# NimbRo RS: A Low-Cost Autonomous Humanoid Robot for Multi-Agent Research

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**Abstract.** Due to the lack of commercially available humanoid robots, multi-agent research with real humanoid robots was not feasible so far. While quite a number of research labs construct their own humanoids and it is likely that some advanced humanoid robots will be commercially available in the near future, the high costs involved will make multi-robot experiments at least difficult.

For these reasons we started with a low-cost commercial off-the-shelf humanoid robot, RoboSapien (developed for the toy market), and modified it for the purposes of robotics research. We added programmable computing power and a vision sensor in the form of a Pocket PC and a CMOS camera attached to it. Image processing and behavior control are implemented onboard the robot. The Pocket PC communicates with the robot base via infrared and can talk to other robots via wireless LAN.

The readily available low-cost hardware makes it possible to carry out multi-robot experiments. We report first results obtained with this humanoid platform at the 8th International RoboCup in Lisbon.

## 1 Introduction

Evaluation of multi-agent research using physical robots faces some difficulties. For most research groups building multiple robots stresses the available resources to their limits. Also, it is difficult to compare results of multi-robot experiments when these are carried out in the group's own lab, according to the group's own rules.

In order to overcome these difficulties, since 1997 the RoboCup Federation holds annual robotic soccer competitions. The game of playing soccer makes it easy to compare the performances of different approaches using a simple metric, the number of goals scored. The competitive game focuses the resources of many research groups to a standard problem. The competitions are accompanied by a scientific symposium. This exchange of ideas fosters the development of multi-agent robotic systems. Hence, robotic soccer can be considered to be the successor of chess as a benchmark for AI research.

The ultimate goal of the RoboCup initiative is stated as follows: by mid-21st 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 [11].

Working towards this goal soccer competitions are carried out in different leagues where different research problems are tackled [2]. For instance, in the Simulation League team play and learning strategies are investigated. Real-robot leagues face the difficulties of dealing with the real world. There are two leagues for wheeled robots, and a league for four-legged robots. In these leagues problems, such as self-localization and ball manipulation are investigated. Since 2002 competitions are also hold in the Humanoid League. Here, bipedal locomotion is one of the research topics.

Humanoid robots are not only a good choice for playing soccer. The anthropomorphic body shape is also helpful for acting in environments that have been designed for humans, in particular for the interaction with people. In addition to speech a humanoid robot can try to use the same means for intuitive multimodal communication that people use: body language, gestures, mimics, and gaze.

Consequently, a number of research groups, especially in Japan, are constructing humanoid robots. A list of projects is maintained by Chris Willis [19]. Among the most advanced humanoid robots developed so far is the 58cm tall Sony QRIO [16]. It contains three CPUs and has 38 degrees of freedom (DOF). QRIO is able to walk and dance. Research on map building and navigation, as well as on human-robot interaction is carried out inside Sony. Currently, it is unclear when this robot will be available to a larger research community, but the costs of QRIO have been compared to the price of a luxury car.

Unlike QRIO, HOAP-2 (25 DOF, 50cm tall), developed by Fujitsu [7], has been sold to some labs for about USD 50,000. A taller humanoid, ASIMO, has been developed by Honda [8]. It has 26 DOFs and a height of 120cm. It is possible to rent ASIMO for about USD 162,000 per year for presentations. Approximately the same size of ASIMO has a trumpet playing humanoid robot which has been announced recently by Toyota [17]. It will be displayed at Expo 2005.

While these humanoid robots developed by large companies are impressive, they are not available to researchers outside the industry labs or are too expansive for academic research. Some universities built their own robots, but due to limited resources, usually only one prototype has been constructed. Hence, multi-robot experiments with humanoid robots are currently not feasible in academic environments and are likely to be at least difficult in the near future.

Faced with similar problems researchers working with wheeled robots came up with creative low-cost solutions. One example of a low-cost robot kit is the LEGO Mindstorms Robotics Inventions System. It has been used e.g. for robotic soccer [13], education [21], and communication with people [12]. Other low-cost robotic platforms include the Tetrixx kit [6], the Trikebot [10], and the VolksBot [1].

To avoid the development of custom processing boards some researchers used off-the-shelf PDAs to control their robots [18, 14]. One of the best know PDA projects is the Palm Pilot Robot Kit [5, 15], developed at CMU. A PDA has also been used to control the Robota and DB humanoid robots [3].

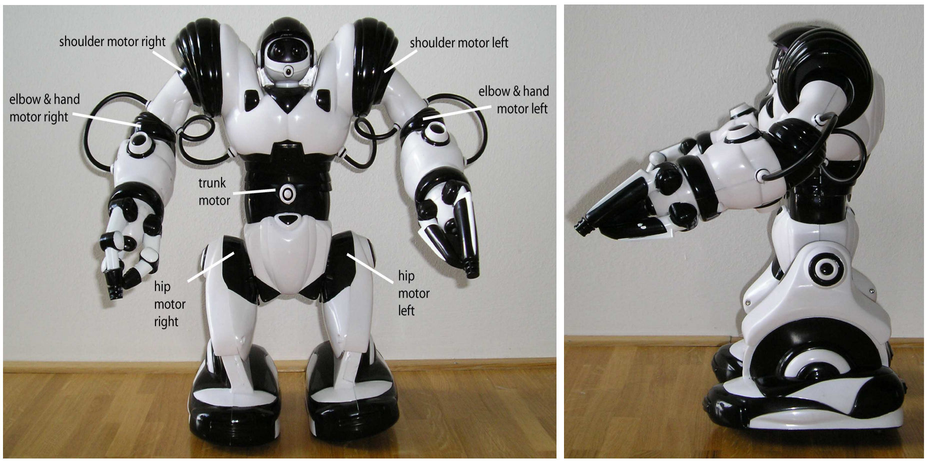

**Fig. 1.** Robo Sapien. Left: frontal view, seven motors move nine degrees of freedom. Right: side view.

In this paper we propose a similar approach to make multi-agent humanoid robot research feasible. We use a low-cost commercial off-the-shelf humanoid robot, RoboSapien [20], which has been developed for the toy market by WowWee and augment it for the purposes of robotics research. We add programmable computing power and a vision sensor in the form of a Pocket PC and a CMOS camera and implement image processing and behavior control onboard the robot. The Pocket PC communicates with the robot base via infrared and can talk to other robots via wireless LAN.

The remainder of the paper is organized as follows. In the next section we describe RoboSapien as it is sold in stores. Section 3 details our modifications to convert it to a research tool. Finally, we report some experimental results obtained with the augmented RoboSapien at the RoboCup 2004 competition in Section 4.

## 2 RoboSapien

RoboSapien, shown in Fig. 1, is a small humanoid robot which can be purchased in stores for a price between EUR 70 and EUR 140, depending on the location of the store. It measures approximately 34cm in height, is 31cm wide and 16cm deep.

RoboSapien has been designed by Mark W. Tilden according to the principles of BEAM robotics (Biology, Electronics, Aesthetics, and Mechanics) [9]. Power is supplied to the robot by four mono (D) type batteries, which are located in the robot's feet. The resulting low center of gravity and the large robot feet ease the balancing problem faced by other bipedal robots significantly.

RoboSapien is controlled by the user that pushes buttons on a remote control unit. These buttons correspond to 67 motion primitives that are carried out by the robot. It is possible to let the robot walk forward or backward with two different speeds and to let it turn on the spot. The motion primitives can be combined, e.g. to have the robot walk a curve. RoboSapien's arms can be raised and lowered as well as twisted.

### 2.1 Actuators and Possible Movements

The robot has a total of nine degree of freedoms which are driven by seven motors. One motor in each leg moves two joints in the hip and the ankle, keeping the foot orthogonal to the trunk. A trunk motor tilts the upper body to the left and right. One motor in each shoulder raises and lowers the arm and one motor in each elbow twists the lower arm.

RoboSapien has two gripper hands consisting of three fingers each. They are specialized for holding larger objects with the right hand and smaller objects with the left hand. While twisting the lower arm outwards opens its gripper, twisting it inwards closes the gripper again.

### 2.2 Basic Sensors

RoboSapien receives the motion commands from the remote via an infrared detector. These motion primitives can be chained and triggered by some basic sensors. Collisions can be detected by bumper switches located at the front and the back side of the feet. They trigger avoidance movements. Similarly contact switches at the tip of one finger of each hand trigger grip motions. A sonic sensor, which reacts to clapping sounds, is located in the trunk of the robot. It can trigger a preprogrammed motion sequence.

### 2.3 Dynamic Walking

Unlike more complex bipedal robots, RoboSapien uses only three motors for locomotion. These are the two leg motors (A and B) and the trunk motor (C). Key to the generation of its gait patterns is the utilization of the robot dynamics. The central idea is to move the upper body like an inverse pendulum to achieve a periodic displacement of the center of gravity projection from one foot to the other. A complete gait cycle consists of four phases:

1. *Tilt rightwards.* Trunk motor (C) tilts the upper body to the right. The center of gravity shifts over the right foot, releasing the left foot which lifts from the ground
2. *Move left foot forwards.* Leg motor (A) moves the right leg backwards, resulting in forward motion of the robot, while the leg motor (B) moves the left foot forward. As the upper body swings back, the left foot regains contact with the ground.
3. *Tilt leftwards.* Symmetrical to Phase 1.

**Fig. 2.** A complete gait cycle of RoboSapien. See text for details.

4. *Move right foot forwards.* Symmetrical to Phase 2.

The robot moves approximately 4cm per step on a laminate floor. With a step frequency of about 2Hz this corresponds to a speed of 8cm/s or 4.80m/min. In the second gait mode the step frequency is increased to about 2.7Hz, but the step length decreases to approximately 2cm. This results in a reduced speed of about 5.2cm/s or 3.12m/min.

RoboSapien walks backwards in a similar way with the difference that in phases 2 and 4 the leg motors move into the opposite direction.

## 3 Augmenting RoboSapien

To use RoboSapien as a research tool, we modified it as follows:

- adding a Pocket PC to provide programmable computational power,
- adding a color camera as vision sensor,
- implementing software for image processing and behavior control.

### 3.1 Controlling it with a Pocket PC

The unmodified RoboSapien receives motion commands from the user who pushes buttons on the remote control. To use the robot as a research tool, we need to make it autonomous by adding programmable computing power.

Due to the relatively low price, the robustness, and the good weight-to-speed ratio, we decided to use a Pocket PC as 'robot brain'. From the variety of available Pocket PC models we selected the Toshiba e755, because it features a CF slot and a wireless LAN interface (802.11b). This model is sold for a price between EUR 300 and EUR 400. The e755 is equipped with a 400MHz Intel XScale PXA255 processor, 64MB of RAM and 32MB of flash memory. It has a touch-sensitive 3.8" transflective display and is powered by a Lithium ion battery, which is recharged in a cradle. The cradle is also used to download software from a PC to the Pocket PC via an USB interface.

Software for the Pocket PC can be conveniently developed on a PC using e.g. Microsoft Embedded Visual Studio 3.0 (can be downloaded free of charge) or Microsoft Visual Studio .NET 2003.

The Pocket PC needs to interface the robot base. Since the remote control emits infrared commands and the Pocket PC features an IrDA infrared interface, we decided to implement a unidirectional infrared interface. Unfortunately, Consumer IR (emitted by the remote) and IrDA are incompatible standards for infrared communication.

Fortunately, it is possible to emulate Consumer IR with IrDA, e.g. by using learning remote software. One such universal remote controller software for Pocket PCs is UltraMote [4], which can be purchased for a price of about EUR 13. UltraMote is able to learn from common infrared remote controls. It captures the remote control signal and replays it when a button is pushed on the screen.

Because UltraMote does not provide an API, we interfaced our robot control program to UltraMote by emitting the same Windows messages that are generated when the user presses the buttons of the UltraMote software.

The Pocket PC does not only need a communication link to the robot base, but must also be mechanically attached to it. We chose to replace the small robot head with the Pocket PC, since this allowed to place the infrared receiver, that we salvaged from the head, next to the IrDA sender of the Pocket PC. As illustrated in Fig. 3, we cut a rectangular opening into the plastic cover to slide the lower part of the Pocket PC between RoboSapien's shoulders. This provided sufficient fixture to hold the Pocket PC while the robot was walking and still allowed to remove it easily when it needed to be reprogrammed or recharged. Another advantage of this placement is that the touch screen of the Pocket PC as well as its CF slot are accessible. Since the dynamic walking of RoboSapien relies on the existing weight distribution, the additional weight added by the Pocket PC (196 g) disturbed the walking pattern of the robot. To compensate for the extra weight, we removed the lower arms of the robot and replaced them by lighter versions that did not include grippers.

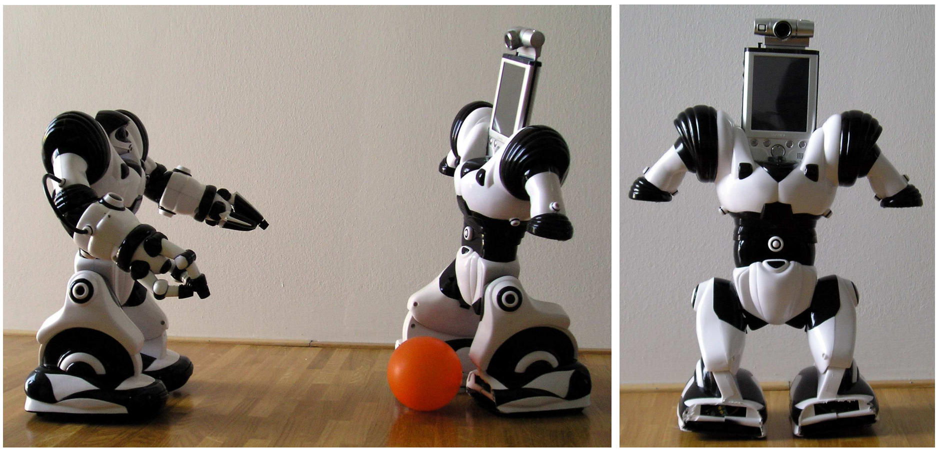

**Fig. 3.** Left: RoboSapien against its augmented version. Right: Frontal view of the augmented RoboSapien.

### 3.2 Adding a Color Camera

Although RoboSapien contains basic sensors for contact and sound, these sensors cannot be used as basis for behavior control for two reasons: They provide only very limited information about the robot's environment and the unidirectional interface from the Pocket PC to the robot base prevents the use of the sensor readings by the programs running on the Pocket PC.

Visual information provides a much richer source of information about the robot's environment. For this reason, we added a miniature color camera to the Pocket PC. From the few available models we selected the Pretec CompactCamera with 1.3M pixels, available for about EUR 107. The camera supports resolutions from 160×120 up to 1280×1024 pixels at frame rates from 15fps@160×120 to 4fps@320×240 to 1fps@1280×1024.

The camera can be interfaced to the Pocket PC via its CF slot. It has a field of view of about 55° and can be manually focused between 5cm and infinity. We also experimented with a wide angle converter attached in front of the camera that effectively doubled its field of view.

An SDK is available from Pretec that allows user programs to capture uncompressed live images in the RGB color space. Lifeview offers a similar camera (FlyCam-CF 1.3M) which could also be used.

### 3.3 Implementing Image Processing and Behavior Control

We implemented a framework for visual perception and behavior control in C# using Microsoft Visual Studio .NET 2003.

Since in the RoboCup domain the world is color-coded, we focused on color-based image processing. RGB images are captured with a resolution of 320×240 pixels. To avoid motion blur, we capture single images when the robot is not moving. The images are analyzed to classify the pixels according to the colors of interest. Depending on the task this might be the green field color, the orange ball, a red pole, or a yellow goal.

The initial color segmentation is done using simple rules on the basis of the RGB values of individual pixels. In a second step spatial information is used as well. For instance, to segment the largest blob of a particular color, we compute the mean location of all pixels classified to have this color. Based on the number of detected pixels, we estimate the size of the blob. Only the pixels located within a window of corresponding size which is centered at the mean location are added to the final blob segmentation.

The mean location of the segmented blob pixels is used as input for behavior control, e.g. to implement a taxis behavior. Other tasks, like the Balancing Challenge shown in Fig. 4, require a different processing. For example, the ratio of green pixels in the left and the right half of the image can be used to walk in the middle of a black ramp that stands on a green field. Another feature which is useful for this task is the number of yellow pixels observed over time. A local maximum of yellow pixels corresponds to the presence of a yellow line which indicates a change of the ramp's slope.

To simplify the behavior control interface to the robot base, we implemented a set of parameterized motion functions, like walking straight for a certain distance with a certain speed or turning a certain angle.

These motion functions use the Windows message queue to send motion commands via the UltraMote program to the robot base. After the robot starts moving, the functions wait a certain time according to the desired distance or the desired turning angle. The waiting time is computed based on the average walking or turning speeds.

To implement more complex behaviors a state machine is used to decompose a complex task into subtasks. States correspond to subtasks and the transition between the states is triggered by the presence of visual features, like the successful detection of the ball. In different states different parameterized motion functions are executed to perform the different subtasks. We will describe the use of this framework to implement control strategies in the next section.

In order to facilitate the debugging of the implemented behaviors, we log all interesting variables, such as the coordinates of perceived objects, the activation of behaviors, and the produced motion commands using an external PC. UDP Messages are sent regularly via WLAN to the PC and stored there. The time course of the logged variables can be visualized live and after the end of a behavior episode.

## 4 Experimental Results

To evaluate the capabilities of the augmented RoboSapien we participated at some Humanoid League competitions of this year's RoboCup, which took place in Lisbon. In order to comply with the league's rules that restrict the robot's foot size, we had to shorten its feet by cutting some plastic material at the front and the back. This did not impact the stability of the robot, but made its movements less precise. Hence, it was not an option to use preprogrammed motion patterns to accomplish the tasks of the competition. Instead we had to rely on visual feedback to correct for deviations of the robot's motion.

### 4.1 Humanoid Walk

The first competition we participated at was the Humanoid Walk. Here, the task is to walk on a green field towards an orange pole, around it and back to a yellow or blue goal. The robot's performance is evaluated according to the stability and the speed of walking.

Our control strategy for this task was to detect the orange pole and to center it on the left side of the image in order to pass it on the right side. If the pole was not visible we scanned for it by turning the robot towards the left and the right side with increasing angle, until the pole was visible again.

If the robot has walked around the pole, the goal becomes visible. Then RoboSapien can center it in the image in order to walk straight back.

In the competition the robot reliably detected the pole and approached it quickly. We never had to touch the robot to prevent it from falling. However, after passing it, the pole left the field of view and the robot kept scanning for it. The implemented scanning strategy was not successful because on the green carpet the robot executed right turns more effectively than left turns, such that the pole was moving behind its back.

After the competition, we implemented an improved control strategy which takes these hardware limitations into account. With this strategy the augmented RoboSapien managed to complete three runs within the allowed time of 15min. The average time for a run was 154s and the minimum time (which would be used for scoring) was 142s. We could improve this time by reducing visual feedback, but this would also impact reliability of navigation around the pole.

### 4.2 Balancing Challenge

This year's Humanoid League Technical Challenge consisted of three parts: obstacle avoidance, balancing, and passing. Due to the lack of time to implement control strategies, we participated only in the Balancing Challenge. Here, the task was to walk on a sloped ramp, as shown in Fig. 4. The ramp was divided into three sections: ascending slope, horizontal, and descending slope. In the sloped sections the robot has to overcome a height difference of 0.1m within a section length of 1m. The borders between the sections are marked with yellow lines. Since the width of the ramp is only 0.5m, the robot must try to walk centered on the ramp in order to avoid leaving it on the sides. Again, performance is evaluated based on stability and the time needed.

To center the robot on the ramp, we adopted the simple strategy to walk straight if the number of green pixels in the left and the right half of the image is

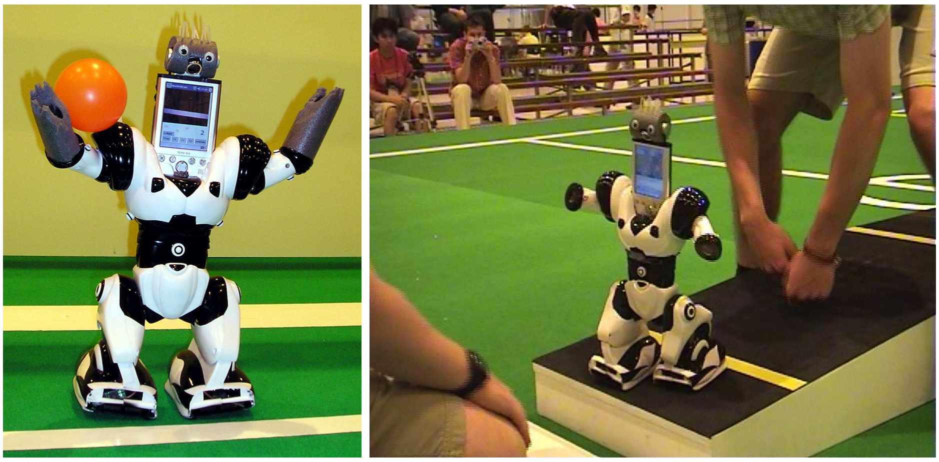

**Fig. 4.** Left: The augmented RoboSapien competed as NimbRo RS at RoboCup 2004 in Lisbon. Right: Performing the Balancing Challenge.

approximately equal. Otherwise, we turned the robot towards the side containing fewer green pixels.

RoboSapien was able to quickly walk uphill and in the flat section, but in the descending section the large steps of the fast walk resulted in stability problems. In this section the slower walk that uses the smaller steps was more stable.

In order to change the walking speed, we needed to detect the section borders. Hence, we monitored the number of yellow pixels in the image over time and switched to the small steps after the second local maximum had been observed.

With this simple control strategy the augmented RoboSapien was able to successfully perform the Balancing Challenge. Only one of the other teams, Persia, was also able to complete this Challenge. The points awarded for balancing were sufficient to secure our robot the third place overall in the Technical Challenge.

Videos from the competition and the Humanoid Walk in our lab can be found on our website: www.nimbro.net.

## 5 Conclusions

In the paper we described a way to augment a low-cost commercial off-the-shelf humanoid robot in order to convert it to a tool for multi-agent research.

For programmable autonomy we attached a Pocket PC to it. The speed of its 400MHz processor is sufficient not only for behavior control, but also for image processing. To allow for visual feedback from the environment, we attached a color CMOS camera to the Pocket PC.

We implemented a framework for image processing and behavior control on the Pocket PC. All relevant variables are transmitted to an external PC for

| Robot | Height Weight | DOF | Speed | Sensors | Control | Price |
|---|---|---|---|---|---|---|
| Augmented<br>RoboSapien | 43cm<br>3kg | 5 | 5.2cm/s or 8cm/s | 1 camera,<br>1 microphone | Pocket-PC, 400MHz | 490-660 EUR |
| Robovie-M<br>Vstone | 29cm<br>1.9kg | 22 | not specified | none | H8 board, 16MHz | approx. 3650 EUR |
| VisiON<br>Vstone | 38cm<br>2.4kg | 23 | not specified | 1 omnidirectional camera | SH2, 40MHz | not available yet |
| QRIO<br>Sony | 58cm<br>7kg | 38 | 10cm/s (walking)<br>23cm/s (running) | 2 cameras,<br>7 microphones,<br>3 accelerom.,<br>1 gyro, ... | 3 RISC CPUs | not available yet |
| ECO<br>iXs Research | 34cm<br>1.2kg | 17 | not specified | none | ext. PC | approx. 900 EUR |
| iHs02<br>iXs Research | 35cm<br>2.5kg | 20 | not specified | 6 force sensors,<br>2 accelerom. | H8/3067, 20MHz | not available yet |

**Table 1.** Augmented RoboSapien compared to some commercial humanoid robots.

visualization and logging. Using this framework, we developed control strategies for the RoboCup Humanoid League competition. The augmented RoboSapien performed well at this year's RoboCup in Lisbon.

The RoboCup experiments also revealed some limitations of the augmented RoboSapien. They include low precision, unidirectional IR, and mechanical limitations. The low precision of walking makes it unfeasible to rely on path integration for navigation. It is necessary to compensate for the quickly accumulating deviations by visual feedback. The unidirectional IR communication from the Pocket PC to the robot base prevents the use of proprioceptive information, touch sensors, and sonic sensors for behavior control. The low number of DOFs as well as the low center of gravity limit the possible movements. For instance, while it is possible to dribble a ball with the robot, RoboSapien is unable to perform the powerful kick needed for penalties.

While RoboSapien is certainly the most frequently sold humanoid robot today, it is not the only option for researchers. Table 1 compares it to other small commercial humanoid robots available today or possibly in the near future. All of the other robots have more DOFs than RoboSapien, but only two of them (Robovie-M of Vstone and ECO of iXs Research) can be ordered today. Because both of these robots have limited computing power and no vision sensor, it would be interesting to augment them with a Pocket PC, equipped with a camera, as well. A question for further research would be to find out if the higher number of DOFs translates to better performance. One possible danger could be that walking stability is compromised in these more complex designs.

The currently most advanced humanoid robot, also included in the table, is Sony QRIO. While it has been presented to the public, e.g. at RoboCup 2004, it is unclear when and to which conditions it will become available to researchers outside Sony. If it were available for a moderate price, it certainly had the potential to become the standard platform for multi-agent humanoid robot research.

As can be seen in the RoboCup Four-legged (Aibo) League, the use of standardized hardware has certain advantages and disadvantages. On the positive side, there is no need to develop and build robots for researchers interested in perception and behavior control. One can start with an off-the-shelf robot to develop software. Standardized hardware also facilitates the exchange of software components and the comparison of experimental results between labs. On the other hand, commercial robots usually are not fully open. The developer has to use the API provided by the manufacturer and cannot modify the software and hardware layers below the API. These changes are done exclusively by the manufacturer, which might limit the exploration of new ideas by researchers. While it is frequently possible to find a work around a limitation, this approach might lead to the use of the hardware in a way not intended by the manufacturer. One example for this is the walking on the knees (instead of the paws) adopted by most of the participants of the RoboCup Four-legged League.

For the reasons above, we think that the availability of capable standard hardware would facilitate empirical multi-agent research on humanoid robots. If such robots were open and well documented, they could be used as a starting point for researchers.

One step towards this goal was to augment RoboSapien. Since the costs for this programmable autonomous humanoid robot are only between EUR 490 and EUR 660, it is feasible to perform experiments with more than one robot even for research groups lacking huge resources. The integrated wireless LAN interface can be used for communication between the robots.

We plan to perform such multi-robot experiments in the future, e.g. in the form of soccer games in the RoboCup competition. Hopefully, this paper will motivate other groups to follow a similar approach so that there will be interesting games. Currently, we are restructuring our framework for image processing and behavior control in order to make it available to other researchers.

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