An Innovative Approach to Vision, Localization and Orientation Using Omnidirectional Radial Signature Analysis

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The greatest risk of innovative design is that it may not prove successful. That does not mean, by any account, that it should not be tried. Nor does it make the idea irrelevant. What is important is that those that follow are made aware of the problems encountered. The Omnidirectional Radial Signature Analysis Network (ORSAN) was an attempt to overcome the problems associated with the Robocup environment that were evident at RoboCup 97. In particular, lighting inconsistencies and a steering problem with the Omnidirectional Ball Based Driving Mechanism developed by this team and presented at Robocup 97. Through a series of difficulties and setbacks following the successful Nagoya event, only 16 weeks were available to produce an entire team of robots for Paris. In the end, only the prototype was ready, and so the Deakin Black Knights attempt at Robocup-98 was really over before it began. This paper details the development of the Omnidirectional Radial Signature Analysis Network, the problems it was designed to solve and the eventual conclusions that were drawn about this innovative approach to Robocup 98.

Introduction

The Omnidirectional Radial Signature Analysis Network, or ORSAN, began as an idea to solve three major problems that were evident in our previous team that competed in the first Robocup competition in Nagoya (Price 1997). The omnidirectional ball based driving mechanism exhibited at Robocup 97 had a steering problem that was exacerbated by the soft carpet of the arena. At the time, the mechanism was not equipped with any form of orientation stabilizer such as a compass. Compass modules were available, but trials before Japan revealed that these modules were severely affected by the magnetic fields of nearby motors as well as the presence of ferrous metals anywhere in the vicinity of the robot. As a result they were of little value in the Robocup environment. During Robocup 97 the importance of directional control on the omnidirectional chassis was demonstrated, and it was clear that an alternative to magnetic compasses had to be found.

M. Asada and H. Kitano (Eds.): RoboCup-98, LNAI 1604, pp. 299-315, 1999.

The most notable problem that was experienced by all teams in Nagoya was the variation in lighting across the field. At the time, we had only a relatively simple RGB based color recognition system that was able to distinguish only a few very distinct colors with any great assurance. The most significant problem however was caused by the fact that we were using an overhead vision system that was configured to observe the entire field at one time.

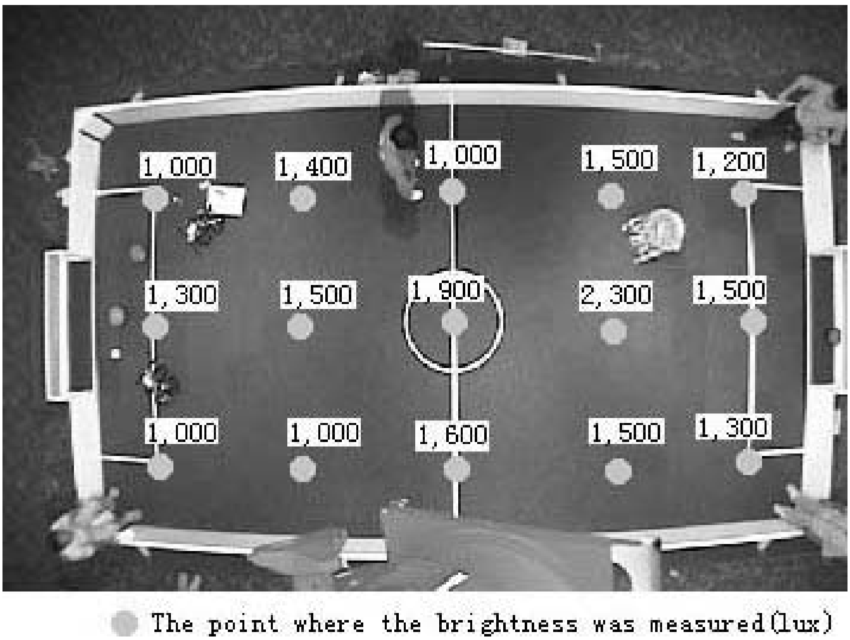

Fig. 1. Variation in lighting intensity at RoboCup 97

Because of the automatic image enhancement of the camera that was used, it was impossible to adjust the vision system to cope with the significant change in lighting intensity across the surface. As a result, when the camera was adjusted for the darker areas (the goals), the brighter areas appeared white. When the camera was adjusted for the lighter areas (down the centre) the darker areas appeared black. Although the steering problem could be corrected to some degree due to the start stop nature of the competition, the change in lighting meant that only 30% of the field was observable at any one time. This created a serious problem. For these reasons, ORSAN was developed. In keeping with this team's ideals on innovative design, we were aware that ORSAN might not be competitive. The significance of examining an alternative approach to vision, that could not only identify surrounding objects without the use of color but also perform self orientation and localization and do it affordably far outweighed the risk.

Vision in an Adversarial Environment

A significant amount of research effort has gone into producing vision systems that can cope with complex environments and difficult conditions (Shoji Suzuki 1997). Many approaches rely on existing camera technology and ‘off the shelf’ hardware (Shen 1997). While many of these systems are very highly competitive, the abundance of design and construction skills available at Deakin University prompted the notion that some improvement in vision might be possible through new and innovative vision hardware.

Examination of the RoboCup environment leads to an interesting set of characteristics that make an alternative approach to vision and orientation possible.

1. The shape of the environment (walls and boundaries, center markings) is known and constant
2. The shape of the ball is known and constant (and also constant in three dimensions)
3. The shape and position of the goals are constant
4. The shape and position of corners are constant.
5. The shape of one team (our own) is known
6. The shape of the opposition team is unknown (other than basic dimensions as per the rules)

There is only one unknown in the environment, the shape of the opposition robots. Opposition robots may thus be deduced, since any object that is not identified by its shape as being one of the known signatures must be the opposition. Actual physical shape is unaffected by color or various effects due to lighting differences, and no artificial markings are required.

The premise of our new vision system is that each component of the RoboCup environment possesses a unique physical characteristic or signature.

ORSAN: Omnidirectional Radial Signature Analysis Network

ORSAN is a shape based vision system that detects and identifies the unique signatures generated by objects within the RoboCup environment when a pattern of concentric circles of laser light is deflected by the object

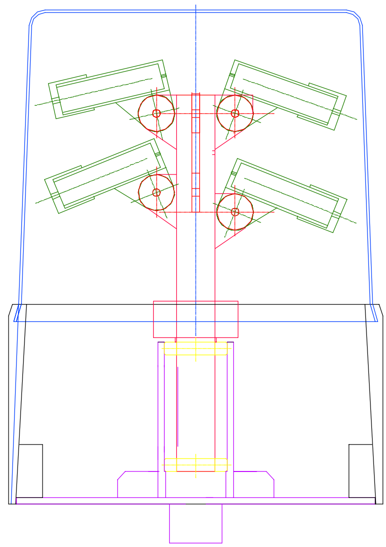

Fig. 2. The ORSAN module

Figure 2 shows the fundamental component of ORSAN: a compact module that generates concentric circles of laser light. This module is mounted centrally on top of the robot so that the circle pattern is generated on the surrounding floor to a distance up to one metre. In practice however the greater the radius, the more powerful the light source required. A distance of 1m is achievable using low cost 1mW laser modules.

Though linear laser striping is fairly common (Liu 1997), ORSAN is a truly omnidirectional image system. At present, speeds of up to 25 frames per second may be analyzed. The limiting factor is the speed of the detector system.

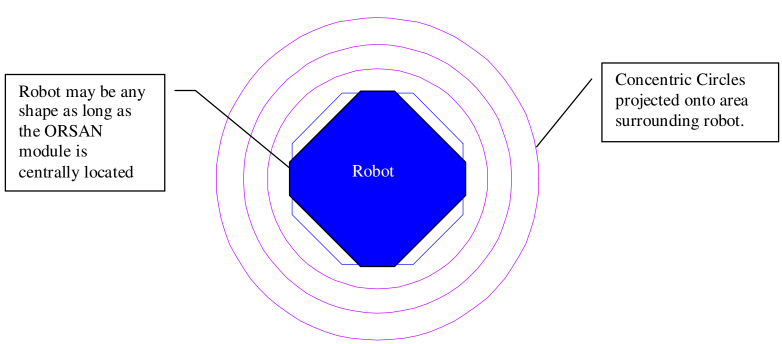

Fig. 3. Robot surrounded by concentric circles of light

The second component of ORSAN is the detector system that is located centrally, directly above the laser module as shown below. At present, the detector is a monochrome CCD camera that has been modified with a wide-angle lens and filtered to accept the red spectrum above 520nm.

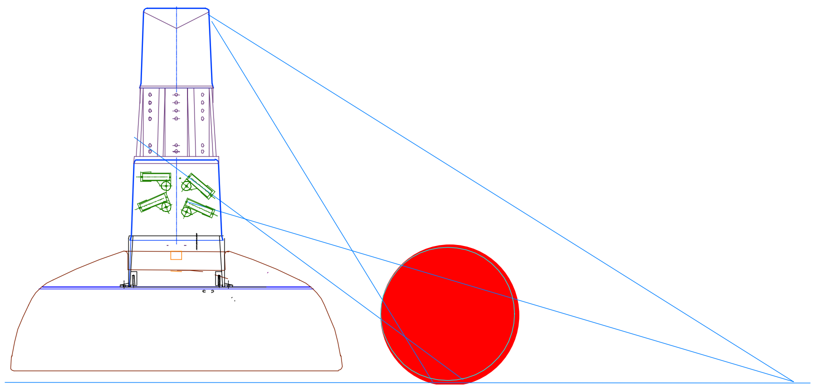

Fig. 4. Robot Chassis complete with ORSAN

Spinning the lasers using a specially designed rotating turret (Figure 2) generates circles. The diameter of each circle may be adjusted such that any combination of circles can be generated within the physical limitations of the light source.
Under normal conditions, when the robot is completely alone on a flat space, the detector records the presence of concentric circles and hence no obstacles present. However when an obstacle, such as the ball, enters the range of the vision system, part of the circle pattern is deflected or obscured. In either case the result is the same. When the detector system scans the circles, it notes that part of the circle is effectively missing. This missing part forms a chord. Multiple chords missing from adjacent circles form a signature. In the RoboCup environment the signatures are unique for each entity. By analysis of the chords an accurate identification and position of each object is obtained.

Figure 5 shows the information that is returned to the sensor. When no obstacles are present unbroken circles are returned. However when the ball is within the circle pattern the circles are deflected or obscured by the curvature. Detection of the difference is achieved by scanning points that make up the regular circles. Only points along the circle are scanned and the ends of each missing cord are identified.

Fig. 5. The chords produced by the RoboCup ball.

Starting with chords from the inner most circle, the following algorithm is applied:

1. Obtain tangent to the chord, (i.e. a line from the centre of the circle perpendicular to the chord)
2. Record the tangent angle.
3. Apply rules for each of the known entities within the environment.
4. If the chord pattern matches, identify object and location based on further rules
5. If the chord pattern does not match, assign contact as hostile robot (given no other unknowns)

Each circle is independent, and does not necessarily have to be equally spaced. This does not affect the complexity of analysis, since the mathematics behind signature recognition is independent of the relationship between two circles. In order to recognize a signature however the object must deflect a minimum of two consecutive concentric circles. One circle does not provide enough information to reliably distinguish objects although it can provide a crude measure of range and baring. The general algorithm of signature analysis is as follows:

If a cord exists on a Circle C_1 of Radius R_1 at an angle of $\square_1$, and a Cord exists on a Circle C_2 of Radius R_2 at angle $\square_2$ then an object exists at X, Y.

Figure 6 shows the relationships between cords and entities within the RoboCup environment.

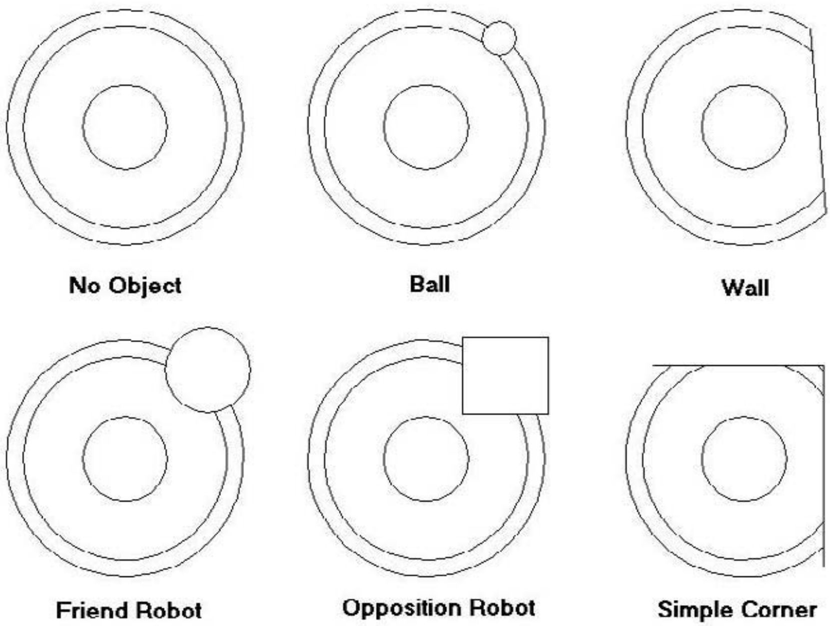

Fig. 6. Characteristic signatures generated by ORSAN

Processing the signatures

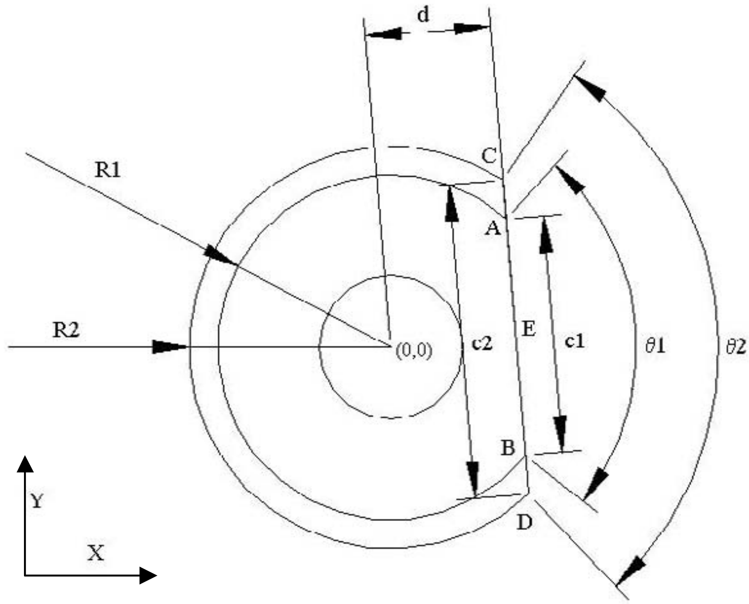

Fig. 7. **Signature diagram for a flat wall or surface**

Since each of the signatures produced are both dynamic and unique it is necessary to establish the relationship between the chords of the circle and the object for each type of object. The simplest example is the flat surface or wall. In this case, two chords should exist whose distance d, from the origin is equal and whose normals O,E are at equivalent angles. For two cords to exist in two independent circles in such a manner, it is probable that they were both deflected by a flat surface

The distance d, is expressed by:

$$d = R\cos(\frac{1}{2}\theta) \qquad \textbf{(1)}$$

if the distance d, is the same for chords of circles with radii R_1 and R_2 then:

$$R_1\cos(\frac{1}{2}\theta_1) = R_2\cos(\frac{1}{2}\theta_2) \qquad \textbf{(2)}$$

d is the distance OE in the right angle triangle OEA. The length of the chord C_1 is the distance AB. In Cartesian form this is the distance between the points (x_A,y_A) and (x_B,y_B) which are the coordinates of the endpoints of the chord AB relative to the Origin O of the circle, hence:

$$C_1 = \sqrt{\left(\left|x_A - x_B\right|\right)^2 + \left(\left|y_A - y_B\right|\right)^2} \tag{3}$$

the distance d may be expressed:

$$d = \sqrt{R_1^{\,2} - \left(\frac{\sqrt{\left(\left|x_A - x_B\right|\right)^2 + \left(\left|y_A - y_B\right|\right)^2}}{2}\right)^2} \tag{4}$$

Equation 2 may therefore be expressed in terms of the coordinates of the endpoints of the chords.

$$\sqrt{R_1^{\,2} - \left(\frac{\sqrt{\left(\left|x_A - x_B\right|\right)^2 + \left(\left|y_A - y_B\right|\right)^2}}{2}\right)^2} = \sqrt{R_2^{\,2} - \left(\frac{\sqrt{\left(\left|x_C - x_D\right|\right)^2 + \left(\left|y_C - y_D\right|\right)^2}}{2}\right)^2} \tag{5}$$

From the captured image, data pertaining to the end points of the chords is acquired in Cartesian form, therefore Equation 5 does not require conversion of the data from its natural form.

If the condition of Equation 5 is met, then two chords of acceptable length exist in circles of radius R_1 and R_2. It is possible, however unlikely that the two chords are unrelated by angle. Therefore it is necessary to test the angular relationship of two chords also.

The normal to the chord OE, may be expressed as the line between the points $(0,0)$ and (x_E,y_E). Therefore:

$$x_E = \frac{x_A + x_B}{2} \qquad y_E = \frac{y_A + y_B}{2} \tag{6}$$

If the angles of the normals are the same then the angle of the line OE and OE' will be identical, hence:

$$\tan^{-1}\left(\frac{y_A + y_B}{x_A + x_B}\right) = \tan^{-1}\left(\frac{y_C + y_D}{x_C + x_D}\right) \tag{7}$$

The angles of equation 7 are in the first quadrant and must be compensated for other quadrants based on the sign of each denominator and numerator.

Thus for two concentric circles a relationship exists such that:

If the distance d, from the centre of the circles to the midpoint of each chord is the same and the angle to the normal of each chord, □ is the same, then there is a high probability that the circles are being deflected by a flat wall at distance d, angle □.

A more complex and dynamic example is that of a cylinder, or cylindrical shaped robot, such as the omnidirectional ball based driving mechanism (Price 1998).

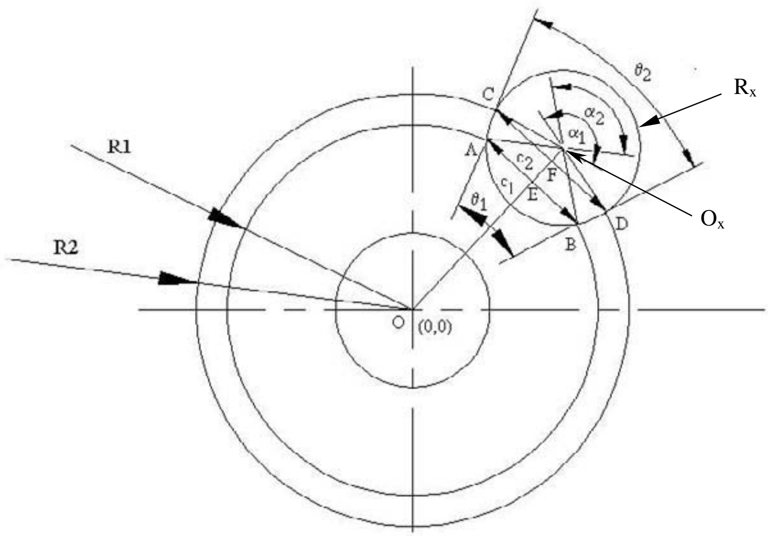

Fig. 8. Signature diagram for a cylindrical object

When the cylinder deflects the circles, two chords are generated as before. In the case of a cylindrical object the distance d, from the origin O, to the midpoint of each chord E, and F respectively, is different, however both chords remain symmetrical about a common radius.

Given that a chord of length C_1 exists in the inner circle, it is necessary to examine all the chords that may exist in the outer circle to see if one of length C_2 exists at the same angle as C_1. This necessitates predicting the length C_2 based on data obtained from C_1, and then comparing this prediction with all the chords in the outer circle to find a potential match.

From Figure 8 it can be seen that:

$$OE + EO_x = OF + O_x F \tag{8}$$

from the equation for the length of a chord it can be shown that:

$$C_2 = 2\sqrt{R_2{}^2 - OF^2} = 2\sqrt{R_x{}^2 - O_xF^2} \quad \textbf{(9)}$$

$$R_2{}^2 - OF^2 = R_x{}^2 - O_xF^2 \quad \textbf{(10)}$$

$$O_xF = \sqrt{R_x{}^2 - R_2{}^2 + OF^2} \quad \textbf{(11)}$$

Combining equations 8 and 11 yields:

$$OE + EO_x = OF + \sqrt{R_x{}^2 - R_2{}^2 + OF^2} \quad \textbf{(12)}$$

$$(OE + EO_x - OF)^2 = R_x{}^2 - R_2{}^2 + OF^2 \quad \textbf{(13)}$$

Let $X^2 = R_x{}^2 - R_2{}^2$ and $Y = OE + EO_x$

Then:

$$(Y - OF)^2 = X^2 + OF^2 \quad \textbf{(14)}$$

$$Y^2 - 2YOF + OF^2 = X^2 + OF^2 \quad \textbf{(15)}$$

$$\frac{Y^2 - X^2}{2Y} = OF \quad \textbf{(16)}$$

Substituting into Equation 9 yields:

$$C_2 = 2\sqrt{R_2{}^2 - OF^2} = 2\sqrt{R_2{}^2 - \left(\frac{Y^2 - X^2}{2Y}\right)^2} \quad \textbf{(17)}$$

Since *X* and *Y* are both in terms of constants or data obtainable from the chord in the inner circle the length of the chord C_2 can be predicted from C_1 if the object impinging on the circles is a cylinder of radius R_x.

Since $Y = OE + EO_x$

$$Y = \sqrt{R_1^{\,2} - \left(\frac{\sqrt{\left(|x_A - x_B|\right)^2 + \left(|y_A - y_B|\right)^2}}{2} \right)^2} + \sqrt{R_x^{\,2} - \left(\frac{\sqrt{\left(|x_A - x_B|\right)^2 + \left(|y_A - y_B|\right)^2}}{2} \right)^2}$$

(18)

Given that a chord of length C_2 exists, its angle must match that of C_1. This may be obtained as per equations 6 and 7 when a chord of suitable length has been found.

Thus a relationship exists such that

If a chord of length C_1, exists on the inner circle and a chord of length C_2 exists on the outer circle and the angle to the normal of each chord, □ is the same, then there is a high probability that the circles are being deflected by a cylindrical object at distance Y, angle □.

Signatures are developed from the inner most laser circle outwards. There are several reasons for this. The most critical region is the space immediately surrounding the robot. The objects that can be determined in this area are of more immediate significance than any other. While more distant objects play a part in planning future motion, knowing if you are holding the ball is of greater value.

Secondly two factors influence the precise shape of the deflections and the visible perception of the deflections. The angle of the laser beam striking the object, and the angle of the camera with respect to both the reflected beam and the object is of significant importance. Signatures are developed from the point of view of the leading surface of the object interfering with the circles. It is quite feasible that the object itself will obscure the view of the camera and the lasers themselves. Signatures may only be detected up to the largest dimension of the object. Beyond that point the actual length of the chords is likely to be obscured. Hence, chords in the smallest diameter circle are examined first and then each circle increasing outwards.

An object such as a sphere creates special problems. Unlike a cylinder a sphere has non-uniform cross section in the vertical plane. Thus a laser beam striking low down on the sphere will actually be obscured from the sensor by the sphere itself.

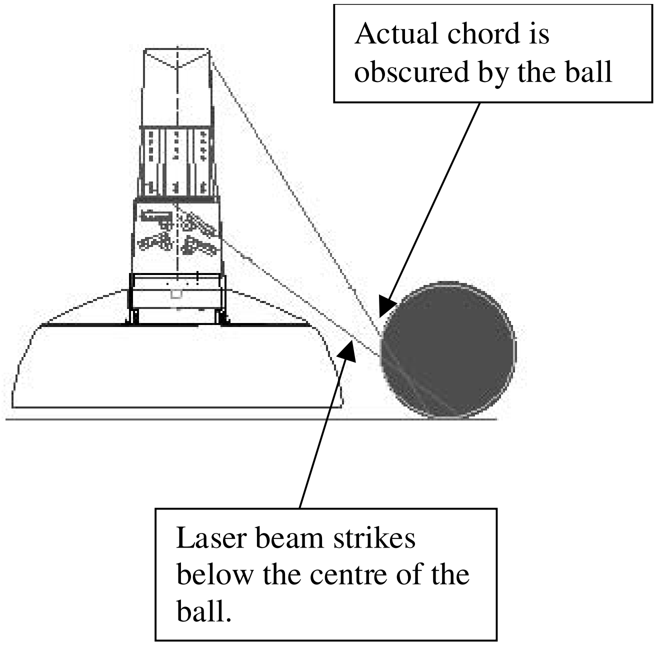

Fig. 9. The curvature of the ball Obscures the true deflection of the laser

The generated chord as perceived by the sensor will not be with respect to the actual point at which the laser strikes the sphere, but to the largest dimension of the sphere. As it happens, this dimension is the diameter of the sphere, and represents a circle in the vertical plane. A sphere may therefore be approximated as a cylinder of radius R_x. Signatures of spheres are thus approximated by cylinders. The important characteristic however is that signatures are significantly unique such that a high degree of certainty is obtained when identifying patterns. Since a sphere, or ball is being approximated by a cylinder the mathematics behind the prediction of each signature is the same. The omnidirectional chassis of the test environment is 400mm in diameter. The standard Robocup ball is 200mm in diameter. While the modelling technique is the same, the results for each object are unique and substantially different:

Suppose a chord of length 100mm is located along the inner circle as shown in figure 10.

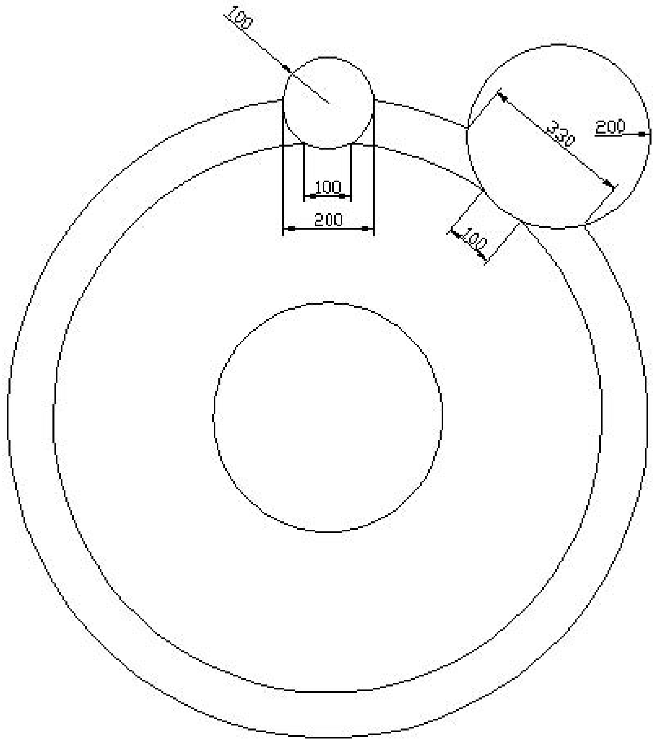

Fig. 10. Comparision of two cylindrical signatures

If the ball caused the chord, a companion chord of approximately 200mm would be expected in the outer circle. If a cylindrical robot caused the chord, a companion chord of approximately 330mm would be expected. The mathematics used in both predictions varies only in the diameters of the impinging objects, however a substantial and measurable difference in the expected signatures exists.

It is evident, that the more complex the shape, the more complex the signature becomes. However as long as there is a relationship between the lengths of chords in two circles and the object, then the object may be classified to some degree. For the test environment of Robot Soccer it has been demonstrated that the ball, friend robots and the walls may all be identified. It is significant however that the shape of the opposition robot is unknown. Given that in the playing area the opposition robots are the only unknown shape, it is possible to deduce their location and identity.

There is a real and limiting factor to the process of signature analysis as evidenced by figure 11. A cube is a shape whose symmetry changes with its orientation. A cube whose face is normal to and bisected by the radius of the circles is symmetrical, as is a cube at 45 degrees.

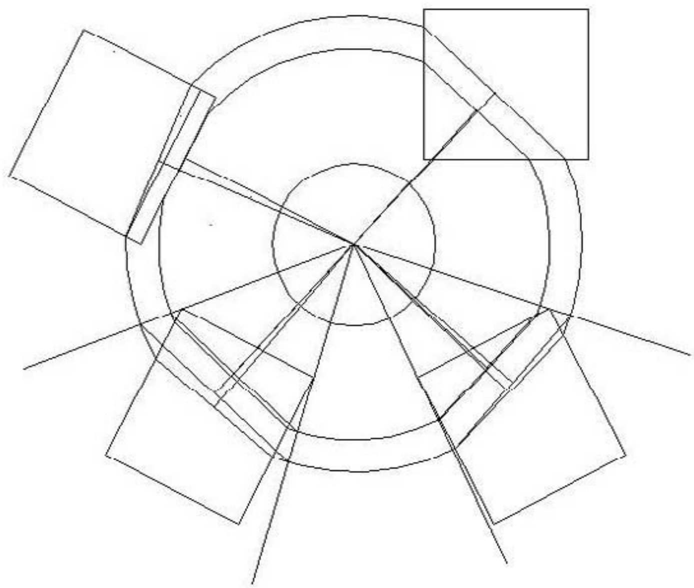

Fig. 11. The multiple identical signature dilemma of a cube

Unfortunately as shown in figure 11, other orientations are not symmetrical about the radius. This leads to an unpredictable length in both chords. To compound this problem, it is highly possible that the cube in many different orientations may generate the same length chord in the inner circle. Unlike the sphere, or ball, where the occlusion effect is predictable due to the nature of the shape, occlusions caused by cubes cannot be reliably predicted using limited information. This severely interferes with the relationship between the object and the chords. It is therefore extremely difficult to make reliable predictions as to the length of the second chord and hence the exact orientation of a cube. While it is not feasible to determine the orientation of a cube or more complex shape reliably using signature analysis, its identity may be inferred from the fact that in a limited test environment such as Robocup, the only unknown shape or object is that of the opposition robots. Hence a secondary relationship exists whereby:

If the signature caused by the impingement of an object on two or more circles does not correlate with any predictable signature, then there is a reasonable probability that the object is an opposition robot of unknown shape.

Evaluation of ORSAN

ORSAN makes it possible to identify objects within the RoboCup environment without relying on color or special markings. The uniquely identifiable shape of each object deflects the concentric laser circles in a predictable and identifiable pattern. The angle of the normal to the chords in a signature allows the robot to orient itself with respect to objects within the environment or to fixed features such as walls and corners. In general, the problems encountered at RoboCup 97 for which ORSAN was designed to overcome have been achieved although success was limited.

Primarily, ORSAN requires that the circles of concentric laser light generated by the ORSAN module be perceptible to the sensor. Several factors hinder this process. For cost reasons and legal reasons, 1mW laser modules were used. Though economically viable, the light from these modules when distributed around the circumference of a 1m diameter circle greatly decreases. This was overcome to a workable level by aligning more than one laser along the same circular path so that the light from one module was only distributed over a quarter of the circle's circumference. In this way the circles were visible on the dark carpet of the RoboCup environment, however the level of ambient light significantly swamped the red of the lasers, limiting the effectiveness of the ORSAN system within the environment. Curiously enough, in low ambient light environments ORSAN works with rather spectacular results. For wall following applications where orientation and range are desirable, ORSAN is able to provide precise baring and distance references to surrounding objects in the range of +/- 2mm using very economical hardware, in all directions surrounding the robot at once.

In a competitive environment such as RoboCup the amount of additional hardware required to carry the ORSAN system borders on excessive. With kicking mechanisms of greatly increased force, damage to the module is a genuine possibility.

The range of the ORSAN hardware was limited by the fact that the CCD sensor was located only 500mm above the ground. This limited the effective range to a radius of 1m. While it is easy enough to increase the height, the value of a compact lightweight robot with high maneuverability is lost.

ORSAN can identify objects if their shape is symmetrical about any given radius from the centre of the concentric circles. Balls, cylinders, walls and corners (a composite of two walls) are all symmetrical. In other words, the signature generated by these objects does not depend on the orientation of the object. Cubes, rectangles and complex shapes may provide a range and baring, but identification is not possible unless it is the only unknown signature in the environment.

Conclusion

The ORSAN system was an experiment to try and overcome problems with the RoboCup environment that were identified at Nagoya. Objects within the environment may be identified using only their shape. In addition, permanent features of the environment may be used to allow the robot to calibrate its orientation, without the need for ferro-magnetically sensitive compass modules. While ORSAN is capable of achieving the objectives for which it was designed, its success was limited due to the high ambient light, and by the amount of equipment that must be carried into a hostile environment. Ideally ORSAN is more suited to omnidirectional range finding in environments with extremely low ambient light levels, or using lasers of higher output. Signature analysis is effective in limited environments, where no more than one unknown signature exists, and objects are symmetrical about the radius of the concentric circles.

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