

HSL Joint Team SPQR

Team Description Paper 2026

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1 Team Information

- **Team name:** SPQR Team
A joint team composed by Sapienza University of Rome (Italy) and International University of Rome - UNINT (Italy)
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SPQR is a growing research team based at the Department of Computer, Control, and Management Engineering “Antonio Ruberti” at Sapienza University of Rome (Italy). SPQR Team has been involved in RoboCup competitions since 1998 in different leagues: Middle-size (1998-2002), Four-legged (2000-2007), Real rescue robots (2003-2006), @Home (2006), Virtual-rescue (2006) and Standard Platform League - SPL (2008-2025). SPQR hosts another Robocup group based in Italy, namely UNIN-Team. SPQR team members have served the RoboCup organization in several ways:

- Prof. Daniele Nardi served as Exec, Trustee, and President of RoboCup Federation from 2012 to 2014 and was RoboCup Symposium co-chair in 2004.
- Prof. Luca Iocchi is Exec member of RoboCup@Home, and was Vice-president and RoboCup Symposium co-chair in 2008.
- Prof. Domenico D. Bloisi is the Italian Regional Committee spokesperson.

SPQR team members published a total of 26 papers in RoboCup Symposia (including best paper awards in 2006, 2015 [2], 2021 [6], 2023 [10], and 2025 [26]), in addition to other RoboCup-related publications in International Journals and Conferences in AI and Robotics (including IROS RoboCup Best Paper Award in 2016 [3]).

1.1 Joint Team Members

- **Sapienza University of Rome: Faculty:** Prof. Daniele Nardi (*Team Founder*), Prof. Luca Iocchi - **Members:** Dr. Vincenzo Suriani (*Team Leader*), Francesco Petri, Daniele Affinita, Flavio Maiorana, Valerio Spagnoli, Flavio Volpi, Michele Brienza, Filippo Ansalone, Eugenio Bugli, Can Lin, Jacopo Tedeschi, Arianna Loglisci.
- **UNINT: Faculty:** Prof. Domenico D. Bloisi, Prof. Marco Romano.

Currently, SPQR Team owns one Booster T1 robot viable for competition.

2 Code Usage

From 2026, SPQR is developing its own framework and simulator. This decision has been taken after RoboCup 2025, in order to fully exploit the capabilities of the new humanoid robot platforms while minimizing external dependencies.

From 2013 to 2025, SPQR Team used the *B-Human Team* framework as base for developing its code. The authors acknowledge the members of the B-Human team for their great contribution and work in the SPL league. In particular, from 2023 to 2025, SPQR has adopted the B-Human 2021 framework, modified in the following areas: *perception, coordination, and decision making*.

Before 2013, SPQR used its own framework, called *OpenRDK*.

3 Own Contributions

In this section, we describe our own contributions related to the following critical areas.

1. SPQR Framework
2. SPQR Simulator
3. Sim2Real

3.1 SPQR Framework

We designed our framework with a distributed architecture organized into three core components: Modules, Nodes, and Topics.

Modules are synchronous processing units where state update rules are programmed explicitly. They can receive inputs from both other modules and topics (with no difference in usage), and publish outputs to topics either entirely or partially.

Nodes are asynchronous logic units that run in independent threads. Each node is uniquely defined by its set of *input topics*, *output topics*, and *internal modules*. Within a node, all modules execute synchronously to ensure components are updated with the most recent state. Nodes communicate with each other asynchronously through topics.

Topics are asynchronous messages that enable information sharing across nodes. They define only the message structure (attributes/fields) and support serialization, deep cloning, and comparison through reflective programming. The entire framework structure is defined declaratively in a single YAML configuration file and automatically instantiated at runtime, eliminating boilerplate code and enabling developers to focus solely on implementing module logic.

Behaviors are managed through the library BehaviorTree.CPP, a hierarchical reactive control architecture that provides modularity, composability, and real-time execution capabilities. It allows to separate the structure from the logic of the behaviors: the former is managed through an xml-based tree definition, which define the decision-making structure (i.e. how behaviors are organized); the latter define the action nodes of the tree, and represent the actual capabilities of the robot (i.e. what the robot can do). They are written in C++ code. The behavior tree of a robot executes in a separate thread with its own update frequency, and the action nodes have the possibility to read topics to access fundamental information for the correct execution of an action.

3.2 SPQR Simulator

We developed a simulator specifically optimized for the RoboCup Humanoid Soccer League, using MuJoCo [24] as the physics engine with a complete C++ implementation. MuJoCo was selected for several key advantages:

- Lightweight compared to alternatives such as Isaac Sim [25]
- Efficient CPU-based execution without GPU requirements
- Extensive open-source ecosystem and active community support
- High-fidelity physics with direct access to low-level data structures

The simulator implements a distributed architecture where the physics simulation runs in the main process, while each robot’s control software executes in an isolated Docker container. This design ensures isolation between robots, supports heterogeneous robot types and frameworks within the same simulation, and minimizes the sim-to-real gap by allowing the same code that runs on physical robots to execute in simulation.

The simulator features a Qt-based graphical user interface designed specifically for the RoboCup Humanoid Soccer League. It integrates an internal Game Controller that replicates the state machine and transitions of the official controller, enabling most match operations available in real competitions to be performed in simulation. Game parameters—including match duration, phase lengths, and penalty times—are fully configurable. The interface provides access to each robot’s sensor suite (IMU,

joint encoders, RGB camera, and depth camera) and allows direct interaction with each robot’s Docker container terminal.

To maintain framework independence, we implemented socket-based communication with each Docker container, enabling direct interaction with robots in a general manner. To support this architecture, we developed SimBridge, a bridge node that acts as a translator between framework-specific commands and the simulator’s communication protocol. SimBridge runs inside each container as a ROS 2 node, managing bidirectional message exchange: it subscribes to joint command topics from the robot framework and forwards them through the socket to the simulator to command its corresponding robot; on the other way, it receives a message from the simulator through the socket and publishes the information inside it, containing sensor data (e.g. joint states and imu), to be accessible from the framework. This implementation is tailored for the Booster framework and Booster-T1 robot, but the architecture supports alternative approaches for different robot platforms. Each framework can implement its own bridge to communicate correctly with the simulator. The generalization of socket-based connection also allows the possibility to define different simulation modalities, where each mode is characterised by different information coming from the simulator.

3.3 Sim2Real

We are developing a vision-based framework that enables robots to acquire and replicate human motions. Starting from videos of humans performing specific skills our approach extracts soccer-related motions and transfer them to a robotic agents. Specifically, we focus on videos of people performing soccer skills, such as kicking. We integrate the extracted motion trajectories into MimicKit, a reinforcement learning framework for motion imitation that trains control policies deployable on physical robots. Our contributions lie in three steps:

- Learning motions from videos of professional soccer players
- Transferring human motions to a robot
- Ensuring that the learned policy is fully deployed in a dynamic scenario such as a soccer match where different variables must be considered such as the position of the ball and the obstacles.

3.4 Contributions in Perception

Until 2025, our goal was to develop a perception pipeline independent of the B-Human framework. Since 2017, the SPQR Team has employed a custom Ball Perceptor using machine learning techniques inspired by our deep learning work on NAOs [1].

In RoboCup 2024, we transitioned to a deep learning-based approach optimized for inference efficiency through separable depth-wise convolutions to minimize computational overhead. The model was trained using self-supervised learning on the **SPQR Multi-Object Dataset**¹, followed by supervised fine-tuning. This hybrid approach reduces the dependence on labeled data while improving generalization. During the

¹<https://spqr.diag.uniroma1.it/datasets>

RoboCup Open Research Challenge 2019, we presented a supervised approach to robot and gesture detection [5] on NAO V6 hardware. At RoboCup 2023, we introduced a pose detection system for NAO robots and human referees, trained via a synthetic data generation pipeline that automatically creates training samples from high-level pose descriptions [23]. This enables rapid adaptation as new referee gestures are introduced in the league.

For RoboCup 2026, we are developing a ball perceptor that fuses RGB-based detection with depth estimation through a consensus algorithm. This approach takes advantage of both the sensors and the computational resources of the Booster-T1 robot to achieve more precise and consistent ball position estimates. The same fusion scheme will be extended to detect other robot players and goals, providing a unified perception framework for all game-critical objects.

Whistle detection For RoboCup 2024 and 2025, we developed a neural network-based whistle detector, inspired by [13], where the main goal is to exploit model-based approaches and make the detection robust to noise, fusing prior knowledge with a convolutional neural network. Beyond that, we made the overall architecture more versatile, modular, and decoupled by adopting continuous convolutional kernels, which allow to lift the neural network architecture from the constraints due to input data length, dimension, and resolution, namely sampling frequency in the case of audio detection. Moreover, the intrinsic adaptability of continuous kernels allows for optimizing the size of the network itself, tailoring it for the task at hand, leading to better computational performance, which is of utmost importance in a real-time scenario. We plan to adapt this approach for whistle detection on the Booster-T1 platform for RoboCup 2026.

Unified Yolo-Based Vision Recognition System Camera images serve as the primary input for world state estimation. Frames are processed to detect field lines, opponents, teammates, obstacles, and the ball. In 2023, we developed a real-time multi-class detection system for the NAO V6 using state-of-the-art structural pruning techniques applied to YOLOv7-tiny [11]. The system detects balls, goalposts, and robots in a single forward pass, balancing speed and accuracy within the computational constraints of the NAO platform. We released the annotated SPQR Multi-Object Dataset containing over 4000 images from RoboCup SPL matches, available at <https://spqr.diag.uniroma1.it/datasets>

For RoboCup 2026, we will continue using YOLO-based detection while integrating depth information to achieve more precise and consistent world model estimates.

3.5 Contributions in Motion

Gait Generation As SPL games become increasingly dynamic, the ability to adapt the robot’s walking patterns efficiently is crucial for maintaining competitive performance. To address this challenge, SPQR is actively developing a gait generation system based on Reinforcement Learning and Model Predictive Control (MPC). The goal is to leverage a hybrid learning/model-based approach to capture strengths from both sides and at the same time mitigate issues arising from both approaches, if used in isolation. We are adopting a hierarchical RL setting, where the MPC controller informs

the low-level RL controller about feasible COM trajectories. This approach allows for real-time optimization of the robot’s walking trajectory by predicting future states and adjusting control inputs accordingly. The robot is modeled as a linear inverted pendulum, thus we may identify the center of mass (CoM) and the zero-moment point (ZMP) as its main components. The latter, which captures the point where reaction forces at the contacts between the feet and the ground do not produce any moment in the horizontal direction, must always lie inside a stability region, called support polygon. By using MPC, we are able to enforce this constraint while tracking a desired trajectory. Practically speaking, the MPC controller generates a trajectory for the ZMP, based on the desired velocity and the planned footsteps, which then needs to be tracked by the CoM. To ensure the ZMP trajectory never diverges, we enforce the so-called **stability constraint** [21], which basically enforces a terminal constraint on the MPC horizon in order to stabilize the unstable component of the LIP dynamics. We formulate all MPC problems (footstep planner and controller) as QP problems. We also adopt heavy domain randomization through terrain variability, sensor noise etc., in order to deploy our walking policies on the Booster T1 and use it during our games.

3.6 Contributions in Coordination

We use an approach that aims to estimate a distributed world model by using the information available without sending specific packets for the purpose, which is then employed within the framework of market-based coordination. This system was recently improved in 2023 [4]. This enhancement integrates spatial information captured by the Voronoi diagram to address limited communication and improve overall robustness. This ensures that the vertices and edges of the diagram maximize the distance to obstacles identifying uncrowded areas. The vertices of the graph represent a desirable position for the robots, and this information is exploited within the coordination to enhance decision-making while facing the lack of communication.

3.7 Contributions in Decision Making

Since 2017, we decided to adapt our framework also to allow the possibility of having some behaviors completely based on a planning system. In 2019, this approach has been extended as a base for efficient Reinforcement Learning procedures for soccer robots. The Monitor Replanning algorithm has been used to lead the exploration during the training of Deep Neural Networks for RL. This method has been used for several behavior applications such as soccer contrasts or shooting decisions, as in [7], publicly released at <https://sites.google.com/diag.uniroma1.it/robocupcoach>.

Network Our current network management approach is a mix of a role-based event-driven system that immediately notifies the team specific circumstances, such as seeing the ball after it had been lost, and a slow periodic update to maintain coordination in calmer situations. For RoboCup 2024, we developed an approach to automatically balance the update period, not only based on player roles and on specific playing circumstances but also on overall game situations. For the platform change in 2026, we

are rewriting the communication system to work on the new robots allowing communication with the GameController and an efficient exchange of the information required for team play among the robots.

3.8 Research Roadmap

SPQR Team is interested in detaching the robot perception system from the RoboCup field peculiarities and in increasing the world representation of the robots. To this end, we started with a ball preceptor that does not rely on ball and field colors and we recently detached the perception from the action of the robot creating a semantic layer capable of inferring the inner capabilities of the perceived elements[10]. To increase the state representation of the robot, we included crowd noise and indication from a human coach as a means to extend the inner representation of the agents.

Robot Behavior Conditioning With Crowd Noise In [6] we exploit the collective intelligence of the audience of a robot soccer match to improve the performance of the robot players. In particular, audio features extracted from the crowd noise are used in a Reinforcement Learning process to modify the game strategy. The effectiveness of the proposed approach is demonstrated by experiments on recorded crowd noise samples from several past RoboCup SPL matches.

Team Behavior Conditioning from Human Coach Although it has not been used in competition yet, in the RoboCup Symposium 2022, we laid the foundation for working on a higher level of abstraction in the decision-making process that can condition the strategies of a robot team through the use of intelligible commands [9]. It uses a modular architecture that is easy to adapt to different teams and other purposes, including ensuring the safety of robots and human operators.

Semantic Conditioning for Playing Everywhere In the path of having robust behaviors on robots capable to generalize when the game environment change, in [10], we propose a temporal logic based approach that allows robots' behaviors and goals to adapt to the semantics of the environment. The proposed approach enables the robot to operate in unstructured environments, just as it happens when humans go from soccer played on an official field to soccer played on a street.

RL-based multi-robot coordination Behaviors can be really difficult to program based on rules, due to the unpredictability intrinsic to soccer. Our goal is try to capture this unpredictability by leveraging a multi-agent RL-based approach to learn behaviors. The idea is to adopt a hierarchical algorithm where we define coarser representations of the continuous environment, in order to use rule-based solutions on the abstract level, to adequately inform and guide the lower levels and learn optimal actions depending on the local observations given in input to the robot. This approach will be also integrated with vision-based policies to leverage all possible sensors available on the robot.

4 Unpublished Results

SPQR Team joined the RoboCup competitions in 1998. The results of all recent competitions we attended are published on the SPL website, specifically:

- RoboCup 2021: all four challenges [14]
- GORE 2022 [15]
- RoboCup 2022: main competition and open research challenge [16]
- RoboCup 2023: main competition and technical challenges [17]
- RoboCup 2024: main competition and shared autonomy challenge [18]
- German Open 2025 [19]
- RoboCup 2025: main competition and technical challenges [20]

In addition to RoboCup 2026, SPQR Team will participate in the German Open 2026.

5 Impact

Impact in SPL/RoboCup Community. The Ro.Co.Co. (Cognitive Cooperating Robots)² laboratory has been participating in the RoboCup since the beginning of the SPL. The aim is to transfer our research in machine learning, behavior formalization and coordination in the RoboCup competition and to contribute to the development of a more reliable soccer team in the pursuing of the goals of the league. In 2017, we proposed a supervised method for detecting the realistic black and white ball in images captured by a NAO robot. In 2019, with the adoption of the new robotic platform, i.e. the V6 NAO robot, Starkit team from Russia has been involved in the competition by using the Code Base released by SPQR. In 2021 we introduced the concept of audio exploitation for capturing the crowd sentiment. Our work has been awarded as Best Paper at 2021 RoboCup Symposium.

In 2022, we presented MARIO[8] a fully-automatic system specifically designed for analyzing NAO soccer robot matches. MARIO ranked first, ex-aequo with the B-Human Team's system, in the Open Research Challenge at RoboCup 2022. Robot and ball tracking in MARIO are done automatically. Game analysis can extract trajectories, passes made, and heatmaps through graphs and tables containing both traditional statistics and more advanced statistics within the field, such as falls and foul actions made by the robots. We recently updated the capabilities of *MARIO*. The latest version is publicly released at <https://github.com/michelebri/MARIO2.0>.

Impact in University/Community. Our university strongly supports our participation in RoboCup competitions, which serve as an excellent testbed for validating research outcomes. The Petri Net Plans (PNP) framework has become the standard tool for robot behavior design and formalization in our laboratory, refined through our RoboCup experience.

²<http://www.dis.uniroma1.it/~labrococo>

Over the past year, we have applied our expertise in computer vision and reinforcement learning to enhance control of the Booster-T1 robots, not only for soccer but also for alternative applications such as human-robot interaction. We actively promote AI and robotics research through multiple media channels to disseminate our results. We maintain a YouTube channel³, LinkedIn page⁴, and Instagram profile⁵ featuring RoboCup-related content.

Our outreach extends to appearances on major Italian television programs (*TG1*, *TG2*, *TGR*, *TG Sport*, *I Fatti Vostri*, *Laudato sii'*, *Quante Storie*) and participation in prominent national exhibitions (IAB Forum, Wired Next Fest, Blue Fest, Unirete, RomeCup, Maker Faire).

We are committed to promoting scientific knowledge through the dissemination of technology culture, using RoboCup to show progress. Demonstrating practical applications of artificial intelligence and robotics becomes pivotal in bridging the gap and engaging people in these fields. We achieve this mainly through events like the Maker Faire. This European event connects businesses, academia, and tech enthusiasts, facilitating discussions on technological advancements and practical demonstrations. This gives us the opportunity to share the latest RoboCup Soccer advancements with thousands of people by organizing friendly matches with other teams. We started this tradition back in 2019 when we invited for the first time two SPL teams (i.e., HTWK and NomadZ). We continued this trend in editions from 2021 to 2024, inviting teams such as HULKS, Nao Devils, B-Human, and HTWK Robots to play in person or remotely, depending on their availability. Recognizing the event’s appeal on social media, we actively share updates to amplify the reach of RoboCup SPL videos. Notably, a video we posted on our Instagram page garnered an impressive 100,000 views in 2024.

6 Other

SPQR published several datasets for the benefit of the community:

- The **SPQR Nao Image Dataset**⁶, a set of annotated images taken in various conditions that we used to train our ball perceptor (see Section 2). [1] [5]
- The **SPQR RoboCup@Soccer Sound Dataset**⁷, a set of annotated audio data gathered from RoboCup finals between 2016 and 2019. It enabled us to identify the waveform pattern in a goal situation and use it as a RL reward. [6]
- The **UNIBAS NAO Pose Dataset**⁸, released in 2022 and consisting of 451 frames containing about 3,000 NAO robot instances in the well-known COCO format. In the annotations, the pose is represented by up to 18 key points.[12]

³<https://www.youtube.com/@SPQRTeamItaly>

⁴<https://www.linkedin.com/company/spqr-team/>

⁵<https://www.instagram.com/spqrteam/>

⁶<http://www.dis.uniroma1.it/~labrococo/?q=node/459>

⁷<https://sites.google.com/unibas.it/crowdsounddataset>

⁸https://drive.google.com/drive/folders/1wY9Xsz30_gYc4BbGb4p_gALotynjch-E

- The **SPQR Multi-Object Dataset**⁹, released in 2023, is an annotated dataset for multiclass classification of several objects relevant to the RoboCup SPL.

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