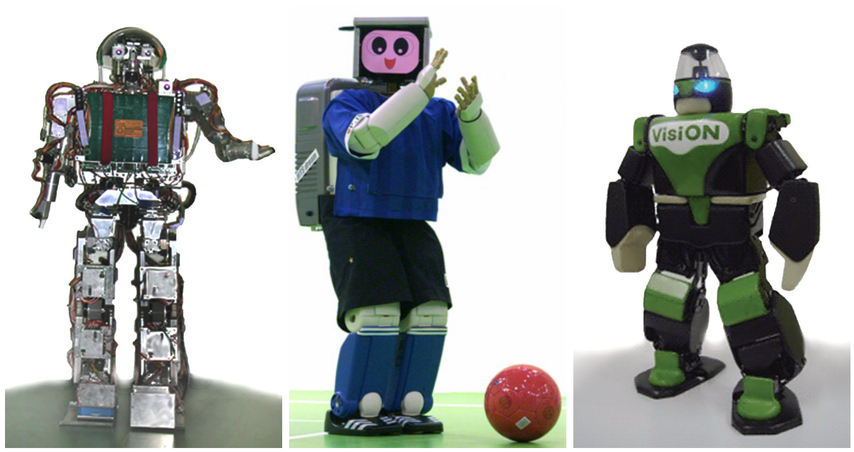
1 Introduction

RoboCup is an international initiative to promote artificial intelligence and robot technology through the organization of robot competitions and scientific meetings. The stated ultimate goal of RoboCup is: "By the middle of the 21st century, a team of fully autonomous humanoid robot soccer players shall win a soccer game, complying with the official rules of FIFA, against the winner of the most recent World Cup." [1] Hence, many of the competitions focus on soccer as a benchmark problem. However, RoboCup also added competitions for domestic service robots, rescue robots, and industry-inspired mobile manipulators.

Soccer competitions started in 1997 with wheeled and simple simulated robots. The RoboCup Humanoid League was first hold in 2002 when walking and kicking were the major challenges. Improvements in mechanics, electronics, perception, and control quickly led to capable individual players. After managing the basic skills, the robots started team play. In recent years, commercially available platforms gave teams the opportunity to concentrate on software only. The future of the league is characterized by a strong push towards larger and more human-like robots, bigger teams, and FIFA-like rules and environments.

2 The Early Years (2002–2004)

The first Humanoid League competition was carried out at RoboCup 2002 in Fukuoka, Japan. At that time, some impressive humanoid robots developed by the Japanese industry like Honda Asimo and Sony Qrio existed, but these robots were not available to other research institutes. The only available commercial platform was the Fujitsu HOAP series of robots, but despite high costs, these robots could not act autonomously due to lack of on-board processing power.



Nagara (1st 2002) HITS (1st 2003) VisiON (1st 2004)

Fig. 1. Early RoboCup Humanoid League Competitors

Inspired by the very ambitious goal, a dozen university teams participated in the first RoboCup humanoid competition. Fig. 1 shows the winning robots of the first years. The robot designs varied significantly within a size range of 20 cm to 180 cm. Many humanoids could not act autonomously and had to be remotely controlled or tethered due to the lack of computation and battery power. The first competition consisted of three challenges: balancing on one leg, penalty kicks (Fig. 2), and free style demonstrations, graded by a panel of judges. Different degrees of autonomy were accounted for by performance factors. In order to encourage teams to build their own robots, commercial platforms were also penalized by a 20% performance factor.

The Humanoid League robots improved quickly and the performance factors became obsolete. The rules evolved to provide entertaining competitions that would still be suitable as a benchmark for autonomous robots. Each year, new technical challenges were introduced to encourage the development of new skills.

By 2004, all robots acted fully autonomously and the main tournament was played as penalty shoot out. Standing on one leg was replaced by a walking competition, where robots had to footrace around a pole. The other technical challenges were passing and balancing across a slope.

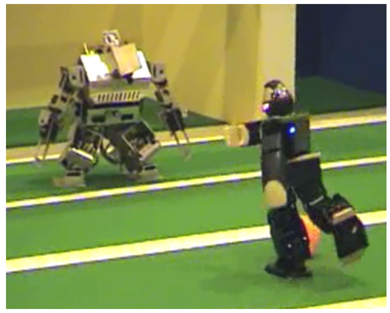


Fig. 2. 2004 Penalty Kick: Team Osaka vs. Robo-Erectus

Different capabilities, in part related to the size of the robots, required subdividing the RoboCup Humanoid League. Rules for the year 2004 characterized three classes: H-40, H-80 and H-120, in line with a maximum size of the robots [2].

The results of the individual challenges were aggregated into a 'Best Humanoid' ranking. However, being aware of the fact that robots of different size classes can hardly be compared directly, the winner of the 'Best Humanoid' award, the Louis Vuitton Cup, was determined by voting of the team leaders. Guiding principles for voting were robustness, walking ability, ball handling, and soccer skills.

3 From Penalty Kicks to Soccer Games (2005–2007)

After demonstration games in 2003 and 2004, 2 vs. 2 soccer matches (Fig. 3) were introduced as main KidSize (<60 cm) tournament in 2005. Initially, humanoid robots were understood to primarily have bipedal kinematics. Human-like appearance and sensors were not yet part of the rules. Team Osaka was among the first to be able to move quickly and reliably across the playing field with the VStone robot that featured an omnidirectional vision system in the head. Consequently, they won the soccer competition two times in succession [3].

The larger TeenSize robots initially continued to play penalty kick, which in 2007 evolved to the dribble and kick competition (Fig. 4). Dribble and kick is played between a striker and the goal keeper. The striker robot starts in the center of the field and the ball is placed randomly on the striker's goal box. It then has to move back to approach the ball, dribble the ball across the center line and kick the ball into the opposing goal.

Further rule changes have been introduced during this period. It was felt that humanoid robots should be limited to human-like sensors. This banned omni-vision or vision systems with three cameras and active sensors like LIDAR, ultrasound and IR distance sensors. In order to have a more objective ranking, quantitative measures like goals scored and time required to perform a given task were introduced. The free demonstration event was removed from the competition.

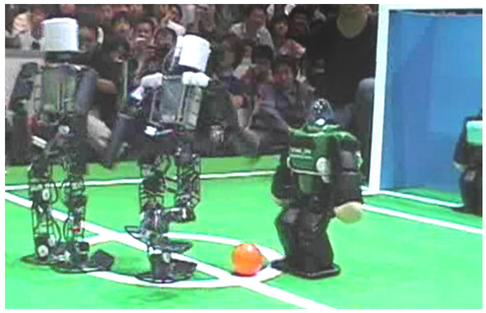


Fig. 3. 2005 2 vs. 2 Soccer: NimbRo vs. Team Osaka

Fig. 4. 2009 TeenSize Dribble-and-Kick: CIT-Brains vs. NimbRo

The rapid improvements in robot capabilities also led to an increase in the complexity and diversity of the technical challenges. The technical challenges introduced during this time included walking over uneven terrain, dribbling around multiple poles, dribbling through randomly placed obstacles, and double passing.

4 From Individual Skills to Team Play (2008–2011)

Until 2008, most teams had successfully solved the problem of locomotion and were able to walk reliably on the flat playing surface that was green carpet. Now, localization and the perception of the game situation became the focus of research. Whereas individual robot skills (fast walking, getting up from a fall, fast and strong kicking) were the key to success in previous years, now team play and coordination became more important. This was further emphasized by increasing the number of KidSize players per team from two to three in 2008. Two teams from Germany (Team NimbRo [4], University of Bonn, and Darmstadt Dribblers [5], TU Darmstadt) won the competition several times.

With the availability of affordable high power servos, the performance of the TeenSize robots improved and 2 vs. 2 soccer matches became possible in 2010. However, the largest (>120 cm) and heaviest robots were still too fragile to survive a fall undamaged. Furthermore, with some robots weighing more than 40 kg, they posed a considerable danger to other robots and participants. As a consequence, only the smaller TeenSize robots (100–120 cm) started to play 2 vs. 2 soccer games in 2010, whilst the AdultSize robots (>130 cm) continued with dribble and kick competitions.

With team play becoming a focus, the potential for cross-fertilization with the simulation leagues of RoboCup has been discussed [6]. Many research groups in the Humanoid league use simulation for robot development and optimization. However, the specific requirements of the RoboCup simulation competitions lead to a stronger link with the Standard Platform League with identical robots.

The major rule changes aimed at fostering a more robust visual perception and localization. Landmark poles in the corners of the field and later on the side lines were removed. In 2010, extra lighting on the field was abandoned in favor of environmental lighting. The size of the playing field was increased, and goals were gradually made more realistic. The blue- and yellow-colored goal back walls were removed, leaving only blue and yellow goal posts.

With increasing interest in the RoboCup, the number of participating teams in the KidSize class had to be limited to 24 and a qualification process was introduced. Teams applied by submitting a team description paper (TDP) and a video of their robot playing soccer. In the video, the robot needed to demonstrate the ability to perceive and approach a ball, line up with the goal, and to kick the ball into the goal. For applications to the KidSize competitions, it also needed to demonstrate the ability to stand up after a fall from various positions.

5 Availability of Standard Platforms (2012–2014)

In 2011, the Korean company Robotis introduced the DARwIn-OP robot, which they had developed with Virginia Tech [7]. In 2014, 50% of the KidSize teams that submitted qualification material used the DARwIn-OP platform or based their robot on it. In 2012, a similar collaboration between Robotis and the University of Bonn was started, which resulted in the development of NimbRo-OP [8], a TeenSize humanoid robot, which is now further developed together with igus GmbH. In 2014, Robotis developed the THOR-OP (Tactical Hazardous Operations Robot - Open Platform) humanoid robot [9] as a general purpose disaster response robot to compete in the DARPA Robotics Challenge (DRC). By modifying the THOR-OP, the University of Pennsylvania RoboCup team was able to take part in the RoboCup 2014 in Brazil where they finished first in the AdultSize sub-league. The introduction of these platforms (Fig. 5) had a big impact on the Humanoid League.

DARwIn-OP | igus Humanoid Open Platform | THOR-OP

Fig. 5. Recent 'out of the box' Humanoid Soccer Robots

Instead of designing and building their robots from scratch, teams could now simply purchase a robot platform that was able to walk and kick a ball and recover from a fall. This made qualification and entry into the league much easier for new teams. However, all robots were open platform such that, unlike in RoboCup Standard Platform League, which uses standardized robots, Humanoid League robots could be altered by the teams. And, however tempting the use of off-the-shelf robots was, many teams still worked on individual hardware solutions, for example using two knee actuators to increase the speed of walking, or parallel kinematics to increase the stability.

The major rule changes for the 2013 tournament were coloring both goals yellow and omitting the previously used landmark poles [10]. This made the field fully symmetrical and increased the difficulty of robot localization. At the end of the 2013 tournament, the RoboCup board of trustees issued a challenge to all leagues as they felt that progress in the leagues had been limited to incremental improvements rather than consequently aiming for the 2050 goal. In response, the maximum height of the robots in the KidSize was raised by 50% to 90 cm [11]. Furthermore, the height limits of the Kid- and TeenSize and the Teen- and AdultSize classes were chosen with an overlap on the upper and lower size limits to foster easier transition towards larger robots.

The changes were adopted fast. Many KidSize teams started to experiment with larger robots. Fig. 6 shows the size range of 2014 KidSize robots. Furthermore, the field area for KidSize was increased by 125% to $6\,\mathrm{m} \times 9\,\mathrm{m}$, and the size of the goals, and the size and weight of the ball were adjusted to accommodate the larger robots. The number of KidSize players was increased to four robots per team. The complexities of the technical challenges also increased. In the AdultSize dribble and kick competition two obstacles, representing stationary opposing players that must be avoided by the striker robot, have been introduced.

Fig. 6. KidSize Soccer Game during RoboCup 2014 in Brazil.

6 RoboCup Humanoid League Achievements (2010–2015)

The main achievements of the RoboCup Humanoid League are building a community of robotics researchers and fostering research in the field of humanoid robots. Fig. 7 shows most of the Humanoid League teams participating in RoboCup 2013. The development of the community can be inferred from numbers.

Records of qualified teams in the Humanoid League competitions are available from the year 2005 onwards (Fig. 8). In 2006, the TeenSize sub-league was introduced; the AdultSize followed in 2010. New sub-leagues initially recruited their members from existing ones. Currently, the numbers stabilized at around 39 qualified teams for all three sub-leagues.

Fig. 7. Teams of the Humanoid League at RoboCup 2013 in Eindhoven, NL.

In step with the RoboCup competition in general, the maximum number of teams that can reasonably be supported within current limits on infrastructure, e.g. number of playing fields and space for the teams, has been reached. This is especially true in the KidSize competition, where a limit of 24 fully qualified teams plus a few, typically one or two, teams qualified for the technical challenges was introduced. The teams are qualified from a group of about 31 applications every year. This number has remained fairly constant throughout the years. However, for the year 2015 the number of KidSize teams will decrease slightly.

Records of geographic origin of teams over the recent years show a significant involvement of countries like China, Germany, Iran, Mexico, Taiwan (ROC) and the USA (Fig. 9). Some countries have a stable contribution, e.g. Germany with four to five teams every year. However, often the individual participation appears to be subject to the host country of RoboCup. Teams report travel costs and logistics effort to become an increasingly relevant aspect of participation. Overall, some locations such as The Netherlands (2013) and Istanbul (2011) had slightly more participating teams than other locations such as Mexico (2012). However, the influence is rather minor though leading to a variance of about two teams per size class.

As in regular soccer, statistics on goals in RoboCup humanoid robot soccer exist (Fig. 10). The number of goals may be considered as a suitable general performance indicator, but the Humanoid League constantly adopts the rules towards the 2050 game. One would therefore expect to have an increasing average goal count, that drops after introduction of new rules. However, goal statistics

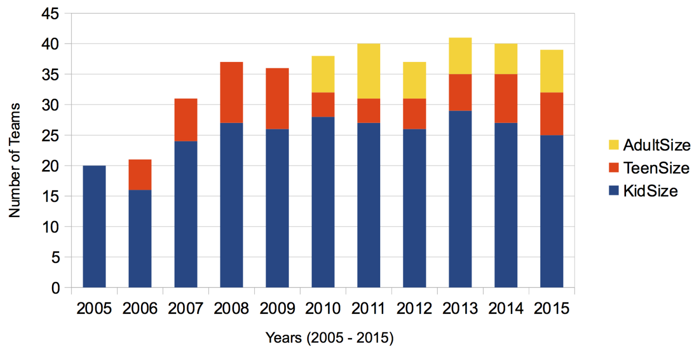


Fig. 8. Number of Qualified Teams for RoboCup World Cup

show only a weak correlation with rule changes. For example, when increasing the field size for TeenSize in 2011, there was a drop in average goals. When doing the same change in KidSize in 2014 with otherwise similar conditions, the average number of goals actually slightly increased. Then again not observing a similar drop in AdultSize in 2012, when field size was increased for this sub-league, can be explained by the specific structure of the dribble and kick competitions with a single robot in each team.

The consequences of the rule change of abandoning blue and yellow colored goals in 2013 are also not reflected clearly in the average goal count. Upon introduction it was discussed if this change would result in less successful strikers and a reduced goal count or in an increased goal count due to more own goals. The drop in the average number of TeenSize goals in 2013 indicates that the strikers may be less successful. However, the drop in average goals in the KidSize sub-league is only minor, if statistically significant at all, for the respective year. The authors expect other underlying influences to exist. With typically more experienced teams in the TeenSize sub-league, own goals may not have played a significant role, unlike in KidSize, where the drop in proper scoring was mostly compensated by own goals. However, no records exist to support the explanation. AdultSize goals do not show a similar effect, which again can be explained by playing on a single goal in this sub-league.

The Humanoid League also introduced a number of technical improvements to robotics. Team NimbRo has been working intensely on the stability of walking and contributed the concept of capture steps to keep robots from falling after bumping into each other [12]. Other examples are the design of a series elastic actuator add-on to the widely used Dynamixel servos, which was presented by a joint team from Universidade Federal do Santa Maria in Brazil and Ostfalia University from Germany [13]. The elastic element was intended to absorb shocks, store energy and possibly, with an additional displacement sensor, allow for dynamic gait in the future. Furthermore, the element may introduce passive compliance to robots, helping to survive falling and possibly help avoid harming humans during interaction. Another novelty was evaporation cooling of drives

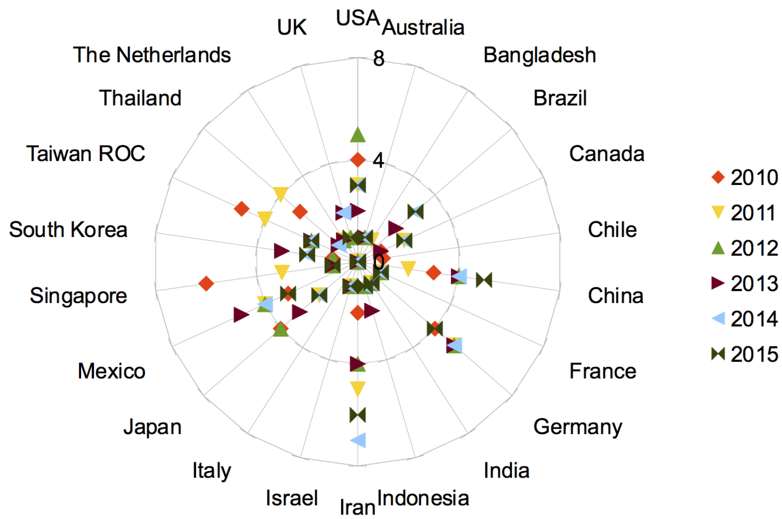


Fig. 9. Distribution of Team Countries in RoboCup Humanoid League.

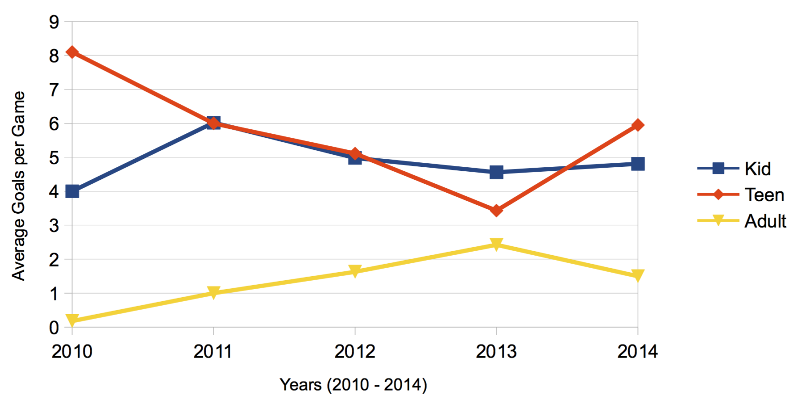
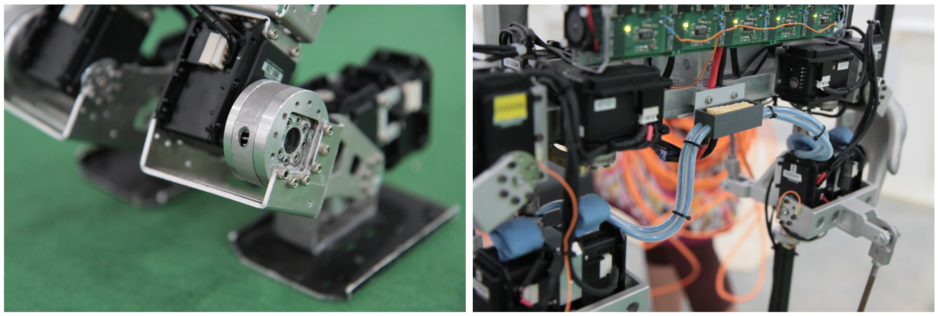


Fig. 10. Average Goals per Game in RoboCup Humanoid League.

introduced by team Sweaty from the Offenburg University of Applied Sciences (Fig. 11).



Series Elastic Actuator (SEA) Evaporation Cooling

Fig. 11. New Robot Details at RoboCup 2014

7 The Future of the Humanoid League (2015–2050)

As the capabilities of the robots improved, the RoboCup Humanoid League started playing with smarter and larger robots that become more and more similar to human players in their kinematics, dynamics, and sensing. However, with three to five years for every robot generation to be developed and mature, only seven to twelve generations of robots remain until the game against the human soccer champion in the year 2050. Relating this to the time a team of humans may require to advance from entry-level to premier league may underline the overall ambition of the project.

Urgent targets for further improvements are compliance and energy efficiency of the robots. The use of compliance in control and construction of the actuators and links as well as soft materials on the outer shells will be necessary for improved soccer capabilities, such as running, falling, high-speed kicking and safe robot-robot and human-robot physical interaction [14]. Currently, the robotic soccer games last only 2×10 minutes due to the limited capacity of the batteries in relation to the relatively poor power to weight ratio of the servo motors. Furthermore, few of the robots are able to use the inherent dynamics of the motion (e.g., the swing leg needs to be actively driven rather than swinging freely, because of the friction in the gear box) or are able to store energy in springs or other mechanics. The targeted improvements strongly link the RoboCup activities with leading new topics in the robotics community. For example, questions like a more efficient movement and soft materials are also reflected by a number of recent technical committees of the IEEE RAS [15], like the ones on Human Movement Understanding and Soft Robotics.

Moving towards larger robots also comes with a number of organizational implications for the competitions. Designing, building and sustaining a full team of robots will become increasingly hard if not impossible for a single team. Furthermore, the entry-level for new teams would raise significantly. The organizers plan to establish rules and procedures to encourage cooperation between teams like between the University of Manitoba and Amirkabir University of Technology (Tehran Polytechnic) [16]. There have already been several initiatives directed at creating suitable communication protocols and infrastructure that will allow robots from different teams to play together effectively. Team FUmanoids received a RoboCup Federation Grant in 2012 and developed a common communication platform for humanoid robots.

Furthermore, many Humanoid League teams have released their source code and hardware designs [17]. However, the benefit of those contributions is much less immediate. Firstly, teams often use different hardware platforms, so inverse kinematics, gaits, device drivers and low level controllers often require significant adaptations for different robots. Secondly, even higher-level functionality in the software are implemented using different and often custom middle-ware. There are now several initiatives to implement soccer robot middle-ware for important modules such as vision, localization, walking engine, and communication. The Robot Operating System (ROS) is a popular candidate to simplify interoperability of software developed by different teams. Improved computational power on the robots and more efficient implementations of the ROS stack now allow to consider this option for mobile autonomous robots.

The rules for 2015 follow the Humanoid League roadmap [17] towards more natural playing fields and environments. Color coding of the environment is completely abandoned, except for cyan and magenta team colors. The previous years' technical challenge of playing with an arbitrary ball now found its way into the regular games. Unlike the early orange balls, balls are now specified according to FIFA rules with a 50% minimum of white. The size of the ball for the KidSize also was increased to FIFA size 1, which is the smallest available official soccer ball. It it used as a so-called skill ball in real soccer training. AdultSize already uses regular-sized soccer balls. Another major advancement is changing the playing surface towards artificial grass. This decision has significant implications for walking and ball handling. Active balancing and uneven terrain walking will become more important for the robots (see Fig. 12).

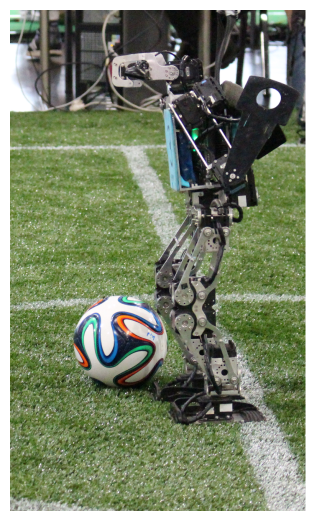


Fig. 12. A robot at RoboCup German Open 2015 on artificial grass using a size 1 FIFA ball.

The catalog of technical challenges moves ahead even further in 2015. Push recovery, i.e. avoiding a fall after contact between two players will become an increasingly important capability as the number and speed of the robots increases and collisions between players are more likely to occur. The high kick challenge has been around for some time now. However, with larger and heavier balls in the KidSize it again needs attention by the teams. The new playing field surface with larger friction and possible deviation of the ball's course is expected to further motivate high kicks in regular games [18]. A receive and kick exercise shall address vision capabilities. A high-jump challenge, expecting the robots to safely land on their feet, shall be the first challenge with a strong dynamic 'flavor'. For the first time in RoboCup competitions, robots will intentionally have a short flying phase. With this being a challenge on its own, furthermore a controlled landing will be required. The high jump is expected to be the first step to having robots run in the game.

For future RoboCup competitions, even more advanced technical challenges are envisioned. Walking on natural grass in the open requires sophisticated balancing and vision skills, as well as suitable hardware. Balancing will be an issue especially for the early phase, when robots of half the size and significantly lower weight than humans have to walk on grass. Furthermore, more dynamic game play is aimed at with a throw, receive and kick challenge. For this a robot should lift up the ball from the ground, throw it towards a team mate and have the ball kicked to the goal.

Some small aspects, however, still require further research, some of them more for organizational than technical reasons. Listening to the referee's whistle is an example for this. Whilst in principle listening to a whistle is feasible, at the competitions with playing fields close to each other and multiple games going on at the same time, the signals of two adjacent fields may not be clearly distinguishable, bearing in mind that the next field's referee may be closer to a robot than the one leading the game.

For the future, the roadmap foresees five-year intervals for major rule changes. In 2020, the minimum size of the robots is envisioned to be raised to 60 cm. Furthermore the field size shall increase to 20 meters, the number of players to six and the duration of the game to two times 20 minutes. Further changes are planed for 2025. The year 2030 is entitled 'It's time to play against humans.' For this year, a technical challenge to outrun the president of the RoboCup and 'competitive games' against an 'unprofessional human team' of eight players is foreseen. For the year 2040, full compliance with FIFA rules shall be reached.

8 Humanoid Soccer Workshops, Schools, and Publications

The Humanoid League fosters development through the organization of competitions, and also has a strong focus on advancing research via publications, workshops, and schools.

Research and development activities are regularly published in high-quality journals. The community contributes to the annual RoboCup International Symposium and major robotics conferences like IROS and ICRA.

In addition, members of the league contribute to the organization of and the submission to the annual humanoid soccer workshop, which is organized since 2006 at the IEEE-RAS International Conference on Humanoid Robots, the flagship conference for humanoid robotics research.

Hamburg, Germany, 2014   Amirkabir UT., Tehran, Iran, 2014

Fig. 13. Participants of Humanoid Soccer Schools

Since 2012, members of the Humanoid League organized a number of humanoid soccer schools and workshops (see Fig. 13). These events provide unique opportunities for researchers and hobbyists alike to learn from some of the leading experts in the field. In contrast to scientific conferences, the humanoid soccer schools include practical components. A considerable amount of time is made available to students to complete exercises and/or test their own ideas on real systems. The humanoid soccer schools also include a series of social events to foster collaboration between the teams.

All these scientific activities ensure (a) that the research developed as part of the RoboCup initiative is widely disseminated to other researchers, (b) that researchers learn about the latest research results from other humanoid robotics researchers and (c) that new teams have a point to start their research.

9 Conclusions

The paper illustrates the development of the RoboCup Humanoid League community and how the league fosters advancements in humanoid robotics. It also gives an outlook on the developments of the capabilities of humanoid soccer-playing robots, rules, and forms of organization for the competitions yet to be expected.

The authors would like to thank previous and current members of the RoboCup Humanoid League community for their input during many years of rule discussions and development. In particular, we would like to thank the other members of the RoboCup Humanoid League technical and organizing committees, Luis F. Lupian, Marcell Missura, Sean Luke, Maike Paetzel, Hafez Farazi, Bente Reichardt and RoboCup trustee Oskar von Stryk.

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