Precision RF Ranging as an Aid to Integrated Navigation Systems

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BIOGRAPHY

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Bradley D. Farnsworth (farnsworth.bradley@ensco.com) is a senior engineer with ENSCO focusing on high-precision RF ranging systems. He was the Sensors Technical Lead for the national semifinalist Team Case for the 2007 DARPA Urban Challenge, won a Best Student Paper award at the 2008 IEEE Sensors Conference, and has a patent pending in the area of RF ranging. Mr. Farnsworth obtained the B.S. (*summa cum laude*) and M.S. degrees in Electrical Engineering from Case Western Reserve University in 2006 and 2010.

ABSTRACT

Radio-frequency (RF) ranging can be an important aid to an integrated navigation system, providing a key element to updating location information when GNSS systems are unavailable, blocked, or otherwise denied. The majority of the recent literature on RF ranging aids has focused on ultra wideband (UWB) ranging methods, due to the increase in ranging precision that comes with increasing RF bandwidth. Practically, challenges exist with UWB due to implementation difficulties and regulatory limitations. This paper presents our approach to band-limited RF ranging [1, 2] that is high-precision (centimeters), flexible in spectrum utilization, and inexpensive to implement.

This band-limited ranging radio architecture has the potential for broad utility as an aid to integrated navigation systems. Several of these potential applications are described in this paper.

INTRODUCTION

The motivation for this approach to RF ranging is a revisit of the Cramer-Rao Lower Bound (CRLB) [3, 4] of the distance measurement variance for direct sequence spread spectrum (DSSS) RF ranging. By properly designing the baseband ranging message structure, it can be ensured that the CRLB is of sufficiently high accuracy, for example providing standard deviation bounds in the millimeter range, such that it is not the limiting factor in the system design. The structure of the CRLB equation can also be exploited to gain insight into system design space trade-offs including signal bandwidth, measurement update rate, range accuracy, and transmit power.

We have implemented a ranging radio designed to operate in the FCC-unlicensed industrial, scientific, and medical (ISM) bands, but is not specific to any carrier frequency or band. The real-time baseband processor is implemented in a Xilinx VIRTEX 5 FPGA and is programmed using high level MATLAB Simulink code. The flexibility of this implementation lends itself well to adaptation and optimization for custom applications, including the potential to integrate a precision ranging functionality with existing software-defined radio platforms. The prototype radio implementation is shown in Figure 1.

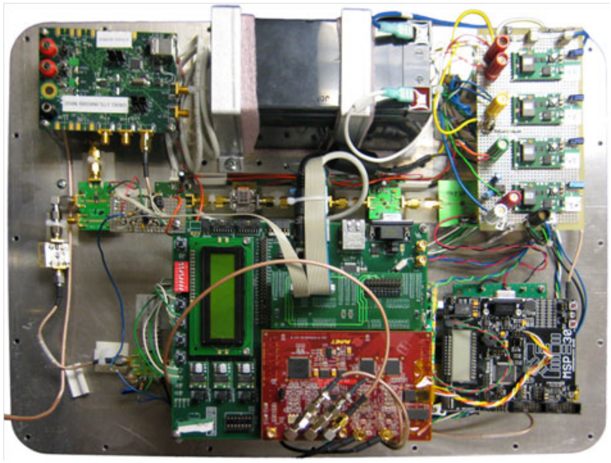

Figure 1: Prototype ranging radio platform.

Asynchronous operation is achieved by continually monitoring and tracking the phase of the received baseband signal through measurement of properties of the PN-code correlator output in the digital baseband processor. These phase estimates allow a direct estimation of the frequency difference in remote radio baseband clocks, and correction for that offset, as well as a precise correction factor to the measurement of the time of arrival of the RF ranging message at each radio. This focus on the digital baseband rather than RF parameters enables a truly carrier frequency agile system.

The implemented direct conversion system uses a carrier frequency in the 915 MHz ISM band, 22 MHz RF channel bandwidth, 11 Mchips/sec chipping rate, and +15 dBm transmit power. The digital baseband system is driven by 44 MHz oversampling A/D converters. Measurement accuracies of 7-cm (1-σ) were demonstrated at up to 100 meters distance, with ranging accuracy mostly limited by correctable implementation issues, and testing extended to 500 meters range with measured standard deviations of less than 20 cm (1-σ). Each fully-independent round-trip time-of-flight measurement occurs within 20 milliseconds, enabling measurement of dynamic motion.

An example of unfiltered static range data collected with the prototype RF ranging radios is presented in Figure 2. This 50-second data set was collected in an open field using patch antennas separated by 52.6 meters. The figure shows a standard deviation of better than 7 cm, no dropouts, and no significant outliers. This quality of data is typical for environments where the radio channel is line-of-sight with low multipath. Efforts are currently underway to improve performance in high multipath environments, but the extremely high line-of-sight precision presents a significant opportunity on its own.

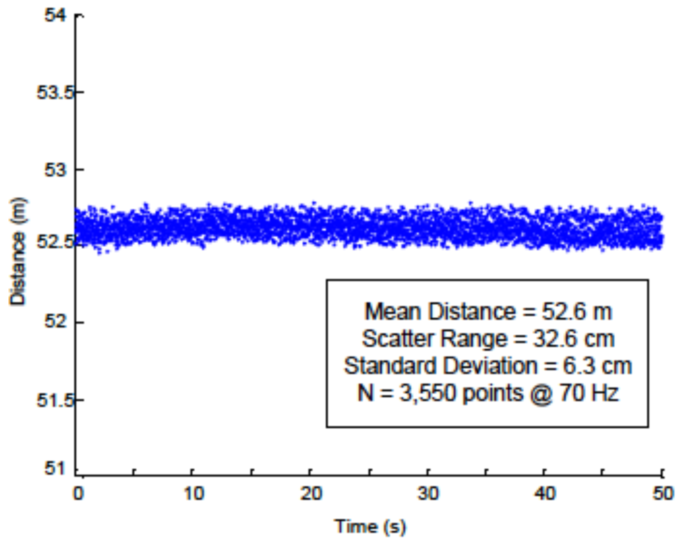

Figure 2: Unfiltered LOS range data.

ADVANTAGES OF BAND-LIMITED RANGING

This asynchronous round-trip RF ranging method could be implemented on a new or existing software-defined radio platform as an add-on function to digital communications or other applications. Since the entire ranging method is defined by the baseband architecture, it is highly portable. The implementation is independent of a selected carrier frequency, so this ranging method could be employed in any situation where there is sufficient bandwidth to achieve required range precision. A variable-bandwidth ranging radio implementation may be an ideal match for a cognitive radio application.

Since this method measures, tracks, and accounts for offsets in the baseband clocks, there is no need for precision time synchronization as a prerequisite for accurate RF ranging. The system is also insensitive to Doppler shifts due to platform motion, as the Doppler shift is added to the baseband clock uncertainty. Since the system accounts for baseband clock errors, inexpensive time references may be used to achieve precision results, provided that they are relatively stable over each measurement period.

By modifying the structure of existing digital radio message headers or payloads, precision ranging functionality may be added to existing systems with minimal impact on existing data communications. This is especially true if the signal used for range measurement is dual-purpose in that it also contains data germane to the primary system.

The design trade space for this ranging method is well-understood; therefore the system is flexible for many applications. In cases where range precision is not the driving factor, a robust range estimation may still be provided with reduced transmit power, less occupied spectral bandwidth, or fewer tracked PN codes. Trade-offs in PN code selection may allow operation in disadvantaged receivers through improved processing gain, or permit integration with CDMA systems.

LINE-OF-SIGHT PRECISION RANGING APPLICATIONS

A small, low-power standalone ranging radio device could be implemented as an independent aid to an integrated navigation solution or other application requiring or benefiting from precise range measurements. High-precision, narrow-band RF ranging technology has the potential to be a critical tool in tracking and navigation applications such as guided munitions such as JDAM, tracking dismounted soldiers, and local-area precision airframe guidance such as in automated aerial refueling.

TRACKING INTERTIALLY GUIDED MUNITIONS

An inertially-guided munition typically integrates a tactical grade inertial measurement unit (IMU) with GPS, and can continue to operate on inertial-only guidance if GPS is jammed. One common example of this is the Joint Direct Attack Munition (JDAM), as shown in Figure 3. Bombs equipped with a JDAM provide approximately 5-meter CEP position errors when GPS is available.

In some situations, GPS may be jammed or otherwise unavailable as the guided munition progresses towards its target. In this case, the munition will default to unaided inertial navigation. Position errors of 30 meters CEP are achieved for free flight times of up to 100 seconds based solely on inertial navigation.

The integration of high-precision range measurements from a RF ranging radio on the weapon and four ranging radios on the extremities of the aircraft could significantly aid inertial guidance in the absence of GPS.

Figure 3: F-15E Strike Eagle equipped with JDAMs.

Simulated positioning accuracy results for a GPS-denied JDAM, dropped from an F-15E Strike Eagle at 15,000 feet are shown based on the integration of GPS, ranging measurements and a Honeywell HG1900 tactical-grade inertial measurement unit (IMU) through the use of an extended Kalman filter (EKF) and an empirically-determined range measurement error model (based on analysis of range data measured in an unobstructed environment). GPS measurements are simulated as available prior to the bomb drop only. The IMU, GPS and range error models are shown in Table 1.

Table 1: Simulated sensor error models.

Sensor	Sensor Parameter	Value
HG1900 IMU	Sample Rate	100 Hz
	Gyro Bias	1 °/hr
	Accel Bias	1.0 mg
	Angle Random Walk	0.125 deg/hr $^{1/2}$
	Angle Rate Random Walk	20 deg/hr $^{3/2}$
	Velocity Random Walk	0. 016 m/s/hr $^{1/2}$
	Acceleration Random Walk	0.0007 m/s ^{2}/hr$^{1/2}$
GPS	Position Update Rate	20 Hz
	Position Error (1-_)	10 cm
Ranging Sensor	Range Update Rate	100 Hz
	Range Error (1-_)	1-100 cm

Positioning results are shown in Figure 4 for a MATLAB-based simulated integration based on range measurements of varying accuracies for a simplified trajectory and four ranging radios notionally mounted on the extremities of an F-15E with a simulated update rate of 100 Hz per radio. The reported circular error probable (CEP) position errors in the plot are based on the position when the bomb strikes the target.

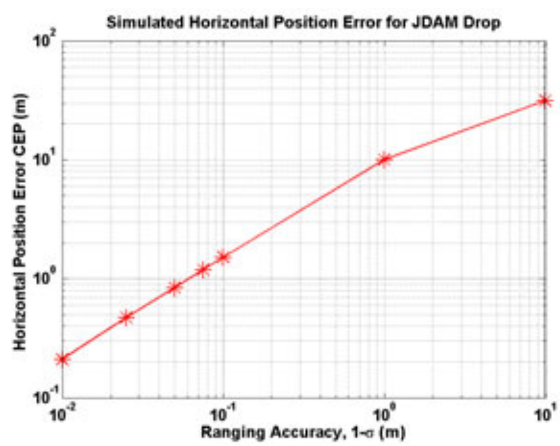

Figure 4: Position errors upon impact of a JDAM based solely on the integration of a HG1900 IMU and range measurements after the bomb drop.

The simulations show that the position error upon impact can be reduced by over an order of magnitude relative to unaided inertial navigation given ranging accuracies of less than 10 cm (1-σ).

TRACKING DISMOUNTED SOLDIERS

Tracking dismounted soldiers in environments where GPS is either unavailable or intermittently available is a difficult problem. It is critical for these systems to be small, light-weight, and low-power.

One approach to tracking dismounted soldiers is via an RF ranging system based up the soldier's vehicle, where their location relative to the vehicle is tracked. Such an RF system could be further enhanced with a boot-mounted inertial system for further precision [5].

Consider a military vehicle with ranging radio antennas mounted on the four corners measuring the distance to a small radio mounted in the helmet of each solider, as shown in Figure 5. A contour plot of the approximate horizontal position of error, based upon the horizontal dilution of precision is shown in Figure 6, assuming a 10 cm ranging accuracy.

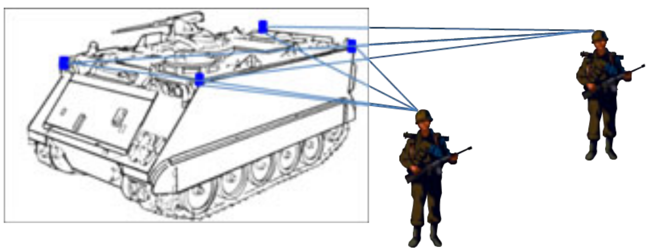

Figure 5: Dismounted soldier concept for integration of RF range measurements from a single ranging radio mounted on top of the troop carrier.

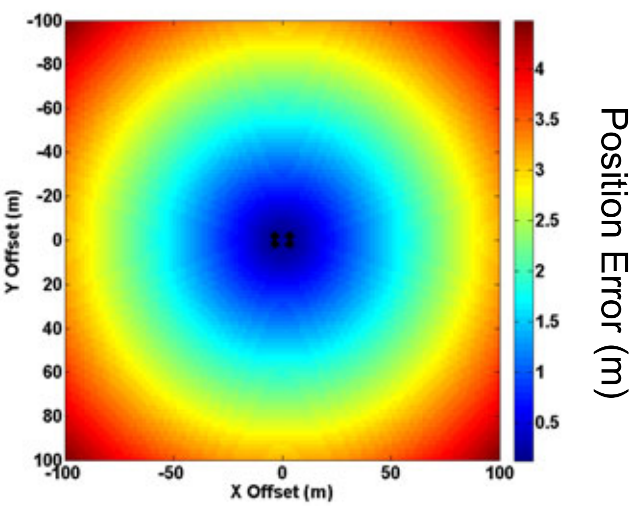

Figure 6: Approximate horizontal position error plot for four antennae mounted on corners of troop carrier.

Based on Figure 6, position errors of < 5 meters can be achieved based solely on range measurements given a ranging accuracy of 10 cm. In reality, however, the presence of clutter in some environments (vehicles, trees, buildings, etc…) will likely introduce multipath ranging errors that prohibit the use of a stand-alone range-based positioning system. Through tightly-coupled integration of range measurements with a boot-mounted IMU in an extended Kalman filter, occasional range measurements that don't fit the expected range variance can be discarded in real-time. The fusion of the inertial and filtered range measurements can significantly increase not only the position accuracy and mission time but also the integrity of the position estimate.

AUTOMATED AERIAL REFUELING

Automated aerial refueling (AAR) with sub-meter relative navigation accuracy has been demonstrated using a fixed refueling boom as shown in Figure 7 based on the tightly-coupled integration of a navigation-grade IMU and GPS [6]. However, in a GPS-impaired environment, unconstrained inertial navigation position errors are insufficient to complete AAR operations.

Assuming a positioning system is available to get the tanker and vehicle being refueled in general proximity, a relative positioning system based solely on high-precision ranging radios can provide a high-precision position estimate in a body-frame fixed to the refueling boom.

Figure 7: A flying boom approaches a Learjet that is being flown as a surrogate for a UAV during a demonstration of automated aerial refueling.

We consider a local, relative system consisting of three ranging radios mounted on the extremities of the refueling boom (two located on tips of the steering vanes and one co-located with the tip of the boom) that provide range measurements to a single radio co-located with the fuel receptacle of the receiving vehicle. Based on a simple position dilution of precision (PDOP) calculation, which relates ranging accuracy to position accuracy based on the radio locations on the boom, the expected 3D position accuracy achievable for a single suite of range measurements is shown in Figure 8. As the boom tip approaches the receptacle, the position accuracy increases. At ranges of less than a meter for ranging accuracies less than 1 cm, position accuracies of less than 5 cm can be achieved.

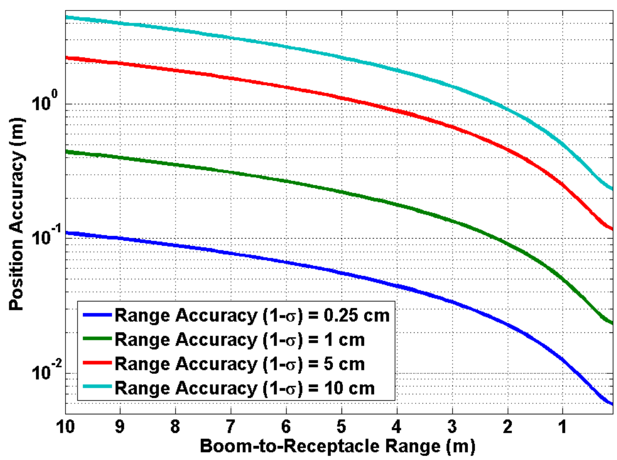

Figure 8: 3D position accuracy for a single suite of range measurements that were simultaneously measuring to a radio located on the fuel receptacle of the vehicle being refueled. The position errors are based on a simple PDOP calculation given the three radio locations (two mounted on the tips of the steering vanes and one co-located with the tip of the refueling boom) and expected ranging accuracies.

CONCLUSIONS

Round-trip time-of-flight RF ranging has been demonstrated on a software-defined radio in a low multipath, line-of-sight environment on a 915 MHz RF carrier. The system is capable of performing high-precision range measurements while operating with minimal synchronization. The method relies on baseband processing and is not tied to a specific RF spectrum. This ranging method is therefore flexible for use in many applications and integration with existing systems.

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