Abstract
Titan is a mobile robot built for outdoor navigation research. In this paper, we report on research into navigation across a field using poles as simple discontinuous landmarks. In the teaching phase, it records leg lengths, leg bearings and landmark parameters as it is manually driven along the path. From the recorded information it plans a navigation path, consisting of a sequence of legs. The visual flight rules strategy is used to navigate the path. At each landmark, Titan measures its location relative to the landmark with an ultrasonic sensor and re-plans the next leg to correct for any errors.

1. INTRODUCTION
Piloting is a navigation strategy that uses known landmarks [15]. These landmarks are used sequentially to find the way to the goal. The navigator must be familiar with the area, and know which landmarks to look for. A landmark is a feature in the environment, whose position can be sensed, that is close enough to the desired path that its direction varies significantly as the navigator moves along the path.

Thomas Gladwin [2] studied the navigation skills of the people of Puluwat Atoll in the Caroline Islands. They navigate over a range greater than 1,000 kilometers through open seas, in their 8 metre sailing canoes. Their journeys are usually broken down into a series of island hops. However, they regularly travel 100 to 200 kilometres across the open sea between islands.

The navigator starts his voyage by imagining the position of his destination relative to the position of other islands. As he sails along, he constantly adjusts his direction according to his awareness of his current position. His decisions are improvised continually by checking relative positions of landmarks (reefs, atolls, etc), sun, stars, wave direction, wind direction, cloud patterns, and depth soundings.

He navigates with reference to where he started, where he is going, and the space between his destination and his current location. If asked where he is, he can tell you relative to the surrounding islands.

When flying a light aircraft across country, a pilot will use Visual Flight Rules (VFR) to navigate. Before the flight, the pilot chooses a sequence of legs between landmarks from an aviation map. Then he calculates the length and magnetic bearing of each leg. During the flight, the pilot flies along the first leg, to the location where he expects to find the first landmark. Above this location, he slows down to scan the area looking for the landmark. When he finds it, he estimates the error in his location and re-plans the next leg. He repeats this process until he reaches his destination.

A few mobile robot researchers have attempted to develop landmark navigation systems using ultrasonic sensing. Kimoto and Yuta [7] used the standard deviation of ultrasonic range readings to detect a hedge from a moving robot. Maeyama et al., [12] used a
combination of vision and ultrasonic sensing to detect trees along a path. Mandow, et al [13] used pulse-echo ultrasonic sensing to navigate along rows of plants in a greenhouse.

Leonard and Durrant-Whyte [8] use an acoustic feature called a Region of Constant Depth (RCD) for navigation. Akbarally and Kleeman [1] identified nine acoustic features that occur in a room where all the planes are vertical or horizontal and meet at right angles. Each feature has parameters that help to identify it including position and orientation in space.

M'Kerrow [9] extracted features representing geometric primitives from arc maps made with ultrasonic sensor data for indoor landmark identification. Wijk and Christensen [16] extracted point features from sensor data which they matched to a map to identify and navigate with landmarks.

In this paper, we apply the visual flight rules approach to navigation of an outdoor mobile robot using a Continuously Transmitted Frequency Modulated (CTFM) ultrasonic sensor to detect the landmark [3, 4, 5, 10]. Following a description of the Titan Robot (Section 2), we derive a set of landmark classes. Then we look at a strategy for landmark navigation using poles as simple-discontinuous landmarks in subsequent sections.

2. TITAN OUTDOOR ROBOT

Titan (Figure 1) is constructed from a 4-wheel drive wheelchair [14]. We replaced the chair with a superstructure to hold electronic racks and sensors. Two encoders (Figure 2), mounted on the rear wheels, measure robot position with a resolution of 0.47mm. A third encoder measures the steering angle of the left front wheel.

Wheel rotation is controlled with back emf control of the motors connected in left and right pairs. Steering is achieved with differential velocity between the two sides, without skid steering. The front wheels are free to turn but constrained to achieve Ackerman steering by a 4-bar linkage. As a result, differential velocity indirectly causes the front wheels to steer. This design makes the steering susceptible to being back driven by bumps. We overcame this problem with a steering control loop using feedback from the steering encoder.

The sensor suite also includes a gyro stabilised compass, inclinometers, a camera and a phased array CTFM ultrasonic sensor. The CTFM sensor produces a depth-area measurement, called an acoustic density profile [4]. Features extracted from this profile are used in landmark detection.

The actuators and sensors are connected to a Macintosh Powerbook by interface cards in a Magma PCI extension chassis. The software is written in LabView [14]. We have developed a library of LabView functions to handle input from sensors and output to actuators.

3. LANDMARK TYPES

An ultrasonic sensor is a geometry sensor, so we decompose landmarks on the basis of geometry. The result of this decomposition is a set of four landmark classes: simple discontinuous, simple continuous, complex discontinuous and complex continuous (Figure 3). The class of the landmark determines the feature set used to detect the landmark, the way in which the sensor is moved to collect data for landmark recognition and the navigation strategy used when tracking the landmark.

Figure 3 has two axes. As we move to the right along the x axis, the complexity of the geometry of the landmark increases. A cylindrical pole is a simple-discontinuous landmark. In contrast, an isolated plant is a complex-discontinuous landmark.

As we move up the y axis the continuity of the geometry of the landmark increases. The isolated plant becomes a crop line or row of plants that overlap. The surface facing the sensor is very rough compared to the smooth surface of a wall or a kerb.
In our research into recognizing plants with CTFM sensors [6], we developed the acoustic density profile model [4]: a graph of echo amplitude versus range. A CTFM sensor transmits a frequency-modulated signal and the echo is a set of delayed copies. We demodulate the echo with the transmitted signal to produce a set of frequencies proportional to the ranges to the reflecting surfaces in the object. A simple object has a small set of frequencies and a complex object a large set.

We obtain a spectrum (Figure 4) of the frequency content of the echo with a Fast Fourier Transform (FFT). A pole has a smooth surface, so it reflects a single high amplitude echo from its front surface. From this spectrum, we extract a profile of echo amplitude versus distance through the object in a window around the location of the object. This profile is the Acoustic Density Profile of the object from a particular sensing direction. From this profile we extract a set of features. Using the features we attempt to classify the object.

4. SIMPLE-DISCONTINUOUS LANDMARKS
A cylindrical pole is a simple discontinuous landmark (Figure 5). Common objects in an outdoor environment including fence posts, light poles and tree trunks are members of this class. The navigation experiments with a sequence of poles as landmarks, discussed in the following sections, demonstrate the robustness of navigation with this type of landmark.

A cylindrical pole is symmetrical, so its echo varies little with rotation. As a result it can be detected from almost any angle, with a single feature set. The advantage is that it gives accurate and robust bearing and range readings relative to the sensor. However, to get the bearing requires panning across the pole.

We control sensor motion by stopping the robot and panning the sensor (Figure 5). The result is a fixed range reading while the pole is in the region of insonification (Figure 6). The range value is fixed because the smooth surface results in specular
reflection, and consequently the echo is from the surface element that is orthogonal to the beam axis.

The amplitude of the echo is high while the pole is within the region of insonification of the main lobe (Figure 6). When the pole nears the edges of the region of insonification the amplitude drops off in accordance with the directivity function of the beam.

The measurements reported here were made with a CTFM phased array mounted on the front left corner of the robot. This sensor produces an elliptical beam of ultrasonic energy with a horizontal beam angle of $3^\circ$ (axis to side of beam) and a vertical beam angle of $30^\circ$.

When the pole is not in the region of insonification a small amplitude echo will be received from the pole. If the pole is isolated from other objects, it will continue to be the largest amplitude echo (Figure 6). In which case, we have to threshold the echo to isolate the reflection from the main lobe, in order to determine the bearing of the pole. As the pole is symmetrical, the vector along which the range is measured passes through the center of the pole. The location of the center can be calculated using simple geometry.

5. LANDMARK NAVIGATION MAP

The visual flight rules strategy plans straight legs between landmarks. At each landmark, a small radius turn is made from one bearing to the next. The distance traveled by aircraft between landmarks is usually much larger than the distance traveled during a turn.

However, for a mobile robot, this condition is true in some applications, such as moving across an open field, but not in others. There are many applications where the length of curved legs is similar to the length of the straight legs.

To implement the visual flight rules strategy, we require a map (Figure 7). The map defines the course to be traveled by the robot as a path. A path is defined as a sequence of legs, where a leg is a path between two points. The end point of one leg is the start point of the subsequent leg.

A leg can be straight or a section of an arc. Also, on the map are the landmarks and the landmark points. A landmark point is the location of the robot at the time when it should sense the landmark. A path with its legs, landmark points and landmark features is stored in a map data structure.

6. TEACHING A PATH

The robot is taught a path by manually driving it along the path. At each sensing point, it is stopped. The distance and bearing from the previous path or landmark point is calculated and stored in the map. The ultrasonic sensor is panned across the landmark and a signature is calculated for use in recognizing the landmark. The ultrasonic sensor is on the front left of the robot, so all landmarks used in these experiments were to the left of the robot.

For a symmetric landmark, such as a pole, the signature is the acoustic density profile. For a more complex asymmetrical landmark, such as a bush, the signature is a set of features that are extracted from the acoustic density profile.

7. PATH PLANNING

We plan a navigation path using the recorded landmark points, leg lengths and bearings. From this information, we can determine whether the distance traveled when turning from one bearing to the next is significant, and therefore, whether we have to plan sharp radius curves or curved legs.
When the path followed during a turn is important or the distance traversed is comparable to the length of the straight legs, we have to plan the segment of an arc as a curved leg. We model the landmark with a bounding landmark circle. When turning to the left around the landmark the robot can pass it safely by following the passing circle. The point where the robot’s path intersects the sensing circle is the point where the robot should stop to sense the landmark.

On leaving the landmark, the curved leg can either turn to the left around the landmark circle or to the right around the turning circle. The radius of either turn can be specified to meet task and path constraints. However, the passing circle is the minimum radius for a left turn.

8. LANDMARK SENSING AND LOCALISATION

The robot navigates the path by traversing each leg in the sequence. It stops at each landmark point and scans for the landmark. Once it has located the landmark, it can determine the error in its location relative to the planned path.

In these experiments, the 22.25 mm poles were detected by taking 50 readings in 1° steps over 50° centered on the expected bearing of the landmark (Figure 6). To find the bearing to the pole, these readings are cross correlated with features calculated from the reference acoustic density profile (Figure 4).

A line from the actual location of the sensor to the pole is one side of a triangle. A line from the planned location of the sensor to the pole is the second side of the triangle. As we know the length (range) and bearing of these two sides, we have sufficient information to calculate the third side. It is the error in the location of the sensor and hence of the robot. From this error, we can calculate the actual location of the robot on the map.

9. RE-PLANNING

Having determined the location of the robot, we can re-plan the subsequent leg with the aim of correcting for the error by the end of the leg. In the case of a curved
leg (Figure 9), the first step is to bisect the angle between the current vector of the robot and the desired vector when it is on the subsequent straight leg. A line orthogonal to the current vector through the turning center of the robot will intersect the bisector at the new turn center. Its length is the new radius.

In the case of a straight leg (Figure 10), we can consider two strategies for error correction. If the current vector of the robot intersects the planned path (Figure 10a) then it can travel along the current vector until it intersects the path and then turn on to the planned path. Alternatively, a new path can be planned from the current location to the path end point (Figure 10b).

10. RESULTS
We implemented the above system on Titan. To test the visual flight rules strategy, we set up paths across a sports field using poles as landmarks (Figure 11). The robot has successfully navigated these paths on several occasions. One such path is given in Table 1. Columns 1 and 2 show the planned distance and compass bearing for each leg. Columns 3 and 4 show the difference in the range and bearing of the landmark when measured by the sensor to the plan. Columns 5 and 6 show the new leg parameters for the leg, calculated from these differences.

<table>
<thead>
<tr>
<th>Leg</th>
<th>Leg length</th>
<th>Leg angle</th>
<th>Range error</th>
<th>Angle error</th>
<th>New length</th>
<th>New angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17m</td>
<td>45°</td>
<td>0.35m</td>
<td>-6.7°</td>
<td>16.96m</td>
<td>44.12°</td>
</tr>
<tr>
<td>2</td>
<td>10m</td>
<td>0°</td>
<td>-0.06m</td>
<td>-6.42°</td>
<td>9.965m</td>
<td>0.296°</td>
</tr>
<tr>
<td>3</td>
<td>25m</td>
<td>75°</td>
<td>-0.04m</td>
<td>-6.9°</td>
<td>25.04m</td>
<td>75.02°</td>
</tr>
<tr>
<td>4</td>
<td>30m</td>
<td>150°</td>
<td>0.000°</td>
<td>1.38°</td>
<td>30.0m</td>
<td>150°</td>
</tr>
</tbody>
</table>

To produce the data in Table 1, the robot was deliberately placed in an incorrect start location relative to the 1st pole. It was 350 mm further from the landmark and the compass bearing from the sensor to the pole (angle error in Table 1) was 6.7° to the previous sensing bearing. To correct for this error, the first leg was reduced in length by 40mm and the bearing changed by 0.88°. These changes reduced the range error at the next landmark to 60 mm and the error in the sensing vector angle to 6.43°.

The data in the table shows that even over relatively large distances, the errors are small. However, these errors can accumulate from one leg to the next and become quite large if not corrected. The corrections serve to reduce the error as the robot travels toward the next landmark, as shown in Figure 12.

11. ACKNOWLEDGEMENT
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12. REFERENCES