AMiRoSoT: An autonomous, vision based, low cost robot soccer league

Joaquin Sitte[1] and Ulf Witkowski[2]

[1] Queensland University of Technology
Brisbane QLD 4000, Australia
j.sitte@qut.edu.au
[2] South Westphalia University of Applied Science
59494 Soest, Germany
witkowski.ulf@fh-swf.de

Abstract. The Autonomous Mini-Robot Soccer Tournament (AMiRoSoT) league that we describe in this article uses small size robots and a small size field to make the league widely accessible for education and research by keeping the entry barrier to the competition low. We describe the motivation for small size soccer robots and the design criteria applied to the formulation of the league's rules. We examine the requirements for the robots capable of playing in the league and discuss possible low cost robot realisations. An analysis of the goal kicking behaviour illustrates the breath and depth, and the educational and research opportunities, of the league.

1 Introduction

The idea of using the soccer game played by robots as a *Grand Challenge* problem in Artificial Intelligence arose in 1992 (8) , at par with other landmark problems such as computer chess. Robot Soccer was to provide a platform for research into design principles of autonomous agents, multi-agent collaboration, strategy acquisition, real time reasoning and sensor fusion (4). Later, in 1998, Kitano and Asada (5) formulated the grand challenge as follows:

> By mid-2lst century, a team of fully autonomous humanoid robot soccer players shall win the soccer game, comply with the official rule of the FIFA, against the winner of the most recent World Cup.
> *H.Kitano and M. Asada IROS 1998*

The robot soccer grand challenge poses an ambitious goal. In contrast to the abstract computer chess challenge, where the IBM Deep Blue team defeated world champion Garry Kasparov in 1997, the robot soccer challenge is grounded in the real world by sensing the environment and acting on it to fulfil a purpose. Winning a soccer game is a collaborative task requiring fast decisions and dexterous motion by the players in an environment made highly uncertain by the actions of the other players on the field. Robot soccer in its various leagues provides a benchmark for fast moving multiple robots that collaborate on a collective task. Meeting the robot soccer grand challenge requires solving most of the problems in the way of building useful autonomous machines for a wide range of task. Most of the engineering and scientific challenges in building mobile factory robots with the versatility of human workers, personal robot assistants, care robots, rescue robots and many others, are also present in the robot soccer game. We can only imagine what a machine that has the dexterity and cognitive abilities of a human soccer player could do.

The robot soccer grand challenge has motivated yearly international robot soccer championships in various leagues since 1996. For a history of early robot soccer see (8) and (2). These competitions have stimulated many lines of robotics research and have contributed to significant technical advances. Despite the advances, a long road is still ahead. The surface has barely been scratched and there is the potential for technical spin-offs along the way. The robot soccer game, or any similar physical team game, provides a well defined, yet evolving benchmark problem, that by lacking any direct commercial value is on neutral ground for private and industrial players to collaborate.

As by 2014, the two largest robot soccer championships are the RoboCup and the FIRA (Federation of International Soccer Associations) championships. RoboCup aligns closely with the robot soccer Grand Challenge. The participating teams typically come from tertiary institutions and are run by research students. The FIRA league has a strong educational focus.

Robot soccer benefits from the world-wide popularity of soccer as a spectator sport. Thereby, robot soccer has been a very successful motivator for students to learn about science and engineering. Robot soccer is open for wide participation at all levels of technical competence from primary to graduate school. Regrettably the educational and entertainment virtues of robot soccer tend to overshadow its unique features as a technological grand challenge and benchmark for autonomous systems engineering.

The structure of this paper is as follows: In section 2 we examine the contributions and limitations of small size soccer leagues; this leads us to specify the new autonomous small size AMiRoSOT league in Section 3. The new league preserves the advantages of a small league while overcoming many of its limitations. In Section 4 we analyse the characteristics of the robots for the league and briefly explore some options for building the robots. One of these options is building a robot using a mobile phone as the main processing unit. This is described in detail in a companion paper. Section 5 addresses some practical issues related to keeping a low entry barrier for competing in the game. Section 6 relates the demands of an autonomous goal kicking behaviour to the hardware and software characteristics of the AMiRoSoT robots. Section 7 presents the conclusions.

2 Small size leagues

Within each of the RoboCup and FIRA robot soccer championships there are several leagues that differ in their resource requirements and educational and research values. Larger size robot leagues always received the most attention. It is easier to make larger robots behave autonomously by equipping them with fast computers for handling onboard vision. In recent years the humanoid robot soccer leagues are drawing the most attention.

The small size robot leagues (180 mm diameter or less) use *global* vision. This means the robots receive movement commands from an off-field computer that processes the video images from a camera that looks at the play field from above. These robots are just small remotely controlled vehicles without on-board sensors. Without their own sensors they cannot be autonomous. Games of up to eleven robots per team are feasible because of the low cost and the small size of the players. The games in the small size leagues can be quite fast and the leagues are well suited for developing game strategies and studying multi-robot cooperation (1)

In the past the only small size robots capable of an autonomous, yet simple, soccer game where the Khepera mini-robots designed by Francesco Mondada at EPFL and produced by the K-Team company (7). The Khepera robots were small (60 mm diameter) two-wheeled differentially steered minirobots. The accessory for the Khepera that made an autonomous soccer game possible was a camera using a single line of 256 monochrome pixels. With this camera the goal, the ball and other players could be detected in a simplified environment. These single line images could be processed on the robot. Together with infra-red proximity sensors and wheel position encoders the robot could be programmed to execute simple soccer player behaviours such as ball and goal location, ball dribbling, goal kicking, goal keeping, evading the opponent and more. The first Khepera robot soccer competition was the Danish Championship in Robot Soccer held in 1997 (6). The game was one robot against one robot played in a box about 1m long and about 0.70 m wide that would easily fit on a desk. The technology available at the time limited the Khepera robot soccer to a slow game.

The great virtue of the Khepera robot soccer was its accessibility by students. At around 3000.- Swiss Francs in 1997 the Khepera robots where not cheap, but they were affordable for university computer science and electrical engineering departments. With the Khepera robots, key ideas of autonomous behaviour in the real world could be demonstrated. In the soccer game students could learn about autonomous localisation and navigation, motion control, sensor signal processing, signal feature extraction, how to deal with sensor signal noise and uncertainty, real time computing, and much more. We used Khepera robot soccer for 8 years as a student term project in teaching Computational Intelligence. Starting from scratch, in a single semester, teams of two students could program basic autonomous soccer playing behaviours that had to be evaluated in end of semester competitions.

After more than a decade the Khepera league was superseded by advances in technology. The need arose for a successor league that providing a quantum leap in capabilities by taking advantage of new low cost technology, such as fast 32-bit processors and cheap cameras, while preserving the accessibility of the league.

3 The AMiRESot league

It was clear that a successor to the Khepera robot soccer game had to be played by autonomous robots that use vision for perceiving what happens around them. Small low cost robots with on board vision processing would enable a robot soccer game with technical and research level challenges that can keep the game interesting over many years to come. A first draft for set of rules defining the AMiRoSoT league was formulated in a workshop at the 5-th AMiRE (Autonomous Mini-Robots for Research and Edutainment) Symposium in Buenos Aires in 2007. In 2008 we published the rules for the AMiRESot league (9)

To keep the hardware costs low the robot players must fit into a vertical cylinder of 100 mm diameter. With this diameter the cross section area of the robot is nearly four times that of the Khepera robot and is sufficient to house the required computation, sensing and communication resources (3).

The other cost and accessibility factor is the play field. The larger the field the more expensive it is to build, to handle and to obtain the floor space for playing the game. The play field must be small enough to be stored in a student's or hobbyist's home and that it can be set up and taken away with little effort. Scaling down a typical FIFA compliant soccer field 50:1 gives a play field of 2.00 m $\times$ 1.4 m. This is not quite desktop size but it will fit into a small school or university laboratory, a living room or a garage. With the specified size of the robots there is enough room on this play field for teams of 5 robots each. The only alteration is the width of the goal. The FIFA goal width cannot be scaled down by 1:50 because a 100 mm wide robot blocks almost the full goal width. Therefore we specify a goal width of 400 mm. At this width the body the robot goal keeper can only obstruct 25% of the goal width, leaving 75% open for scoring a goal.

Despite the recent trend towards humanoid soccer robots we decided to stick to wheeled robots. Low cost wheeled robots are already capable of fast movement on the play field. The same cannot be said about humanoid robots, even though in the future biped robot soccer players will be capable of a much more human-like ball kicking and dribbling than wheeled robots ever can. At the current state of humanoid robot locomotion the cost and effort required in building, or even just programming, a humanoid robot capable of agile walking is out of proportion. This is because, a humanoid configuration is not necessary for any of the other key capabilities needed for a successful robot soccer game, such as fast visual localisation and navigation, and fast execution of cooperative game strategies.

Fast locomotion is essential for a game that is interesting to watch as well as for a game that serves as a performance benchmark for autonomous behaviours. Any advances in fast, resource efficient vision and cooperative game strategies will be transferable to larger humanoid robots. The AMiRESot league has all the essential elements of autonomous behaviour. It is goal driven, there is uncertainty arising from the other players action, it relies on vision as human players do and the time available for sensor information processing is strictly limited by the physical dynamics of the game.

4 Robots for AMiRoSoT

The cost of the soccer robots for the AMiRoSOT league must be such that students and hobbyist can own one. Friends may come together to form impromptu teams, unpack a field and let their robots play. Although it is possible to construct such robots with current technology, there are not any available for purchase.

The simplest choice for wheeled locomotion of the AMiRoSoT robots is to have a two-wheel differentially steered drive train such as that widely use for mobile robots. The two wheels are on an axis that is a diameter of the cross section of the vertical cylindrical body. Each wheel is driven by its own motor. The difference in speed of the two motors determines the turning rate of the body. With such a drive train robots can turn on the spot, which gives them great agility. In addition a vertical cylinder shape avoids that the robots get stuck in corners. A two-wheeled, differentially steered mobile base is cheap and can be built by students and hobbyists. All that is required are a pair of wheels, a pair of good quality DC motors with gear box and motor axle position encoders, a motor power control circuit, a base plate and some brackets to attach the motors, and of course, a battery. The cylindrical body case can be made of PVC pipe or by 3D printing.

Even if mechanical construction of a soccer robot is relatively simple, the electronic hardware requires advanced electronic design capabilities. At least a 32 bit processor in the class of a high end ARM Cortex, a camera, half a dozen infra-red proximity sensors, a microphone, a power management and an USB interface are the minimum required. Putting all the hardware together, even from off-the-shelf parts is a major undertaking beyond the capacity of most students and hobbyist. And, it has to fit all into that 100 mm diameter cylinder. Finally to make it all work the right software has to be installed and configured.

To remain true to our goal of a league with a low entry barrier, a supplier for at least the ready made computation part had to be found. The computing part must be in the form of a few compatible circuit boards that fit into the available robot body space. To meet that goal turned out more difficult than expected. A suitable high performance and low cost robot could not be found on the market. The successor model of the Khepera II robot, the Khepera III, produced by K-Team company was too big for the league's size limit and too costly. Combining off-the-shelves components into a package for self assembly by prospective participants would not meet the accessibility demand either. This only left the option of a custom design to be manufactured by a third party and offered for purchase. In 2011 Tetzlaf and Witkowski (10), presented a prototype mini-robot for the AMiRESot league and Herbrechtsmeier et al. (3) described a full featured design, still under construction, of an autonomous mini-robot for research and education suitable for the AMiRESot league. Both designs required the fabrication of custom designed printed circuit boards (PCB). Thus the barrier for entering the AMiRESot soccer league remained still too high for the majority of interested teams.

A custom designed board set manufactured in small quantities will never be able to come near or beat the cost advantage of the computing power of a mass produced mid-range mobile phone. Therefore in early 2013 we decided to try an alternative approach that would take advantage of the extraordinary performance/cost ratio of the new generation of smart phones. Even if smart phones are not designed for educational robotics, it is well worth the effort to adapt them to our application.

The prototype mini-robot for the AMiRoSoT league build by Ulf Witkowski's group at the South Westfalia University of Applied Sciences and shown in Figure 1 is described in a companion paper presented at this conference. An Android smart phone provides computing power, communication, camera and inertial sensors. For Android phones, Google provides the Android Software Development Kit (SDK) that has all the necessary tools for writing application software and is free of charge. The motor controller and infrared sensor board for the mobile base is available for purchase.

Fig. 1. Prototype for the mobile phone soccer robot

5 Practical aspects of the game setup

The price to pay for the simple differential steering is the need for rear and front castors that prevent the robots from falling over. Ready made castor wheels on the market are too big for our size of robot. Spherical rollers have been tried, like those in perfume and deodorant flasks, but they easily clog with dirt and end up sliding, instead of rolling. The simple alternative is to use small support posts that have rounded low friction ends that slide on the ground. We will refer to these supports as castors as well.

The problem with castors is that ground contact is on four points, which restricts to moving on flat surfaces. Whenever the front castor moves over an elevation one or both drive wheels are lifted off the ground and the robot becomes uncontrollable or simply gets stuck. An elastic suspension of the castors or the drive wheels can overcome this problem. However, the mechanical complexity of these improvements is not worth the effort because soccer fields are supposed to be flat. To alleviate the problem in a simple way the sliding supports are made such that, when the robot is level they do not quite reach the ground. In this way three points will touch the ground and small irregularities of the ground will not lift off the drive wheels. The result is that the robot will either be slightly tilted forward or backward. Upon acceleration or deceleration the robot will flip from one inclination to the other. For a camera rigidly attached to the robot body the image will shift on each flip, complicating the video processing.

The surface of the play field must be flat without irregularities and it also must be such that the two-wheeled robot can move with good grip, without excessive friction. It is unlikely that these conditions are met by simply marking a soccer field and using the ground as the field surface. A portable play field with a suitable surface has to be provided. Again a simple solution could be a sanded and painted panel of plywood. A 2 m by 1.4 m wooden panel is awkward to carry and to store. To facilitate transport and storage the panel might be cut into two or more smaller panels. It may be difficult to lay out the panels for a game so that no uneven joints appear that hinder the movement of the robots. Rolling out a carpet sounds like the ideal solution. A 1.4 m long roll of carpet is easy to carry and store, and has no joints. The problem here is that ordinary carpet, looped or otherwise, causes too much friction for the small wheels. Instead of carpet a vinyl floor covering offers a smooth surface that can be rolled up and stored away quite easily.

Another issue is the field boundary. It would be ideal to delimit the play field with line markings as on a real soccer field. To make the robot stay inside the field by using visual recognition of the field markings is not too difficult. It is much more difficult to make the robots keep the ball inside the field. In human soccer there will almost always be a player to intercept the ball before it leaves the field and the game is not disrupted too often by the ball being kicked out of the field. This is not the case for the AMiRoSoT league. Therefore a low height frame around the field to contain the ball is needed. The frame should only be slightly higher than the radius of the ball to make sure the ball rebounds back onto the field when hitting the field border. To stand out from the surroundings, the frame is painted white, the same as the line markings on the field. The frame also needs to be easily assembled and disassembled for transportation and storage. The goals are openings in the frame to which goal boxes are attached. For easy visual distinction the inside of the goal boxes are painted black. Vertical cylindrical goal post are fitted onto the frame at each end of the goal. The goal posts are round so that they have the same apparent thickness when viewed from any angle. This is a concession to vision algorithms because the goal posts are the main landmarks for the robot localisation and navigation on the field.

Finally, it is also useful to gain a rough estimate of the dynamics of the game to gauge the time available for the various actions of the robots. The mass of the base of the smart phone robot is around 320 g and the mass of the phone is 110 g, for a total mass of 430 g. The stall torque of the DC motors is around 5 mNm which results in an acceleration of around 1 m/s^2 for 40 mm diameter wheels. With these parameters robot speeds of up to 0.5 m/s are possible. At 0.5 m/s the robot need 4 s to cross the field lengthwise. A squash ball has a mass of 25 g. For the ratio of ball mass to robot mass the final speed of a stationary ball when kicked by the robot is nearly twice the speed of the robot. Therefore ball speeds may reach 1 m/s. At a video frame rate of 30 frames/s the ball can travel up to 33 mm between frames.

6 Ball kicking with a cylindrical robot

To illustrate the variety of tasks to be carried out in a game let us investigate the ball kicking behaviour in its simplest form: when the ball is at rest and there is no goal keeper nor any other robots on the field. In the ball kicking behaviour we would like to see the robot moving swiftly to a position somewhat behind the ball, in line with the ball and the centre of the goal. From there it should gather some more momentum in direction to the goal until it collides with the ball. The momentum transferred to the ball in the collision must be in the direction to the centre of the goal and the ball should speed off in that direction. As soon as the robot collides with the ball the robot should stop. The trajectory to be followed by the robot might look like trace A in Figure 2.

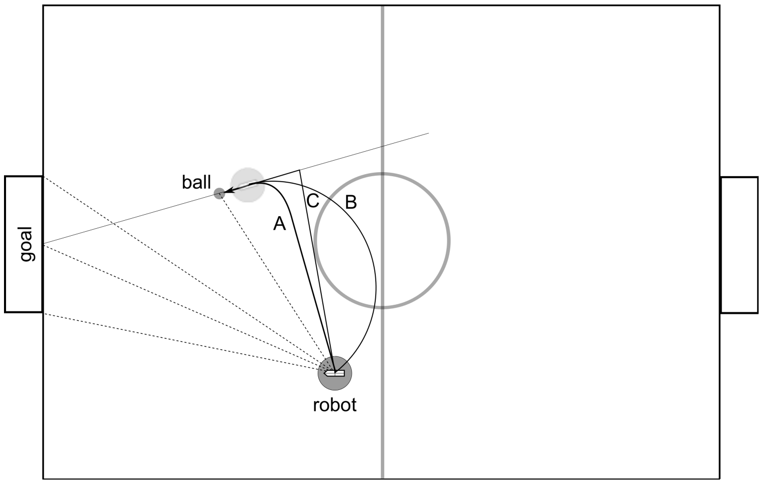

Fig. 2. The most desirable robot trajectory for kicking the ball into the goal is trace A.

The sensors available to the soccer robot for the ball kicking behaviour are the video camera, wheel encoders and infra-red proximity sensors. With the camera the robot can perceive all the objects relevant to the soccer game across the whole play field. The robot also has accelerometers, gyroscope and a compass, but for the time being we shall rely mainly on the camera and the wheel encoders to assess the situation on the play field and to find the ball and shoot it into the goal.

There are always two perspectives for designing a behaviour: the perspective of the external observer and the perspective of the robot. What we just did was looking at the task from external observer's perspective, which is for us human designers the most intuitive approach. An external observer sees the robot on the play field in its position relative to the other objects in and around the play area. A person watching could easily steer the robot by remote control to kick the ball. This is also how the task appears in the leagues that use *global vision* from an overhead camera.

An autonomous robot player has to carry out the task from its own perspective, which makes the task very different from that of the external observer. First, the viewpoint of the robot is only slightly elevated above the play field surface. This view is almost a sidewise projection of the objects on the field. Contrary to an overhead viewpoint, which projects displacements of objects on the field surface as proportional displacements on the camera's image plane, in the sidewise projection only the lateral displacement component appears as horizontal displacement in the image plane. The radial displacements component appears only as a change of size (depth). Second, the limited field of view of the robot's camera, typically around $40°$, only shows a fraction of the play field. Third, when the robot is placed on the play field its position relative to the goal and the ball is unknown. The 2D positions of the objects of relevance to the goal kicking task have to be calculated from the camera images. The objects of relevance are the ball and the goal opening. The latter being identified by the black and white transition at the goal edges or alternatively by the goal posts.

The first action the robot might do when waking up on the play field is to turn on the spot until it finds the ball in the field of view. Finding the ball could mean to use a colour blob detection algorithm on the camera image. Once the ball is in view the robot could turn until the vertical middle line of the field of view passes through the centre of the ball. The ball would then be straight ahead of the robot and the robot could move towards it. However to kick the ball the robot has to reach a position some distance from the ball, leaving the ball between the goal and the robot. For this the robot has to move to a position somewhere to the side of the ball, instead of heading straight to the ball. But, to which side? To decide this the robot needs to know whether the goal is to the left of the ball or to the right. There is no guarantee the goal is visible to the robot while it approaches the ball and therefore the robot cannot decide to which side of the ball it should steer. Without this information the robot could decide to move towards ball but stop at a distance that leaves room to manoeuvre. If the goal is not in the field of view of the camera the robot could now start turning on the spot to find the goal. Once the goal has been found the robot has enough information to move to a position behind the ball, relative to the goal, suitable for kicking the ball into the goal. In this scenario it is clear that there is no need for the robot to move to the ball before searching for the goal. The robot can do this from where it was first placed on the field. By determining its position relative to the goal and the ball, before making any movement, leaves more room for deciding on the best way to approach the ball. Whatever the position of the robot is, it needs to measure its position relative to the ball and the goal for a successful kick.

Following a trajectory like A, in Figure 2 is likely to be quite difficult. Trajectory C is an approximation to A easier to achieve. Once the robot has localised itself, calculating a suitable position behind the ball for kicking only requires a simple geometric calculation and the robot can move towards it using odometry. However all locations computed from image data are likely have a substantial error, therefore the robot needs to relocalise visually once it has moved the calculated distance. Errors in odometry will also add to the uncertainty because the actual position may differ from the calculated position, which already was affected by visual measurement errors. It may require several repositions before the robot has aligned itself with the ball and the centre of the goal for carrying out the kick. Each reposition is an iteration of the first computation because it requires the computation of the next movement and the estimation of the kicking position.

6.1 Robot localisation on the play field

For the robot localisation means knowing it's relative position to some chosen landmarks (reference objects). When the robot is first placed on the play field it does not know what objects there are in the world around it and where they are. The robot motion on the play field is in two dimensions and therefore we only need two stationary landmarks to uniquely find the position of the robot relative to the landmarks by triangulation. The required measurements are the distances to the landmarks and the observed angle between them.

On the play field the goals and the markings on the field are at known relative positions. The edges of the goals are suitable landmarks and they should be made easy to detect in the camera images. In the AMiRESot field the inside of the boundary frame of the goals is painted black, while the rest of the play field frame is white. From any point of the play field the edges of the goal are visible as a black-white transition on the play field border frame.

When the robot is placed on the play field it can begin its visual exploration of the environment by turning on the spot in a predefined direction, say, anti clock wise, searching for the ball and goal edges in the video images. Whenever one of the searched objects is detected and centred in the image the wheel encoder readings are stored and the distance of the object is estimated from the image.

The distances to the goal edges can be estimated (with a calibrated camera) from the apparent height of goal edges in the image because the true height of the vertical transition edge is the height field frame. The angles are obtained from the readings of the wheel encoders while the robot turns on the spot. The reference direction, that is the direction where the angle is zero, is arbitrary because only differences in direction readings are relevant. Before the robot starts to turn it can read the wheel encoder counts and take this value as the reference.

7 Conclusion

After almost twenty years the robot soccer game continues to appeal to hobbyist, students and robotics researchers. It appeals to the wider public because of its competitive nature and its similarity with the very popular human soccer game. It appeals to teachers and students because by participating in the game through building and programming, robot soccer offers hands on learning opportunities on widespread topics of high relevance across our technological civilisation. It appeals to researchers for the variety of scientific and technical problems posed by the robot soccer grand challenge.

Advances in technology are quickly incorporated in the game to give the robot players ever more dexterity and cognitive abilities. The game is played in various leagues that have different educational, research and entertainment values. We have described a new league for small sized robots that has a lower entry barrier than the other mayor leagues while maintaining a high degree of relevance to the aims of the robot soccer games. The league sticks to the use of wheeled robots which contributes to keep the cost low. At the current state of technology it is much easier to play a fast game with wheeled robots where fast visual localisation and navigation, and cooperative game strategies can be put to the test.

The educational benefits of robot soccer can only be realised if the game is accessible to a wide student population. The high cost and the large amount of work required to derive an intellectual reward are the main deterrents to participating. By attending to practical accessibility aspects the AMiRoSoT stimulates maximum exploitation of cost reducing technology. An example of this is the use of the sensing and computing capabilities of mobile phones. Furthermore robotic technology can only play a role in society if it is affordable. This was convincingly shown by market penetration gained by autonomous vacuum cleaners once their cost benefit ratio became attractive. The small size autonomous robot soccer league stimulates advances in this direction by widening the pool of contributors.

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