Animal and Robot Navigation[1]

Ulrich Nehmzow

Department of Computer Science
Manchester University
Manchester M13 9PL
United Kingdom
u.nehmzow@cs.man.ac.uk

Abstract

It is argued that the following three properties are foundations of robust robot navigation:

- The use of landmarks (and, in particular, the use of a compass sense),
- the use of canonical paths, and
- the use of topological rather than geometrical maps.

Some examples of successful animal navigation are presented that support this view. We have performed initial experiments with mobile robots to investigate mechanisms suitable to implement such navigational architectures. Experiments concerning navigation by dead reckoning are presented, and a differential light compass is introduced to aid robot navigation.

1 Introduction

Most of the work to date concerning navigation of mobile robots uses internal geometrical representations of the robot's environment to perform navigational tasks. MOBOT III, for example, constructs such a geometrical representation autonomously from sensor data ([Knieriemen & v.Puttkamer 91]), other robots use maps supplied by the designer ([Kampmann & Schmidt 91]). Usually the maps are altered in the course of operation, depending on sensory perception.

This "classical" approach has the advantage that the resulting map is intelligible to the human operator, which means that a special interface between the robot's representation of its environment and the way a human sees it is not necessary. This allows for easy supervision of the robot operation by the designer. On the other hand, the approach is time consuming and requires large amounts of memory. Furthermore the resulting maps contain information not necessarily needed for the immediate task ahead. If, for example, the robot's task was to move ahead, avoiding one obstacle in front of it, information concerning objects *behind* the robot as well as in the *far distance* to the sides or ahead is not needed. To store such information puts an additional burden onto memory and processing requirements.

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Alternatively, one could merely use information concerning the neighbourhood relationships between certain landmarks the robot perceives. Such topological mappings occur, for example, in animals and humans in the mapping of sensors onto the cortex ([Knudsen 82, Sparks & Nelson 87], see also [Churchland 86]). As they only represent the topological relationship between locations, but not the distances, they require less time to build and less memory to store.

Topological maps have been used for robot navigation, too. Examples are *Toto* ([Mataric 91]), *Alder* and *Cairngorm* ([Nehmzow & Smithers 91]). In Toto's case landmarks are defined by an environmental property such as "wall" (predefined by the designer) and a compass heading, in Alder's and Cairngorm's case landmarks are identified by the excitation pattern of a self-organising feature map (regarding self-organising feature maps, see [Kohonen 88]).

In this paper we argue that successful and robust robot navigation can be achieved by using (computationally cheap) topological maps, if two further restrictions are satisfied: firstly, the environment contains features which can serve as landmarks detectable by the robot (in particular, that reference landmarks — a compass sense — are used); and secondly, the robot follows canonical rather than arbitrary paths in order to disambiguate sensor signals and allow for reliable landmark recognition.

The paper is structured as follows: Section 2 discusses the various types of landmarks suitable for robot and animal navigation and gives examples of how animals use them. Section 3 discusses the role of canonical paths in navigation, section 4 describes human navigational skills using the example of navigation between Hawaii and Tahiti, and section 5 presents experiments in dead reckoning navigation with mobile robots. The use of a *differential light compass (DLC)* and its effect on the reliability of navigation is discussed in this section as well.

2 Landmarks

2.1 Local Landmarks

Local landmarks we define as those landmarks whose relative position to the robot or animal changes as a result of motion. Typically such landmarks are trees, rocks, rivers, buildings *etc.* in the animate world, and beacons, reflective strips, colour markings *etc.* in the robot environment.

Ants

Wehner and Räber ([Wehner & Räber 79]) report that apparently desert ants (*Cataglyphis bicolor*) use visual stimuli to identify a home location. Their experiment (see figure 1) suggests that in order to move to a particular location ants try to match the current retinal image with a stored one. Figure 1 (top) shows the initial situation: two identical markers at equal distances to the left and the right of the mound serve as landmarks. The small dots indicate homing positions of individual ants. If these markers are moved apart to twice the original distance (thus halfing their angular extent) the ants return to either of the two markers (figure 1, middle). If, then, the size of the markers is doubled (returning their angular extent to the original size) the ants return to the original home location (figure 1,

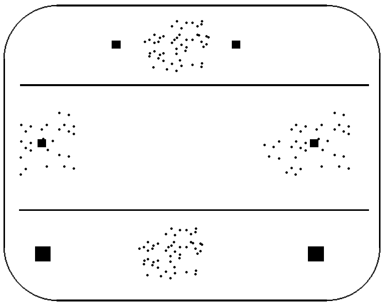

Figure 1: Landmark use in *Cataglyphis bicolor* (after [Wehner & Räber 79]).

bottom).

[Cosens 93] reports that wood ants *Formica aquilonia* change their paths in his laboratory in relation to large rocks (which are part of the laboratory environment) being shifted. Again, this indicates that ants use local landmarks for navigation.

Bees

Gould and Gould ([Gould & Gould 88, p.148]) report von Frisch's findings concerning the use of landmarks in the navigation of bees: bees who have been trained on a dog-leg route with the turn near a prominent tree will continue to fly to the food by way of the tree, whereas bees trained on a similar dog-leg route in the open country will fly along the shortest route. Prominent landmarks such as forest edges will be used predominantly for navigation by honey bees, the sun is merely used as a reference point in the dance, indicating the direction to the food source ([Gould & Gould 88, p.148ff],[Waterman 89, p.177]).

Cartwright and Collett ([Cartwright & Collett 83]) report experiments with bees that show a striking similarity to the experiments with ants by Wehner and Räber ([Wehner & Räber 79]). As in the ants, bees seem to use the angular extent of local landmarks for navigation, displacement of artificial landmarks leads to a corresponding displacement in return position. Cartwright and Collett: "We conclude that bees learn the angular size of the landmark when viewed from the position of the food source and use this to guide their return." They also report that "the compass bearings of the landmarks on the retina are of more importance than their apparent size". This suggests that the actual physical features of a landmark, although being taken into account once near the desired location, provide only a secondary source of information.

In summary of their experiments they say that "the conclusion to be drawn from the experiments ... is that bees do not find their way using anything analogous to a floor plan or map of the spatial layout of landmarks and food source. The knowledge at their disposal is much more limited, consisting of no more than a remembered image of what was present on their retina when they were at their destination".

Waterman ([Waterman 89, p.176]) confirms this by reporting that honey bees stop foraging if artificial landmarks are introduced (or removed) into their territory and make orientation flights before they continue to forage; similarly they make reconnaissance flights in unknown territory before they begin to forage.

2.2 Reference Landmarks

Reference landmarks we define as those landmarks that do not change their relative position due to robot or animal motion. Typically these are distant forests or mountains, the sun and stars, the polarisation of the sky, the magnetic north pole *etc.*

Ants

Desert ants (*Cataglyphis bicolor*) are able to return to their nest directly after completion of a foraging trip. They do not retrace their outward journey (by, for instance, following a pheromone trail). Once near the nest, they start searching for the nest in spiral-like motions of ever widening circles ([Gallistel 90, p.61]). Experiments in featureless planes show that the ants' navigation is, in those cases, based purely on dead reckoning ([Wehner & Srinivasan 81]). In order to achieve this, they orientate their direction according to polarisation patterns of the sky ([Wehner & Räber 79]). Such patterns can be regarded stationary over the relatively short foraging time of desert ants and therefore provide reliable directional cues. As an ant does not perform pitching and rolling movements during foraging and homing, the sky pattern changes only in relation to rotations about the vertical axis.

Bees

Gould and Gould's experiments ([Gould & Gould 88, p.126]) show that honey bees *Apis mellifera* orientate their flight paths with the help of the sun (and, as Waterman reports ([Waterman 89]), also using the polarisation of the sky).

The results relevant for the discussion here are depicted in figure 2. They show that bees' paths in relation to the hive are determined by the position of the sun. If the hive is moved by several kilometers over night (figure 2, top), the bees will leave the hive in the morning in the same direction as they did the previous day. If the hive is moved while the bees are away feeding (figure 2, middle), they will return to the old location, discover their error and fly to the new location of the hive. In experiments with the *Edinburgh R2* and *Grasmoor* (see section 5.1 for a description of these robots) a similar effect can be observed: if the position of the main light source is moved laterally on the return leg of the robot's journey, the robot will return to a location which is deflected in relation to the apparent movement of the light source[2].

If, thirdly, the hive is moved over whole continents, i.e. the apparent movement of the sun is a different one to what it was at the original location, bees will fly off in the same angle they used to fly at the original location, but get confused in the course of the day (figure 2, bottom).

Birds

Planetarium experiments with indigo buntings (*Passerina cyanea*) about to migrate show that birds can use the stars for navigation. In the planetarium the birds orientated themselves in the same direction they would have done in the open country. If the artificial sky was shifted, their flight orientation changed accordingly ([Waterman 89, p.109]). Through

[2] This experiment is described in section 5.2.3 of this paper.

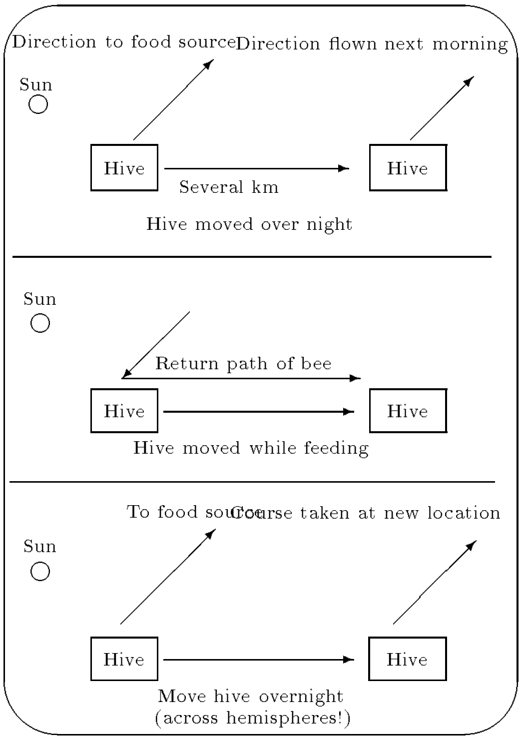

Figure 2: The use of reference landmarks in *Apis mellifera*.

another set of experiments it was also shown that the birds *learn* to interpret the star patterns for navigation.

3 Canonical Paths

The use of unchangeable (canonical) paths improves navigation reliability greatly: the task of navigating to a goal location is simplified to one of staying on a (possibly learned) path. Gallistel ([Gallistel 90, p.38]) reports that human navigators prior to the latter part of the eighteenth century used to "sail the parallels", that is sail due North or South and then due East or West[3](even at the expense of making detours), thus reducing the error introduced by trigonometry and furthermore exploiting trade winds and ocean currents (which are both parallel to latitudes). If landmarks are known that describe the desired path piloting (navigating with respect to internal representation and observed landmarks) can be used instead of the more unreliable dead reckoning. Preliminary experiments with *Grasmoor* have been conducted that demonstrate this type of navigation: the robot navigates using local landmarks and a differential light compass (see section 5.2.1). Canonical paths are indeed used by insects for successful navigation between (stationary) food sources and the nest.

[3]We have used a similar behaviour for some of our experiments with the *Edinburgh R2* — the robot first moves parallel to the x-axis, then parallel to the y-axis of its coordinate system.

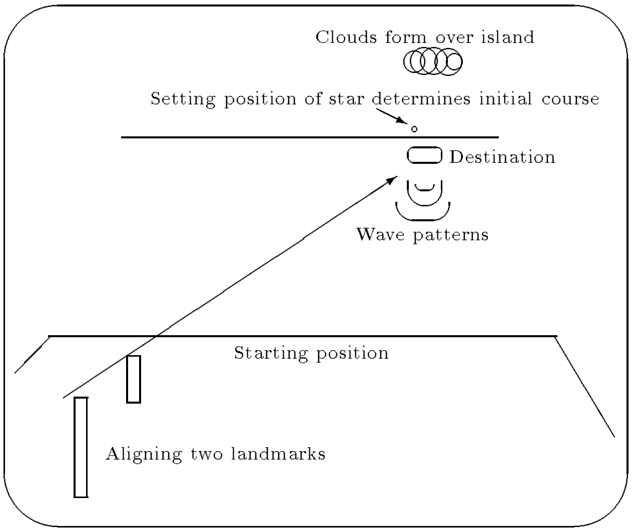

Figure 3: The use of reference landmarks and local landmarks.

Wood ants (*Formica rufa*), for example, use the same paths between their food sources and their nest so intensely that the forest floor shows these paths clearly: in the course of many years the covering vegetation has been removed and black trails indicate the usual way of the ants ([Cosens 93]).

A further example for the use of canonical paths in animal navigation are Canvasback ducks. They have, for example in the Mississippi valley, very narrow flight paths which they follow each year during migration ([Waterman 89, p.176]).

The knowledge of these paths seems to be *acquired* in some cases (bees), in others they must be genetically *preprogrammed*. First-year juvenile terns, for example, do not depend upon the leadership of an adult to find their migratory paths ([Waterman 89, p.177]).

4 Polynesian Navigation

Without using compasses or geometrical maps the inhabitants of the Polynesian islands were able to navigate successfully over several thousand kilometers of open sea (the journey between Tahiti and Hawaii — 6000 km long — has been performed recently by the *Hokulea*, using traditional navigation methods ([Kyselka 87, Lewis 72],[Waterman 89, ch.3])). Such navigation was successful, because all available sources of information (local and reference landmarks as well as special properties of the environment) were exploited by the navigators.

To determine an initial course, the navigators used the stars, moon and sun as reference landmarks. The direction of setting or rising of a particular star, for example, would give the direction for a particular island (reference landmark, see figure 3). They also use local landmarks of the island they are departing from to adjust their initial course ([Waterman 89, ch.3]).

During the journey wind and wave patterns (which are usually unique for certain parts of the ocean, because they are influenced by the position of islands) were used as local landmarks; in fact the weather patterns in many parts of the world are so reliable that they are used for navigation not only by humans, but also by animals. Sparrows and warblers, for example, fly 2000 to 3000 km from Canada and New England to South America's north coast. Computer modelling suggests that, provided the departure time is closely timed (which indeed seems to be the case, according to observations), the birds will be directed to their destinations by the repeating wind patterns ([Waterman 89, p.27]).

Although a navigator in a canoe has a view of only 15 km, islands can be detected from a much greater distance: because land is warm in comparison to the sea, air masses rise over land, cool down in the process and form clouds (see figure 3). These clouds are stationary over an island. Furthermore, atholls reflect a green light onto the underside of these white clouds. Certain land birds fly out over the sea for a certain distance and can therefore be used as an indication of nearby land.

In addition to the intelligent use of reference and local landmarks, however, successful navigation would not be possible if the environment wasn't "benign", that is if certain properties of the environment didn't help to achieve navigation. The Hawaiian islands, for example, are stretched out in a chain 750 km long (but only 150 km wide). This means that the navigator has to get the bearing only roughly right; as soon as one island is detected, local landmarks can be used to sail to the actual destination of the journey. This principle applies to robotics as well: we believe that robot performance (and therefore navigation as one aspect of robot performance) always has to be seen with respect to the robot's environment. A general purpose robot does not exist.

5 Experiments in Robot Navigation

Robot navigation based on pure dead reckoning is unlikely to succeed if the path of the robot is complicated and long. This is due to inevitable sensor and actuator inaccuracy (e.g. variation of sensor readings due to surface, colour and position variation as well as electrical noise, or the fact that turning angles cannot be determined more accurately than a few degrees), as well as effects stemming from the interaction with the environment (e.g. wheels turning, although the robot is pressing against a wall: the robot is *not* moving, yet seems to measure forward motion!).

Instead of using pure dead reckoning, we propose a robot navigation system that uses local landmarks such as passive or active beacons, walls and corners, *and* reference landmarks (a compass sense), canonical paths and a topological representation of the environment. We have already shown that such a system can be used for successful location identification and limited navigation ([Nehmzow 92]). The robots used in those early experiments were equipped with tactile sensors only, whereas the robots used here have far more sensors (see section 5.1).

For short travelling distances (up to four infrared sensor ranges, approximately 4 m) we propose a navigation system that is based on both navigation in relation to reference landmarks (see section 5.2) and local landmark recognition and identification. How local landmarks can be identified has been described earlier ([Nehmzow & Smithers 91]), experiments regarding navigation by means of reference landmarks are presented here.

5.1 The Robots

Initial experiments were conducted by us at Edinburgh University (Psychology Department), using the *Edinburgh R2*. This robot is shown in figure 4, it is a mobile robot of roughly quadratic shape (25cm x 25cm).

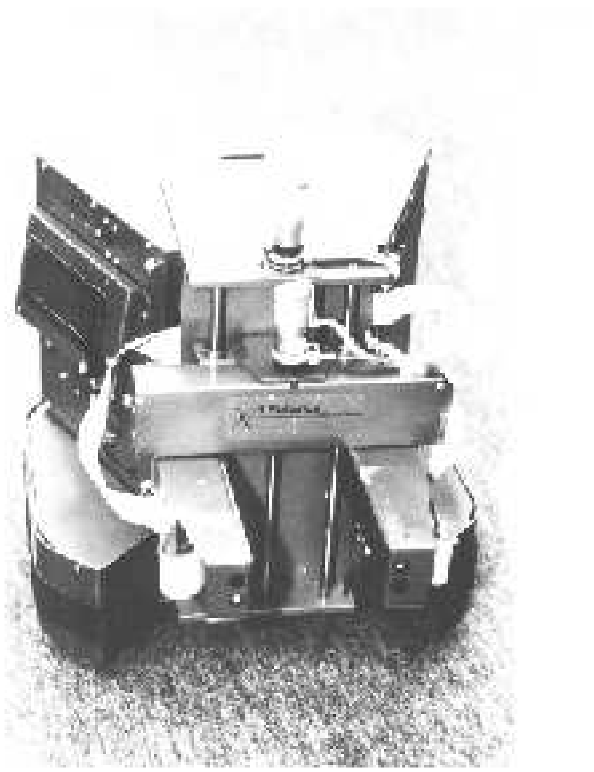

Figure 4: The *Edinburgh R2*.

It has a gripper with two degrees of freedom. Eight infrared proximity sensors are mounted around the robot, 25 cm above ground. White objects are detected as far away as 40 cm, objects coated with reflective tape can be seen from distances of 1 m and more. In addition to the infrared sensors the robot has six light sensors (five around the perimeter, one pointing upwards), two break beam sensors and one colour sensor in the gripper. Mounted at a height of 5 cm are five tactile sensor pads, two additional tactile sensor pads are fitted inside the gripper. Through wheel encoders the robot can also sense the velocity of each of its two wheels (passive caster wheels are mounted at the front). The speed of the robot can be controlled by software and goes up to 40 cms^{-1}.

Subsequent experiments, confirming the suitability of the differential light compass for robot navigation, and additionally using a series of local landmarks, were conducted at Manchester University (Department of Computer Science), using the mobile robot *Grasmoor* (see figure 5). This robot is equipped with four infrared range-finding sensors, two tactile sensors and four light sensors. The infrared sensors detect local landmarks at a distance of approximately 30 cm.

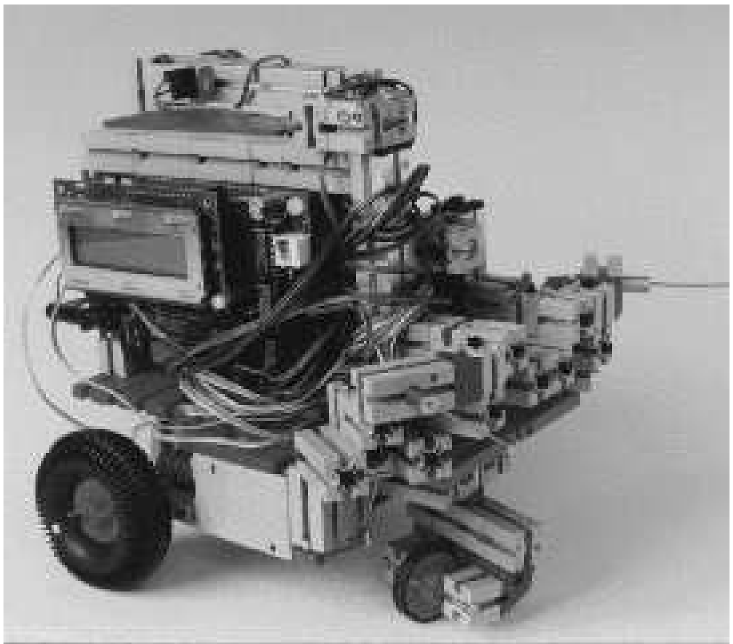

Figure 5: *Grasmoor*

5.2 Navigation with the Differential Light Compass

5.2.1 The Differential Light Compass

The *Edinburgh R2* is equipped with six light sensors, of which five are used for the light compass. *Grasmoor* has four light sensors[4]. The arrangement of the sensors of these two robots is shown in figure 6.

The differential light compass is based on the assumption that a continuous gradient of light intensity in the environment exists (provided, for instance, by the sun or a distant light source), and that the robot's light sensors all have similar sensitivity. The current heading of the robot (dx,dy) is then estimated by the following equations[5]:

$$dx = \frac{S1 - S4}{|S1-S4|+|S2-S3|}$$
$$dy = \frac{S2 - S3}{|S1-S4|+|S2-S3|}$$

where S1 ... S4 denote the signal values of light sensors one to four, dx the heading in x-direction and dy the heading in y-direction (scalars). During the outward journey the current position of the robot is estimated in discrete time steps according to the following equation, assuming constant travelling speed:

$$x(t+1) = x(t) + dx$$
$$y(t+1) = y(t) + dy.$$

[4] The light sensors are based on cadmium sulphide light dependent resistors (dark resistance greater than 20MΩ, resistance at 100 lux typically 5kΩ, rise time at 10 ft candle 45ms, fall time at 10 ft candle 55ms).

[5] Equations are given for *Grasmoor's* case.

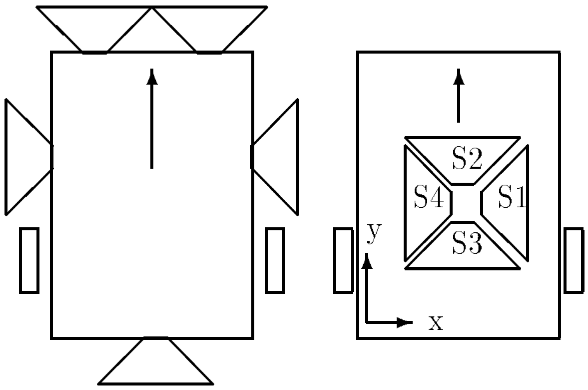

Figure 6: Arrangement of light sensors on the *Edinburgh R2* (left) and *Grasmoor* (right).

During the return journey, the *Edinburgh R2* moves such that x and y coordinate decrease[6]. The robot stops once they lie below a predefined threshold. *Grasmoor* acts similarly, but because the robot also uses sequences of several landmarks for navigation it initiates a landmark searching behaviour once the differential light compass indicates the robot is close to the desired location. The robots' behaviour is, in fact, not unlike that of navigating desert ants ([Wehner & Srinivasan 81]).

5.2.2 Performance with and without Differential Light Compass

To assess the reliability of navigation based on dead reckoning, we have conducted two experiments with the *Edinburgh R2* that compare a navigational system that uses a reference landmark (in this case a light gradient) with one that uses proprioception alone.

In the latter case the robot's current position is constantly computed, using the wheel encoders and an estimate of the current heading. The latter is determined by the fact that the robot is programmed to perform only 45 degree turns when avoiding obstacles.

It turns out that there are many sources of perturbation that render such a system unreliable for complex navigational tasks. For once, the supposedly 45 degree turns of the robot are never precise, furthermore, the speed of each individual wheel varies slightly in between measuring intervals. For long paths the error accumulates beyond the level where dead reckoning alone can still successfully be used for navigation.

Dead reckoning, using the DLC, uses basically the same algorithm as the previous experiment, but instead of *estimating* the current heading it is *measured*, using the DLC. Again, while the robot is moving through its environment, the current position is constantly updated. On returning to the starting location, the robot first moves in the "correct" direction along the x-axis, then along the y-axis. It then repeats this procedure until the total error lies below a predefined threshold. Moving along both axes instead of returning home on a straight path is computationally cheaper and avoids rounding errors due to the fact that for all computations integer arithmetic has to be used.

[6] The origin is, by definition, at the starting location.

Results

In the first experiment the robot had to avoid two obstacles, and then return to the starting location. Figure 7 shows the results of this experiment (Numbers indicate the final returning positions if the DLC was used, letters those where the DLC was not used). Both approaches work satisfactorily; as the robot has a infrared sensor range of ca. 100 cm (for especially prepared passive beacons) the actual starting location was visible from all returning positions.

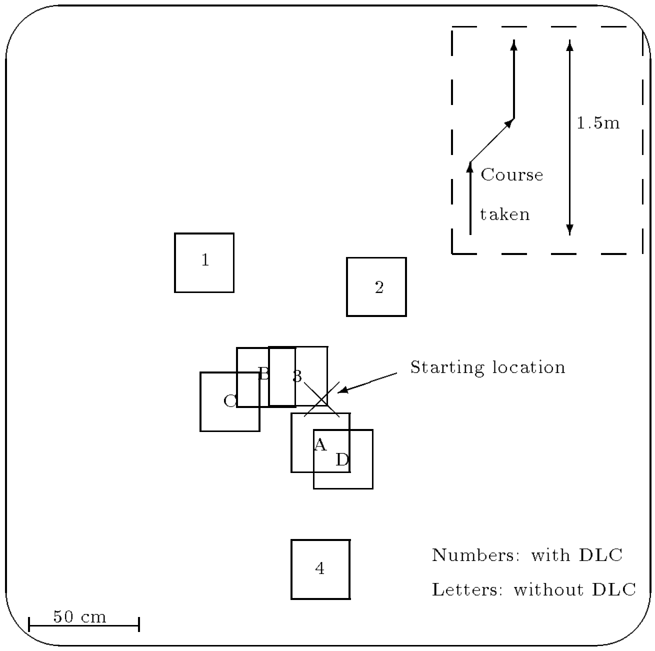

Figure 7: Navigation with and without DLC. 1st Experiment.

If, however, a more complicated path as shown in figure 8 is followed, pure dead reckoning quickly becomes so unreliable that it can no longer be used. Figure 8 shows that without using the DLC the robot ended up too far from the actual starting location to be able to see a beacon, whereas when using the DLC a successfull return was achieved.

A further experiment to measure the navigational error was conducted as follows: the robot followed a path as shown in figure 9. At the location marked 'R' the robot was manually instructed to return to the starting location (marked 'S'). The current heading of the robot was determined, using the DLC, the current position was computed using dead reckoning. Figure 10 shows the return position of the robot in x/y coordinates in cm (eleven runs), as well as the distance of the center of the robot from the starting location in cm (in the run marked '*' the robot crossed the starting location several times). Also shown is the displacement in per cent of total distance travelled.

To interpret figure 10, it should be born in mind that the sensors of the robot are 12 to 25 cm away from the center, and have a range of another 100cm for passive, reflective beacons. In other words: a beacon would have been visible from all return positions in the eleven

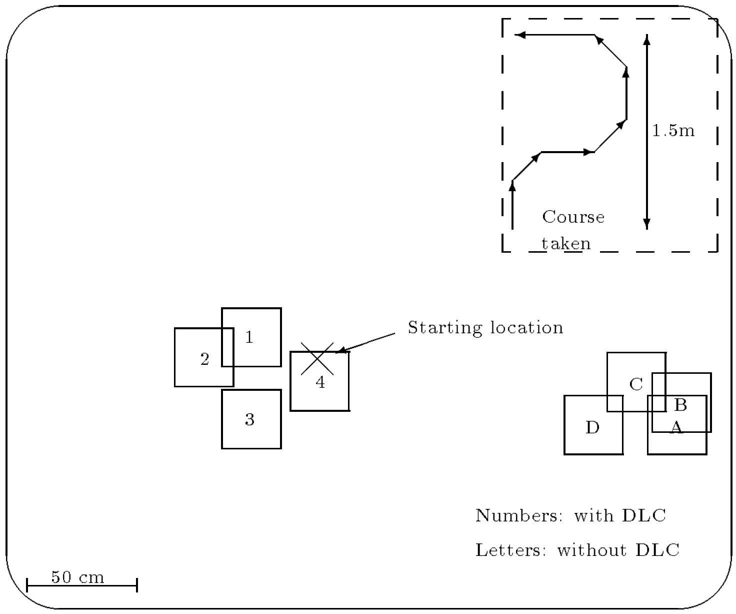

Figure 8: Navigation with and without DLC. 2nd Experiment.

runs of the experiment. Another interesting point to make is that the typical navigational error of a human navigator is 5 to 10 per cent of the total distance travelled, the same can be observed in desert ants ([Gallistel 90, p.41]). The robot's navigational error of about 8 % falls within this range.

Subsequent experiments with *Grasmoor* have confirmed the findings presented above.

5.2.3 The Influence of a Reference Landmark on Robot Navigation

In section 2.2 we described an experiment that shows that bees orient their paths according to the position of the sun.

A similar experiment was conducted with the *Edinburgh R2*. Our robotics laboratory has two windows, next to each other. The robot's task was to move in a straight line, and upon the experimenter's command return back to the starting location, using the differential light compass. On the outward journey (straight line of about 150 to 200 cm) the left window was bright, whilst the right window was darkened by blinds. For the return journey, the left window was darkened and the right one was bright. The resulting end position of the robot was shifted in relation to the shift of reference landmark, as in the experiment with the bees (see figure 11). A control experiment was conducted in which the lighting remained unchanged throughout the experiment, the results of this experiment are also shown in figure 11.

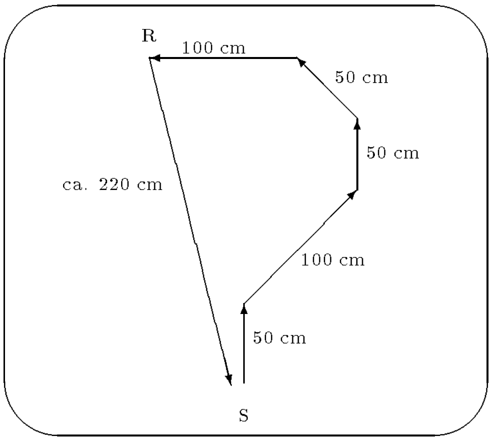

Figure 9: Course steered to measure navigational error.

x [cm]	70	0	20	-30	-10	0	-5	-25	-25	-25	-30	-5,5
y [cm]	30	60	35	0	25	75	-10	-10	0	60	-50	19,5
d [cm]	76	60	40	30	27	75*	11	27	25	65	58	44,9
Error [%]	13	10,5	7	5,3	4,7	13,2	1,9	4,7	4,4	11,4	10,2	7,9

Figure 10: Navigational displacement, using the DLC and dead reckoning.

5.3 Local Fluctuations in Light Gradient

Local fluctuations in light gradient occur for instance if the robot moves into shadows, or approaches a window off-center. As long as a gradient exists at all this does not affect navigation, provided the robot returns along the exact same path it used during the outward journey. However, as this is impossible, local fluctuations in light gradient do introduce an error. We have found, though, that if the starting location is marked by a passive beacon, and journey distances do not exceed the range of about four sensor ranges (4 m), the robot reliably returns to the starting location, despite the fact that local fluctuations in light gradient are encountered. We have not only conducted experiments in the laboratory, but also in the open, using a natural light gradient for navigation. At the time of the experiment the sky was still bright, but the sun had set. The robot twice returned to the starting location after two journeys of about 3 m each, travelling over rough terrain and thus being forced to realign repeatedly towards the intended travelling direction.

6 Summary and Conclusion

There is good evidence that animals use local landmarks such as prominent trees, rocks, forest edges *etc.* as well as reference landmarks such as sun, stars and magnetic senses to navigate successfully. It is also observed that in order to navigate between two known locations animals seem to prefer well defined and constant paths, even if this means longer travel distances.

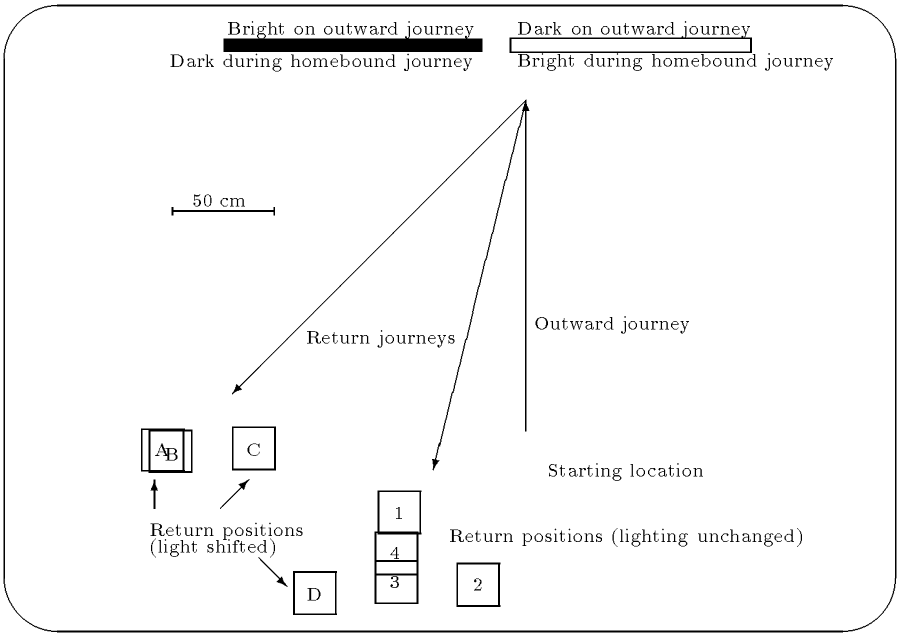

Figure 11: The use of reference landmarks in the *Edinburgh R2*.

As animal navigation is proven to be reliable and successful it is suggested that a robot navigation system should be based on the following three principles:

- It should use local and reference landmarks,
- it should use canonical paths, and
- it should be based on topological rather than geometrical maps.

First experiments with two mobile robots are presented and the reliability of navigation based on dead reckoning is investigated. The experiments show that for simple navigational tasks pure dead reckoning is sufficient, but that this method becomes unreliable if paths are complicated and long. Using reference landmarks (such as, in our case, the sun) greatly improves navigational competence in the latter case. This finding leads us to conclude that for reliable robot navigation a compass sense is *essential.* In the experiments presented here this compass sense has been implemented by means of a differential light compass that uses a light intensity gradient to define a reference direction.

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