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Design Article

Determining Mobile-Equipment Location with RF Transmitters

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The difficulty in determining the location of a robotic device such as an automated lawn mower creates a problem in controlling it to follow a predetermined path. Some approaches implement buried wires, employ metallic objects as calibration points, or use above-ground wires.

However, these methods are inflexible and cumbersome. Other means, such as global positioning systems, may be too expensive and coarse in resolution for this application. The following method describes a practical

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means of determining the x-y coordinates of a mobile, robotic vehicle ¹.

The approach taken to solve this problem was to utilize a mathematical technique of determining a set of circle equations and to solve them simultaneously for the x-y coordinates. You can determine the position of a mobile object, such as our automated lawnmower, by the simultaneous solution of circle equations. You arrive at this solution by measuring the angle between a set of three points positioned in a right-angle manner outside the roaming object's range, and knowing the distances between those points. Sonic or electromagnetic transmitters of a continuous signal can represent these points.

The approach uses high-frequency RF transmitters. Mounted on the mower is a rotating directional receiving device, such as a loop antenna. The angle is measured by the rotating antenna, which detects the line of sight of the continuous wave signal from each of the transmitters. The antenna controls a counter to count the number of clock pulses of an appropriate frequency that is converted to an angle between each transmitter. Knowing the distance between the first and second transmitters and the angle between their lines of sight, a circle is defined that includes the transmitters and the position of the robot. Since the robot's position could be anywhere on that

circle, another circle is needed to uniquely define its position. Similarly, a second circle is determined for the second and third transmitters, and the simultaneous solution of those two circles determines the necessary x-y coordinates.

You can transmit this information to a remote computer for processing, or process it with an on-board computer. Knowing the mower's location and having defined a predetermined path for the mower, it's easy to generate the required steering and motive-control signals.

Potential system errors include LSB errors in the counter, directional-antenna rotation accuracy, straight-line moving errors, and accuracy of the measured angle. The latter error is caused by turning the vehicle, affecting the angular rotation of the directional antenna.

Transmitter Configuration

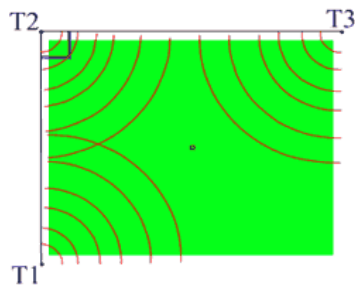


Figure 1: Three RF transmitters are located in a right-angle configuration just beyond the mower's travel area. They are designated T1 for the lower left, T2 for the upper left, and T3 for the upper right.

Each transmitter transmits a continuous signal on different frequencies to allow for unique identification. The distances between each transmitter is a known parameter used in calculating the circle equations.

Directional Sensing Means

A high-frequency directional-loop antenna makes a good RF directional sensor. Loop antennas have been around awhile and have relatively good directivity. Since the sensitivity of a loop antenna is rather low, it employs an amplifier. The device uses a single-turn loop and a wideband transconductance amplifier to provide a 20 dB gain with a 75-ohm load ². The balanced amplifier tunes the loop to preserve the symmetry of the figure-eight polar antenna pattern.

A phase-locked loop (PLL) controls the loop antenna, which rotates in a clockwise direction. The desired transmitter-signal sequence is T1, T2, and T3. Because of the figure-eight polar antenna pattern, in certain areas of the lawn the sequence will be reversed.

Circle Equations

All that is needed to determine a circle equation is the distance between two transmitters, and the angle between them as seen from the location of the mower. The distance (d) between transmitters T1 and T2 then becomes the chord of the circle. Angle A is found by a point on the circle between the transmitters and is constant regardless of where the point is on that circle. Basic trigonometry yields a single offset for this first circle in the X direction.

Radius of circle 1: $r_1 = \sin(A)/2d$

Offset for circle 1: $a = r_1 - (d/2)/\tan(A/2)$

Equation of circle 1: $(x + a)^2 + y^2 = r_1^2$

The second circle is one that passes through transmitters T2 and T3 with the distance (e) between them and again the angle B measured by the loop antenna is from the location of the mower. You calculate the offsets in a similar fashion, but in this case there are both X and Y offsets.

Radius of circle 2: $r_2 = \{[(e/2)/\sin(B/2)]/2\}/\cos(B/2)$

X offset for circle 2: $b = e/2$

Y offset for circle 2: $c = d/2 - [(e/2)/\sin(b/2)] \cos(B/2) - r_2$

Equation of circle 2: $(x - b)^2 + (y - c)^2 = r_2^2$

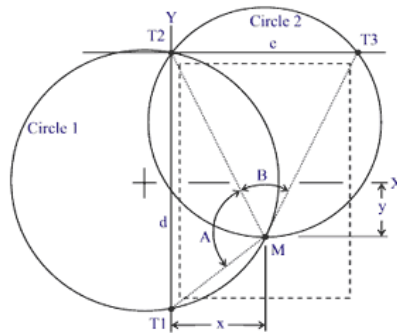


Figure 2: You can determine the mower's location using simple trigonometric relationships between the three transmitters and the mower

Now both equations are defined and can be solved simultaneously to find the X-Y coordinates. There are two solutions of course, one being the location of transmitter T2 that is already known, and the other is the desired coordinates of the mower's location as shown in **Figure 2**.

The simultaneous solution of the two circle equations yields:

$$X = \sqrt{r_1^2 - a^2 - H^2 + [(a - HK)/(1 + K^2)]^2} - [(a - HK)/(a + K^2)]$$

$$\text{Where } H = (r_1^2 - r_2^2 - a^2 + b^2 + c^2)/2c, \text{ and } K = (a + b)/c$$

$$Y = [r_1^2 - r_2^2 - a^2 + b^2 + c^2 - 2X(a + b)]/2c$$

Now that the location of the mower is known, it becomes an easy matter to use a predetermined path to generate the required steering and motive-control signals. You can easily generate the stored path information, initially by manually controlling the mower while storing the sequence of X-Y points. Since the predetermined path takes into consideration any obstacles such as trees or buildings, it doesn't have to "see" anything to follow the path. The mower will automatically follow the path and go around any obstacles that you have programmed into the system. If a new obstacle appears in the mower's path, that object will be unknown. You should have some means of detecting a new obstacle, such as bumper switches, so you can stop the mower. However, any

new obstacle is a good reason for reprogramming the mower's travel.

Antenna Pattern Effects

It was mentioned earlier that the loop antenna has a figure-eight antenna pattern. As the loop rotates, it will produce a sequence of T1, T2, and T3 signals from the transmitters when it is in a certain section of the lawn area. If it is in the area of the lawn enclosed by the triangle formed by the three transmitters, the sequence reverses. Therefore a sequencing circuit is needed to assure that the sequence remains in the proper order. Also when the mower is directly on the line between transmitters T1 and T3, it receives the signals from both of those transmitters simultaneously. This situation creates an ambiguity for which the accompanying logic must account.

The pulses generated from the transmitters' signals, after appropriate filtering, are produced by passing the signals through an envelope detector, an inverter, differentiator, zero crossing detector, and pulse generator. The received signal has a broad maximum and a very sharp null, produced twice for each complete rotation of the loop antenna. After the signal is inverted and differentiated, we get a signal that has a slow positive zero crossing for each maximum, and a very fast negative zero crossing for each null. The fast zero crossing is the desired event because it will be an unambiguous mark in time when the normal of the plane of the loop antenna is directly in-line with the transmitter's line of sight. The fast zero crossing is used to produce the pulse to control the counter for measuring the angle between transmitters.

Differentiator Noise

Differentiators are notoriously noisy. Fortunately there are methods to handle this problem. Tony Huen has provided a practical means of handling analog differentiation ³. Richard Panosh proposed another circuit to compute the first derivative ⁴.

Error Budget Analysis

This system displays two major error types: static errors and dynamic errors. Static errors occur with a stationary vehicle and include hardware and electronic errors. Vehicle movement causes dynamic errors.

Static Errors

12 bits represents a 360-degree rotation of the loop antenna. An error of ± 1 LSB represents an angle of 0.175 degrees. Assuming a square area of 100-feet per-side and calculating the x-y coordinates for this difference yields ± 1.60 inch, an error of 0.267%.

The rotation accuracy of the loop antenna using a crystal-controlled PLL depends on the crystal's stability. With a ± 25 PPM total temperature and long-term aging stability of the crystal, the difference in x-y coordinates amounts to ± 0.066 inch, an error of 0.009%.

You can prevent mechanical slippage of the loop antenna drive system by using a notched belt or gear arrangement.

Dynamic Errors

There are two types of dynamic errors: translation and rotational.

Translation errors are a function of the speed of the vehicle and also its location within the area of interest. Assuming a speed of 1 ft/sec, zero turn rate, a location at the center of the travel area, and the same size area as before, the difference in the measurement of angle A and angle B is -0.0323 degrees and +0.0373 degrees respectively. Calculating the x-y coordinates from the simultaneous solution of circle equations yields a difference of 0.530 inch compared with that of a stationary vehicle. This error can be corrected in software by taking into consideration the speed, location, and turn rate, or you can stop the vehicle to get a static check of its location.

Rotational errors are a function of the vehicle's angular rotation during a turn. The speed of rotation is a function of the vehicle's linear speed, the distance between wheels, and the amount of steering. This rotational speed is added to the rotation of the loop antenna in a right turn and subtracted in a left turn. This error is relatively easy to compensate for in the software.

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