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RoboCup Humanoid Challenge

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We describe here the humanoid challenge that is part of RoboCup robot soccer competitions. We focus on how relevant research issues of humanoid robotics –for example biped walking and human-like sensors and actuators– can be addressed and we investigate how teams proceed to solve the given tasks. Thus, new technologies like artificial muscles and artificial skin might find their way into the competition very soon. We detail examples of these technologies and discuss in which way they may contribute to RoboCup, and in return how RoboCup may serve as a benchmark for achievements within these technologies. Further we describe hows RoboCup works as an open, worldwide cooperative project in robotics and AI.

1. Introduction

RoboCup is an attempt to foster intelligent robotics research by providing a standard problem of which the ultimate goal is to build a team of eleven humanoid robots that can win against the human world cup champion soccer team by 2050. It's obvious that building a robot to play the game of soccer is an immense challenge. RoboCup is designed as a vehicle to promote robotics and AI research, by offering a publicly appealing but formidable challenge [18,4].

A unique feature of RoboCup is that it is a systematic attempt to promote research using a common domain, mainly soccer. Also, it is perhaps the first to explicitly claim that the ultimate goal is to win against the human world cup champion team. Building a robot to play soccer would certainly be considered as a major achievement in the field of robotics, and numerous technology spin-offs can be expected during the course of the project. We call this kind of project a *landmark project*, and RoboCup is definitely a project of this kind.

Since the first RoboCup in 1997 [17], it has grown into an international joint-research project in which about 4000 researchers from 40 nations and regions around world participate (see Figure 1), and it is one of the most ambitious landmark projects of the 21st century. RoboCup currently consists of three divisions:

RoboCupSoccer aiming towards the final goal, RoboCup Rescue, a serious social application to the rescue activities for any kind of disasters, and RoboCupJunior, an international education-based initiative designed to introduce young students to robotics. Recently, RoboCup@home was added to promote daily life applications from technology advances fostered by the other existing RoboCup divisions, and some experimental demonstrations were also shown at RoboCup 2007 towards future official leagues. For more details, please refer to [25,6,9,27,29,3,30,28,7,15,1,10]. Figure 1 shows that the number of participants has continously grown until the year 2006, although in 2006 some leagues already had a slightly lower number of participants. In the year 2007 we had a drop in the number of participants. The reason was that the space of the competition sites was limited, therefore the local organizers had to specify the maximum numbers of teams in each league although we had almost the same number of applications as in the previous years.

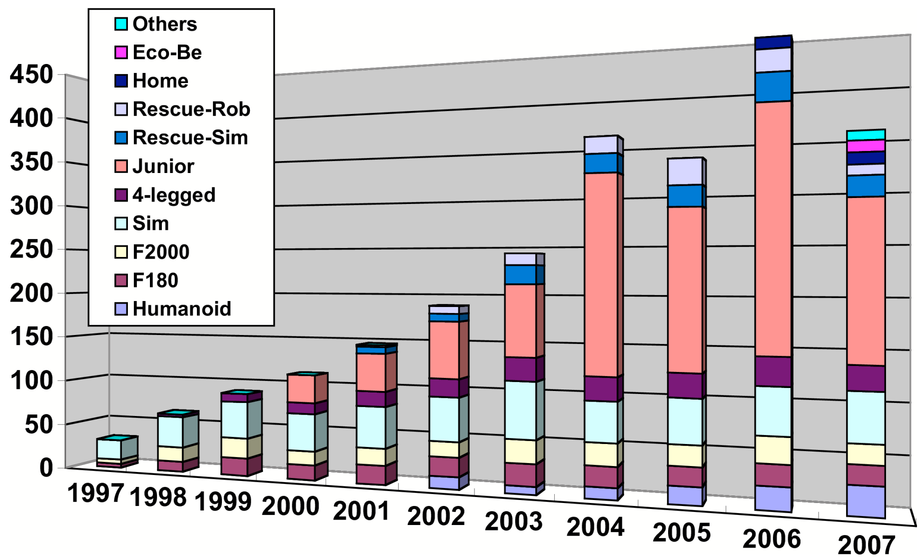

Fig. 1. The number of teams at RoboCup competitions in recent years. Last year we saw a drop, which can be explained by the location of RoboCup 2007 was conducted in Atlanta, USA.

At RoboCup 2007 the first match between a human team (the trustees of the RoboCup Federation) and the Middle-Size League (MSL) champion team (Brainstormers Tribots Univ. of Osnabrueck) has been held. Figure 2 shows a picture taken during the match. Unfortunately, the robot team lost the game, but the match itself was a lot of fun and new research issues related to human-robot interactions were found. The match showed that the robot team was able to pass and interact. However, the robots were too slow to be really competitive to humans. The speed of the robots is also a safety issue. In addition, the humans were still far bet-

Fig. 2. The first match between a human team and Middle-Size League robots (courtesy of Prof. Tucker Balch, general chair of RoboCup 2007)

ter with respect to cooperation. Within moments they were able to communicate strategies and recognize intentions of teammates and opponents. In the second half of the game, one of the trustees, Peter Stone, entered the robot team and tried to show the cooperation with the robots. However, the robots were not programmed to do so. In order to seek for new research issues on human-robot interaction one has to consider not only competitive but also cooperative behaviors. These kind of experimental games are going to be held in future RoboCups.

While the first RoboCup was held in 1997[a], the Humanoid League (HL) has no sooner been established than 2002 at RoboCup in Fukuoka[5]. The reason for this rather late start in comparison to other RoboCupSoccer leagues is due to the fact that biped walking was and partly still is a challenge in robotics. However, in recent years better and better solutions to this problem have been found, presented and tried out at RoboCup. Following the trace from the first competition in 2002 one can see how closely RoboCup follows the state of the art. For example, the Best Humanoid Award of the RoboCup 2003 in Padova was a platform based on a prototype of the Honda Asimo robot. At that time the Honda Asimo was considered as the best and most advanced humanoid robot by far. Since its start, the HL underwent a profound development. Competitions and challenges have changed in

[a]Actually, pre-RoboCup was held in 1996 in Osaka in conjunction with IROS 1996 Osaka.

Year	
2002	Start of the Humanoid League 3 size classes 40cm, 80 cm, 120 cm 3 competitions
2005	self-contained robots 2-2 games replace the free style competition 2 size classes: KidSize and TeenSize
2007	Humanoid robots in the Soccer Simulation League

Table 1. Overview of the RoboCup HL history

various ways; rules matured in many points and gained more focus on the issues that are essential from a technical point of view; and of course the robots became better. The focus has shifted to smaller robots for several reasons which we are going to point out below.

The most important aspect from a viewpoint of the RoboCup project is to provide the appropriate environment to address current research issues in general and the research issues of humanoid robotics and biped walking in particular with respect to the HL. At the moment the most interesting research issues are to encourage dynamic motions – in particular walking – and human-like sensors. In this paper we discuss these issues and outline how we intend to design the rules in order to encourage the research in the best way possible.

The rest of the paper is organized as follows. First, the brief history of the league is described. Next, the future issues not restricted to HL but to humanoid research in general are given in the discussion.

2. History of the Humanoid League

Fig. 3. The first HL robots and team members at RoboCup 2002

In the first years (2002-2004) the robots participating in the HL were quite diverse in many respects and had to be sorted into three sub-leagues in order to cope with the variety of heights ranging from 10cm to over 2m (see Figure 3). The competitions consisted of walking challenges, a free style competition, and a penalty kick competition for all size classes. At that time external processing – even remote control – was allowed. In order to make results of the competitions comparable between the very different robots, performance factors had been introduced. These performance factors had to be applied to commercial platforms, remote control and external processing.

The emergence of Team Osaka in 2004 in Lisbon showed an unprecedented performance with regard to technical compactness and general perfection in their size class and in relation to the manufacturing costs. They received the Best Humanoid award in that year. Their robot kindled hope that regular soccer games were indeed possible with robots of a size of roughly 40-60 cm and certain design features. These features have hitherto been adopted by most teams of the later established KidSize class.

Starting from these experiences many changes have been introduced into the competition making the technical constraints more specific than the in the previous rules (compare the rules of 2004 [32] to the current rules). Performance factors were abandoned, and external processing as well as remote control were banned from the competition. Thus, processing of sensory information, behavior processing, etc. has to be completely self-contained within the platform. A maximum ratio between foot size and height of the center of mass had been introduced in order to encourage dynamic walking. The number of size classes was reduced from 3 to 2, of which the smaller class was called Kidsize class($<$ 60cm) and the bigger TeenSize class. The total number of competitions remained the same, however, the free style competition was replaced by the regular 2 on 2 games in the KidSize class. In the TeenSize class the conductance of 1-1 games was discussed, but could not be carried out. One aim of the technical committee was and still is to lead the development towards current research problems. Dynamic walking and stability have been the most important issues then and still are up to now, which have been enforced by the technical challenges between the years 2005 and 2006. In the years 2005 and 2006, a rough terrain challenge has been conducted in which the robots have to cross a field of hexagonal tiles of random height. The technical challenges change every year.

The rules have been further refined for the competitions in 2006 and 2007 in many aspects, in particular with respect to the conductance of the 2 on 2 games. Also the footrace competition was introduced to the TeenSize class in order to have an equal number of competitions in the Teen- and KidSize classes.

The rules of 2005 and 2006, and the example of relatively cheap and powerful robots gave a new perspective to many interested people in the RoboCup community and also people from outside who were interested in setting up a team.

In 2005 a total of 20 teams from 9 nations and regions participated. This is about twice the number of the year 2004. For the first time a qualification process had to be introduced. Several teams had some background from other leagues and took the

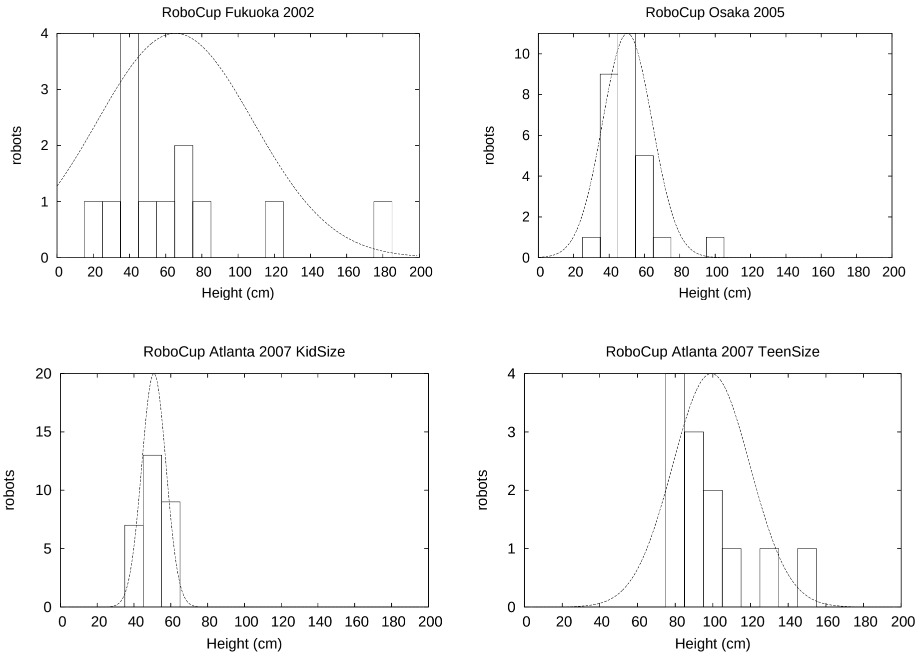

Fig. 4. Histograms of the heights of robots that participated at several HL competitions between 2002 and 2007. The upper line shows histograms of the heights of robots in the competitions in the year 2002 and 2005. The lower line shows the histograms of 2007 KidSize class ($< 60cm$) and TeenSize class ($> 80cm$) separately. Please note that some teams participated with several robot types. Thus, the number of teams differs from the number of participating robots.

advantage to customize their software rather successfully for the new league. Team Osaka received the Best Humanoid Award again, as well as in 2006. At RoboCup 2007 in Atlanta a total of 29 teams participated, of which 22 were from the KidSize class and 7 from the TeenSize class. The technical level of the participating teams increased significantly. Although the finals of the 2 on 2 games in the KidSize class were won by team NimbRo (who appearantly used closed loop control for walking [11]) for the first time, due to a better performance in the Technical Challenge Team Osaka was able to win the Best Humanoid award once again.

In the following section we outline the evolutionary process that boosted the development of the league and describe a rather typical robot of the HL: VisiON TRYZ (used by Team Osaka and JEAP). Then we describe further plans of the HL that are currently under discussion.

3. Evolutionary conversion and current typical robots

In the first years quite a variety of different types of humanoid robots participated. Fig. 4, upper half, shows the histograms over the heights of the participating robots in 2002 – the first year of the Humanoid League, and 2005 – which was the first year of the 2 on 2 competitions. In each graph, the plotted Gaussian distribution shows the same mean and variance as the data-set of the respective histogram. In the top pair of graphs one can see the histogram of heights of *all* robots that participated in 2002 and 2005. Robots of the year 2005 showed a significantly smaller variance in size than the robots that participated in the first year of the Humanoid League[b].

Using only this one parameter one can clearly see a developmental and convergent process towards robots of sizes between 40-60 cm. More and more robots participating in the RoboCup Humanoid League are exclusively manufactured for this event. The convergence is partly caused by the rules in the KidSize class that allow a maximum height exactly at the size of 60 cm, but mainly it is due to constraints that come with considerations of the mechanical design and costs: Taller robots face the problem to handle a high center of mass during walking. Shorter robots have to deal with the fact that there is not much space for the actuators and the electronics. The convergence process happens mainly in the KidSize class, where the typical design concept of the robots' hardware consists of the following parts:

- Servo motors (initially designed for RC toys). In particular many teams switched to RC servos that can be linked together in the RS 485 bus (similar to the well known RS 232; one example are Dynamixel DX 117 and AX 12 actuators). The power to weight ratio of the RC servo motors seems optimal for the current heights.
- Small reliable mini PCs (e.g. handheld computers, industry one board mini PCs, like PINON PNM SG3F): In order to process the vision stream of about 15 frames at a resolution of 640x480 a 600-800 MHz processor is sufficient.
- Micro-controller: these are necessary for real time control of the servos.
- Sensors: camera (connected via USB or Fire-wire to the PC) and attitude sensors (gyro, acceleration sensors). Except for the feedback from the joint angles most robots do not use additional sensors.
- Wireless network (IEEE 802.11): permitted to be used for communication between the robots and in order to send start and stop signals to the robots. However, wireless networks are not reliable during RoboCup. A fallback solution is highly recommended. The rules state that the robot has to be able to perform even if the wireless network is not working.

Team Osaka and Hajime are examples of teams that showed benchmark performance in dynamic walking. Other teams seem to focus more on vision systems and total system integration. Although focusing on the latter part shows already a good results, we have to remember that biped locomotion technology is far from maturation. No robot is able to run as of yet. All robots are still very sensitive to

[b]Only those robots were counted that showed movement at all during the competition.

external disturbances. These are still points for the future and have to be considered when we go into discussion of the rules in the next several years.

Whereas the KidSize robots evolved rapidly during the past 2-3 years, we expect the same development in the TeenSize class yet to come. Typically, TeenSize robots are either derived from KidSize models (typically just on the lower limit of the permitted size of the TeenSize class) or we see that robots participate from initially unrelated fields of research.

It is very much to hope that in the near future a TeenSize class with its own profile and own technology evolves.

For this purpose a size gap has been introduced between TeenSize class and KidSize class. This gap has been increased from initially 5cm (2006) to 20cm (2007) and is going to be increased further to 40cm (2008). In addition, from 2008 the penalty kick (PK) competition is going to be replaced by a dribble and kick competition, in which the striker robot has to show more advanced abilities for finding the ball: As in PK the striker robot is placed in the first half of the playground to which it is supposed to score the ball. However the ball is placed in the other half. The robot has to find the ball, dribble it back to the first half and score it from there. It is not allowed to score a goal from the other half.

RoboCup 2007 indicated a first positive development of the TeenSize class. The lower half of Fig. 4 shows histograms of the heights of robots in TeenSize and KidSize class, respectively. In the TeenSize class 7 teams with a total of 12 different robot types participated. One can see that most robots have a height on the lower end of the permitted height span. In addition, most robots of the class were manufactured for RoboCup.

The variance is still high. The histogram of the KidSize class shows a rather narrow height distribution and a further increase of the number to almost the maximal value of 24 teams. More teams are hard to organize within one competition, and also normally not permitted by the local organizers. In the TeenSize class a wide variety of technological solutions have been presented and as of 2007 no standard has been established.

In the following we describe the current and previously used robots VisiON TRYZ and VisiOn 4G (Team JEAP [23] and Team Osaka[20]) in more detail, which – with respect to the criteria outlined above – can be seen as typical robots of the KidSize class. We also briefly outline a typical software environment.

The body structure of the 4G is made of aluminium whereas the body of the previous TRYZ robot was made of carbon fiber reinforced plastic (CFRP). The motors are RC servos manufactured by the robot's manufacturer VStone. The motors can be connected in series in a proprietary bus hardware that bases on the RS 232 serial bus. Their functional design is similar to the above mentioned Dynamixel servos. The still experimental servos of the VisiON TRYZ have a plastic chassis, the newer servos in the 4G are made of aluminium, which results in a significantly higher robustness and extended lifespan. The foot size of the VisiON 4G robot became smaller and thus easily complies with the 2007 rules. In the 4G robot the number

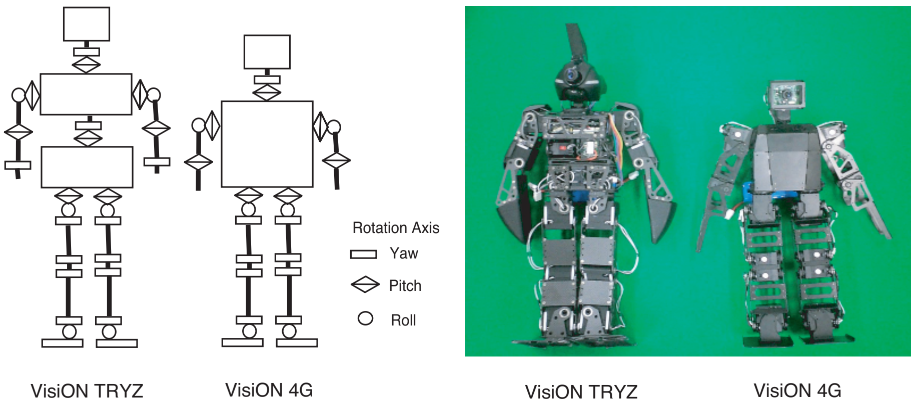

Fig. 5. The VisiON TRYZ and VisiON 4G robot: On the right side, a photo from the front view of the robots is depicted. One can see the camera (Philips chip-set) and the USB connectors for servicing in the head of the robot. On the left side is a schematic overview of the actuators and their attitude in relation to the bodies.

of DOF is reduced to 22 (from 26 in the TRYZ robot). The system of a camera and other sensors such as acceleration sensors are similar to the TRYZ robot, however the bus system utilized in the 4G is rather sophisticated. The 4G internally uses three different serial buses: Two customized RS 232 and an I2C, which is a challenge for the real time paradigm. Theoretically also a USB bus can be used for the communication between the mini PC and the motor controller. The I2C-bus serves for the communication between the acceleration and gyro sensors, and the motor controller.

VisiON TRYZ			VisiON 4G	
Height (mm)	475		445	
Weight (kg)	3.1		3.2	
DOF	26		22	
Actuators	VStone Servo		VStone Servo	
Camera Type	Quickcam		Quickcam	
Controller	Main Controller	Sub controller	Main Controller	Sub controller
CPU	Geode LX 800	SH2 F7054F	PNM-SG3	ARM
ROM	4GB (Flash HDD)	384KB	4GB (CF Flash)	512 KB
RAM	512 MB	64 KB	512 MB	40 KB

Table 2. VisiON TRYZ and VisiON 4G hardware specifications

4. The current status and near future research issues

The two size classes, TeenSize and KidSize, in the Humanoid League are separated basically by the height H of the robots. In order to have a sound definition, currently the height of a robot is defined as

$$H = min\{H_{top}, 2.2 \times H_{com}\}, \tag{1}$$

where H_{top} is the actual height and H_{com} is the height of the center of mass of the robot.

The aim is that two different sets of research issues are addressed in the two leagues, on the basis of what is technically possible currently.

Due to the size and the weight constraints, the KidSize class has an advantage over the TeenSize class in applying commercially available parts such as motor controllers and sensor units. The walking behavior in this class is much more stable than in the TeenSize class. Accordingly, the current research issues are action planning and team coordination. For this reason it seems preferable to coordinate activities with other leagues such as the Standard Platform League (SPL) and Soccer Simulation League 3D. The SPL is going to be introduced in 2008 instead of the 4-Legged League (the league of the Sony Aibo dogs).

Currently, the Humanoid League allows the use of omnidirectional vision systems to capture the whole scene. The next challenge is to use, perspective vision systems more similar to the human vision system.

For the TeenSize class, the suggestion of the authors would be to set the focus more on issues like experimental actuators, motor skills and human machine interaction. The number of participants in the TeenSize class is much smaller than in the KidSize class. Beside the cost issue, the reason seems that motor controllers in this class are not commercially available yet even though this class is closer to the final goal than the KidSize class. Thus motor controller units currently have to be designed by the teams themselves.

The common research issues are vision and cognition. It is intended to permit only human-like sensors. For 2008 it is planned to reduce the allowed visual field of all cameras to 180 degrees. In particular omnivision cameras are going to be banned.

One classic field of RoboCup is cognition and team strategy. At present team strategy is of minor importance in comparison to other factors in the competition. This could change within the next several years. The following changes could provide the right environment for the team strategy.

- Increase the number of players. This has been a very emotional discussion in the past years, because the costs increase significantly with each additional player. Various test games of mixed teams have been conducted during RoboCup 2005 and 2006 competitions. The number of players in each team is going to be increased from 2 to 3 in the competition in 2008.
- Closer collaborations with other RoboCup leagues that already have a bet-

Year	
2008	3-3 Games Omnivision banned Start of standard platform league
2010	5-5 Games in KidSize 3D2Real no color keying
2025	start of full size league 150-200 cm games real human-like sensors like skin etc. robots interact directly with referees team play

Table 3. Road map for the Humanoid League and related leagues within the RoboCup competition.

ter developed culture of team strategy and cognition. The optimization of the interaction between the leagues is going to be an important issue within the next several years in particular since additional leagues turn towards humanoid robotics. Currently this step has been done in the Soccer Simulation League 3D (SocSimL 3D) which since 2007 simulates humanoid robots and the former Four-Legged League which is going to become the "Standard Platform League" that is using a standard humanoid robot platform.

In table 3 the road map of the humanoid league in near future is depicted.

5. More fundamental research issues in future humanoid robotics

In this section, we review the future research issues described in [16], especially focusing on the recent progress. With regard to human-like sensors and actuators the the recently introduced humanoid "Child-robot with biomimetic body (CB^2)" for cognitive developmental robotics developed by researchers of the JST ERATO Asada Project [2] may serve as an example – although it cannot walk.

CB^2 has a whole-body soft skin (silicon surface with 197 high sensitive tactile sensors underneath) and flexible joints (51 pneumatic actuators). The height and the weight are 1.3m and 33kg, respectively. It also has two eyes, two ears, and a vocalization unit (a simple version of the vocal system used in [31]). Figure 6 shows pictures of CB^2, where the left one indicates its whole body and the bottom right ones indicate its mechanical structure and the attachment of 197 tactile sensors underneath of the whole body silicon surface.

5.1. *Surface Materials and Tactile Sensing*

Towards the final goal, safety becomes more and more important since we have to deal with intensive robot-human interaction. Thus, the humanoid robots at that

Fig. 6. A child-robot with Biomimetic Body (CB^2): toward a developmental robot through interaction with humans (from http://www.jeap.org/web/pressrelease.html)

stage must have soft surface materials in order to avoid damages and injuries. However, at the same time, a mechanism is needed that protects internal mechanics and electronics from external force. The competitions do not include any human players yet. Still, the TeenSize class robots require a more serious consideration of these issues. Currently, hard plastics or metals are usually used as the surface materials of the robots. Damages caused by falling down or any collisions with other robots or objects in the KidSize class are not as serious as those of the TeenSize class. Therefore, it has been suggested that human assistants should be allowed to stay closer to the TeenSize robots than in the KidSize class. In the KidSize class human assistants are not allowed to stay on the playground during the match. So, in the next several years one would expect a more serious discussion about safety in human-robot interaction at least in the TeenSize class.

Silicon materials are often used as a soft skin for robots, and CB^2 has a whole body silicon surface to realize such a soft skin considering the physical interactions with humans. In the future, such soft skin is necessary for RoboCup humanoid players in order to interact with human ones. At the same time, tactile sensing is a very important perception to detect collision (or to feel pain). In the case of CB^2, 197 PVDF (polyvinylidene fluoride) units are used for tactile sensing. They are attached to the surface silicon skin. Additional sponge rubbers absorb the external force to protect the internal machinery. Recently, a super-flexible sensor system has been developed for humanoid robots which comes together with another type of artificial skin [26]. The skin has elastic properties and is at the same time capable of tactile sensing without any structured sensor harness in or underneath the sensing area. It could turn out to be very useful if it would be applied in the larger robots, say in the TeenSize class.

Anthropomorphic fingertips with multi-modal sensors have been developed for human-like hand perception with fingers and palm[14]. The fingertip consists of two silicon rubber layers of different hardness containing two kinds of receptors: strain gauges and PVDF films distributed randomly as receptors. In the future these technologies can be used for the hands of goalies to keep the goal or that of players to throw the ball in the field.

Actuators and Mechanical Design In general, electric motors are widely used for humanoid behavior generation, and in the RoboCup Humanoid League, many teams are utilizing RC servo motors to generate walking and ball kicking behaviors.

The electrical motors and reduction gears play a great role to achieve high-performance trajectory tracking, but on the other hand, it is relatively difficult to realize joint compliance by utilizing them. As a result, such a robot that consists of electrical motors and gears is not suitable for studying dynamic whole body motions such as running, dribbling, jumping, heading, and so on. Toward the generation of such motions, anthropomorphic biped walkers driven by antagonistic McKibben artificial muscles have been developed [13]. These robots have shown jumping and running behaviors. However, these behaviors are still difficult to be stabilized. CB^2 adopts another pneumatic actuator of an air cylinder type to generate elastic motions. These pneumatic actuators have no backlash, however, due to their compressible fluid property, it is hard to realize high performance of responsibility and accurate position control. Recently, a new linear actuator with long stroke, high response, and large thrust using a Halbach array of magnets was developed and analyzed [24]. This seems promising for future humanoid actuators owing to preferable features such as high responsibility, high power, robustness against dynamic motions due to the lack of gear backlash, and so on. We note here that already at RoboCup 2006 a robot with shape memory effect (SME) wire muscles [19] was presented. However, the movements of these muscles are slow (in particular the relaxing time is very long).

Currently, most robotic joints adopt one DoF type and therefore one DoF actuators are used. Sometimes, more DoFs joints are devised, but with a set of several one DoF actuators. Recently, a spherical resonant actuator was proposed as a multi-joint with a multi-DoF actuator [12]. These sorts of actuators are intended to be used at shoulders, wrist and ankles of humanoids. Figure 7 shows the basic structure of these devices.

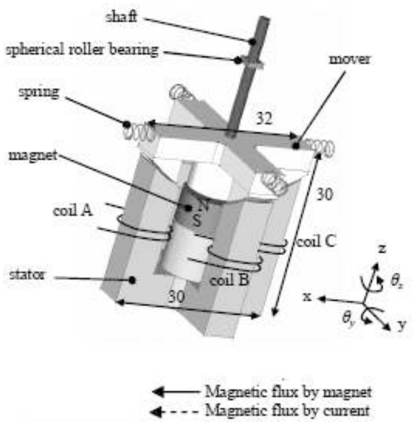

Fig. 7. Basic structure of the proposed model of the spherical resonant actuator (through the courtesy of the authors from the reference [12]).

6. Discussion

In this overview we intended to describe which current research topics can be addressed in the RoboCup Humanoid League. In this way the HL can be a forum for discussion for interested researchers. It is also a benchmark to test new technologies under rough conditions for their applicability with respect to robotics and AI. Further we see the HL as an educational tool that can help to bring students into intensive contact with problems and methods of robotics. Also, the media interest during the last 2 years has been a great help in this respect. For example, the finals of the Humanoid League were covered as live television events. Thus, Humanoid League can be a nice way to present research to a broad audience.

One important challenge from the point of view of the organization is how the activities of the new leagues that deal with humanoid robots (Soccer Simulation League 3D, Standard Platform League) can be integrated into an overall concept. Here, a much closer collaboration between the two new leagues is under discussion. One has to see how this can be done in order to maximize the research output and at the same time to minimize parallel work with regard to technical issues.

One initial step towards the coordination of the Soccer Simulation League 3D and leagues of real robots is the 3D2Real project[21,8,22], which may serve as a blue print for other collaborations. The aim is here to port the tactical know how of the simulation league to real humanoid robot platforms and to test how synergies of the two different leagues can be used for the benefit of the RoboCup project and the year 2050 goal. The formal target is to conduct the finals of the 3D simulation league some day in real robots. Part of the project is a suggested environment that makes participants' behaviors applicable to both the simulation and the real robots. The intention is of course that the behavior is identical in both cases. Research issues there are going to be which sensor statistics are realistic and what kind of physical simulation is sufficient to give realistic results.

All in all we see a rapid change in the structure of the soccer playing leagues towards humanoid robots. Assuming the enormous energy effort that is usually invested into the competition by the participants it is to expect that these new humanoid leagues are going to evolve in similar way like the Humanoid League.

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