RoboCup Soccer: Humanoid League

[DRAFT] Roadmap

June 13th 2019

RoboCup Humanoid League Mailing List (for important announcements):
`https://mailman.cc.gatech.edu/mailman/listinfo/robocup-humanoid`

RoboCup Humanoid Forum (for rule discussion and questions):
`https://hl.forum.robocup.org`

RoboCup Humanoid League Home Pages:
`https://www.robocuphumanoid.org/`
`https://www.robocup.org/leagues/3`

1 Introduction

This document is a proposal to replace the roadmap proposed in 2014 for the RoboCup humanoid league [1]. Criticisms have emerged with respect to establishing a long-term schedule for evolution of the rules in a research context where evolution is mainly guided by breakthrough rather than by linear development. Some of the changes planned revealed to be difficult to implement: the removal of the KidSize initially planned for 2020 seems now unrealistic since this league still received more applications than TeenSize and AdultSize together in 2019. Finally, the relationship between missing skills and research topics was not explicit.

In order to avoid facing these issues, a different approach is used. Rather than establishing a long-term schedule, the document describes the scientific challenges for the league and the steps required to play against humans. Upcoming changes in the next 5 years are described in more detail in order to allow teams, local organizers and the RoboCup Federation to have a better insight on the evolution of the league.

In order to produce a roadmap satisfying for both the trustees and the league, a workshop was run at IROS2018 and polls have been proposed[2]. While a consensus was obtained on most of the questions, this process has also shown that for some propositions it is difficult to reach an agreement.

While the focus is on perspectives for the league, the document also contains information on the history of the league, thus allowing an improvement of the understanding of the league evolution. Updating this document regularly will allow to assess progress within the league and ensure that modification to the rules are consistent with the level of the teams. An evolution of the rules consistent with the level of the teams and scientific breakthrough is crucial to improve the attractiveness of the league for both researchers and public.

The structure of the documents is as follows. Section 2 introduces the scientific challenges related to the league and their importance in the games. The major upcoming changes to the rules are presented in Section 3. The global evolution of the leagues is discussed in Section 4 through an event-triggered Roadmap and the history of changes which occurred since the creation of the league.

2 Scientific Challenges

2.1 Issues in Motion Generation and Control of Humanoid Robots

The first humanoid robot built was the WABOT-1 which was completed in 1972. While WABOT-1 was already able to walk, controlling the walking gait of a humanoid robot a challenging problem today. From designing dynamic walking gait to running and real-time adaptation of multi-objective motions, motion control of humanoid robots is an active research topic.

While bipedal locomotion is still one of the main issues of the RoboCup humanoid league in 2019, other motions are also important. At the moment these are mainly motions for standing up and kicking a ball on the ground. In the future, this will also include jumps, headers, volleys, and other highly dynamic motions. Given the adversarial nature of RoboCup, one of the key elements is also the transition between different motions in order to reduce the time required to achieve complex tasks. Finally, a major concern from a mechanical point of view is achieving satisfying performances while using low-cost hardware and ensuring the robustness of the hardware despite the fact that the robots are falling.

2.1.1 Bipedal locomotion

Most approaches to humanoid walking nowadays use the Zero Moment Point ZMP stability criterium first analyzed by Vukobratović et al [Vuk+01]. Vukobratović proved that the ZMP criterium is a sufficient condition for dynamic stability.

Sugihara developed stable online walking trajectories using an inverted pendulum model. Many teams in the humanoid league have developed stable walking gaits in the forward directions or omni-directional walking engines [Sug+02].

Just like in human soccer, collisions between players with players from the opposing or own team are common. The increased speed of the robots as well as the increased number of players on the field also necessitates that the robots can compensate for collissions (push recovery). Pratt et al. introduced capture steps to control a robot during push recovery after a collision[Pra+06].

[1] `http://www.robocuphumanoid.org/wp-content/uploads/HumanoidLeagueProposedRoadmap.pdf`

[2] Detailed results are available at `http://www.labri.fr/perso/lhofer/content/robocup/roadmap_workshop_slides.pdf`

2.1.2 Offline and Online Learning of Motions

Since the development of walking gaits and push recovery motions for humanoid robots is non-trivial and many approaches require complex models of the dynamics of the robot, there has been continuous interest in optimizing motions or even learn motions from scratch using machine learning. Many approaches to learning of motions have been explored by RoboCup teams and other researchers. Genetic algorithms [Hua+18], Support vector machines SVMs [Wan+13], artificial neural networks ANNs [Kim+12], cerebellar model articulation controllers CMACs [Sab+05], and reinforcement learning (RL) [Mor+04] have explored for learning trajectories for walking, push recovery, and other motions. These approaches have led to some impressive results, in spite of the fact that applying these techniques to robotics domains is difficult since the perceptions, states, and actions of the robots are continuous, instead of the more common discreet representations (e.g., attribute-value representations).

In recent years, many areas of Artificial Intelligence have been revolutionized by deep learning approaches. Deep learning approaches have also been used increasingly by other humanoid robotics researchers and RoboCup participants [Hwa+19].

Early approaches focused on offline learning approaches, where the motions of the robots are learned prior to a competition. The training data is usually labeled training data from actual experiments with the robot. Several algorithms also seed the learning of the robot using synthetic training data generated from simulation or a combination of real-world and simulation data. Deep learning approaches in general have a higher sample complexity and the generation of good training data is therefore challenging.

More recently several researchers have also applied online machine learning approaches, that is the system learns to optimize its motions during game play. The aim of these approaches is to reduce errors in the kinematic and dynamic model of the robot. Another motivation for online learning is to compensate for faults in the robot. For example, a robot that damages one of its hip ervos may learn to adapt its motion during the match, so that it can still help its team albeit less effective than if it were in perfect working order.

2.2 Compliant Actuators and Soft Robotics

The most common technology for humanoid robotics use servo motors with spur gears as actuators. The MX, RX, X series products of Robotis Inc. are used by many teams in the humanoid league, especially in the kid and teen sized leagues. In the adult sized league, robots usually use actuators build from a combination of servo motors with additional gears to increase the torque. Several teams now also use harmonic drives (e.g., Robotis Dynamixel Pro series).

The mechanical structures are stiff and built from aluminium or carbon fibers.

Affordable servo motors have poor power to weight ratios and highly dynamic motions are severely limited due to insufficient power output. Currently, the robots in the humanoid robot league are unable to run.

Furthermore, the first problem with these kinds of robots is that it is hard to see how these robots will ever be able to run dynamically. The high impact forces when landing would result in damage to the gear box.

Researchers are actively investigating the use of compliant actuators or new actuation models (e.g., cycloid motors, linear actuators, artificial muscles)

The second problem is that these kinds of robots cannot safely operate in joint environments with humans, especially in soccer, where collisions between players frequently occur.

Researchers are investigating protection of the robot mechanics, detection of entangling of robots, and soft materials to ensure that robots do not injure human players. The safe game play with humans does not only require improved mechanics, but also requires improvements in perception, reasoning, and actions.

2.3 Perception

2.3.1 Visual Perception

Humanoid soccer robots perceive their environment exclusively through cameras. Recent changes in the Humanoid League rules resulted in a soccer environment with less color-coded objects, which makes the perception of the game situation more challenging. The robots have to perceive the game situation in real-time under realistic conditions. The simple color segmentation and blob detection approaches that were quite popular in the past [Far+15] have become unsuitable, and many teams are using deep learning approaches now [Fic+18] [Sch+17]. Aggregation of information and filtering the perception are also crucial to analyze the state of the game with high accuracy.

To reduce the amount of work required to label the dataset for visual perception — especially for data-hungry machine learning methods like deep learning — tools have been developed to allow multiple teams to mutualize their efforts toward producing a dataset for the community [Fie+18]. One of the scientific challenges which is specific to

Humanoid robots, and other lightweight robots like drones, is the limited computational resources that are mainly due to weight limitations.

2.3.2 Robot Detection and Identification

The use of a team of humanoid robots to collaborate in completing a task is an increasingly important field of research. One of the challenges in achieving collaboration is mutual identification and tracking of the robots. One of the scientific challenges in visual perception is a real-time detection and tracking of robots of known and unknown appearance. Online humanoid robot detection, tracking, and identification are the foundations for good cooperation between the robots. There are already some papers for this research topic in a humanoid soccer environment, using filtering [Far+16], and deep recurrent networks [Far+17].

2.3.3 Localization

Currently, most of the localization modules are based on particle filters which allow to track multi-modal distributions. While these approaches have proved their efficiency, recent advances in the SLAM domain suggest that localization based on factor graphs rather than filtering are more accurate [Str+12]. To add another source of information for supporting robot localization especially when the robot is kidnapped, visual odometry can be considered. By utilizing the input of the camera system, the 6-DOF motion of the camera can be estimated. SVO 2.0 [For+14] and DSO [Eng+18] are two examples of these approaches for monocular vision. A sample output of DSO on the soccer field in illustrated in Fig. 1. Both systems offer built-in support for integration into ROS and allow real-time processing of image data. While DSO uses a direct approach based on pixel density, SVO 2.0 additionally considers features for analyzing visual input. When testing these approaches with smooth camera movements over short periods of time, both can calculate stable and accurate motion traces. However, extended periods of time or abrupt and fast movements often lead to wrong results or complete failure of these systems. One interesting research direction would be integrating IMU information into the visual odometry system to achieve more stable results. Almost all of the teams in the humanoid league try to solve the localization problem in 3-dimensions.To have more interesting planning, a 6D-localization would be desired.

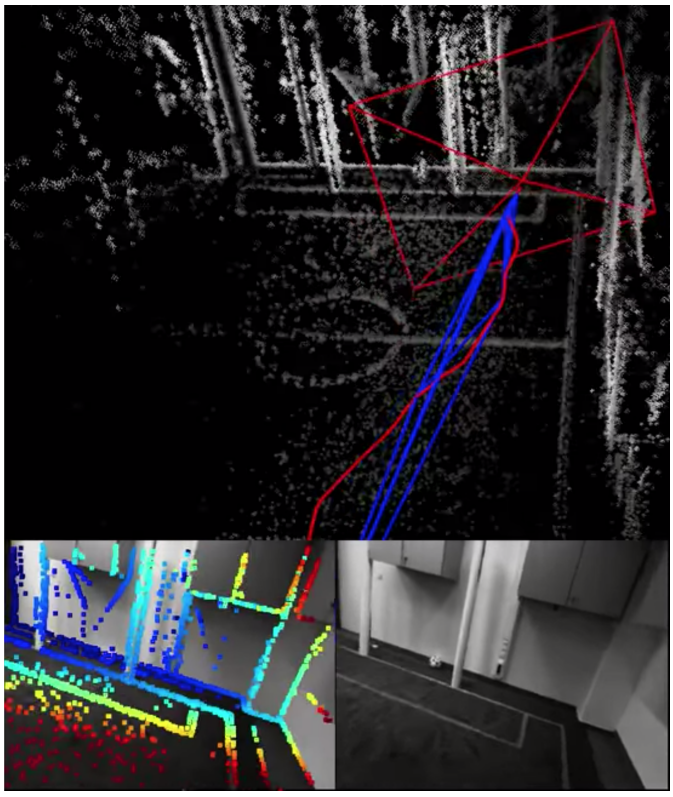

Figure 1: Output sample of DSO on soccer field.

2.3.4 Dynamic Model Calibration

Most of the information used for localization relies on information provided by the camera. Having the exact kinematic model of the robot is not always possible. Therefore it is necessary to calibrate variations from the designed CAD model to prevent potentially large projection errors for distant objects. A calibration of the kinematics on each robot that tunes translation and rotation offsets between the torso and the camera is required. These offsets are crucial for a good performance of the pixel to egocentric coordinate projection algorithms. During the last years, multiple teams have started to work on automatic kinematic calibration. These approaches are generally based on the use of visual markers easily detectable such as Aruco Tags [GJ+14].

3 Short-term: upcoming changes

3.1 RoboCup 2019 changes

The major rule changes for RoboCup 2019 are as following:

- Natural lightning conditions are now explicitly allowed. It provides more flexibility for the local organizers and helps to prepare for moving outdoors while stimulating research on perception. Since SPL has already had some success in these conditions, it is reasonable to expect teams to be able to adapt.
- Throw-in, corner kicks and goal kicks will be introduced. This will make games closer to FIFA games, thus making it easier for public to understand referee's interventions on the field. It is also expected that this will encourage teamplay since stoppage of games allow robots to position themselves.
- The rules with respect to pick-up of robots and penalties for invalid behavior have been reworked to reduce the number of interventions from the referees. It also encourages team to have robust robots playing during the whole game by increasing constraints on penalized robots.
- The presence of an emergency stop button will be required but without constraints on appearance. It is a mandatory step toward allowing robots to play with humans.
- For the adult size league, the size of the field increases to 14×9 meters (previously 9×6 meters) and the games are now played 2 vs 2 robots. These changes will allow teamplay options for this league and is taking into account the fact that the locomotion speed for this league has significantly evolved for the past few years.

There are also some minor adjustments:

- Time for repositioning during some stoppage of the game has been increased. In 2018, several teams had trouble to reach their own half within the time constraints after scoring a goal. This led to frequent interventions from handlers which can be reduced by slightly increasing the time allowed for robots to position autonomously during stoppage of games.
- A new phrasing regarding constraints on foot design has been introduced to reduce the risk of misunderstandings.
- The surface of teams markers is increased and the restriction regarding the location of the markers on the robot has been reduced. This change will make it easier to detect opponents, thus improving the chances of presenting satisfying gameplay to the public.

3.2 RoboCup 2020 changes

The process of updating the roadmap allowed the identification of immediate changes which could benefit the humanoid league. One of the most important element is the organization of the league. Since 2010, the league is composed of 3 leagues, KidSize, TeenSize and AdultSize. While this structure was adapted at that time, evolution of the field and of the teams at the RoboCup over the past years show that there are way for improvements.

For RoboCup2020, we intend to bring major modification to the league structure in order to achieve the following objectives: allow more diversity in the league, increase the coherency of the structure with actual status of the competition and finally propose a more flexible structure which can be easily adapted.

The scheduled changes are as follows:

- Restructuring regular tournament
- Open Humanoid Leagues
- Humanoids Demo Events
- Reduction of the handlers interventions
- Update of the technical challenges

This section starts by describing the changes and then summarize the impacts on organization.

3.2.1 Restructuring regular tournament

While the number of teams involved in the TeenSize league has globally increased since 2010, the height of the robots in this league is globally decreasing and entering the buffer zone between KidSize (max 90cm) and TeenSize(min 80cm).

RoboCup 2017: 5 teams had robots larger than 90cm.

RoboCup 2018: Only 1 team had a robot above 90cm (94cm).

RoboCup 2019: According to the qualification material, all teams have robots between 80 and 90cm.

In regard of these elements, we propose to integrate the small robots from TeenSize to the KidSize and the larger robots to the AdultSize.

Increasing the number of participants in each league would also make it easier to separate the main league in two divisions, allowing experienced teams to have more competitive games and new teams to have a more interesting event. It would also be interesting to increase the average number of robots on the pitch without losing teams due to financial issues. Finally, while Drop-In games have triggered the interest of multiple teams, some teams find that it overloads the schedule, especially during the knock-out phases.

In order to solve these problems, the tournament will use the following structure:

1. The tournament will start by all the Drop-In games. This phase will require only one robot per team.
2. Teams who do not have the maximum number of robots allowed for their league are required to form combined teams in order to form a full team of robots.
3. If there are fewer than 16 teams in the league after the merge procedure, all teams play in division A. If there are more than 16 merged teams, repartition of the teams is based on the result of the teams during Drop-In games and play-off games.

   Division A: Best 6 teams + winners of play-offs for teams 7-10.

   Division B: Losers from play-offs teams 7-10, teams 11-20, winners of play-offs for teams 21-28.

This structure ensures that teams who have a single robot can participate and play a fair number of games. Teams with more resources are allowed to present a full team in order to work on their teamplay during the year. Finally, this method ensures that the fields will have the appropriate number of robots, from the Drop-In to the regular tournaments.

3.2.2 Open Humanoid Leagues

The current implementation as led to some constraints on robot design (passive sensors, size limitations) and complex rules in order to ensure fair games and to focus on human-like structure and perception. While this allows to bring the rules of the competition closer to the FIFA rules, it increases the entry cost for newcomers. In order to attract new teams, the Open Humanoid League will be opened. This league will have a very limited number of rules and reduced hardware constraints.

Since it is difficult to anticipate how many teams will apply for this league, implementation details will be chosen depending on the teams interested in this competition. Trophies will be awarded to the teams according to the same rules as regular leagues.

3.2.3 Humanoids exhibition events

Increasing the diversity of approaches used inside the league and broadening the views of participants is important to avoid stagnation and uniformity in design. In order to reduce this risk, exhibition events will be introduced.

Each year, research themes relevant to the league will be chosen by the TC. Both, teams from the RoboCup and research teams in robotics will be invited and selected to present their work during the RoboCup.

Demonstrations will not be limited to soccer playing humanoid robots, they will also include innovation on specific themes (e.g. soft robotics). The aim is to reserve space and time slots to present innovation in technology or research in order to stimulate the apparition of new ideas in the league. Constraints on the exhibitions will be avoided in order to allow original elements, no awards will be provided in order to keep it as a competition-free event.

3.2.4 Reducing handlers interventions

Presenting autonomous robots performing complex tasks is one of the strength of the RoboCup community. In this context, every opportunity to move robots on the field given to handlers reduces the constraints on autonomy and therefore the achievement. Moreover, interactions of the handlers with the robots reduce the interest from the public.

Currently, handlers are allowed to place manually a striker and a goalie. In 2020, all robots will have to perform autonomous placement, starting from the side of the field. The aim of this change is to focus on autonomy and robustness in localization while reducing the frequency of human interventions.

3.2.5 Update of the technical challenges

From 2020, it will be mandatory for teams to have multiple robots in their team or to merge with other teams in the regular tournament. Therefore, we will start introducing technical challenges requiring collaboration between robots.

One of the current challenges is based on performing a kick on the goal from a moving ball. Currently, the pass can be performed by either a robot or a human. In 2020, pass will have to be performed by a robot. By enforcing this as a technical challenge we intend to promote dynamic gameplay.

The high-jump challenge will be changed toward a landing challenge which will focus on absorbing shocks and thus on soft robotics.

On the same trend, a standing-up challenge will be introduced for adult size robots. This technical challenge will then evolve toward falling robots with the aim of removing robot handlers on the long-term.

4 Long-term: event-triggered roadmap

While the previous roadmap was based on a schedule planning the year of the appearance of some skills, this roadmap bases the evolution of the rules on the performance of the robots. The current version also presents evolution of the rules since the creation of the league in order to provide a better understanding of past evolution in order to anticipate the impact of upcoming changes. Moreover, by analyzing in-game performances of the robots and storing them, it will be possible to assess properly the evolution of the league.

First, the guiding principles of the event-triggered roadmap are presented in section 4.1. The list of the metrics used to assess progress of the robots and evaluate which rules changes should be applied is detailed in section 4.2. Finally, detailed rules changes and the conditions to trigger them are discussed in section 4.3.

4.1 Guiding principles

Changes in the rules will be triggered by either research breakthrough or continuous improvement of some skills. Those improvements will be ensured through either measure of metrics during the game such as walking speed or success at technical challenges. This will ensure that the rules improvements are coherent with the capabilities of the robots in the league.

During the roadmap workshops and the polls, several teams requested to have updates rules known sooner, in order to plan their development for the competition. Similar issues arise for local organization with changes regarding the size of the fields. In order to provide more time to teams and local organizers while still allowing adaptation of the rules, we propose to separate the evolution of the league in three categories depending on the

number of years required between the announcement of the rule change and its application. Note that we consider a 4-month period to allow the TC to implement the changes inside the rulebook.

1Y: Changes which can be made from one competition to the other without requiring previous announcement. This is limited to rule changes which have a low impact on the robot design and do not require additional space for the competition. These changes have to be announced at least 8 months prior to the competition.

2Y: Changes which might require significant hardware investment for the teams or important modifications for the local organizers. These changes have to be announced at least 20 months prior implementation.

4Y: Major changes which require drastic modifications on robot design. These changes shave to be announced at least 44 months prior to the competition.

4.2 Metrics used

Continuously assessing the performances of the robots is a crucial point to ensure that evolution of the rules is consistent with the improvements of the league. Another benefit of gathering metrics on the performance of the robots is the possibility to measure the impact of rule changes and the progress made.

In order to capture the performances of the robot during the games, we propose to record logs of the game including: videos, messages from the referee box and messages from the robots. Teams will be strongly encouraged to share information on the perception and intention of their robots which is a required element to assess their performance. Ground truth will be obtained by human annotation of multiple calibrated video streams.

Gathering the metrics presented in this section will strongly improve the possibilities to assess improvements in the league, allow teams to publish quantitative results to support their claims and provide large amount of data to run learning algorithms. However, those benefits will come at a cost: significant software development will be required, human effort will be needed to validate the data and teams will have to agree on a common protocol. Therefore, extraction of the metrics will be introduced progressively during the next years.

4.2.1 Motion metrics

Peak speed: Reaching high-speed bipedal locomotion is one of the key research themes of the league. This measure is based on the highest distance traveled by a robot over 5 seconds.

Approach time: Efficiently controlling a locomotion engine based on perception is a difficult problem. The time required to travel the last meter before kicking is a good indicator of its controllability.

Kicks and throw-ins: Kicking the ball in soccer is one of the most important skills. From a robotic point of view, kicking is a highly dynamic motion task where a maximum of energy has to be transmitted to the ball while keeping balance and preserving accuracy. Keeping track of the different types of kicks and some of their properties helps to better understand the evolution of the game

- **Kick type:** There are many different types of kicking in soccer: forward kicks, side kicks, heel kicks, throw-ins (with hands) and even bicycles.
- **Ball status:** Robots can kick in ball which is static, rolling or flying at the moment of the impact. The number of kick from rolling balls or flying balls is a strong indicator of the dynamics of the games.
- **Kick power:** Powerful kicks give a strong incentive toward teamplay. This measure is based on the distance traveled by the ball before stopping or bouncing.
- **Kick accuracy:** In order to play as a team or to score goals, it is important that robots are capable of kicking accurately. Measuring the difference between the intention of the robot and the result of his kick with respect to direction and power helps to assess the quality of kicks.
- **Execution-time:** Smooth transition between motions is an important research theme. Time required to go from walking motion to the end of the kick motion measures both, the transition and the dynamic aspect of the motion.

4.2.2 Perception metrics

The comparison between ground truth and belief of the robot will allow the measurement of the quality of the perception of the robots.

Ball Localization and prediction: The measure of ball localization takes into account the percentage of time where the ball is located and the quality of the position estimation in an egocentric basis. On long-term, estimation of the speed of the ball and prediction of the trajectory will be considered.

Self Localization: Accurate localization in natural environment is a difficult problem which includes detection of features, odometry and filtering. It is an essential skill for teamplay and high-level behaviors. The measure of self-localization includes position and orientation of the robot on the field.

Opponent recognition: Measure of the quality of opponent recognition will be based on estimated position and orientation of the opponents in an egocentric basis. On long-term, recognition of other robots intentions will also be evaluated.

4.2.3 Gameplay metrics

High-level metrics related to gameplay are used to measure global performances of the teams and the quality of the teamplay.

Shots on goal: The number of shots on goal during each game.

Diving saves: The number of successful and failed dives from goalies.

Robots on field: The average number of robots on the field per team during games can be compared with the maximum number of robots authorized in order to estimate robustness.

Don't Mess Up Period (DMUP): The DMUP is another robustness measure which indicates the level of autonomy of the robots. The DMUP is the period during which a robot played fully autonomously. Increasing the DMUP is a preliminary to remove the handlers.

4.3 Detailed rule changes

This section presents briefly recent and future evolution of the rules of the competition. It can be used to have an overview of the path traveled recently and on the steps remaining to reach the 2050 goal. For past evolution and short-term changes, the year of the introduction of the change is indicated. For long-term changes, the conditions required to implement the changes and the delay between the announcement of the change and its application are indicated. Conditions for changes are based on the metrics presented in section 4.2. In order to ensure competition is viable for multiple teams, at least 3 teams need to fulfill the conditions to trigger the changes.

4.3.1 Field evolution and number of robots

Playing on real soccer fields with eleven humanoid robots per team is a long-term challenge which requires multiple breakthrough in research, particularly in locomotion. On the other hand, there are also technical and financial concerns: few teams are able to train on an entire field due to space constraints and building eleven robots per team would be too expensive.

Since the beginning of the league, the number of robots per team has been increasing slowly and several changes have been made to the fields:

- The size has increased with the walking speed of the robots.
- While the initial fields contained extra information, those elements have been progressively removed, causing a shift in methods used for ball detection and localization.
- Introduction of artificial turf has proven to be a major challenge for locomotion and has led to original hardware solutions to tackle the problem [Pas+15]. It has also strongly reduced the distance traveled by the ball when kicking, thus putting more constraints on shoots.

Since bipedal locomotion is one of the main research themes of the league, increasing the size of the field in order to match the increasing speed of the robots will be required. In order to keep the gameplay interesting, it is mandatory to ensure that the size of the field stays coherent with the capacities of the robots. Further increases in the size of the field will allow more robots on the pitch, a crucial aspect to encourage collaboration between robots.

The roadmap for evolution of the field and the number of robots per team is presented in Fig. 2. Changes will be triggered by the following conditions: robots should be able to cross the current field in 20 seconds and they should be able to kick the ball across half the field. Due to the major impact of field changes to the organization of the event, changes with respect to the size of the field need to be announced 2 years prior to their application.

With the increase of the size of the field, moving toward outdoor games seems imperative. However, a consensus regarding the requirements to trigger this change has not been found yet.

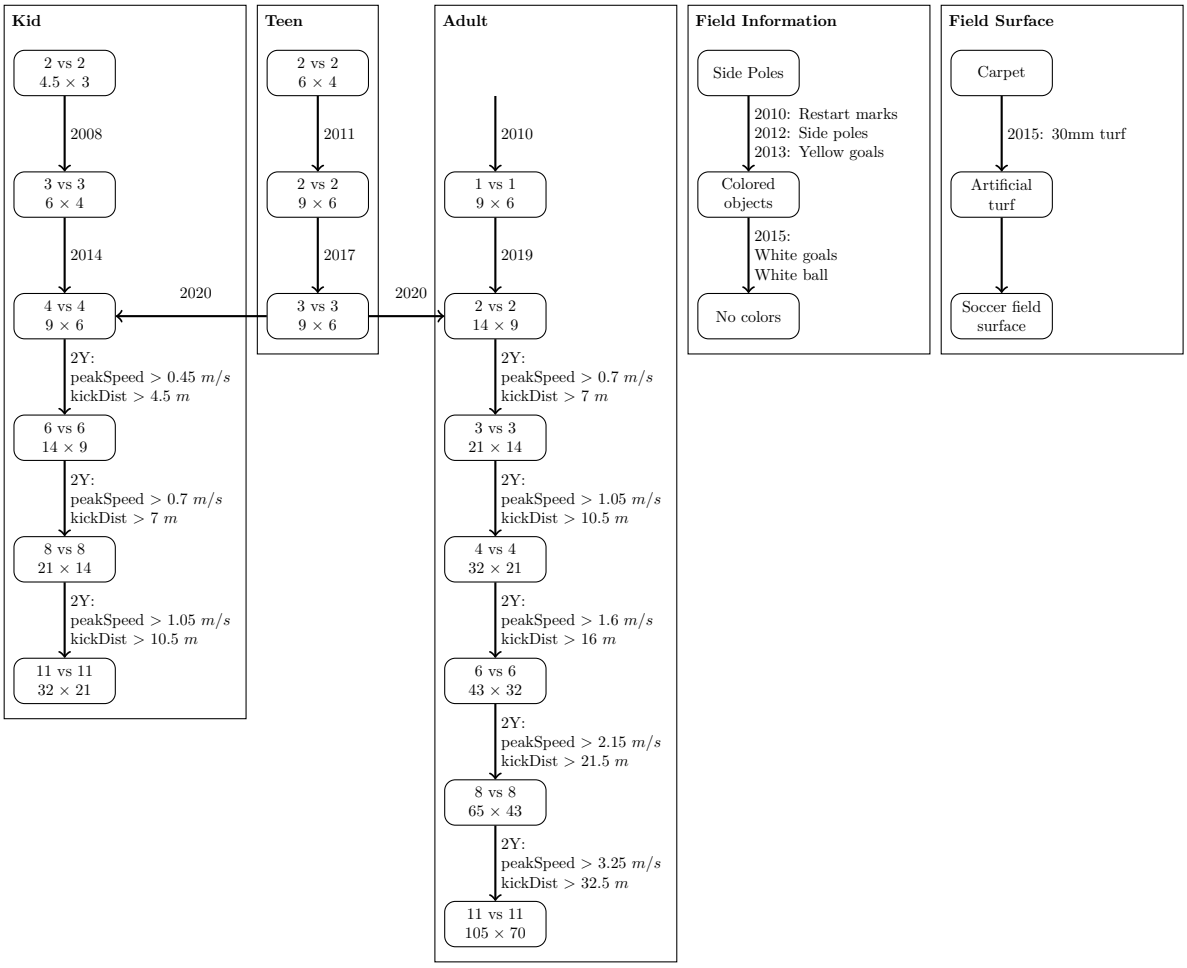

Figure 2: Evolution of the field and number of robots, dimensions in meters.

4.3.2 Handlers and game duration

Activity of the handlers and duration of half-time are related to three important research themes: autonomy of the robots, robustness and energy efficient locomotion. This section presents the roadmap along with some motivations, Fig. 3 summarizes those evolution.

In KidSize and TeenSize, robots are requested to be able to fall and stand-up autonomously, a prerequisite to remove constant presence of handlers on the field which is a key point regarding autonomy for humanoid robots. For AdultSize robots, falling and standing-up is an important research question, while it is necessary to push toward this direction, it is not mature yet. Incentive towards improvements on this topic will be given through technical challenges. Once the problem has been tackled, requirements will be added to the rules and handlers will not be allowed nearby robots.

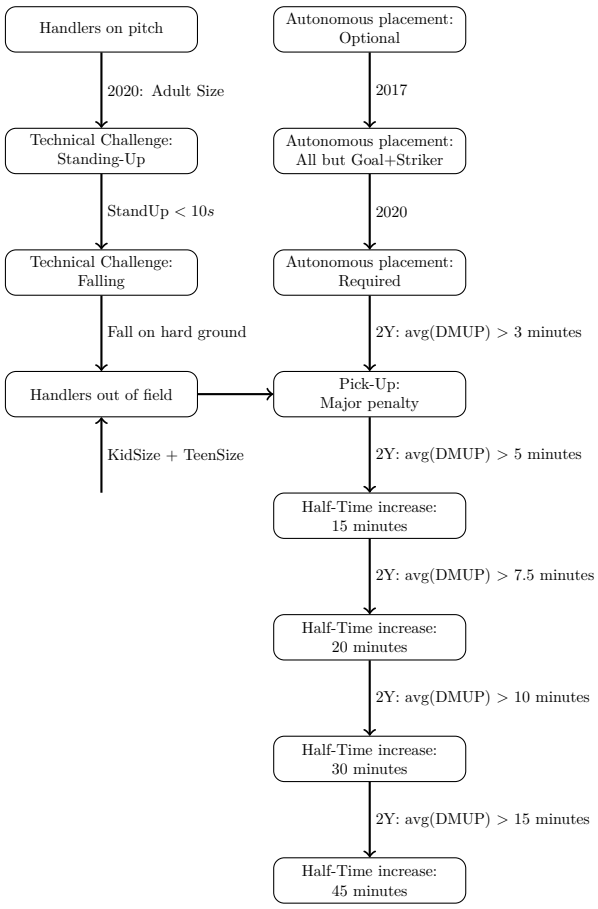

Figure 3: Evolutions regarding handlers and game duration

For robots able to fall and stand-up autonomously, the main challenge for autonomy is to reduce the frequency of human interventions in the league. This implies constraints on the robustness of both, software and hardware. Currently, several teams are relying on the possibility to pick up robots every few minutes to reset their status. In order to create a higher incentive for robustness, it is necessary to have harsher penalties for Pick-Up. However, stricter rules would risk resulting with fewer robots on the field which would not be suitable for the public. Therefore, before changing the rules, a minimum value of DMUP should be ensured.

Once interventions of handlers are reduced to a minimum and robots are capable to play autonomously, increasing the duration of half-time will bring high incentive toward energy efficient locomotion. In order to ensure that increases of the duration are coherent with capacities of the robots, it will be required that teams can play at least half a period without intervention from the handler in average before increasing time duration.

4.3.3 Gameplay rules

In order to reach the 2050 goal, robots have to be able to play according to rules similar to the FIFA rules[3]. However, robots have to reach very high-level of autonomy in order to play according to soccer rules. As an example, respecting the offside rules is particularly challenging with respect to perception.

At the origin of the league, the competition was centered around technical challenges and penalty shootouts. Since 2006, the competition has moved toward real soccer games with rules tending to get closer to the FIFA rules. The latest implemented change is the introduction of goal kick, corner kicks and throw-in or kick-in for RoboCup2019.

There are 2 major gameplay changes remaining to have the gameplay rules similar to FIFA. The first is enforcing that throw-in are performed using hands, this rule will be introduced once the throw-in capacities are performed quickly and strongly enough. The second and most challenging remaining rule is the offside rule. It will require to

[3]It is inevitable to bring modifications to the rules, at least to impose some constraints on the size of the robots, see [Sto+10] for more details the relationship between rules of soccer and robotic soccer.

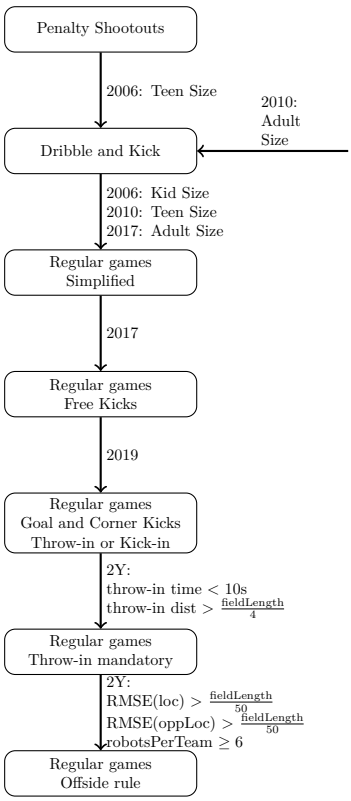

Figure 4: Evolutions of gameplay rules

ensure that three key points are achieved: Self-localization, localization of opponents and a minimum number of robots on the field. Evolution and perspectives for the gameplay rules are shown in Fig. 4.

5 Evolution of the document

Since breakthroughs in research and evolution of the games is very difficult to predict, the following document should be frequently updated in order to match. It should also be possible for the league and for the trustees to request for modifications because some elements seem unrealistic with respect to the current status of the league.

In order to highlight that the document needs to be updated frequently, we present here the minimal frequency for updating the different sections of this document:

- Section 2 emphasizes research related to the RoboCup Humanoid League and on contributions from the league. While major publications from the teams should be added to the document regularly, updating this section requires significant work from the TC and is based on global progress in research areas linked with the league. Next mandatory update is planned for 2024.
- Section 3 presents upcoming changes in the rules. Since it has been made pretty clear by the team that updating the rule book every year was too frequent, it is not mandatory to update it every year. Next mandatory update is planned for 2021.
- Section 4 presents the global evolution of the league. Since it includes metrics on the performance of the robots, it should be updated yearly, after each major competition. Next mandatory update is planned for 2020.

Acknowledgements

This version of the humanoid league roadmap is proposed by the Humanoid League Technical Committee of RoboCup 2019 composed of Jacky Baltes, Hafez Farazi, Reinhard Gerndt, Ludovic Hofer, Maike Paetzel, Soroush Sadeghnejad and Michael Stattler.

The roadmap was established based on multiple feedback from both, member of the leagues and trustees. First opinions for the content were collected at RoboCup 2018 and during a workshop in ICRA 2018.

Special thanks go to Daniel Polani and Oskar Von Stryk for their support and their useful comments.

References

[Eng+18] Jakob Engel, Vladlen Koltun, and Daniel Cremers. "Direct sparse odometry". In: *IEEE transactions on pattern analysis and machine intelligence* 40.3 (2018), pp. 611–625.

[Far+15] Hafez Farazi, Philipp Allgeuer, and Sven Behnke. "A Monocular Vision System for Playing Soccer in Low Color Information Environments". In: *Proceedings of 10th Workshop on Humanoid Soccer Robots, IEEE-RAS Int. Conference on Humanoid Robots*. Seoul, Korea, 2015.

[Far+16] Hafez Farazi and Sven Behnke. "Real-time visual tracking and identification for a team of homogeneous humanoid robots". In: *Robot World Cup*. Springer. 2016, pp. 230–242.

[Far+17] Hafez Farazi and Sven Behnke. "Online visual robot tracking and identification using deep LSTM networks". In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2017, pp. 6118–6125.

[Fic+18] Grzegorz Ficht, Hafez Farazi, André Brandenburger, Diego Rodriguez, Dmytro Pavlichenko, Philipp Allgeuer, Mojtaba Hosseini, and Sven Behnke. "NimbRo-OP2X: Adult-sized Open-source 3D Printed Humanoid Robot". In: *2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)*. IEEE. 2018, pp. 1–9.

[Fie+18] Niklas Fiedler, Marc Bestmann, and Norman Hendrich. "ImageTagger: An Open Source Online Platform for Collaborative Image Labeling". In: *RoboCup 2018: Robot World Cup XXII*. Springer. 2018.

[For+14] Christian Forster, Matia Pizzoli, and Davide Scaramuzza. "SVO: Fast semi-direct monocular visual odometry". In: *2014 IEEE international conference on robotics and automation (ICRA)*. IEEE. 2014, pp. 15–22.

[GJ+14] S. Garrido-Jurado, R. Muñoz-Salinas, F. J. Madrid-Cuevas, and M. J. Marín-Jiménez. "Automatic generation and detection of highly reliable fiducial markers under occlusion". In: *Pattern Recognition* (2014). ISSN: 00313203. DOI: 10.1016/j.patcog.2014.01.005.

[Hua+18] Tran Thien Huan, Cao Van Kien, Ho Pham Huy Anh, and Nguyen Thanh Nam. "Adaptive gait generation for humanoid robot using evolutionary neural model optimized with modified differential evolution technique". In: *Neurocomputing* (2018). ISSN: 18728286. DOI: 10.1016/j.neucom.2018.08.074.

[Hwa+19] Jemin Hwangbo, Joonho Lee, Alexey Dosovitskiy, Dario Bellicoso, Vassilios Tsounis, Vladlen Koltun, and Marco Hutter. "Learning agile and dynamic motor skills for legged robots". In: *Science Robotics* (2019). ISSN: 24709476. DOI: 10.1126/scirobotics.aau5872.

[Kim+12] Dong W. Kim, Nak Hyun Kim, and Gwi Tae Park. "ZMP based neural network inspired humanoid robot control". In: *Nonlinear Dynamics* (2012). ISSN: 0924090X. DOI: 10.1007/s11071-011-0027-1.

[Pas+15] Gregoire Passault, Quentin Rouxel, Ludovic Hofer, Steve N'Guyen, and Olivier Ly. "Low-cost force sensors for small size humanoid robot". In: *15th {IEEE-RAS} International Conference on Humanoid Robots, Humanoids 2015, Seoul, South Korea, November 3-5, 2015*. IEEE, 2015, p. 1148. ISBN: 978-1-4799-6885-5. DOI: 10.1109/HUMANOIDS.2015.7363498. URL: http://dx.doi.org/10.1109/HUMANOIDS.2015.7363498.

[Pra+06] Jerry Pratt, John Carff, Sergey Drakunov, and Ambarish Goswami. "Capture point: A step toward humanoid push recovery". In: *Proceedings of the 2006 6th IEEE-RAS International Conference on Humanoid Robots, HUMANOIDS*. 2006. ISBN: 142440200X. DOI: 10.1109/ICHR.2006.321385.

[Sab+05] Christophe Sabourin and Olivier Bruneau. "Robustness of the dynamic walk of a biped robot subjected to disturbing external forces by using CMAC neural networks". In: *Robotics and Autonomous Systems* (2005). ISSN: 09218890. DOI: 10.1016/j.robot.2005.02.001.

[Sch+17] Fabian Schnekenburger, Manuel Scharffenberg, Michael Wülker, Ulrich Hochberg, and Klaus Dorer. "Detection and localization of features on a soccer field with feedforward fully convolutional neural networks (fcnn) for the Adultsize humanoid robot Sweaty". In: *Proceedings of the 12th Workshop on Humanoid Soccer Robots, IEEE-RAS International Conference on Humanoid Robots, Birmingham*. 2017.

[Sto+10] Peter Stone, Michael Quinlan, and Todd Hester. "Can Robots Play Soccer?" In: *Soccer and Philosophy: Beautiful Thoughts on the Beautiful Game*. Ed. by Ted Richards. Vol. 51. Popular Culture and Philosophy. Open Court Publishing Company, 2010, pp. 75–88.

[Str+12] Hauke Strasdat, J. M.M. Montiel, and Andrew J. Davison. "Visual SLAM: Why filter?" In: *Image and Vision Computing* 30.2 (2012), pp. 65–77. ISSN: 02628856. DOI: 10.1016/j.imavis.2012.02.009. URL: https://www.sciencedirect.com/science/article/pii/S0262885612000248?via{\%}3Dihub.

[Sug+02] Tomomichi Sugihara, Yoshihiko Nakamura, and Hirochika Inoue. "Real-time humanoid motion generation through ZMP manipulation based on inverted pendulum control". In: *2002 International Conference on Robotics and Automation*. IEEE, 2002.

[Vuk+01] Miomir Vukobratović, Borovac Branislav, and Dragoljub Šurdilović. "zero-moment point - proper interpretation and new application". In: *Int. Conf. on Humanoid Robots*. 2001.

[Wan+13] Liyang Wang, Zhi Liu, Chun Lung Philip Chen, Yun Zhang, Sukhan Lee, and Xin Chen. "Energy-efficient SVM learning control system for biped walking robots". In: *IEEE Transactions on Neural Networks and Learning Systems* (2013). ISSN: 2162237X. DOI: 10.1109/TNNLS.2013.2242486.

[Mor+04] J. Morimoto, G. Cheng, C. G. Atkeson, and G. Zeglin. "A simple reinforcement learning algorithm for biped walking". In: *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*. Vol. 3. 2004, 3030–3035 Vol.3. DOI: 10.1109/ROBOT.2004.1307522.