

## A MODULAR ARCHITECTURE FOR HUMANOID SOCCER ROBOTS WITH DISTRIBUTED BEHAVIOR CONTROL

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This paper presents an embedded control architecture constructed for Robo-Erectus, a soccer-playing humanoid robot developed at the Advanced Robotics and Intelligent Control Centre of Singapore Polytechnic. The Robo-Erectus team has participated in the KidSize category of RoboCup's Humanoid League since 2002, collecting different awards. The latest version of Robo-Erectus has many capabilities that can be exploited to improve the robot's behavior. The new embedded controller has made possible the first stage of the performance (displayed during RoboCup 2007), including network communication, mapping, and localization. The new mechanical, electronic design, embedded control architecture, and control schemes are described in this paper. In addition to the hardware, the paper presents details of the modules for gait generation, vision, behavior control, and communication.

*Keywords:* Behavior control; embedded control; humanoid soccer robots.

### 1. Introduction

The Robo-Erectus project ([www.rob-erectus.org](http://www.rob-erectus.org)) is carried out at the Advanced Robotics and Intelligent Control Centre (ARICC) of Singapore Polytechnic. Robo-Erectus is a humanoid robot used to study human-like tasks. One of these applications is humanoid robots playing soccer. RoboCup is an international project, whose ultimate goal is to develop, by 2050, a team of fully autonomous humanoid robots which can win against the human world champion team in soccer.<sup>1</sup> Robo-Erectus is one of the foremost soccer-playing humanoid robots in the RoboCup Humanoid

League in KidSize. It has collected several awards since its first participation in the Humanoid League of RoboCup in 2002. The awards include the second place in the Humanoid Walk competition at RoboCup 2002 and first place in the Humanoid Free Performance competition at RoboCup 2003. In 2004, Robo-Erectus won second place in Humanoid Walk, Penalty Kick, and Free Performance.

The challenges in the RoboCup competition are becoming tougher every year, and the competitive level of the humanoid teams has risen. To keep the Robo-Erectus project as one of the leading teams, a robust and reliable control system that allows the robot to exploit its full hardware capabilities is imperative. Teams like Darmstadt Dribblers, NimbRo, and Team Osaka are in a permanent evolution; specially focusing on their control systems.<sup>2-4</sup> The games bring many challenges that robots must take into account to play soccer. Simple control systems are infeasible for satisfying the requirements of a soccer game. Several teams have also felt the need to migrate to a more powerful processor to endow the robot with a high computational capability. Nevertheless, the structural limitation of the robot size presents a challenge to provide the balance between power and size. Embedded solutions and small PCs are popular approaches to such problems.<sup>5-7</sup> Every team adopts its approach and improves it according to the experience. This paper contributes to the RobotCup community and humanoid researchers showing the current stage of progress.

The development of Robo-Erectus has gone through many stages in the design of its mechanical structure, electronic control system, and software control. The latest version of Robo-Erectus, namely Robo-Erectus Jr-AX (REJr-AX), has been designed to cope with the complexity of a two-versus-two soccer game. Robo-Erectus is able to perceive different colors and to track them. It also contains a dedicated processor for controlling its behavior, wireless communication with the control PC and teammates, and a subsystem for controlling sensors and actuators. This paper presents the inside of the architecture for Robo-Erectus, which controls not just the robot but also displays an emergent behavior of a team. For more detailed information about the Robo-Erectus humanoid soccer robots, refer to the team's website, [www.robo-erectus.org](http://www.robo-erectus.org).

This paper summarizes the current state of the project developed for the 2007 RoboCup competition. The rest of the paper is organized as follows. In the next section, details of the mechanical and electronics design are presented. Section 3 describes the developed software: the image processing, the hierarchy of the control system for the robot behavior, and the infrastructure needed to support a team of soccer-playing robots. Section 4 takes a special look at the research efforts to generate better locomotion for REJr-AX. Section 5 presents experiments and findings with the whole system. Finally, some concluding remarks are made in Sec. 6.

## **2. Robo-Erectus Hardware**

The Robo-Erectus project aims to develop a low-cost, fully autonomous humanoid platform that could be used for competition, education, and research purposes.<sup>8</sup>

The previous generations of humanoid soccer robots, namely RE40I, RE40II, RE40III, and RE70, have provided the team with experience and knowledge about the hardware and software design. This section provides an insight into the mechanical and electronic characteristics employed for REJr-AX.

### **2.1. Mechanical design**

Figure 1 shows the design of the humanoid robot Robo-Erectus Jr-AX. The skeleton of the robot is constructed with aluminum braces. The head, forearms, and backpack of the robot are made of plastic materials. Despite its simplicity, the mechanical design of the robot is robust and of lighter weight in comparison with its predecessors. Its human-like body stands at 50 cm and weighs just 3.2 kg, including batteries.

REJr-AX has a total of 24 degrees of freedom. Further details of the body parts and their associated degrees of freedom can be found in Table 2. Each degree of freedom uses as actuator a Dinamixel DX-117 digital servomotor. These servomotors have a typical torque of 28.89 kg·cm and a speed of 0.172s/60°. Each has a microcontroller in charge of receiving commands and monitoring the performance

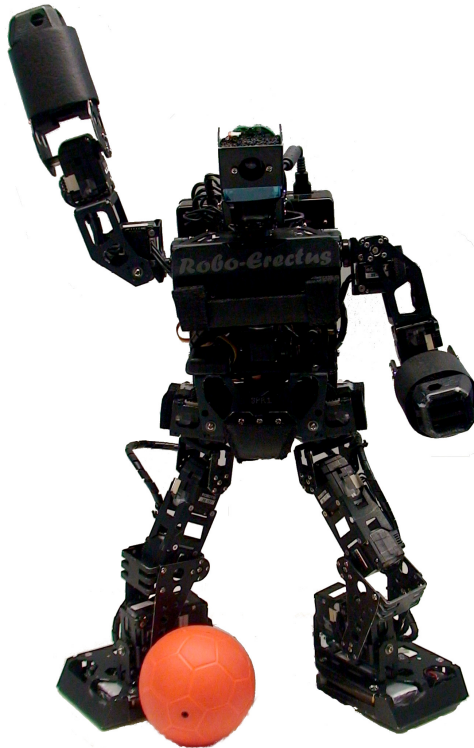


Fig. 1. Robo-Erectus Jr-AX, one of the foremost soccer-playing humanoid robots in the RoboCup Humanoid League.

Table 1. Physical specifications of Robo-Erectus Jr-AX.

Dimensions			
Weight	Height	Width	Depth
3.2 kg	480 mm	270 mm	150 mm
Walking speed		Running speed	
5 mts/min		—	
Sensor		Details	
Camera	320 × 240 resolution 30 fps		
Compass	1° heading accuracy		
Tilt	Two dimensions		
Sonar	Distance range 5–250 cm		



of the actual motor. An RS485 serial network connects all the servomotors to a host processor, which sends positions and receives the current data (angular positions, speed, voltage, and temperature) of each actuator.

## 2.2. Electronic design

Table 3 shows the network of three processors and the main devices that control REJr-AX. Each processor is dedicated to different tasks. The use of processors for particular tasks improves the performance of the system. However, this distribution comes with a price, i.e. coordinating and synchronizing the processors and their tasks. The tasks of each processor are as follows:

- (i) *The main processor* coordinates and synchronizes the rest of the processors. Being the brain of the robot, it manages all the robot's behaviors, receives the sensor information and transmits data to motors. All communication with other robots and the PC is handled by this processor via a wireless network.
- (ii) *The vision processor* is in charge of obtaining images from the USB camera connected to it. It can alter the format and resolution of the image according to the requirement of the main processor. The grabbed image is then processed to produce color and object information, which is sent to the main processor. This processor is then connected to the main processor by RS232.
- (iii) *The sensor/actuator processor* is actually a dual microcontroller that receives the motor commands from the main processor. These commands are validated and finally sent to the servomotors by RS485. The servomotors are connected to three networks, one for each leg and another for the upper body. This reduces the amount of information sent to and from the motors. The motor feedback is sent back to the main processor every 16.6 ms via RS232. This system is also responsible for collecting the sensors' values for the main processor.

The main processor and the vision processor are commercial boards running embedded Linux as the operating system. In contrast, a small program controls

Table 2. Physical specifications of the degrees of freedom for REJr-AX.

Joint	Roll	Pitch	Yaw
Head		✓	✓
Body		✓	✓
Shoulder	✓	✓	
Upper arm			✓
Elbow		✓	
Hip	✓	✓	✓
Knee		✓	
Ankle	✓	✓	


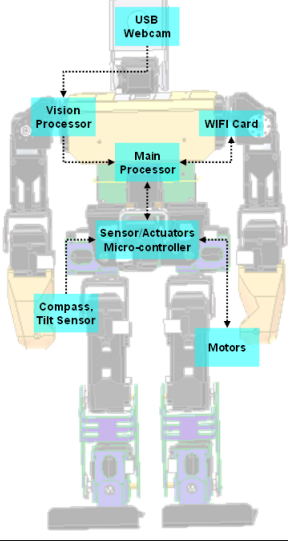


Table 3. Specifications of the boards of REJr-AX.

Main Processor	
Processor	Intel ARM XScale
Speed	400 Mhz
Memory	16 MB
Storage	16 MB
Interface	RS232, WIFI
Vision	
Processor	Intel ARM XScale
Speed	400 Mhz
Memory	32 MB
Storage	16 MB
Interface	RS232, USB
Sensor/Actuator	
Processor	Dual PIC18F8720
Speed	25 Mhz
Memory	8 KB
Storage	256 KB
Interface	RS232, RS485



the sensor/actuator processor operation, which was developed at ARICC. These processors are located at the *backpack* of the robot.

REJr-AX has four main sensors: a *camera* to capture images, a *tilt* sensor to recognize whether it is standing or falling down, a *compass* to detect its own orientation, and finally a couple of *ultrasonic* sensors to measure distance from front and rear objects. As mentioned earlier, the servomotors send back the feedback data, i.e. angular positions, speed, voltage, and temperature. To communicate with its teammates, REJr-AX uses a wireless network. The WIFI interface is connected to the main processor. The details of each processor and the connection of the main building blocks are shown in Table 3.

Finally, REJr-AX is powered by two high-current lithium–polymer rechargeable batteries, which are located in each foot. Each battery cell has a weight of only 110 g, and provides 12 V for about 20 working minutes. The batteries are connected in series to power the motor, but only the right battery power is supplied to the processors.

### 3. Software Architecture

The software control architecture for the robot is distributed into a network of three processors. The main and vision processors run *embedded Linux* as the operating system. The footprint of embedded Linux is very small, yet powerful enough to permit one to use all the advantages of this operating system, such as threading, networking, and connectivity. The main processor runs a robust system that coordinates the work with the other two processors. The vision system runs a program that processes each image from the USB webcam as well as any command from the main processor. This section describes in further detail these two programs.

The team behavior in a game emerges from interaction of the robots and the role selection. The functionality of REJr-AX is divided into several software modules, which are described in detail below.

#### 3.1. Image processing

Vision is the main source of information for the robot to detect the environment. The vision system consists of a 70° USB webcam mounted on a pan-tilt system that allows the robot to scan 240° wide. It is capable of grabbing 30 fps at  $320 \times 240$  resolution with a depth of 24 bits. The processing of the grabbed images occurs in a dedicated embedded system; color and object information about the relevant features inside the image is transmitted to the main system.

The first operation on the image is a *color segmentation* based on the HSI color space. Each image's row is scanned pixel by pixel. During this scan, the pixels are classified according to color. A look-up table is employed to classify the pixels by colors described by an HSI range for each color. Since the image is received as RGB, the use of the look-up table speeds up the classification process.<sup>9,10</sup> This look-up table consists of the possible combinations of red, green, and blue; each combination is evaluated when the table is created and marked as a relevant color with an index, or zero to indicate that such a combination is not relevant. The generation of the look-up table is a slow process that is performed in a PC and then transmitted via WIFI to the system. Furthermore, the generated look-up table is also compressed by using a method RLE-like to save space in the disk. The PC runs a client program to tune the color information and the look-up table in the embedded system to suit the different light conditions (see Fig. 2).

The classification of each pixel is the first step; insignificant colored pixels are discarded and colored pixels grouped into blobs [see Fig. 2(b)]. Recognition algorithms for the most important features (i.e. lines, goals, corners, robots, and the

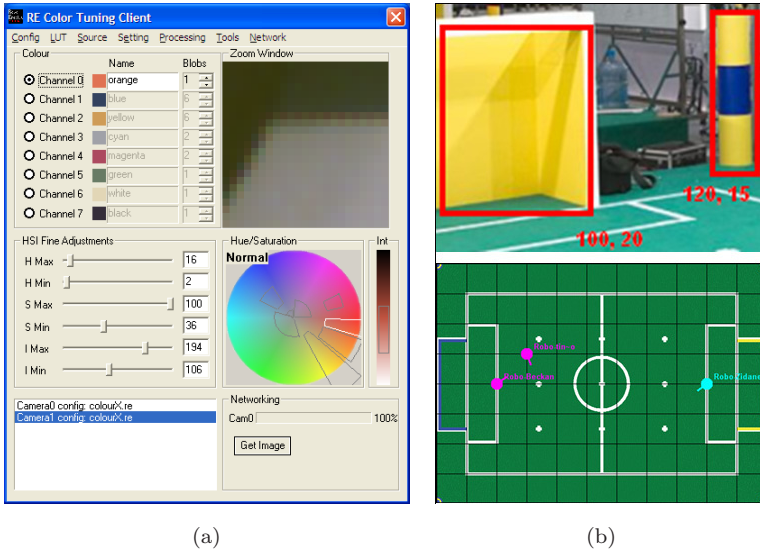


Fig. 2. The image client software allows one to tune the HSI ranges look-up table to be sent to the embedded solution.

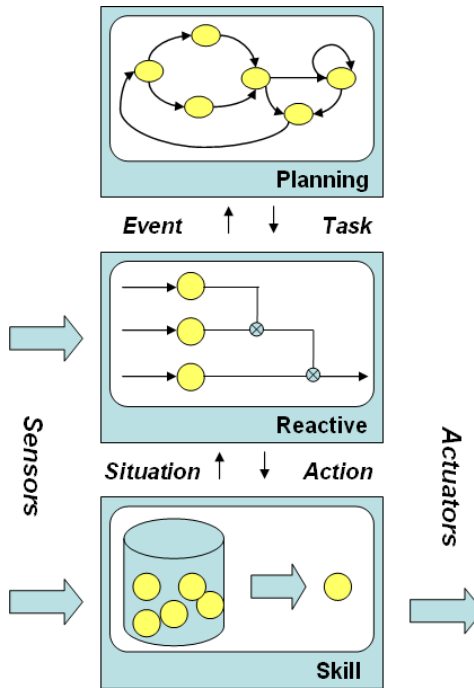


Fig. 3. The behavior control has been implemented as a hierarchical reactive framework, which is organized in three layers. Asynchronous communication between these layers is implemented, due to the variation in time span of each task.

ball) are implemented, avoiding wrong identification. In addition, previous observations provide confidence for their identification.

A map is the next level of perception from this information. Field lines along with corner information are used to estimate the position of the color objects in the scene. This information also includes the camera's position and the orientation of the image when it is taken. An egocentric map is then created where the position of each object (the distance from the robot and its orientation) is estimated according to the robot frame. Finally, the main system uses this egocentric map to merge it along with sensory data and teammate information into an allocentric map, which provides a robust world representation.

The gaze control uses a *fovea* as the main tracking area. When the detecting object is found inside the fovea, the pan and tilt motor keep still. Otherwise, the pan and tilt motor will move to compensate for the distance from the center of the fovea if the object is still in the image. In the worst case, where the object is not found on the image, it is reported and the motor will not move.

### 3.2. Behavior control

The module provides the control and strategy for the autonomous mode of the robot when it is playing soccer. A framework of *hierarchical reactive behaviors* is the core of this control module.<sup>5,11</sup> This structure restricts interactions between the system variables and thus reduces the complexity. The control of the behaviors occurs in three layers: skill, reactive, and planning layers (see Fig. 8).

These layers respond in a different way to sensor data. The interaction of these layers produces the final behavior of the robot. Besides the physical sensor data, the system employs abstract sensors, and takes decisions. These abstract sensors are built by merging data from different sensors and their history records. The best example of this type of sensors is the map, which is generated with camera information, compass data, and previous positions. The details of the three layers are given in the following.

*The skill layer* controls the servos, and monitors targets, actual positions, and motor duties. It receives actions from the reactive layer and converts them into motor commands. After the motor commands are performed, feedback is sent to the reactive layer.

*The reactive layer* implements the robot behaviors, like walking, kicking, and getting up. It determines the parameters for the behavior and these parameters can be adapted with time. This makes it possible to correct deviations in the actual data and to account for changes in the environment by using the sensor feedback. Each of these behaviors consists of several actions, which are sent to the skill layer. The selection of the behaviors depends on the desired tasks of the planning layer. The behaviors in this layer are implemented as a subsumption architecture to enable the robot to satisfy the task while navigating safely in the environment. The subsumption prioritizes *surviving behaviors* triggered by raw sensorial data, this ensures the

robot’s safety in the environment while carrying out its tasks. An example of surviving behaviors is the recovery behavior, which allows the robot to recover after a fall.

The *planning layer* uses the behaviors of the reactive layer to implement some soccer skills, like approaching the ball, dribbling, attacking and defensive behaviors. It guides the robot in coordinating its efforts with teammates to score and to defend their goal. The behaviors of the planning layer are abstract goals. These goals are passed to the reactive layer to be sent to the actuators. The response of the planning layer is slower than that of the reactive layer; the abstract sensors are used by this layer.

With each robot having the same hierarchical reactive framework. The emergent team behavior is the product of communication and cooperation between players. Although the robots each has a particular role, they can dynamically switch their roles based on a particular strategy, e.g. defending or attacking.<sup>5</sup>

Each role is defined in the planning layer as a state machine with transitions triggered by a combination of sensorial information, strategy, and messages received from the teammates. The implemented roles are *goalie*, *defender*, and *attacker*; Fig. 4 shows the state machine for the goalie role. Each robot takes decisions based on its role, perceptions, and the information it receives from teammates. The robot broadcasts its state to the teammates, which use this information to decide on the role.

### 3.3. Communication

REJr-AX is equipped with wireless network adapters. The robots communicate with each other to negotiate roles and to share perceptions. The wireless communication is also used to transmit information to an external computer for recording and

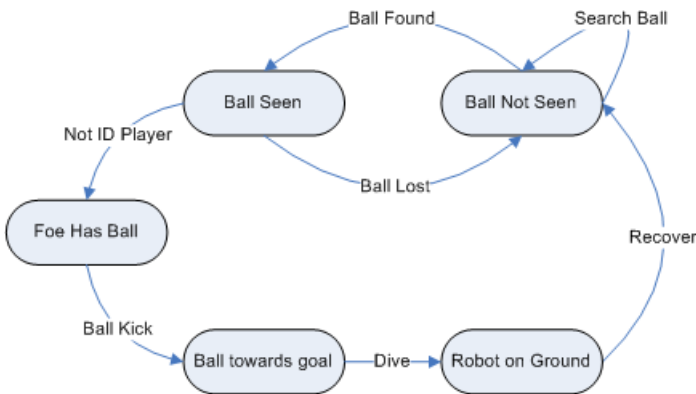


Fig. 4. Finite state machine for the role of goalie. The nodes represent the state of the robot and the environment. The transitions are the actions performed by the robot to change to another state.

visualization purposes. A monitor system was developed to follow the state of the robots during a game. This system also broadcasts to the players' information about the game, e.g. kickoff, finish, penalty, free kick. The information received from each robot can be recorded for analysis. The communication was implemented with the use of UDP sockets, which are not connection-oriented sockets, and do not ensure the delivery of the messages.

#### 4. Motion Control

The Robo-Erectus team has studied the locomotion control, and research is still going on to improve the robot locomotion. Our team has studied different approaches to motion control, including kinematics, dynamics, fuzzy logic, neural networks, and genetic algorithms.<sup>12-14</sup> The method to generate a dynamically stable gait for the humanoid soccer robots with consideration of various constraints is still an important research topic in this area.

To add the research about motion with REJr-AX, a simulator was developed, namely Virtual-RE, by providing several possibilities of visualization and interaction with the simulated world.<sup>15</sup> To simulate rigid body dynamics, Virtual-RE uses the Open Dynamics Engine (ODE), which has a wide variety of features and has been used successfully in many other projects.<sup>16</sup> The visualization as well as the computation of imaging sensor data is based on OpenGL libraries, because this standard offers the best performance with modern hardware on different platforms.

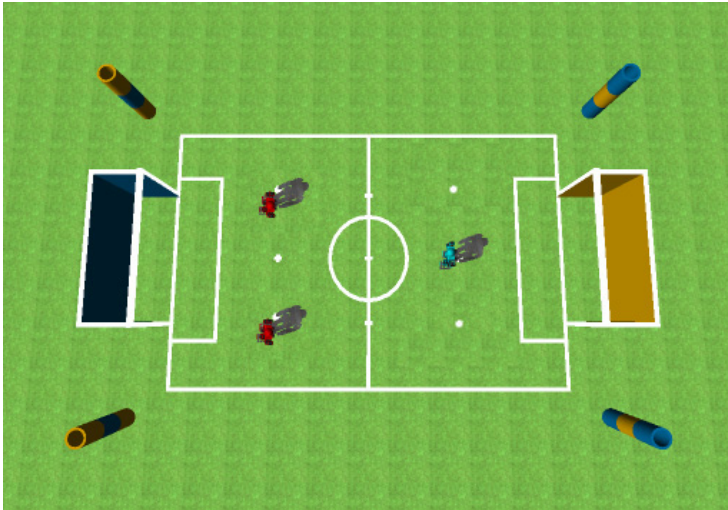


Fig. 5. Virtual-RE is a 3D simulator for REJr-AX. A setup environment can be specified and for each robot a client program is connected to the simulator.

### 4.1. Optimization of a gait

Our latest approach employs the Estimation of Distribution Algorithm (EDA) for gait optimization.<sup>17</sup> The problem of biped gait has grown into a high-dimensional problem, where parameters are involved and interrelated. The EDA depends on less parameters than other methods used for gait optimization.<sup>14</sup> This approach speeds up the search in a high-dimensional coupling space constructed by the permutation of the optimization parameters in order to establish a periodic orbit in biped locomotion, based on the maximum entropy principle.

Like other evolutionary algorithms, the EDA maintains and successively improves a population of solutions to find promising solutions. Furthermore, the EDA’s selection and recombination manipulators generate new solutions through the sampling of a probability distribution which is calculated from the selected promising solutions. In other words, the probabilistic model generated by the EDA is an explicit model of promising regions of the searching space.

We have also developed a Factorized Distribution Algorithm (FDA) — based gait optimization method to better understand how information is transferred between these parameters so that we may progress towards better understanding human locomotion and extend the results to the design of humanoid robots.<sup>18</sup> The proposed EDA and FDA have been successfully used to generate biped gaits that satisfy the criterion. The gaits have been efficiently used to drive the humanoid robot REJr-AX.

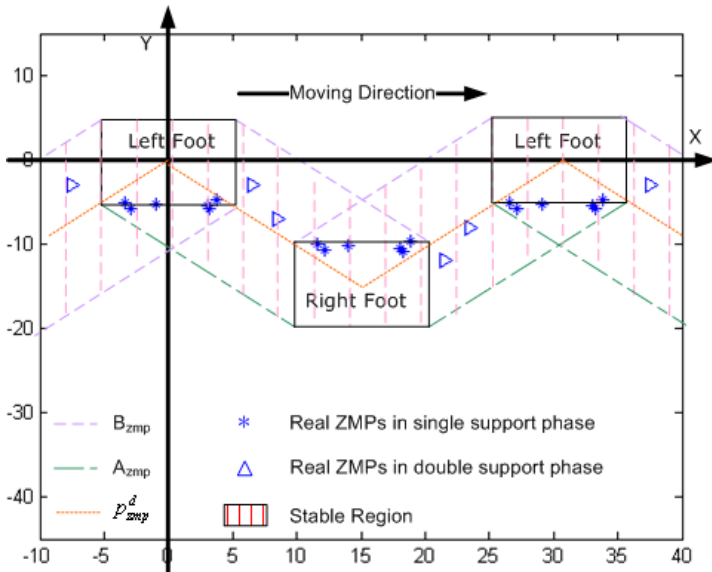


Fig. 6. ZMP trajectory of the robot moving forward. The joint trajectory in the gait was optimized by the EDA method.

## 4.2. Imitation of a human gait

Humanoid robots are organized in a human-like fashion; they have to deal with dynamic constraints such as balance as well as geometrical constraints. The large number of extra joints makes the humanoid robots advantageous in avoiding obstacles and joint limits, and in attaining more desirable postures. However, redundancy also complicates the control with a high number of variables to evaluate. While utilization of human data can outline the trajectory required to solve the task, but the kinematic and dynamic consistency still needs to be solved.

Imitation was employed to obtain human trajectories and to generate human-like trajectories while reducing the data to be optimized. A humanoid has fewer joints and a more restrained workspace, and it is weaker and slower than a human. The difference in body structure prohibits the direct use of human capture data to control a humanoid robot. Hence, it is imperative to find an appropriate way to translate the human capture data into useful data for the robot.

Imitation has previously been used successfully in robotics. It has been reported that humanoid robots learned how to swing a tennis racquet, draw letters, and move objects.<sup>19–21</sup> However, most of these researches has focused on the upper body, leaving stability aside. Meanwhile our work deals with the lower body movements, where stability is our primary concern. We have applied imitation previously to acquire some parameters from a human gait.<sup>22</sup> However, we extended this work to use the human data as a guideline for each motor in the robot. The method involved generates human-like locomotion from an observed human gait while preserving as much as possible the fundamental aspects of the demonstration.

The first step refers to choosing the key points of the observed trajectory. This process can be done manually or automatically by applying algorithms that detect relevant features of the predefined trajectory, as described in Ref. 21. The key points are used to perform scaling of each joint angle independently. This does not preserve the overall configuration of the robot's limbs. It only produces a guideline or model that the robot still needs to be optimized. The optimization adjusts the trajectory to relevant features of the system and selects feasible positions to generate a stable trajectory. The optimization procedure dynamically achieves stable movement for the robot while specific requirements are satisfied.

Figure 7 presents a comparison of the objective function output for this approach with the original EDA method described in Ref. 13. The objective function using the human data converges in less iterations to a stable, human-like walking gait. The results of this approach showed that using human data to drive the optimization method will produce faster convergence to a reliable gait. In addition, the use of human data to seed the system (probability distributions) will bias the distribution functions towards better results rather than just starting from a random seed. The distribution functions also provide information about similarity when new gaits are observed in comparison with the seed gait.

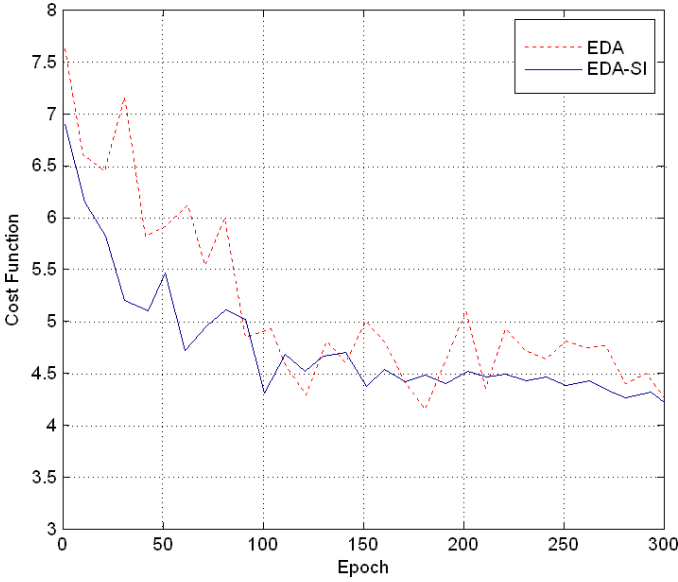


Fig. 7. Comparison of the cost function between the EDA with random initial data and the EDA with the human data extracted from a demonstration (EDA-SI).

## 5. Results

Experiments were performed to test different behaviors, including walking, kicking, ball passing, turning right and turning left implemented for Robo-Erectus Junior. Experiments for walking towards the ball and kicking the ball are shown in Figs. 8(a)–8(c). The robot detects the blobs in the images received from the camera and recognizes the objects of interest, including the ball, goal, goalpost, corner poles, field lines, the opponent, and the teammate, upon evaluating the blobs. The planning layer of the control system accounts for the vision and other sensor information, and uses the behaviors of the reactive layer to implement the soccer skills, like walking toward the ball, kicking the ball, and dribbling.

Figure 8 also presents other behaviors, such as the goalie diving for a front kick [Figs. 8(d)–8(f)] and the goalie diving for a side kick [Figs. 8(j)–8(l)]. The recovery behavior is also shown in Figs. 8(g)–8(i); this recovery is for the goalie after the front dive. Every behavior is tested first using the simulator Virtual-RE and then in the actual REJr-AX. Figure 9 presents the robot walking forward and also the simulator using the same gait.

Repeated experiments were performed to test the effectiveness of the developed vision system in terms of reliability and robustness. Under the RoboCup soccer setup, the system reported 91.67% of the objects on the field. The reliability of the module is measured by the number of false positives detected by the system. Experiments were performed on a RoboCup soccer field set up in our lab, with

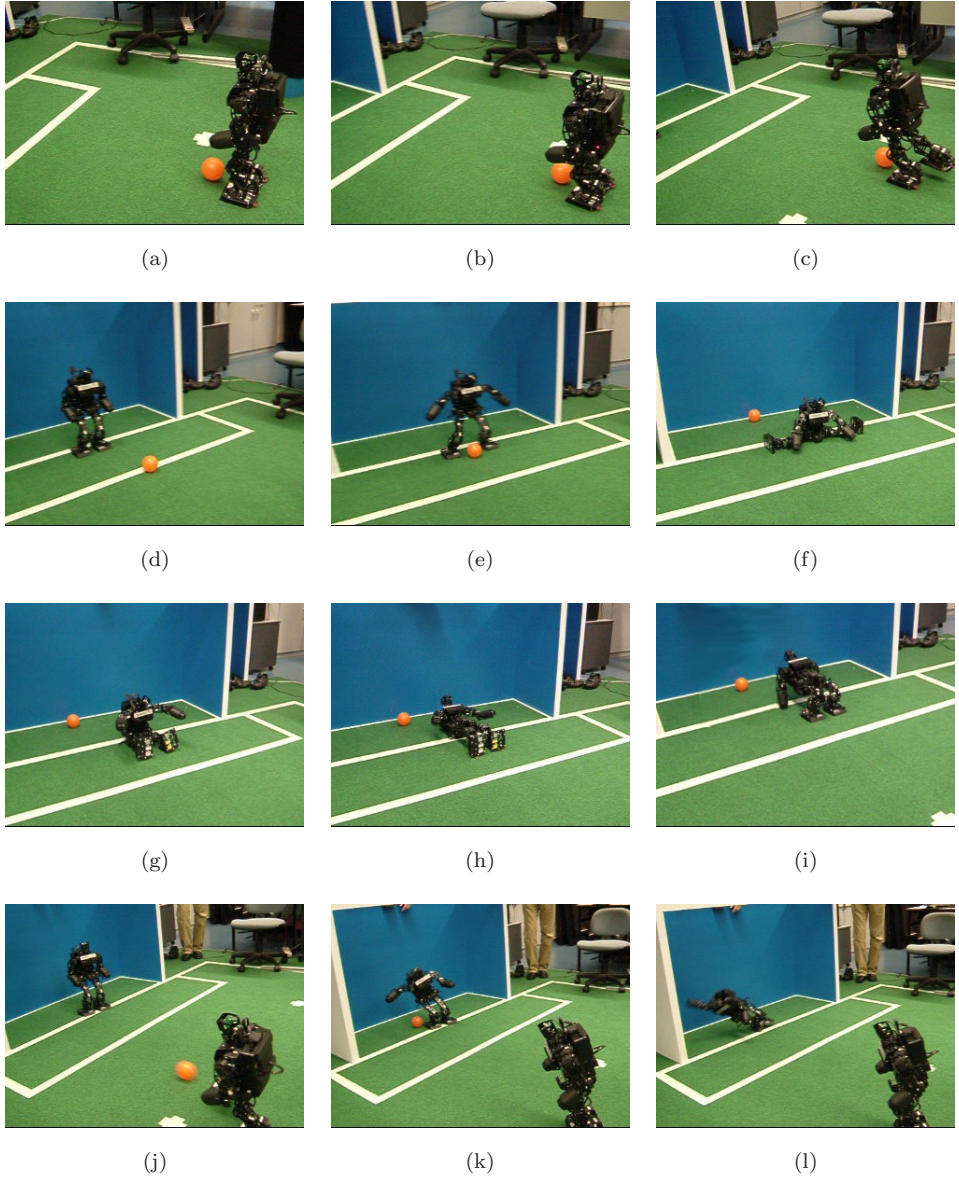


Fig. 8. REJr-AX in action. There are four different behaviors: kick, 8(a)–8(c); goalie front, 8(d)–8(f); recovery, 8(g)–8(i); and goalie side, 8(j)–8(l).

real match scenarios for durations of 10 min each. Results showed that only one or zero false positives were detected per match. Such high reliability in terms of false positives was achieved only because of the repeated verification performed on the blobs as a part of the vision algorithm. Due to the dynamic nature of the operating conditions in a RoboCup soccer setup, the robustness of the vision system against

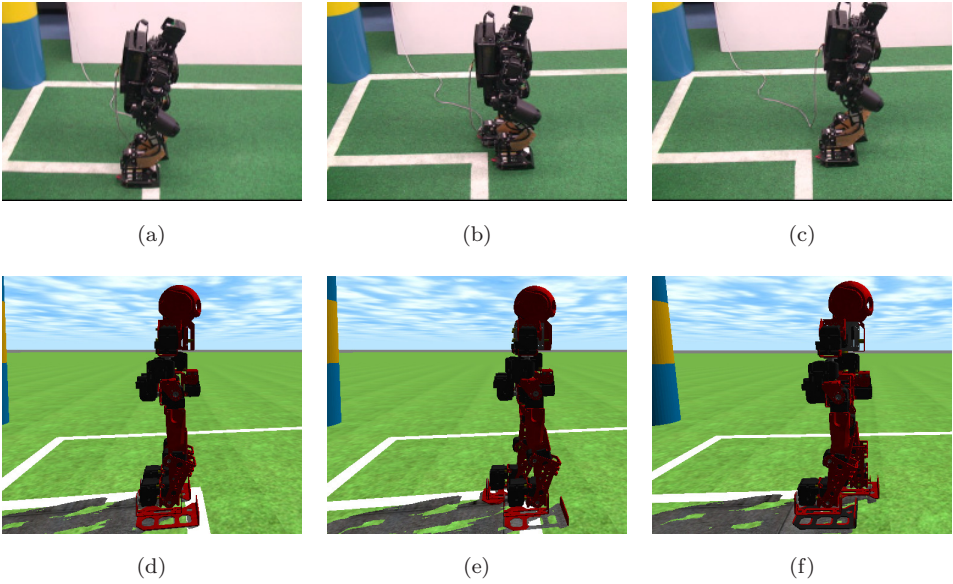


Fig. 9. REJr-AX and its simulator, Virtual-RE, walking forward.

Table 4. Performance of Robo-Erectus for varying lighting conditions.

Experiment Number	Illumination (lux)	Reliability (%)
1	1200–1000	91.67
2	1000–800	83.33
3	600–300	70
4	300–100	56.67

changing lighting conditions becomes essential. Table 4 shows the performance of our vision system for robustness in terms of lighting changes.

For field illumination between 1000 and 1200 lux, the number of objects reported was 91.67%, with no false positives. From Table 4, it is evident that the percentage of objects reported decreases with the drop in the field illumination. Even with the illumination dropped to between 100 and 300lux, the vision system continues to function with no modification but the number of objects reported is now reduced to 56.67%, with no false positives.

## 6. Conclusion and Future Work

This paper has presented the state of the art of the Robo-Erectus project, which took part in RoboCup 2007. Robo-Erectus Jr-AX is an autonomous humanoid robot with a network of three embedded systems, 24 degrees of freedom, and several kinds of sensors that serves as a platform for education, entertainment, and research. The latest version of Robo-Erectus has several advantages, in contrast with the previous

generations. REJr-AX is faster and more reliable, thanks to its robust control, improved gait, and vision system.

The new features of REJr-AX were displayed in the 2007 RoboCup competition. Although the potential of the robot is fully appreciated but there is still a long way to the pinnacle. New development tools were conceived from the gained experience of the previous versions of Robo-Erectus. In addition, the improvements in the robot platform allows a more robust and efficient performance of the robot in the autonomous mode. Research with this platform has led to the development of a new approach to better control of humanoid robots, in particular for RoboCup.

Many efforts have been made regarding the control and vision system, but such systems need more improvements. Future work will involve a better analysis of the camera's images, improve the team's coordination, and map information. Current work is underway to investigate new ways to endow the robot with various types of basic soccer skills, such as kicking the ball and goalie diving. Future work will focus on better understanding how information is transferred between joints and gait transition, aiming at the better understanding of human locomotion, and extend the results to design of humanoid robots. Future work will also include an interface with Microsoft Robotics Studio.

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