An Outdoor High-Precision Local Positioning System for an Autonomous Robotic Golf Greens Mower

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Abstract—This paper presents a high-precision local positioning system (LPS) for an autonomous robotic greens mower. The LPS uses a sensor tower mounted on top of the robot and four active beacons surrounding a target area. The proposed LPS concurrently determines robot location and orientation. To perform localization, the sensor tower emits an ultrasonic pulse that is received by the beacons. The time of flight to each beacon is measured and transmitted back to the sensor tower. To determine the robot’s orientation, the sensor tower has a circular receiver array that detects infrared signals emitted by each beacon. Using the direction and strength of the received infrared signals, the relative angles to each beacon are obtained and the robot orientation can be determined. Experimental data show that the LPS achieves a position accuracy of 3.1 cm RMS, and an orientation accuracy of 0.23° RMS. Several prototype robotic mowers utilizing the proposed LPS have been deployed for field testing, and the mowing results are comparable to an experienced professional human worker.

I. INTRODUCTION

Outdoor mobile robots have many practical applications including transportation, lawn mowing, snow removal, large-area cleaning, and security patrolling. Many of these applications desire autonomous operation rather than remote operation with an operator’s assistance. This requires the robot to automatically plan and execute tasks and make decisions while performing tasks when necessary. One of the enabling technologies for an outdoor autonomous robot is outdoor localization, which provides critical robot pose information to a navigation system. Typically, a localization process collects and fuses sensory measurements to locate a robot in a map. With the robot pose information, the robot can make decisions for path planning and motion control, and finally achieve its goal. Different applications require different types of sensors and varying specifications including precision, accuracy, and sampling frequency. In our application, a golf green mowing task requires a sensor system with 30 m by 30 m working area, 5 cm accuracy, and must be cost effective to produce and deploy. In addition, this sensor system must operate reliably within a wide range of environmental conditions.

At Precise Path Robotics Inc., our goal is to design a commercial grade autonomous greens mower called the RG3 that can provide a high-quality, daily greens mowing service. Typical greens range in size from 275 to 900 m², and consist of unobstructed, often undulating, immaculately maintained turf. To match the mowing quality of an experienced worker, the robot needs a high-precision localization system. Additionally, the robot must be able to operate before sunrise in complete darkness. These requirements prohibit the use of common outdoor localization sensors. Specifically, the robot must operate on greens as large as 900 m² with monotonic scenery. Thus, the robot does not have an adequate number of unique features in its vicinity for feature-based localization methods. Therefore, a laser-range finder with feature detection [1], [2] or a vision-based localization system [3], [4] is not suitable for our application. Interestingly, this monotonic scenery is also problematic for human workers and may lead to a poor mowing pattern with banana-shaped or unparallel lines instead of the desired parallel, straight passes.

Global Position System (GPS) is widely deployed in outdoor robots. GPS accuracy ranges from 5 m to 10 m [5]. Although WASS improvement reduces the error to 1.2-7.6 m [6], the accuracy is insufficient for our application. Differential Global Positioning System (D-GPS) has an accuracy about 1 m [7]. NavCom’s StarFire system, which reduces initial setup costs by not requiring a local D-GPS base station, can only provide decimeter accuracy which is still insufficient for our application [8]. At an accuracy of 1 cm RMS, RTK-GPS has the potential to exceed our accuracy requirement. In [9], the authors proposed a low-cost RTK-GPS receiver. However, similar to D-GPS, a RTK-GPS system also includes a permanent base station, which dramatically exceeds the cost of a laser ranging system or an ultrasonic positioning system. In addition, RTK-GPS does not provide sufficient orientation information in static conditions.

Ultrasonic (US) positioning systems have been demonstrated as a successful low-cost and high-precision positioning system for indoor applications. The Cricket system achieved 1.2 m accuracy within a 9 m radius from a beacon [10]. By increasing the beacon density, Cricket improved the accuracy to 5 cm [11]. In [12], a broadband ultrasonic location system was proposed and achieved 2.2 cm accuracy in a small room. For outdoor applications, environmental conditions need to be carefully considered and compensated. In [13], the authors presented an ultrasonic positioning system for localizing archaeological
findings which achieved an accuracy of 5 mm in a volume of 2 m × 2 m × 0.4 m but was only suitable for static measurements in a limited working space.

To overcome these limitations, we proposed a high-precision cost-effective local positioning system for dynamic outdoor environments. The backbone of our LPS is an ultrasonic positioning tower with online wind-speed and temperature compensations. Four portable beacons are placed around the perimeter of a green. To estimate the distance to a beacon, the robot measures the propagation time as an emitted ultrasonic signal travels from the robot to the beacon (i.e., the time-of-flight, TOF). Additionally, the robot utilizes a 32-element infrared-sensor array to measure the relative angle to each beacon and estimate the robot’s orientation. This system achieves a sampling rate up to 10 Hz. The proposed LPS system has several advantages over existing local positioning systems: first, the accuracy of the proposed LPS not only meets our specification but also, to our best knowledge, exceeds current outdoor ultrasonic-based positioning systems; second, the installation and maintenance of LPS is both simple and affordable due to the modular design and portable/interchangeable beacons; third, the proposed LPS has been extensively tested to verify its reliability and performance in an outdoor environment. Prototype robots have been deployed at several testing sites across the United States to evaluate performance in a wide-range of environmental conditions. Experimental data and field tests show that the proposed LPS meets our specifications, reliability requirements, and target cost.

The paper is organized as follows: in Section II, the RG3 robotic greens mower and its operation are briefly described. Section III presents an overview of LPS. Section IV details lateration measurements, and Section V discusses angulation measurements. Section VI presents experimental results, and Section VII contains concluding remarks.

II. THE RG3 ROBOT AND ITS MOWING OPERATION

The RG3 is a specialized mower designed specifically for the upkeep of golf course greens. Table I lists the range of environmental conditions encountered during daily operation.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ambient temperature</td>
<td>0 to 40° C</td>
</tr>
<tr>
<td>wind speed</td>
<td>15 m/s max</td>
</tr>
<tr>
<td>ambient light level</td>
<td>near 0 to &gt;100 klx</td>
</tr>
<tr>
<td>terrain slope</td>
<td>±5° (on green)</td>
</tr>
<tr>
<td>green size</td>
<td>275 to 900 m²</td>
</tr>
</tbody>
</table>

To achieve locomotion, a traction drive is located at the rear of the robot, and the entire traction drive is rotated to steer the robot. The RG3’s mechanical specifications are provided in Table II.

To perform a mowing operation, four beacons are manually placed onto permanently installed platforms surrounding a green and automatically power on. The RG3 measures the distance and angle to each of the four beacons, and determines which green it is on based on the geometry of the quadrilateral formed by the four beacons. The RG3 begins autonomous operation and maneuvers a cutting head across the green in straight, parallel passes to create a striped pattern demonstrated in Fig. 1. The readers are encouraged to visit our website for more details and related videos at http://precisepath.com.

To meet or exceed the performance of a human operator, the RG3 uses a typical overlap between successive passes of 8 cm. Full mowing coverage of a green must be achieved; failing to mow a region of turf between passes is unacceptable for daily golf course maintenance. To achieve these objectives, LPS must have accuracy less than 5 cm and must achieve this level of performance at all positions on a green as large as 900 m².

III. SYSTEM OVERVIEW

The system architecture of the RG3 is shown in Fig. 2.
The LPS measures laterations and relative angles from four beacons and sends this information to the sensor fusion module. To estimate the robot’s pose, the sensor fusion module utilizes a Bayesian filter to combine LPS’s information with data from an odometer and inertial sensors. With the estimated robot pose, the motion controller determines the necessary steering and velocity commands, which are actuated by a drive-by-wire module.

The LPS consists of the Local Positioning Module (LPM) located on the RG3 and a set of 4 battery-operated beacons. As illustrated in Fig. 3, the LPM measures the distance to each beacon using US TOF, and asynchronously measures the relative angles of infrared (IR) light emitted from the beacons. Additionally, the LPM maintains a bidirectional radio-frequency (RF) communication link with each beacon that is used for time synchronization.

IV. LATERRATION MEASUREMENT

The LPM, equipped with a circular array of 12 piezoelectric US transmitters, achieves 360° angular coverage for US signal emission. These transmitters were selected for maximum sound output to overcome various sources of attenuation encountered in an outdoor environment. To initiate a lateration measurement, the LPM uses the array of transmitters to generate an ultrasonic pulse at time \( t_t \). This pulse propagates across the green and is received by all of the beacons. Each beacon has an US receiver with a hemispherical reception pattern, and has an internal clock which is synchronized with the LPM. When the ultrasonic pulse is received, the beacon records the time \( t_r \) that it subsequently transmits back to the LPM over RF. Because the LPM has achieved time synchronization using the RF connection, the TOF measurement for beacon \( i \) can be converted to a distance \( d_i \) according to (1), where \( c \) is the local speed of sound.

\[
d_i = (t_r - t_t) \ast c \quad (1)
\]

Fig. 4 illustrates the geometric placement of four beacons and the lateration and angle measurements with respect to a robot. To establish the coordinate frame of our local positioning system, we arbitrarily select one of these four beacons as the origin and label that beacon as index 0. The remaining beacons are enumerated in a clockwise fashion. Using the beacons indexed 0 and 1, we define the orientation of the coordinate system (y-axis). From the lateration and angle measurements, we calculate the robot’s pose \((x_r, y_r, \theta)\) where \((x_r, y_r)\) is the robot’s location and \(\theta\) is the orientation.

LPS contains a sensor noise model for lateration to predict the accuracy of a given measurement. For a measured \( d_i \), this noise model returns a standard deviation, \( \sigma_{d_i} \), that is utilized in an iterative Bayesian filter inside the sensor fusion module. For the purpose of characterizing the performance of LPS, however, a closed-form position solution with minimal filtering is desired. To this end, (2) is minimized to calculate \((x_r, y_r)\) using only four lateration measurements.

\[
\min \left( \sum_{i=0}^{3} \frac{d_i - \sqrt{(x_r - x_i)^2 + (y_r - y_i)^2}}{\sigma_{d_i}} \right) \quad (2)
\]

Because all beacons receive the same ultrasonic pulse transmitted from the LPM, the lateration measurements are inherently synchronized. The absolute position of the LPM at the time of the US transmission \( t_t \) can be determined without the need for interpolation to compensate for the robot’s motion.

A. Laterration Environmental Compensation

LPS must meet the design objectives in the wide range of environmental conditions encountered in daily outdoor operation. Specific sensors and algorithms allow LPS to compensate for variations in ambient temperature as well as prevailing winds.

A forced-air temperature sensor measures the ambient
temperature $T_c$ (in Celsius) and updates the local speed-of-sound in real time according to (3).

$$c = 331.5 \sqrt{1 + \frac{\frac{T_c}{273.15}}{1}}$$

(3)

An ultrasonic anemometer is located at the top of the LPM and measures the local wind speed and direction, $s_w$ and $a_w$, respectively. For a lateration measured to beacon $i$, LPS calculates a wind correction $w_i$ using (4).

$$w_i = d_i \cos(a_i - a_w) \cdot \frac{s_w}{c}$$

(4)

In higher, gustier winds, wind speed compensation becomes less certain and the lateration noise model predicts an increased standard deviation accordingly.

**B. Lateration Interference Scenarios**

Other than environmental conditions that can be measured and compensated, several scenarios exist which can degrade lateration accuracy. The beacon uses a high-gain, narrow-band receiver, which is very sensitive to ambient acoustic noise in its passband. LPS employs several algorithms to detect this case including analysis of the envelope of the received US waveform. Additionally, each measurement is verified using the robot’s predicted pose and outliers are rejected.

One problem commonly encountered by TOF measurement systems is multipath; when the direct path between transmitter and receiver is blocked, the receiver detects an echo and measures an incorrect TOF. In the proposed LPS, we can reject the multipath solution because the beacon ignores all subsequent US signals following detection of the initial pulse. In addition, when the robot is in motion, this issue is transient and short-lived.

One issue that LPS shares with GPS is the geometric dilution of precision (GDOP), which refers to the reduced positional accuracy when the physical location of the satellites relative to the GPS receiver is poorly constrained. Unlike GPS, LPS can use angle measurements to constrain the region of possible robot positions as illustrated in Fig. 5(b). Also, during the setup phase, beacon locations are selected to minimize GDOP.

**V. Angulation Measurement**

Outdoor robots can either directly measure their orientation, or can derive this value from successive position estimates. The latter approach suffers significantly at slow speeds, particularly while rotating. Because the RG3 executes tight, near zero-radius turns at the end of each mowing pass, this technique is not viable. The typical approach to directly sensing orientation in an outdoor environment is to use a magnetometer. It is well known that local electrical and magnetic interference degrade the accuracy of this class of sensors. In the RG3, proximity to high-current electrical motors precludes the use of a magnetometer.

To measure orientation, the LPM uses the RF connection to schedule a beacon to emit an IR signal. The LPM receives this IR signal using a 32-channel circular array of photodiodes. Using the amplitude measured on each channel, the angle to the beacon, $a_i$, can be interpolated as illustrated in Fig. 6.

This sensor configuration can be considered to be a 1 by 32 array of pixels with each pixel separated by 11.25°. The angular response of a photodiode was empirically determined in situ; this characterization allows angles to be measured with an accuracy of less than 1° despite the sparse placement of the sensing elements. Each channel measures the amplitude of the IR signal received; the receiver’s high dynamic range prevents saturation when the beacon is very close yet allows a maximum range of 35 m.

For angulation measurements, LPS also contains a sensor noise model which predicts the accuracy of a given measurement, $\sigma_{ai}$. Using the estimated robot position from (2), the following equation is minimized to calculate $\theta$.

$$\min \left( \sum_{i=0}^{3} \frac{\theta + a_i - \tan^{-1} \left( \frac{y_i - y_f}{x_i - x_f} \right)}{\sigma_{ai}} \right)$$

(5)

To quantify the accuracy of angle measurements, a 2-
axis spin table was used. As illustrated in Fig. 7, angles were measured to a stationary beacon as the LPM was rotated about 2 axes. As the LPM is rotated about the horizontal axis in discrete steps, and the measured angle to the beacon is compared to \( a_k \) as reported by an encoder. Testing is repeated at different vertical angles. The angulation measurements should be independent of the vertical angle \( a_v \); that is, changes in \( a_v \) should have no effect on the measured angle \( a_i \). Data was collected over the nominal range of vertical angles encountered during a mowing operation. Fig. 8 displays the results of this test; the angle error is 0.12° RMS.

**Fig. 8.** Histogram of the measured angle error over the nominal range of vertical angles.

### A. Environmental Considerations for Angulation

Although less sensitive than lateration measurements, certain environmental conditions can affect angulation. It is well known that sunlight contains significant near-IR content. To prevent interference during the brightest parts of the day, the photodiodes are positioned such that they are shaded by the structure of the LPM. When the sun is low in the sky, the shading is no longer effective. However, the sunlight is attenuated by the atmosphere, and direct low-angle sunlight does not impede angle measurements. Through testing, LPS has been found to show no degradation in angulation performance throughout the day.

### B. Angulation Interference Scenarios

Several conditions exist which could degrade the accuracy of angle measurements. IR signal collisions occur if the LPM receives IR signals from multiple beacons simultaneously. The overlap of the signals from two different sources generates an erroneous angle measurement as illustrated in Fig. 9(a). To prevent IR signal collisions, the LPM staggers the trigger times for IR transmissions from each beacon.

The most common cause of angulation interference is occlusion and can be caused by severe terrain, equipment, or individuals performing maintenance tasks on the green and is illustrated in Fig. 9(b). The angulation noise model employs algorithmic evaluation of the received signal to detect this occurrence and increase the predicted standard deviation. If a beacon is occluded, redundancy provided by the other three beacons prevents performance degradation.

When the beacon emits an IR signal, a unique identification code is encoded into the signal. The LPM decodes the identification code when the IR signal is received. Hence, the angle response can be conclusively associated with the beacon. The design of this protocol includes error checking to prevent incorrect IR decoding. In the event of signal corruption, the response will be ignored. This mechanism also serves to reject any spurious in-band IR signals that might be received by the LPM.

### VI. EXPERIMENTAL RESULTS

To quantify the accuracy of LPS, specialized test equipment was designed and built. The LPM was mounted to a belt-driven cart which traveled along a straight track. During static testing, data was collected at positions A through F.

**Fig. 10.** Position of the track during data collection. During static testing, data was collected at positions A through F.
Testing was performed on a golf course green and the position of the track relative to the local coordinate system was carefully measured. The accuracy of \((x, y)\) and \(\theta\) were analyzed separately. Position error was defined as the Euclidean distance between the measured \((x, y)\) and the position of the cart along the track. Lateral error (perpendicular to the track) and longitudinal error (parallel to the track) were also calculated. The measured \(\theta\) was compared against the known orientation of the cart to determine the orientation error. For all data sets, measurements outside \(\pm 3\sigma\) were determined to be outliers, which resulted in the rejection of less than 0.5% of measurements.

The static performance of LPS was analyzed at several locations along the track as shown in Fig. 10. The position and orientation errors are summarized in Table III.

<table>
<thead>
<tr>
<th>Location</th>
<th>Lateral Accuracy (RMS)</th>
<th>Longitudinal Accuracy (RMS)</th>
<th>Position Accuracy (RMS)</th>
<th>Orientation Accuracy (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.3 cm</td>
<td>2.6 cm</td>
<td>3.4 cm</td>
<td>0.22°</td>
</tr>
<tr>
<td>B</td>
<td>2.0 cm</td>
<td>2.8 cm</td>
<td>3.4 cm</td>
<td>0.04°</td>
</tr>
<tr>
<td>C</td>
<td>2.7 cm</td>
<td>2.5 cm</td>
<td>3.6 cm</td>
<td>0.05°</td>
</tr>
<tr>
<td>D</td>
<td>2.4 cm</td>
<td>1.8 cm</td>
<td>3.0 cm</td>
<td>0.39°</td>
</tr>
<tr>
<td>E</td>
<td>1.5 cm</td>
<td>2.1 cm</td>
<td>2.6 cm</td>
<td>0.06°</td>
</tr>
<tr>
<td>F</td>
<td>1.4 cm</td>
<td>3.4 cm</td>
<td>3.6 cm</td>
<td>0.27°</td>
</tr>
</tbody>
</table>

To characterize the dynamic performance of LPS, ten data sets were collected as the cart travelled approximately 18 m along the track at 1.5 m/s. Histograms of the lateral and longitudinal position errors are shown in Fig. 11(a) and 11(b), and the combined position error is 3.1 cm RMS. The orientation error has a standard deviation of 0.23° RMS as shown in Fig. 11(c).

VII. CONCLUSION

This paper has presented the design and evaluation of the LPS used by the RG3 robotic greens mower. The approaches detailed herein describe the use of US TOF technology that enables the RG3 to match the performance of an experienced human worker. This system has been found to be reliable and robust in a moderately structured outdoor environment. Among currently available absolute positioning systems, LPS fills a gap between low-cost, low-accuracy sensors and precision, high-cost outdoor systems.

Several opportunities exist to extend the range of LPS. Lateration can benefit from an alternative mechanism to generate a US signal with increased sound pressure level and the capability to modulate data into the transmission. Enhanced filtering in the beacon can improve noise rejection, and the modulation of the US signal could improve the signal-to-noise ratio. Additionally, automatic redeployment of beacons serves to extend the working area indefinitely.

LPS is being considered to facilitate automation of several other golf course maintenance activities, including raking sand traps and mowing other regions of the golf course. Outside of the golf course industry, this technology can be applied to maintenance of other sports fields as well as commercial landscaping. Although this paper has discussed an application which can be considered to be a two-dimensional environment, LPS can be utilized in fully three-dimensional spaces. Through enabling technologies such as LPS, automation can continue to pervade daily life.

REFERENCES


