A High-Precision Millimeter-Wave Navigation System for Indoor and Urban Environment Autonomous Vehicles

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***Abstract* — This paper presents a mm-wave based navigation system capable of measuring and tracking a vehicle's position with centimeter scale accuracy. The system uses two 144 GHz transmitters modulated with 13 and 14 MHz tones combined with quasi-optical lenses to establish a mm-wave beam that defines navigational pathway for a vehicle to follow. The system is suitable for applications where precision guiding of small autonomous vehicles along a precise path is required such as navigating indoors or in cluttered urban environments.**

Index Terms — millimeter-wave navigation, UAV navigation

I. Introduction

While navigation at the meter scale for large vehicles remains dominated by global positioning systems (GPS), the appearance of small autonomous vehicles [1] has led to the emergence of air and ground navigation scenarios where centimeter scale accuracy is required to define a path through obstacles or to approach a point through a specific path of travel. These situations include navigating autonomous ground vehicles through urban or indoor environments filled with obstacles and navigating in places where GPS satellite signals are intermittent. Even landing on meter scale runways in highly cluttered environments with small autonomous aircraft has become a possibility with recent advances in UAV technology.

CMOS radar technologies for automotive applications based on frequency modulated continuous-wave (FMCW) ranging and centered at the 77 GHz band have recently emerged [2]. The bandwidth of these CMOS radar systems is still limited to the 100-500 MHz regime due to the difficult linearity requirements placed on the frequency sweep generation circuitry. While this bandwidth definitely provides useful meter-scale resolution for local and highway driving scenarios, it does not offer the cm-scale accuracy required for precision navigation through indoor environments containing many obstacles.

The typical indoor navigation scenario however, is distinctly different from the automotive radar driving scenario in that the desired pathway can be known at the time the system is designed. In automotive navigation the roadway shape relative to the vehicle (turns, slopes, intersections, etc.), and relative position of other cars on the road is constantly changing, and the system must adapt. In an indoor navigation scenario, the positions of obstacles are relatively static (furniture, walls, etc.) and the navigation system can be designed with specific knowledge of where these objects are located and what pathway can be taken to avoid them.

A similar scenario to this indoor environment is the instrument landing system (ILS) localizers adopted by all major US airports for guiding commercial aircraft during landing [3]. These navigation systems define the pathway an aircraft must follow as it lands on the runway in order to avoid tall buildings, power lines and other dangerous obstructions. The operation of the ILS system is relatively straight-forward compared to GPS. As shown in Fig. 1, a ground station (stationary) is placed at the end of the runway and uses two highly directional antenna arrays to transmit two radio beams at slightly different angles. While each beam operates on the same UHF carrier frequency (110-130 MHz), they are AM modulated with different baseband tones. For systems in the USA, the left beam (from the aircraft's vantage point) is modulated with a 50 Hz tone while the right beam is modulated with a 75 Hz tone. At the receiver's output on board the aircraft, these two tones will be superimposed. By comparing the relative amplitudes of the received left and right tones, the position of the aircraft relative to the runway can be determined.

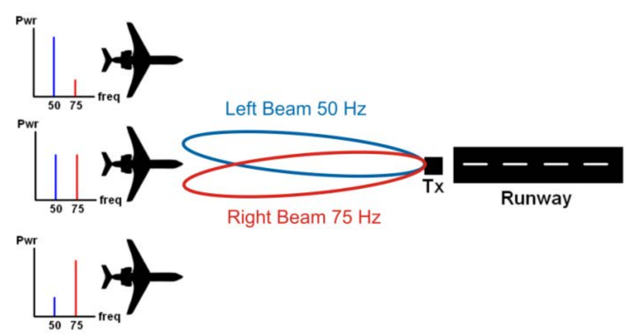

Fig. 1. Operation of existing ILS navigation system for commercial aircraft navigation.

Operation of the system occurs as follows: In the center of the pathway both tones (50 and 75 Hz) will be received with equal amplitude as the geometry is symmetric and the vehicle is an equal distance from the center of each beam. If the vehicle moves towards the left side of the pathway the 50 Hz

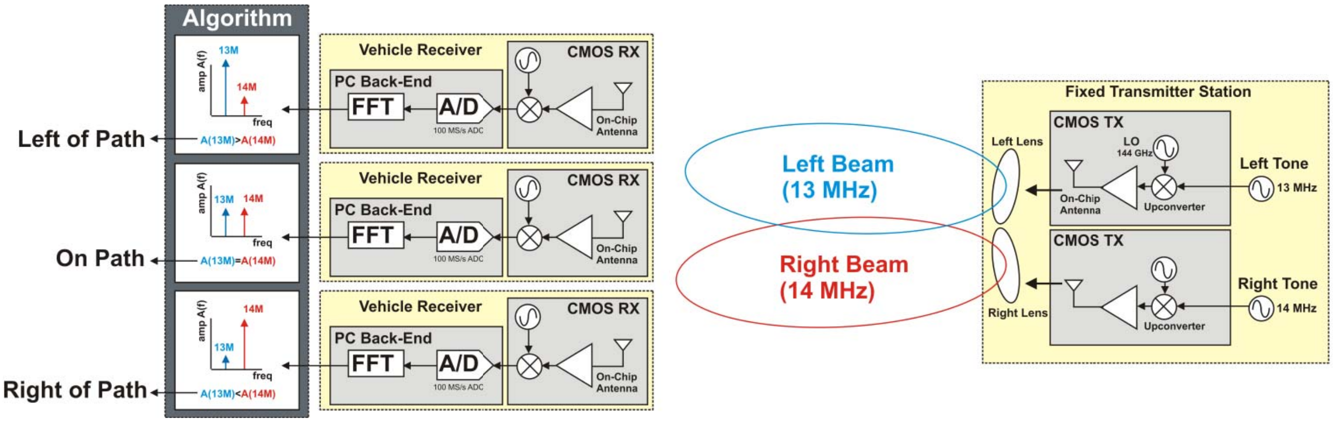

Fig. 2. Simplified block diagram of mm-wave navigation system including receiver system and back-end processing algorithm placed on the vehicle (left) and simplified block diagram of the fixed transmitter station using CMOS mm-wave transmitters (right).

tone will have higher amplitude than the 75 Hz tone as the vehicle will be closer to the center of the left beam and further from the center of the right beam. At the right side of the pathway the situation is reversed and the 75 Hz tone will have higher amplitude than the 50 Hz tone. While this ILS technology is an excellent solution for alignment of large aircraft to large runways, its UHF nature limits the attainable resolution and requires antennas on the order 1-2 meters, making it inapplicable to indoor applications where such large antennas would not be practical.

II. PROPOSED MM-WAVE NAVIGATION SYSTEM

In order to address the needs of indoor cm-scale navigation while overcoming the resolution and antenna size limitations of a UHF system, we propose a mm-wave based navigation system. Similar to the commercial aircraft landing system our proposed system uses a fixed transmitter station, except with the carrier operating at 144 GHz in the millimeter-wave band. 144 GHz was chosen based on available hardware. Unlike the commercial aircraft system where the two transmit beams are established with antenna arrays, our proposed navigation approach uses quasi-optical lenses (manufactured at JPL) to focus the transmitted radiation. The system level diagram of the fixed transmitter station is shown on the right-hand side of Fig. 2. A pair of CMOS mm-wave transmitters are AM modulated with 13 MHz and 14 MHz tones to define the left and right navigation beam. While other technologies will work equally as well, the CMOS circuits employed were readily available for our experiments.

The detailed design and measured performance of the CMOS transmitter and receiver components are reported in [4] and outside the scope of this discussion. Once radiated from the two transmitter chips, the two signals are collimated by a pair of dielectric lenses which have an angular offset of 3 degrees. This allows for the correct optical geometry to establish the beams that will define the pathway the indoor vehicle will follow. Onboard the vehicle itself we first use a CMOS mm-wave receiver to down-convert the two beams from the 144 GHz carrier frequency and recover the modulated tones which we use to determine position. The design of the receiver again is described in detail in [4]. In order to compare the two tones we quantize the receiver output with a commercial ADC and compute the FFT. In our prototype this is done on a PC with labview. After taking the FFT we compare the amplitude of the FFT-bin containing the 13 MHz tone with the FFT-bin containing the 14 MHz tone in order to determine the vehicle's position relative to the navigation system's pathway. Fig. 3 shows the receiver (block diagram) placed in 3 different positions relative to the transmitter station. At each position the algorithm that determines where the vehicle is located relative to the transmitter station is shown.

To characterize the operation of the proposed mm-wave navigation system we constructed prototype setup shown in Fig. 3. The fixed transmitter station is implemented with two CMOS Tx chips, two dielectric lenses and two signal generators (one tuned to 13 MHz, the other tuned to 14 MHz). On the vehicle side the receiver system is constructed on a push-cart so its position relative to the fixed transmitter station can be changed. The FFT function and position algorithm are implemented on a PC combined with a commercial ADC.

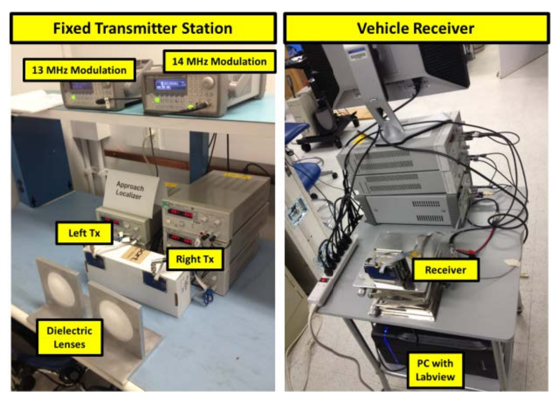

Fig. 3. Prototype setup of the mm-wave navigation system.

III. SYSTEM LEVEL CONSIDERATIONS

The attainable accuracy of the proposed navigation system is highly dependent on the quality of the beams from our transmitter station in terms of the beam shape and SNR. These depend greatly on our lens properties so we first measured the beam shape of our transmit lenses directly. Figure 4(a) shows the measured beam pattern of a single lens at 144 GHz. Note that readings below -20dBi are not possible as our CMOS transmitter chip's output power and PM4 power meter's sensitivity are limited.

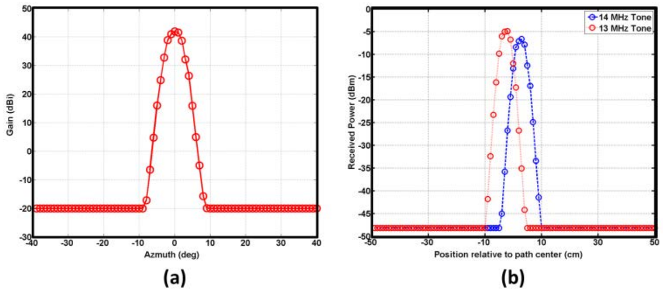

Fig. 4. (a) Measured dielectric lens directive gain. (b) Measurement showing receiver output power for modulated tones as position is varied across the navigation beams of the fixed transmit station at 2 meters range.

The commercial ADC chosen offered 60 dB of spur-free dynamic range with 50 MHz bandwidth (100MS/s) which allows it to directly quantize the two modulating tones. The FFT unit is an 8192 point structure implemented in software which provides a resolution bandwidth of 12 KHz per bin. With the receiver's reported noise figure of 10 dB in [4] and a detection requirement of at least 20 dB SNR (reasoning for this provided below) this gives the system a sensitivity S of:

S = -174 dBm/Hz + 20 dB SNR + 10 dB NF + 10log(12KHz)
S = -103.2 dBm

With the transmitter effective isotropic radiated power (EIRP) reported from [4] of 0 dBm and our 40 dBi dielectric lens gain at a reasonable application distance of 100 m (path loss = 115 dB at 144 GHz) the received power will be -76 dBm providing approximately 27 dB of link margin. If we set a 20 dB SNR requirement we can use the lens gain in Fig. 4(a) to determine the angular error at the worst case range of 100 m due to system noises. Using the same -76 dBm of received power and considering the 20 dB SNR requirement, the noise power will be -96 dBm. This will create a total received power of -75.91 dBm and translate to an error of 0.09 dB when both left and right beams are considered at worst case. Fig. 4a estimates an RMS angle error of 0.06 º which is a worst case position error of 100sin(0.06º) or 10.4 cm from the ideal pathway centerline at 100 m. Note that this resolution does not account for vibration and other mechanical noises.

IV. NAVIGATION SYSTEM VALIDATION

In order to validate the accuracy of the proposed mm-wave navigation system we first position the push-cart with the receiver at a distance of 2 meters from the fixed Tx station (limited by indoor testing). Moving the position from left to right across the pathway we record the amplitude of each tone to produce the right plot in Fig 4(b). As expected the individual tones are stronger at the left and right of the centerline of the pathway the vehicle will follow. Note although the peak power is mismatched the crossover still occurs well within 1 cm of the centerline. Since directly measuring the beam pattern in space would require many points to be taken (IE 100x100) we instead use the lens data from Fig. 4(a) and a best fit of the cross-section in Fig. 4(b) to generate an extrapolation of the beam pattern out to 100 meters distance using numerical methods. The generated result is shown in Fig 5.

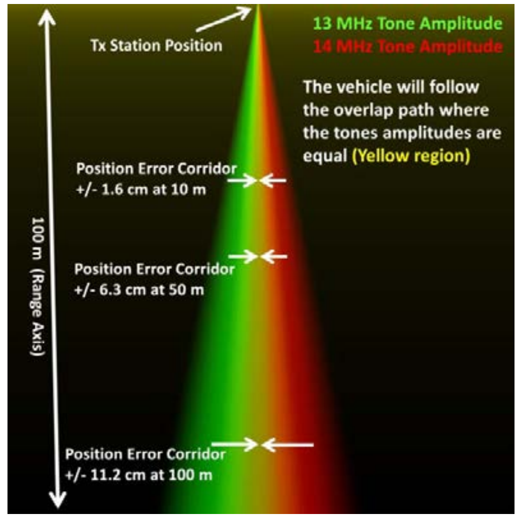

Fig. 5. Numerically generated beam pattern from lens and beam cross-section measurements.

As seen in Fig. 5 the resolution of the proposed navigation system remains below 10 cm beyond 50 meters range, making it highly suitable for indoor applications.

V. CONCLUSIONS

In this paper we demonstrated a new approach for guiding autonomous vehicles through cluttered indoor and urban environments. The approach uses dielectric lenses to form navigation beams at mm-wave frequencies and define cm accurate pathways for autonomous vehicles to follow.

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REFERENCES

[1] Li Juan et-al, "Indoor Water-Dispensing Robot with Two-Stage Localization", IEEE RSVP 2011, pp 303-307, Nov 2011.
[2] Yi-An Li et-al, "A fully integrated 77GHz FMCW radar system in 65nm CMOS", IEEE ISSCC 2010, pp 216-217, Feb 2010.
[3] FAA Pilot's Handbook of Aeronautical Knowledge. 2008.
[4] A. Tang, et.-al, "A 144 GHz 0.76 cm Resolution Sub-Carrier Phase Radar for 3D Imaging Applications" IEEE ISSCC 2012.