Reactive Behaviours and Agent Architecture for Sony Legged Robots to Play Football

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Abstract. It has been an ultimate long-time dream in robotics and AI fields to build robotic systems with life-like appearance, behaviours and intelligence, reflected by many science fiction books and films. This is also an extremely challenging task. This paper introduces our current research efforts to build a multi-agent system for cooperation and learning of multiple life-like robots in the RoboCup domain. A behaviour-based hierarchy is proposed for the Essex Rovers robot football team to achieve intelligent actions in real time, which includes both a neural network based color detection algorithm and a fuzzy logic controller. Preliminary results based on legged locomotion experiments of Sony walking robots were presented.

Keywords: Mobile Robots, Agent Architecture, RoboCup, Entertainment

1. Introduction

Recently the success of the Honda Humanoid robots P1 and P2 has demonstrated the technical feasibility of building life-like robots [3] [14]. At the same time, the advanced-legged robots have been recently announced by Sony at Japan, which resemble the basic behaviour of dogs [7]. These robotic pets have been equipped with all the necessary hardware such as the brain, sensors and actuators. Their software enables them to have emotions, instincts, learning ability and capability to mature [8]. Each Sony robot turns out differently, as its behavioral patterns continuously change. This is because Sony robot acts based upon its feeling and instincts then learns from the results of experience, until maturing [16]. In a good mood, it may entertain you with its favorite performance such as stretching and chasing, whereas in a bad mood, it will lie on the floor and do nothing at all except sleep.

These exciting new robots not only establish a new dimension for the Robot Entertainment industry [7], but also provide complete new testbed for robotics and AI researchers to work on many fundamental research issues such as behaviour adaptation, human-like thinking, evolution, and learning [17][18]. These will also provide a great potential for successful robotic systems in industry and domestic applications. More specifically, the Sony Legged robot League is an international robot football game that has been launched recently based on Sony legged robots [13]. This is a very challenging task since

the robot posture and its head position constantly change during legged locomotion. Also the planning and control of a team of walking robots is extremely complex.

RoboCup provides a challenging environment for research in systems with multiple robots that need to achieve concrete objectives, particularly in the presence of an adversary team [12]. The methods to handle the complexity within the RoboCup domain include a centralized approach and a decentralized approach [1]. More specifically, in a centralized approach planning and decision-making functions are handled by a single control center. Each mobile robot contains few simple sensors for control and guidance, the actuators for operation, and the communication facilities for data exchange with the control center. All the movements of mobile robots in the system are controlled from the control center and conflicts among multiple robots are easily solved. This method has been widely adopted in manufacturing industry and warehouses where multiple mobile robots are used to transfer parts and clean warehouses [9]. One major disadvantage of the system is that the whole system will stop functioning immediately if the control center fails.

In contrast, a decentralized control method is to equip each mobile robot with multiple sensors and embedded computers in order to sense its environment, build maps, and plan actions [3]. In any unforeseen situation, the robot is able to plan a new path or find a solution without waiting for commands from the control center even if there is one. The function of the control center is only limited to the broadcasting of traffic flow information received from all robots and the allocation of tasks in the system. Inter-robot communication becomes necessary since competition for resources should be avoided and sharing experience could improve system performance. This paper is to address how to adopt the decentralized approach to a team of Sony walking robots in the RoboCup domain.

The rest of this paper is structured as follows. In the next section the Sony legged robots and their environment are briefly introduced. Section 3 describes the agent architecture of our Essex Rovers team and a number of robot behaviours being defined, including both low-level behaviours for autonomy and high-level behaviours for cooperation. Object recognition and colour learning are presented in section 4. Section 5 addresses the motion control problems in the locomotion of quadruped walking robots, with initial experimental results. Finally, brief conclusions and future work are summarized in section 6.

2. Sony Robots and RoboCup Legged Robot League

2.1 Life-like Robots

Each Sony legged robot has dog-like appearance and a quadruped design, approximately 30cm long and 30cm tall including the head. The merit of the quadruped configuration has two folds: one is that the robot has superior static and dynamic stability as opposed to a biped robot, and another is that two front legs can be used to express emotion and communicate with other robots or human. The neck and four legs of each Sony legged robot have 3 degrees of freedom (DOFs). The neck can pan almost 90 degree to

each side to scan around the surrounding for interesting objects. The head/neck module has 3 DOFs, allowing the head to roll, pitch and yaw. Importantly, the robot has an internal gyroscope and accelerometer, and is able to return to a standing posture after a fall by using the legs to tilt the body from whatever side it has fallen on. A total of 18 degrees of freedom makes Sony legged robots exhibit rich body languages, including joy, sorrow, anger, surprise and fear, as shown in figure 1. Also they can express their emotion and internal states by emitting sound or blinking their eye lamps: the red lamp means anger and the green lamp means happy [16].
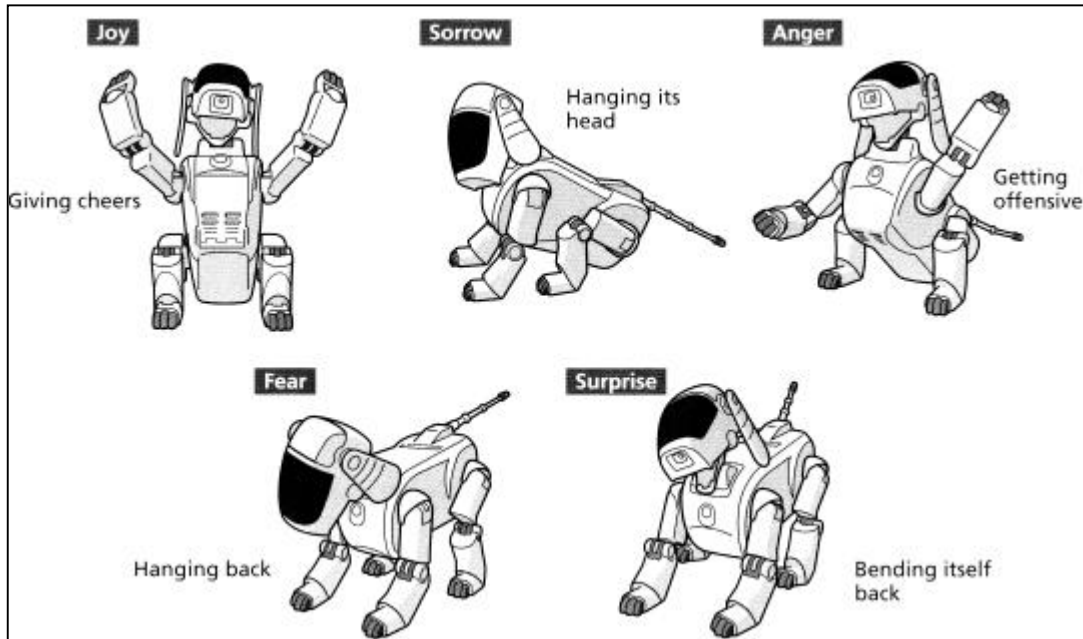

Figure 1 Rich body languages exhibited by Sony AIBO robot [16]

The Sony robot has a specially designed color CCD camera on-board, capable of 492x364 pixel resolution at a color depth of 24 bits. There is an IR range finder for range detection, as well as stereo microphones and loud speakers for inter-robot communication. The robots are controlled by one embedded 64bit R4000 RISC processor with over 100 MIPS performance. A vision-processing chip is able to perform user calibrated colour detection on the images it receives. The dedicated ASIC modules are used to make the robot small in size and in power consumption [12]. There is also an 8MB of DRAM chip installed in the robot and up to 16MB Sony memory stick as a storage device.

Sony Corporation has proposed a standard interface, namely "OPEN-R", for the entertainment robot systems in general [7]. This interface expands the capability of the entertainment robot through a flexible combination of hardware and interchangeable software to suit various applications [8]. Currently, Sony robots, AIBO ERS-110, conform to the specification of OPEN-R version 1 [16]. The development system for Sony legged robots is called *Aperios* which supports the object oriented programming paradigm from the system level with several types of message passing among objects [13].

2.2 RoboCup Legged Robot League

The environment for these robots in the RoboCup event is a playing field with the dimension of 3m in length and 2m in width. At each end of the field there is a goal that is 600mm wide, 300mm high and 350mm deep. There is also a penalty area marked around each goal. Figure 2 shows that four Sony robots are playing a game in the football pitch. The goals are centered on both ends of the field, with a size of 60cm wide and 30cm high. The colour of one goal is yellow and the colour of another goal is blue. Six unique colored landmarks are placed around edges of the field, with one at each corner and one on each side of the halfway line. Each landmark is painted with two different colors of which the pink color is either at the top of landmarks on the one-side or at the bottom of landmarks on the other side. These landmarks are used for robots to localize themselves within the field. The walls surrounding the field are at 45-degree slant, with a small triangular slanted wall for each corner. These slanted walls effectively return the ball to the field when the ball is pushed against board. The ball, walls, goals, landmarks and robot labels are painted with 8 different colors distributed in the ultraviolet color space so that they can be easily distinguished by Sony robots.
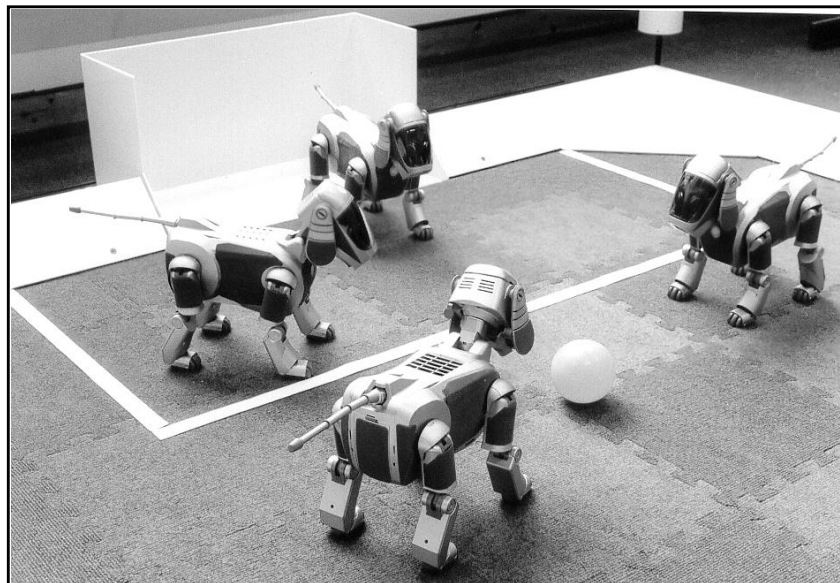

Figure 2 Sony Legged robot league competition in RoboCup

Like human football, robot football is played by two opposing teams, each of which has three robots. One of these robots plays the role of Goalkeeper who is the only robot allowed to remain within its own penalty area. Each team of robots wears its own colour uniform -- either red or blue. The red team always attacks the blue goal, and the blue team attacks the yellow goal. The robots on the field have to function autonomously, and no remote computer or vision system is allowed. Each game consists of two halves. Each half lasts for 10 minutes, not including penalty time. When two or more robots become entangled

during the match, the referee is allowed to pull all robots a small distance apart so that no advantage should be given to either team.

To enable Sony legged robots to play football, we have to train each Sony robot to gain the basic behaviours for kicking, dribbling and passing the ball by using their legs. To win the game, the cooperative behaviours are also needed for a team of Sony robots to do team formation and strategy.

3. Agent Architecture of Essex Rovers

The main objective for our Essex Rovers team is to build a firm research platform on which future work on multi-agent systems can be done. Currently, a multi-agent approach is adopted here to achieve real-time performance [15][16].
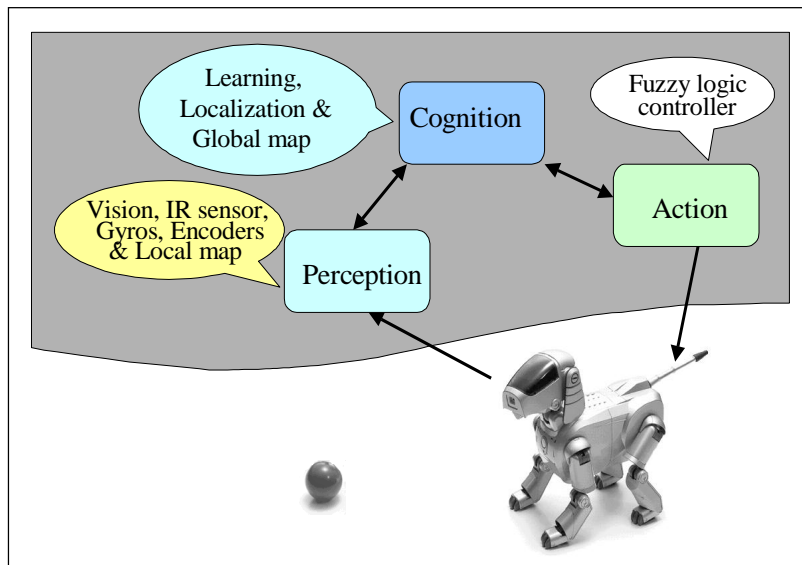

Figure 3 Agent architecture for the Essex Rovers team

3.1 Modular Design

The modular architecture is adopted in overall agent implementation as shown in Figure 3. More specifically:

- Perception -- This module includes a multi-sensor system and a local map. The sensors being used are a color vision system, a PSD (Position Sensitive Device), five touch sensors, 18 optical encoders, two microphones, and 3 gyros. Incoming visual, proximity, ranging and auditory information is processed by on-board computer. Neural networks based CDT (Color Detection Table) is used to handle uncertain and changing lighting condition as shown in figure 4. A local map is then built and updated dynamically as long as new sensory data is available.

- Action -- This module includes one speaker and 18 micro servomotors. Each leg has three joints driven by three servomotors. The synchronization of quadruped legs for each robot is extremely important for robot actions such as kicking the ball and moving towards the goal. A fuzzy logic controller in figure 5

is used here to deal with uncertainty in sensory data and imperfect actuators. The speaker is used to communicate with teammates for team formation and cooperation.

- Cognition -- This module consists of both high-level behaviours for learning and team formation and low-level behaviours for safeguard and game playing. This is a typical hybrid architecture [17] that is to merge the advantages of traditional planning based approach and the behaviour-based approach. Based on information from the perception module, it selects an action to perform and sends the result to the Actuators module for execution. This is the most complex module since it does the "thinking" and "reasoning" for each robot agent. More details are given in the next section.
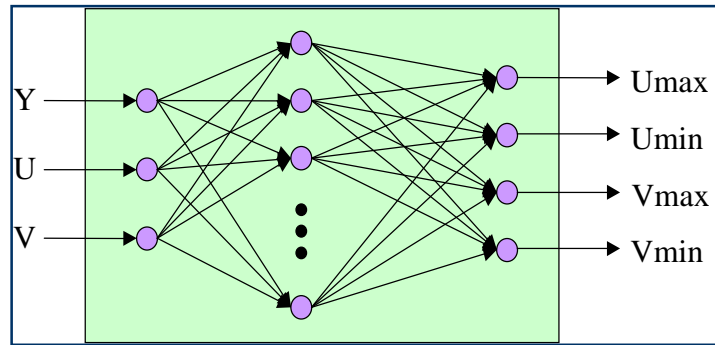

Figure 4 Adaptive threshold for CDT

3.2 Agent Behaviours

A primary aim in the development of teams of co-operative mobile robots in general, football robots in particular, is to synthesis low-level basic behaviours and high-level cooperative behaviours of multiple mobile robots. Low-level behaviours enable individual robots to play a role in a specified task or game. However, high-level behaviours enable a team of mobile robots to accomplish missions that cannot easily be achieved with individual robot [11]. Although many behaviours can be synthesized for the co-ordination of multiple robots in general [2][6], only several useful behaviours are identified in this application, as shown in Figure 6. The behaviours can be in general categorized into two levels as follows:

Low-level behaviours for mobility

- Safeguard behaviour – to keep a safe distance among mobile robots during competition, and to protect robots from colliding with other objects.
- Game-playing behaviours – to enable each robot to play a role in the competition, including kicking the ball, dribbling the ball, passing the ball, intercepting and shooting the goal.

High-level behaviours for cooperation

- Communication behaviour – to realize inter-robot communication by either an explicit way using loud speakers and microphones when possible or an implicit way by observing the motion of other robots [4][10].
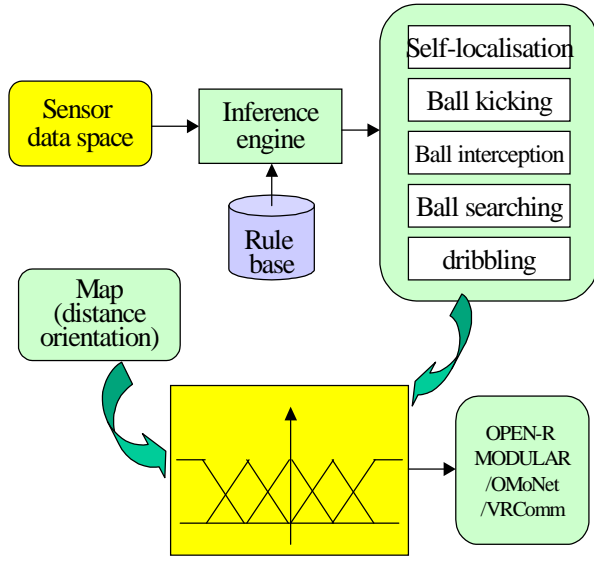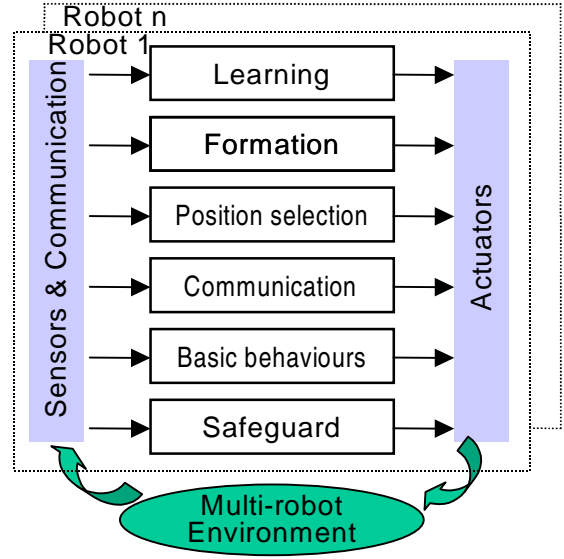
Figure 5 Fuzzy logic controller   Figure 6 Robot behaviour hierarchy

- Position selection – to find out where each robot is and where is the goal in order to position itself at the optimal position at any moment. This is a reactive planner to generate locally optimal strategies to direct the low-level behaviours of each robot. It is very important for each robot to play an effective role in the competition.

- Formation behaviour – to enable multiple robots to form a team where each robot makes its own contribution towards a common goal [4]. Note that the role of each robot should be able to swap dynamically in order to achieve optimal performance.

- Learning behaviour – to learn from its own experience and from other mobile robots. This is a key factor for each robot to improve its performance under an uncertain and dynamic environment [15]. Learning here includes both evolving fuzzy rules for low-level behaviours and searching optimal parameters for high-level reactive planning [17].

Additional cooperative behaviours can be synthesized during the next stage of our research, for instance homing behaviour and role switching behaviour. This should be easy to implement in our modular design.

4. Object Detection and Colour Learning

During a football game, the objects for each robot player to identify include the ball, six markers, two goals, teammates, and opponents with 8 different colours. The task of the on-board vision system is to report the robot's location relative to the robot local map. The image processing procedures are:

- Image capture – Sony legged robot provides the colour images in YUV space and each pixel in the image is represented by 3 bytes of Y, U, and V values. It also provides 8 colour images after each

captured image being threshold by hardware. The hardware threshold makes use of 32 Y levels and there are 2 thresholds for U and other 2 thresholds for V at each level. This will lead to 32 rectangles in U and V frames for each colour. In order to select the thresholds for the hardware, we developed a software tool that can manually label the different colour and find the thresholds among the labelled pixels.

- Image segmentation – The threshold image may contain noise due to the luminance condition, as shown as in figure 7(b) and figure 8(b). We choose morphology filter to de-noise the image since the detected object's shape is known a prior [11]. For a binary image, there are two operators normally used in a morphology filter, namely dilation and erosion.

$$\textit{Dilation:} \qquad X \oplus B = \left\{ p \in \mathrm{E}^2 : p = x + b, x \in X .and. b \in B \right\} \qquad (1)$$

$$\textit{Erosion:} \qquad X \otimes B = \left\{ p \in \mathrm{E}^2 : p + b \in X . for. every. b \in B \right\} \qquad (2)$$

where X is image, B is structuring elements, and E^2 is 2–D image space. In practice, dilations and erosions are usually employed in pairs, called opening and closing for different employing sequence.

$$\textit{Opening:} \qquad X \circ B = (X \otimes B) \oplus B \qquad (3)$$

$$\textit{Closing:} \qquad X \bullet B = (X \oplus B) \otimes B \qquad (4)$$

Morphologically filtering an image by an opening or closing operation corresponds to the ideal non-realisable band-pass filters of conventional linear filtering. The image in figure 7(b) is processed by closing operation and the result is shown in figure 7(c). Similarly, the image in figure 8(c) is generated by closing operation from figure 8(b).

- Image representation – Before the phase of object understanding, the similar adjacent pixels have to be grouped into the connected regions. This is typically expensive operation that severely impacts real time performance. We calculate the run length encoding (RLE) to represent the image in order to make our next image operation based on RLE not on individual pixels. Region identification can be performed in two passes as follows.

PASS ONE:

− Use a new label for each continuous run in the first row that is not part of the background.
− If a run in a row does not neighbour any run in the previous row, assign a new label.
− If a run neighbours precisely one run in the previous row, assign its label to the new row.

- If the new run neighbours more than one run in the previous row, a label collision has occurred. Collision information is stored in an equivalence table, and the new run is labelled using the label of any one of its neighbours.
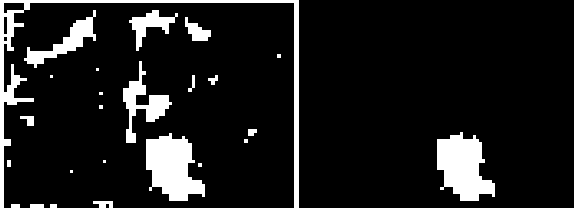
PASS TWO:

- Search the RLE again and re-label the image according to the equivalence label information.

- Image understanding: based on the labelled RLE, objects can be identified according to their shape, size and position. For example, the maximum size blob located in the ground in the orange image will be the ball, as shown in figure 7(d) and figure 8(d).
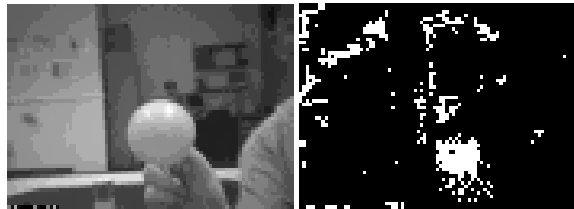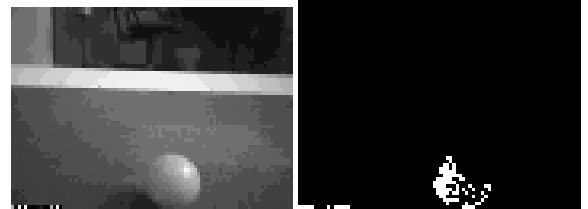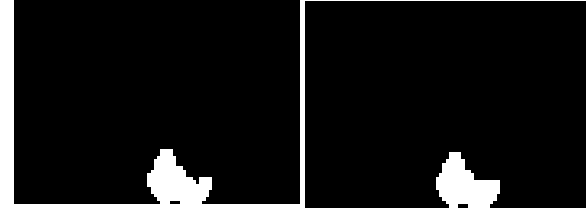

(a) Original image	(b) After threshold
(c) Filtered image	(d) Final object

Figure 7 Image Processing to find a ball at hand

(a) Original image	(b) After threshold
(c) Filtered image	(d) Final object

Figure 8 Image processing to find a ball on the pitch

5. Motion Control and Walking Experiments

One of the most important advantages of legged robots is their superior mobility and terrain adaptability to wheeled/tracked mobile robots. Legged robots only require a few discrete footholds to travel around for off-road locomotion where the surfaces may be inaccessible to wheeled/tracked robots. To make such attractive characteristics more practical, a motion control algorithm should be developed to search and plan an optimum path and the foothold points, and to keep dynamic stability on a rough terrain [18]. Although serious hardware limitations exist, teams with efficient coordination of quadruped leg motion can have major advantages in the RoboCup Sony Legged robot competition.
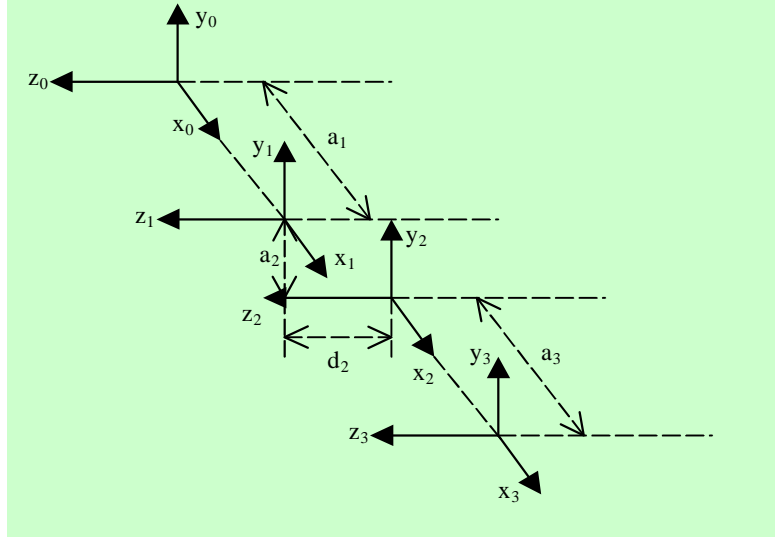
Figure 9 Joint co-ordinates of the front left leg

As the first step of our implementation, we started from the low-level motion control of the robot. Each leg should be adjusted before their coordination. Figure 9 shows the left front leg of the Sony robot. Assume that the frame (x0, y0, z0) represents the root joint, and the frame (x2, y2, z2) is the knee joint which has the coordinates (0, -a2, -d2) in the auxiliary frame (x1, y1, z1). The foot joint is located in the frame (x3, y3, z3). Here we consider a two-joint link with joint angles θ_1 and θ_2, which is rotated around axes z0 and z2.

The matrixes, A_i, for this two-joint link are:

$$
{}^0A_1 = T_{z_0,\theta_1} T_{x_0,a_1} =
\begin{bmatrix}
c_1 & -s_1 & 0 & 0 \\
s_1 & c_1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & a_1 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

$$
{}^1A_2 = T_{z_1,-a_2} T_{y_1,-d_2} =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & -a_2 \\
0 & 0 & 1 & -d_2 \\
0 & 0 & 0 & 1
\end{bmatrix}
\tag{5}
$$

$$
{}^2A_3 = T_{z_2,\theta_2} T_{x_2,a_3} =
\begin{bmatrix}
c_2 & -s_2 & 0 & 0 \\
s_2 & c_2 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & a_3 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

where $a_1 = 61.00mm$, $a_2 = 5.50mm$, $a_3 = 53.62mm$, $d_2 = 13.00mm$.

Then the leg's direct kinematics is:

$$^{0}A_{3}={}^{0}A_{1}{}^{1}A_{2}{}^{2}A_{3}$$

$$=\begin{bmatrix} c_1c_2 - s_1s_2 & -c_1s_2 - s_1c_2 & 0 & a_1c_1 - a_3c_{12} + a_2s_1 \\ s_1c_2 + c_1s_2 & c_1c_2 - s_1s_2 & 0 & a_1s_1 + a_3s_{12} - a_2c_1 \\ 0 & 0 & 1 & -d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

where $c_1 = \cos\theta_1, s_1 = \sin\theta_1, c_{12} = \cos(\theta_1 + \theta_2), s_{12} = \sin(\theta_1 + \theta_2)$.

Two PID servo controllers are used in our experiment to drive two motors to rotate from 10° to 80° around θ_1 and θ_2. The corresponding encoders' readings are recorded. The rotation of the robot's root joint is plotted in figure 10 where the horizontal axis is the cycle time. The motion trajectory of one of the robot's feet is shown in figure 11. In contrast, figure 12 presents a motion trajectory for one of the robot legs. The experiments on synchronization of quadruped leg motion at different speeds for games playing are currently carried out.
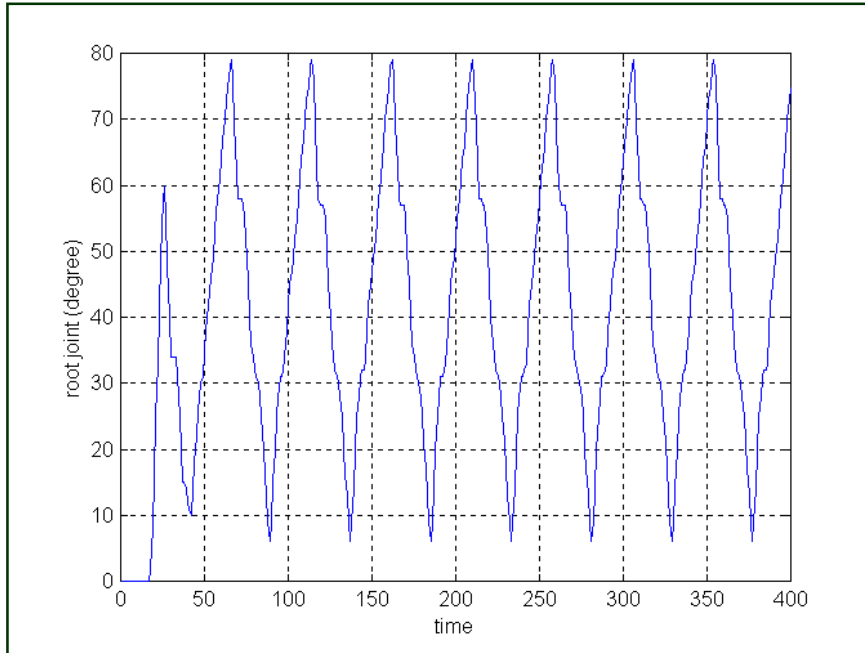

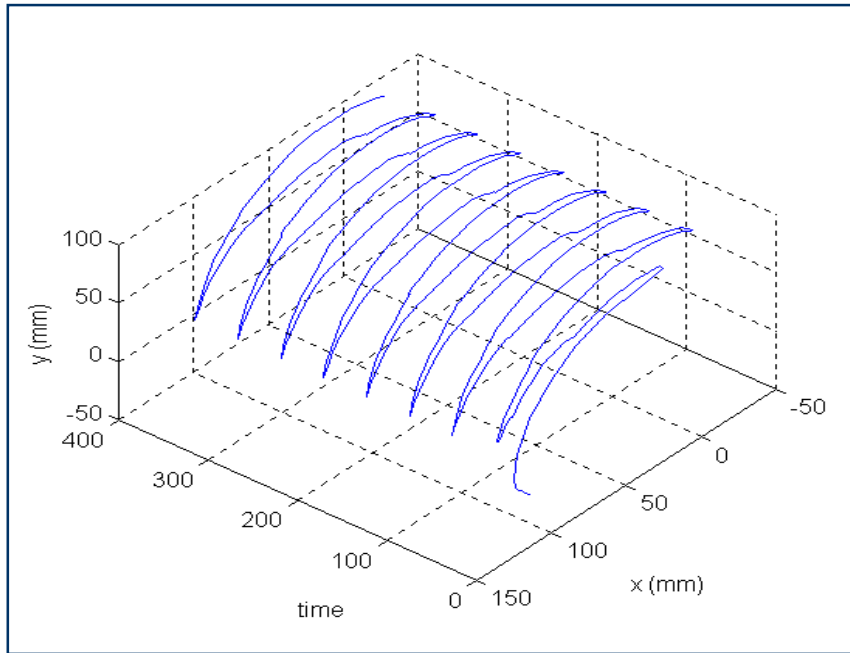Figure 10 Encoder readings from the root joint of one robot leg

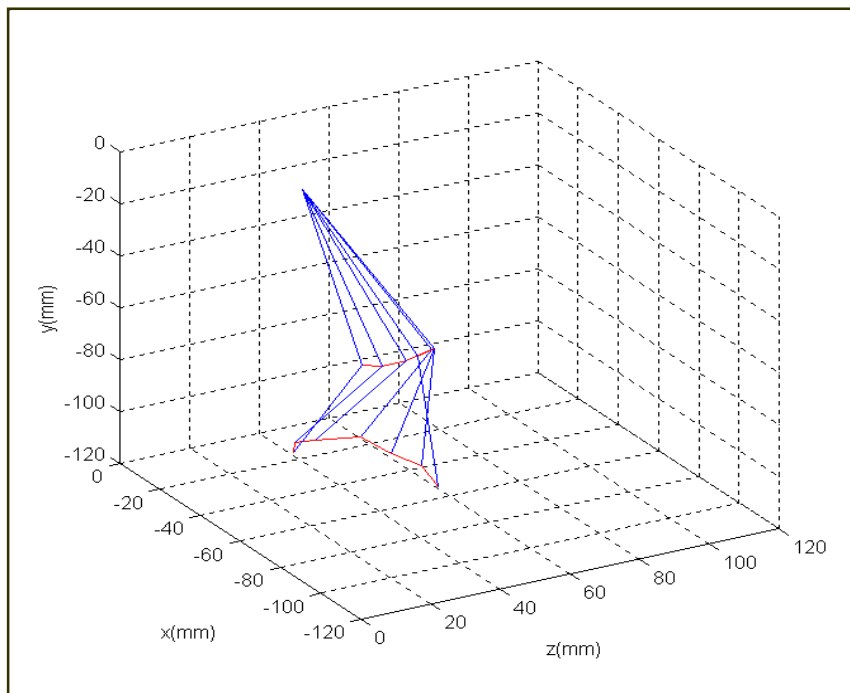Figure 11 A motion trajectory of one of the robot's feet

Figure 12 A motion trajectory of one of the robot's leg

6. Conclusions and Future Work

This paper presents a multi-agent system for Sony legged robots in the robot football domain in order to investigate both behaviour coordination and embodied intelligence. Each Sony robot requires sensor-motor-skills to shoot the ball, to dribble and pass the ball, to avoid serious crashes with other players, and so on. This is very challenging task, as the strategies and behaviours of the opponents are uncertain. Since Sony legged robots have very limited on-board computing power, many useful image processing algorithms can not be adopted directly for real-time implementation. It remains a big challenge to produce an effective vision algorithm for Sony robot to play a fast football game. At the same time, the disadvantages of using legged robots is their moving speed is not as fast as wheel-based robots. How to improve motion speed is a key for success in the RoboCup challenge.

We are currently investigating (i) how low-level behaviours such as kicking, passing and intercepting are effectively integrated with high-level behaviours, i.e. position selection and team formation; (ii) what data fusion algorithms are required to capture environment features effectively and deal with uncertainties; (iii) how adaptation and learning algorithms should be adopted to make robotic systems more flexible in a dynamic environment. These tasks are not only useful in the RoboCup domain, but also significant important for many real-world applications. The advantages of cooperative mobile robots over single complex mobile robot include the potential for increased fault tolerance, simpler robot design, and wide application domain.

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