Building and integrating a goalkeeper robot for the small-size RoboCup competition

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Abstract

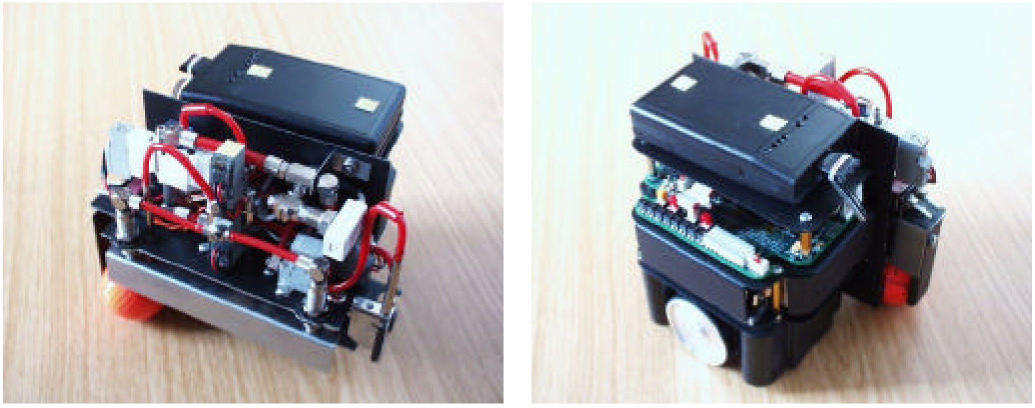
This paper details the design and development of a highly specialised goalkeeping robot for use in the RoboCup small-size league, and its integration into the Cambridge University Robot Football Team (RFT). The goalkeeper described is novel in its shape, in its use of CO_2 as a power source, and in its ability to actually catch the ball and subsequently 'kick' it out at high speed. The last of these attributes also means that the goalkeeper has to coordinate with the rest of the team much more than it would otherwise have to.

The Cambridge RFT came top of their group and subsequently fourth overall in the Paris 1998 RoboCup small-size league. In the later stages of the competition the goalkeeper proved highly valuable, and enabled extended periods of play. Although it is difficult to provide empirical data to show the skill of a given team, or the effectiveness of its individual players, descriptions of the goalkeeper in use in a penalty shoot-out, and whilst in play against the CMU '98 team in the semi-final are provided.

1. Motivation

The Laboratory for Communications Engineering at the Cambridge University Engineering Department is interested in a number of technologies related to sensing and control, in addition to networking and communications. For this reason, RoboCup provides an ideal test-bed for the work of the Laboratory. RoboCup '98, Paris, was the first competition for the Cambridge RFT[4]; indeed, work on the team only started at the end of 1997. Therefore, effort was concentrated on building a basic football-playing team onto which further developments could be made. Some ideas for future modifications are given in Section 6.

Despite the tight schedule for building a working team of robots, an additional aim was to introduce some novelty. The authors decided that the goalkeeper was a good candidate for innovation – most goalkeepers are rectangular 'boxes' which simply block shots to goal, moving from side-to-side in front of the goal. (In fact, some are *only* capable of moving from side-to-side.) As an alternative to this approach, a goalkeeper which can actually capture the ball (hence removing it from play), and then 'kick' it out at high speed was conceived. Given the constraints of the rules, building such a robot turns out to be quite an engineering challenge, and integrating it with the rest of the team raises some interesting problems. However, one advantage of choosing a particular player as a candidate for trying out new ideas was that it could be developed separately from the rest of the system, and if it had been unsuccessful, a 'regular' player could have been used in its place.



(a) (b)

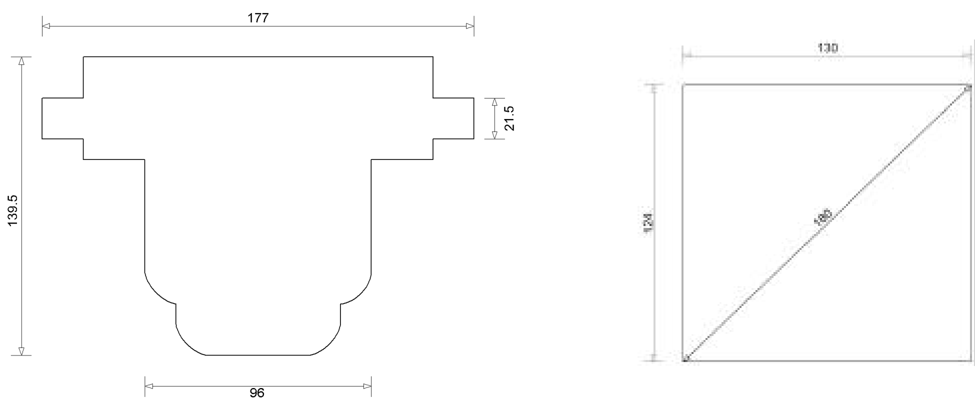
Figure 1 Photographs of the Cambridge RFT goalkeeper. (a) Front view showing the pneumatic subsystem which makes up most of the front section. The end gate pin is clearly visible at the right-hand end. (b) Rear view, showing the battery compartments to either side of the wheels, the main PCB and the Piconet radio unit (at the top).

2. The design of the Cambridge RFT goalkeeper

2.1 Layout of the robot

The goalkeeper robot has a roughly 'T-shaped' appearance from above (Figure 2(a)). This design was chosen in preference to a more straightforward rectangular shape because it allows the keeper to block very nearly 18 cm of the goal whilst still maintaining a maximum dimension of 18 cm and a maximum area of 180 square cm. In comparison, a square or rectangular shape only presents up to around 13 cm if nearly all of the allowable area is to be used (Figure 2(b)). A photograph of our goalkeeper appears in Figure 1.

Functionally, the robot can be divided into two parts. The front section (herewith referred to at the *catcher* section) contains a pneumatically operated gate mechanism for capturing the ball and a pneumatic cylinder for ejecting the ball at velocities of a few metres per second. A small pneumatic pin cylinder is also used to position the ball within the robot once it has been captured. The operation of this section is described in more detail in Section 2.2 below.



(a) (b)

Figure 2 (a) Plan view of the Cambridge RFT goalkeeper. (b) Comparison with a rectangular shape with maximum diagonal length and near maximum area. Dimensions in mm.

The rear, *motor* section houses the motors, electronics and power sources (batteries and a regulated CO_2 system) used by the robot. Two stepper motors are used to drive the robot and two pairs of PTFE skids provide low friction supports. The robot is controlled by two micro-controllers (Microchip PIC 16C73A). One of the micro-controllers is dedicated to driving both stepper motors while the other is responsible for controlling all the pneumatic operations associated with ball capturing and firing.

2.2 Communications

The goalkeeper, like the other players, is equipped with a Piconet node[2] for radio communications. Developed by ORL, Piconet is designed for low power, low bandwidth embedded networking, and as such is quite suitable for RoboCup. It can be used to provide a robust, bidirectional 9600 baud serial communications link with error detection and recovery. Although the player robots only require unidirectional communication, the goalkeeper uses the back channel to inform the rest of the system system when it has captured, loaded and subsequently fired the ball.

2.3 Power sources

The power for the motors and the electronics is supplied by a number of lithium manganese dioxide primary cells, which were chosen because of their high energy density (both in terms of mass and volume). The motors and solenoids are powered by a separate battery system from the control electronics, in order to minimise any supply line noise. In addition, the former is smoothed with an LC filter. The Piconet node uses its own internal battery.

One of the more novel features of the robot worth mentioning in further detail is the compressed $C0_2$ regulated supply. This uses a disposable canister containing 16g of liquid CO_2 (approximately 60 bar or 840psi at room temperature[3]) followed by two stages of regulation resulting in outlet pressures of approximately 10 and 5 bar. The higher pressure outlet is used for the main firing cylinder where it is important to generate the maximum possible force. The lower pressure line is used to energise the smaller cylinders (for ball capturing and breeching) – here it is more important to conserve gas at the expense of slightly slower actuation. The pneumatic system has enough capacity for up to around 50 ‘load and fire’ cycles.

2.4 Catching, loading and firing the ball

Figure 2 shows a side view of the ball capturing process. An array of infrared (IR) sensors is positioned across the capture area (Figure 3(a)). These sensors have been set such that they trigger when more than 50% of the ball enters into the capture area. One of the micro-controllers is used to constantly monitor the state of all IR sensors. When the ball rolls into the capture zone (Figure 3(b)), one or more of the IR sensors is triggered and the micro-controller immediately reacts to close the main gate and the exit gate, thereby capturing the ball within the robot.

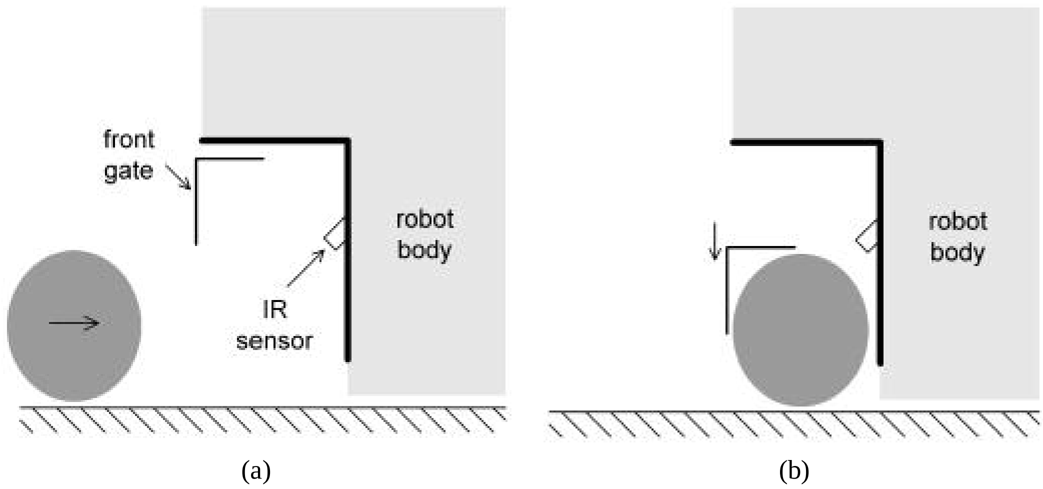


Figure 3 Side view of the ball capturing process. (a) The ball approaches the open gate. (b) The ball enters the catchment area, thereby triggering the IR sensors and consequently causing the front gate to close.

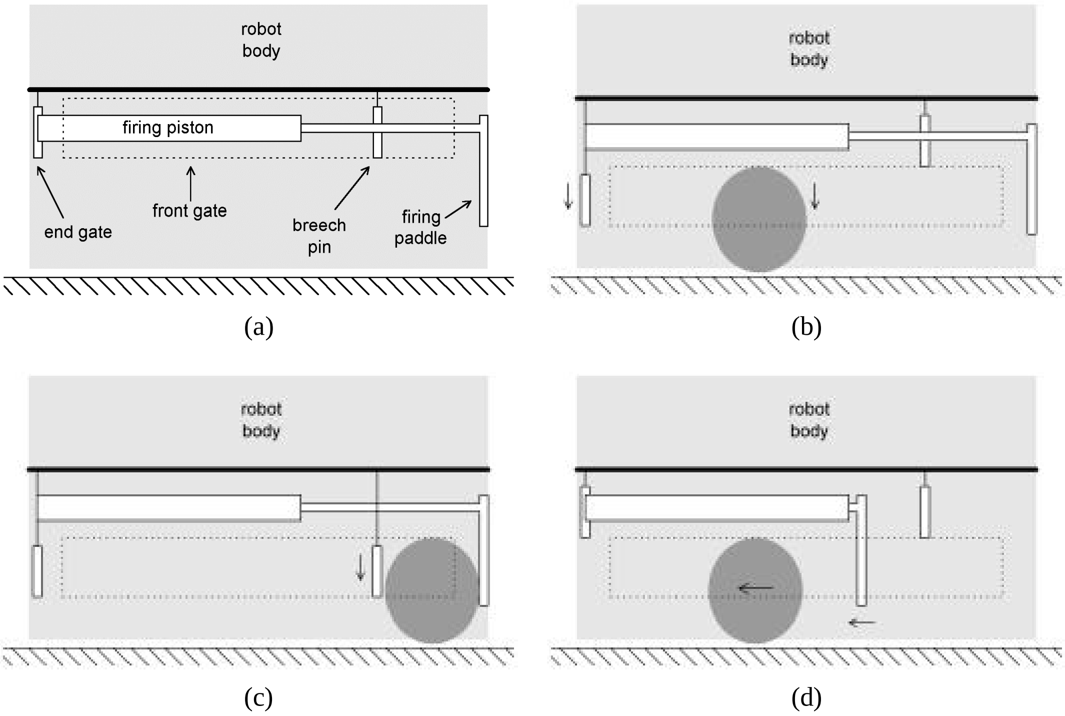


Figure 4 The ball loading and firing process. (a) The position of the various actuators when the keeper is defending, ready to catch the ball. The gate is shown only in outline (the dashed line), so as not to obscure the diagram. (b) As the ball enters the catchment area, the gate comes down thereby trapping it. At the same time the end gate closes to prevent the ball escaping to the left. (c) The robot moves to the left (from the reader's point of view), thus forcing the ball to move to the right-hand end relatively, and the breech pin closes to hold it in place. (d) When the keeper rotated through 90º and then aimed, the end gate and the breech pin are released, and the main cylinder pulls the paddle to the left, thereby firing the ball out into the pitch.

After catching the ball, the robot moves to one side, thereby forcing the ball towards the paddle (a move of about 10-15cm was shown to be sufficient in practice). Once the ball is detected in front of the paddle a small pneumatic pin (called the breech pin) is activated which holds the ball in this position until the command to shoot is received. Without a breech pin, it is possible for the ball to move away from the paddle if there is any delay before firing (e.g. when aiming) – this will result in low ball velocities or in the worst case a complete misfire (i.e. the ball remains inside the robot after firing).

The command to fire is given over the radio system, and causes the breech pin and the exit gate to deactivate and the main piston to be pressurised to 10 bar. The ball is thereby accelerated along the length of the catcher section and out into the playing field. The firing piston is then retracted ready for the next 'save'. Figure 4 shows the ball loading and firing procedure in more detail.

3. Following the letter of the law

There are a number of rules which are particularly pertinent to the design and use of the goalkeeper. Extracts of these along with a brief elucidation of their relevance to our design are given below. Where the rules are perhaps ambiguous, the different possible interpretations are highlighted. (The extracts are taken from the small-size league rules for RoboCup '98 [1].)

3.1 Size

> *"The total floor area occupied by a robot should not be more than 180 square centimeters, and the maximum length of the body shall not be more than 18 centimeters. Height of the robot, if the team is using a global-vision system is restricted to less than 15 centimeters."*

This rule presents a hard constraint on the size of the robot. There is ambiguity in the 'maximum length' criterion, which we understood to refer to the maximum length of the robot in *any* direction (thereby excluding 10cm by 18cm robots, which have a diagonal of 20.6cm).

To comply with the size rule, we ensured that no part of our goalkeeper robot is more than 180mm from any other part, and the total area occupied by the goalkeeper is just under 18000mm^2. Similarly, the robot is just less than 150mm tall. We are *very* close to these limits.

3.2 Holding the ball

There are a number of rules relating to holding of the ball by the goalkeeper – these are all replicated here. Note that we assume that the 'penalty area' and the 'defense zone' are one and the same.

> *"A player cannot 'hold' a ball unless it is a goal keeper in its penalty area. Holding a ball means taking a full control of the ball by removing its entire degrees of freedom; typically, fixing a ball to the body or surrounding a ball using the body to prevent accesses by others."*
>
> *"The goal keeper can hold and manipulate a ball for up to 10 seconds within its penalty area."*
>
> *"If a robot is deemed to be holding the ball then a free kick will be declared. If this happens in the defense zone by the defense team, a penalty kick will be declared."*
>
> *"Given the size of the defense zone a robot is said to be in the defense zone if any part of it is within the area."*

There was some disagreement over the interpretation of 'hold and manipulate'; we had assumed it would be perfectly acceptable to take the ball into the body of the goalkeeper (hence removing it from view, similar to a human goalkeeper pulling the ball into his chest when making a save). However, many of our opponents needed to be able to see the ball at all times, and had assumed that holding the ball did not prevent this. In the spirit of friendly competition, we made every effort to make sure that the ball could be seen at all times (even when captured by the goalkeeper), by modifying our front gate mechanism for play against teams which were concerned about this.

There is also ambiguity concerning whether it is legal for the goalkeeper to be holding the ball whilst the robot itself is within the penalty area (i.e. some part of it is) but the ball is outside the area. Keeping the robot (and possibly the ball) within the penalty area is potentially quite challenging, especially for a large robot – the area is only 22½ cm deep, whilst the goalkeeper may be up to 18cm across in places. However, if this rule is broken, a free kick is declared (robot holding the ball outside the defence zone).

3.3 Backing off

> *"Once a defending robot (goal keeper) has hold of the ball or is facing and in contact with the ball then the attacking robot must leave the area. The attacking robot can not interfere with the goal keeper."*

With a goalkeeper which actually 'swallows' the ball into its body, it is important that the opposition backs off – otherwise it may not even be possible to expel the ball. The more the attacker does back off, the better the chance the goalkeeper has of kicking the ball out past it (and hence avoiding a rebound back towards the goal).

3.4 Futsal rule

> *"If the ball is released by the keeper and it reaches the half way line of without touching any other robots, the opponent is given an indirect free kick positioned anywhere along the half way line (borrowed from Futsal rule)."*

As outlined in the next section, we make every effort to ensure that the ball does hit a player before passing over the half-way line. However, we consider the risk of not meeting this criterion (an indirect free kick) to be worthwhile.

4. Integration with the rest of the team

With a fairly sophisticated robot player such as the Cambridge RFT goalkeeper, integration with the rest of the team becomes a critical issue. Although the goalkeeper hardware was developed in isolation from the rest of the system, in order to be able to make good use of its functionality, coordination of the keeper with the other players is central. This section describes the behaviour of the goalkeeper and the rest of the team as the ball approaches the goal.

4.1 Goal tending during normal play

The goalkeeper's behaviour during normal play is similar to that of the defenders – it simply moves from side to side, trying always to lie on the path between the ball's current position and the goal. At the two ends of the goal mouth, the keeper rotates to face the ball if necessary.

4.2 Capturing the ball

If the ball passes through the defence, hopefully the goalkeeper will have had enough time to position itself correctly, and the ball will roll into the catcher section. As this happens, the IR sensors trigger the front gate to close, and at the same time a message is sent over the radio to flag this event. The keeper is then commanded to move in such a way as to force the loading of the ball (see Section 2.4) without leaving the penalty area. Whilst the ball is being loaded, the defender robots are moved to the edges of the pitch, and are rotated so that their sides are suitably oriented to allow deflection of the ball down the pitch. (A deflection in this way provides compliance with the Futsal rule, Section 3.4.)

4.3 Aiming and firing the ball

When the ball is loaded, a second message is sent over the radio to indicate that the goalkeeper is ready to fire. At this point, the keeper is rotated so that the line of fire (which is parallel with the front of the robot) is aligned with one of the two defenders (whichever appears to have the best chance of a successful deflection). If necessary, the goalkeeper will move laterally within the penalty area before aiming, in order to improve the chance of a successful pass. Of course, it is very difficult to account for sudden movements of the opposition during this process, and it is always possible that the ball will actually hit one of the opponent's attackers before reaching the selected defender. In this case it is difficult to predict where the ball will end up, and it may even come straight back towards the goal, before the goalkeeper has had time to prepare. Another problem is the ten second holding rule, which means that it may be necessary to abandon accurate aiming and just fire the ball quickly, if time is running out. If no suitable path to a defender appears to exist, the keeper simply aims at the side wall midway between the goal line and the half-way line, in an effort to rebound the ball across the pitch and hopefully hit a player before passing over the half-way line.

After the keeper has been aimed, the ball is fired out, and the goalkeeper and defenders return to their 'in play' home positions

5. Success in play

In the small-size league competition at RoboCup '98, Paris, the Cambridge University RFT finished top of their group and then came fourth overall in the subsequent knock-out rounds. There were several factors that contributed to the team's successful performance, and one of these was the use of the highly specialised goalkeeper robot described above, and its ability to remove the ball from play and subsequently eject it out of the defence zone into the opponent's half of the pitch. The combination of our goalkeeper and two of our standard player robots acting as defenders gave us a particularly effective defence.

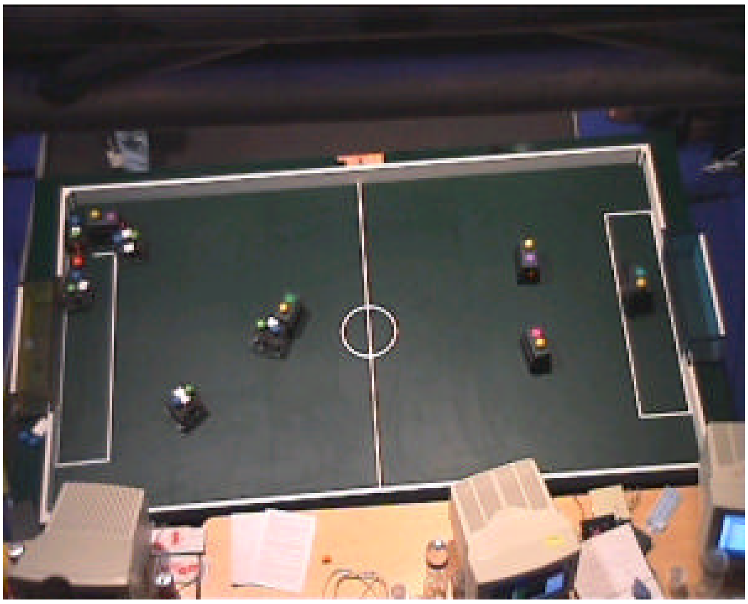


Figure 5 An example of the ball (at the top of the left-hand goal) being trapped between the goalkeeper and a number of players. Such stalemate situations were quite common in RoboCup '98, Paris, and they almost invariably result in a 'free ball' being declared.

Paris '98 was our first foray into robot football. Due to this lack of experience in RoboCup matches, in addition to the experimental nature of our goalkeeper, we thought it prudent not to use the full functionality of the goalkeeper until any teething problems with the rest of the team were ironed out. (If the goalkeeper isn't aiming correctly, for example, an 'own goal' can be scored very easily!) In practice, this meant that we didn't try to capture and fire the ball until the group matches were complete.

However, during the knockout part of the competition, we made full use of the goalkeeper's potential. Being able to actually remove the ball from play, and then fire it up the pitch, into the opposition's half is potentially a big advantage; our team was certainly unique in its ability to do this. In practice, what frequently happened with other teams was that the ball would get trapped between a 'crowd' of several players and the goalkeeper (and possibly the wall) following an attacking play by one team (see Figure 5). This deadlock invariably resulted in a 'free ball' on the half-way line, which also has the effect of getting the ball away from the goal area. Whilst our goalkeeper can potentially get the ball right down the other end of the pitch (i.e. well past the half-way line), it also runs the risk of an unwanted deflection and a quick goal for the opposition.

In play against teams where ball crowding was less common, extended periods of play occurred. In our semi-final match against CMU '98 we witnessed two minutes of continuous end-to-end play, which included the goalkeeper removing the ball from the penalty area following shots on goal and firing it up the pitch (via a deflection from one of our defenders) twice. Figure 6 depicts a sequence of stills from the video footage of this match, which show the ball being caught, the keeper loading the ball, the defenders positioning themselves and the ball being fired up the pitch. In other matches 60 seconds of continuous play was considered exceptional, and our goalkeeper was certainly a big factor in extending the play in our matches.

Our goalkeeper was also successful in the penalty shoot-out we were involved in (against the Belgian team in the quarter final). Although this scenario was completely un-rehearsed (it is not mentioned in the rules), we were simply able to place our system into its standard play mode, whereupon the goalkeeper moved smartly to intercept the ball as it approached the goal. Despite the large mass of the robot (around 2½kg), it was able to respond quickly enough to prevent the goal. By actively catching the ball, the risk of any rebound into the goal is minimised. A sequence of stills from the video of one of the penalties is shown in Figure 7.

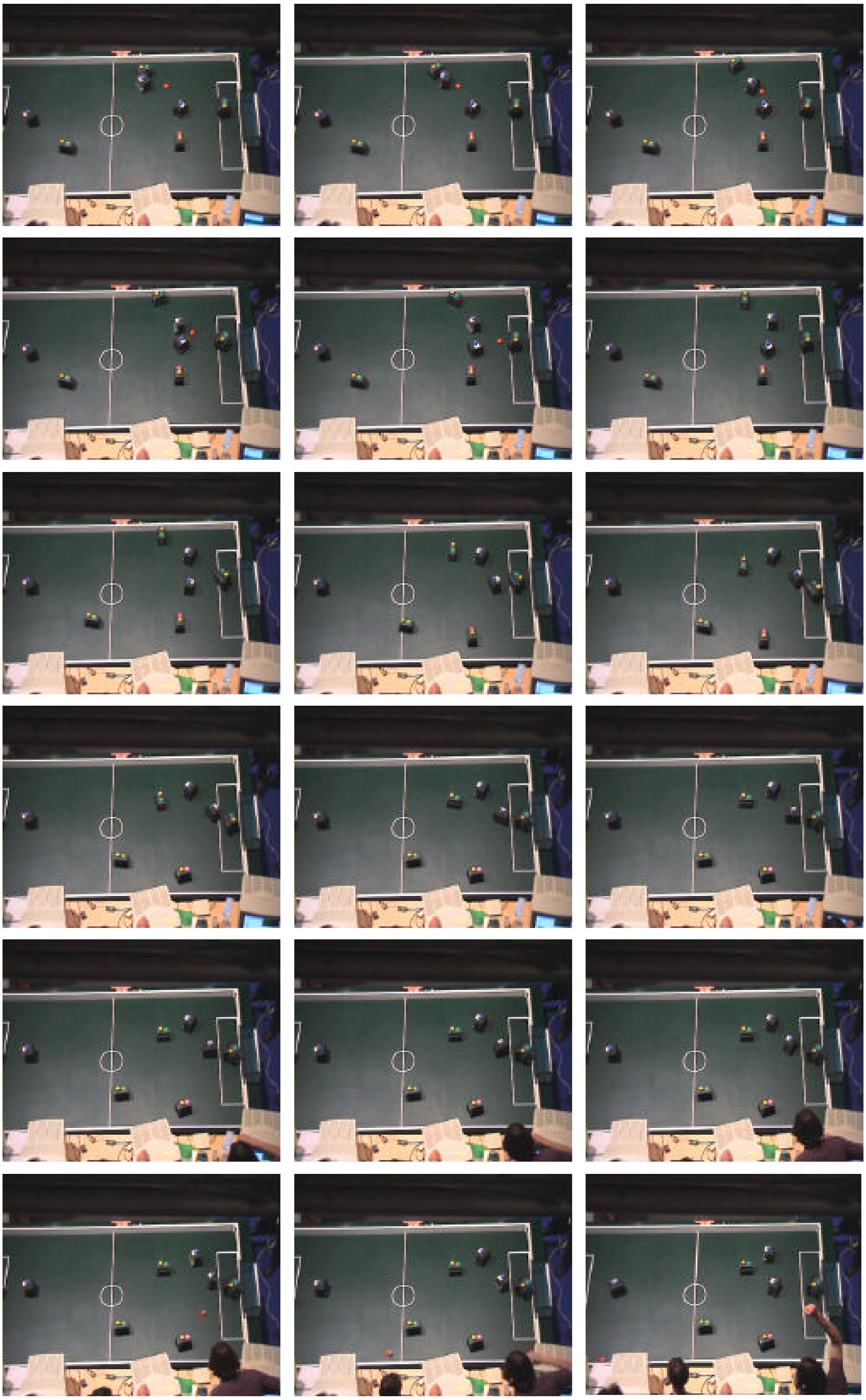


Figure 6 A sequence of stills from the video footage of the Cambridge vs. CMU semi-final at RoboCup '98, Paris. The sequence runs from left to right, and then top to bottom. The ball is initially towards to the top of the pitch, in the centre of the right-hand half as viewed in the images. The CMU shot on goal essentially happens in frame 3 (top right), and the goalkeeper catches the ball in frame 6. The ball is then out of play as the keeper moves along the face of the goal and aims the goal kick (fine tuning the aim occurs in frames 11 to 15). During this time the defender in the bottom of the image positions itself ready for a deflection from the forthcoming goal kick. The last three frames (16 to 18) show the ball being fired out towards the defender, rebounding down the pitch (frame 17), and out of view (the ball is just visible in the bottom left of frame 18). The frames are all taken at ½ second intervals; as can be seen the ball is held by the keeper for just five seconds, well within the ten second limit (Section 5).

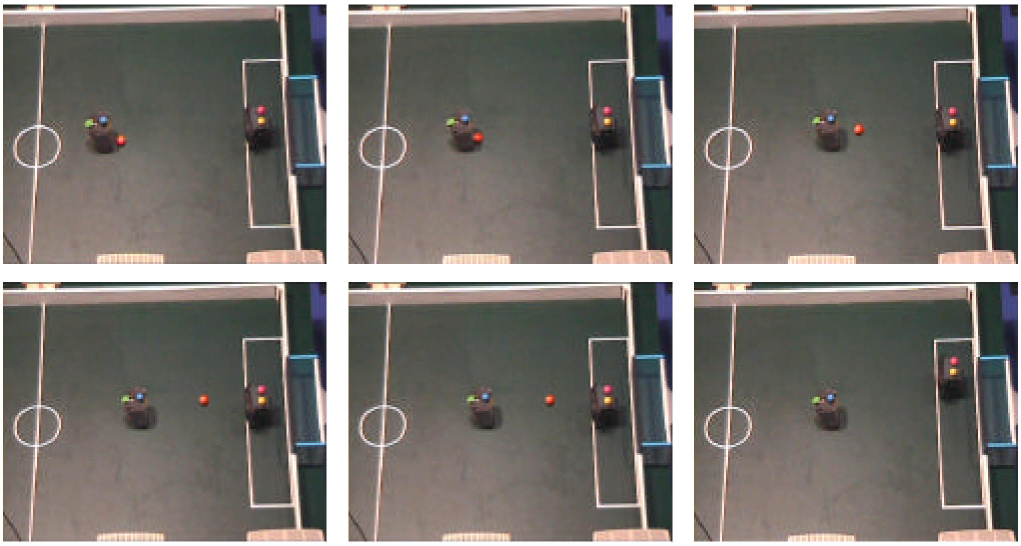


Figure 7 A sequence of stills from the video footage of the penalty shoot-out following a 1-1 draw in the Cambridge vs. Belgium quarter-final at RoboCup '98, Paris. The sequence runs from left to right, and then top to bottom. The Belgian robot shoots to the left-hand side of the goal (from its perspective), and the goalkeeper moves to make the save (and remove the ball from play) as soon as the path of the ball has been predicted. The frames are all taken at ½ second intervals.

6. Closing observations and comments

We lost our semi-final against CMU '98 3-0, and the subsequent 3rd/4th place play-off against Portugal 1-0. This was due to several reasons, but primarily because we need to strengthen our attacking play, by both using faster player robots and improving our strategy. One of the difficulties we encountered was the problem of deadlock due to crowding of the ball – we feel that it would be beneficial to alter the rules to try and eliminate this as much as possible. This would encourage more flowing play, thereby favouring our approach more. Another problem is the possibility of the rebound from a goal kick coming straight back towards the keeper; there will always be a chance that this will happen, but with more sophisticated planning it should be possible to further reduce the incidence of unwanted deflections.

In Paris '98, many of the teams had custom goalkeepers, but in most cases these were basically a standard player robot with mechanical modifications to maximise their blocking ability. We believe that making our goalkeeper completely different to our players prevented us form making any design compromises for either platform, and thereby made our play stronger. In the future, we expect that teams may experiment more with heterogeneous players with various specialisations (e.g. attacker, defender, pass receiver etc.). Also, many of the goalkeepers in Paris '98 relied on the feedback of physical contact with the bar of the goal and the walls to the side of the goal to maintain their position on the goal line. Our keeper used purely visual feedback to maintain its position.

It will probably be apparent from the description given in this paper, that the design and integration of the goalkeeper was approached as a largely engineering problem. The authors feel that this is the most practical approach; whilst 'intelligent behaviour' is needed, the most effective way to produce this is by encapsulating as much 'human intelligence' as possible into the design and programming of the system. In turn, it is inevitable that as the sophistication of systems increases, the robots are increasingly engineered to be just within the limits of the rules. This makes it very important to have a clear and concise definition of what is and isn't allowable, so that innovations can be introduced without any contention.

The Cambridge RFT aims to continue to innovate in its use of technology and engineering in RoboCup. Having experimented with the goalkeeper, other aspects of the team (such as detecting the position of the players or looking at how much intelligence to distribute into each robot) are likely candidates for future experimentation. We were very pleased to make it to the semi-finals in RoboCup Paris '98, and hence finish in the top four. However, as explained earlier, our primary motivation was to innovate rather than simply to win, and we feel we were doubly successful in this respect.

Acknowledgements

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