RF/RADIO SIGNAL DELTA-POSITION CALCULATION PROJECT (DELTARF)
ASELSAN

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Abstract. In this project, a GNSS-independent radio-navigation subsystem was developed to estimate delta-position using RF signals. Requested by ASELSAN, the system addresses navigation needs in GNSS-denied environments such as urban canyons and military zones. The project has two phases: Phase 1 estimates one-dimensional (1D) displacement using phase and frequency differences from two transmitters and one receiver; Phase 2 targets two-dimensional (2D) vectorial movement using three transmitters. Signal processing on ADALM-Pluto Software-Defined Radios (SDRs) uses Phase Locked Loop (PLL) for frequency synchronization and Delay Locked Loop (DLL) for signal separation. MATLAB and GNU Radio were used for simulation and real-time processing. External clocks replaced unstable internal ones, with polynomial-based drift compensation enhancing stability. Frequency Division Multiple Access (FDMA) was employed for signal separation, and a doppler-based method was used to extract velocity and compute displacement. A Raspberry Pi with LCD provides live feedback. The system achieved ±5 cm accuracy and offers a compact, modular solution for defense applications.

PROJECT DESCRIPTION

This project aims to develop a Software-Defined Radios (SDRs)-based navigation system that calculates delta position using RF signals. The real-world problem addressed in this project is the vulnerability of GNSS signals to the interference of jamming, spoofing, and multipath distortions especially in urban environments and military zones [1, 2]. In such places, the visibility of the satellites is limited which compromises the accuracy and reliability of position tracking systems. This poses major risks, especially for military operations that depend on precise navigation data. This work was carried out in collaboration with ASELSAN, one of Turkey's leading defense companies. The main objective is to design a system that calculates the relative movement of a receiver from the transmitter, by processing phase and frequency information of the received RF signals. By computing the relative displacement of a moving object, the need for absolute position information obtained from the satellites will be eliminated.

ASELSAN's interest in this solution is driven by the need for secure and accurate alternatives that can be integrated into various defense systems. Technologies such as LiDAR-based navigation, fiber-optic networks, or hybrid GNSS-IMU systems offer high precision but require expensive infrastructure and additional energy sources [3]. Some other SDR-based solutions like SDR-Fi are still dependent on external references such as Wi-Fi which limits the portability and operational range [4]. This project introduces a novel approach using cost-effective ADALM-Pluto SDRs with developed signal processing algorithms. Unlike GNSS systems, our method only determines the delta position instead of the absolute position reducing the complexity and improves signal acquisition time.

The system is implemented in 2 phases. Phase 1 involves a one-dimensional (1D) setup with a single receiver and two transmitters. In Phase 2, three transmitters and one receiver estimate two-dimensional (2D) movement. A Raspberry Pi module is integrated with the receiver to provide a compact and portable final product with an LCD screen interface. Signal processing is a key element of the system by incorporating Phase-Locked Loop (PLL) and Delay-Locked Loop (DLL) structures which were developed and optimized on both Matlab and GNU Radio. Kalman filtering was implemented to enhance the stability and accuracy of the phase tracking by reducing noise, handling frequency drifts and sample losses caused by the analog-to-digital converter of the SDRs. Additionally, external clock usage is preferred due to the instability of the internal clocks of the SDR devices. The distance estimations were done by tracking the doppler frequency. This frequency is separated from the frequency offset by Kalman filtering. At the transmitter side, frequency division multiple access (FDMA) is used to differentiate between signals. At the receiver side, modulation and filtering were done to recover these transmitted signals. The signals were transmitted at 1.5 GHz with a bandwidth of 2 MHz. With these specifications and methods, the system can clearly demarcate where the movement occurs and the phase discrepancies of the SDRs. Its performance target is a maximum error of ±5 cm in position estimation.

The Big Picture of the project is provided in Figure 1. It illustrates the Phase 2 setup, where three ADALM-Pluto SDRs act as transmitters and one as the receiver. The transmitters are pre-programmed using MATLAB via USB 2.0 protocol to transmit signals assigned at different center frequencies and are powered by a 5V supply. The receiver is mobile and initially connected to a computer for algorithm development using GNU Radio and MATLAB. Later, it is connected to a Raspberry Pi to ensure portability. The Raspberry Pi, powered by a 5.1V supply, is connected to an LCD via GPIO and displays distance data through a Python-based user interface via the HTMI protocol. It is pre-programmed using a computer through an Ethernet connection.

The end product is both cost-effective and modular, making it scalable and compatible with ASELSAN's wide range of products. Unlike existing solutions which require additional infrastructure, this system offers a highly adaptable alternative.

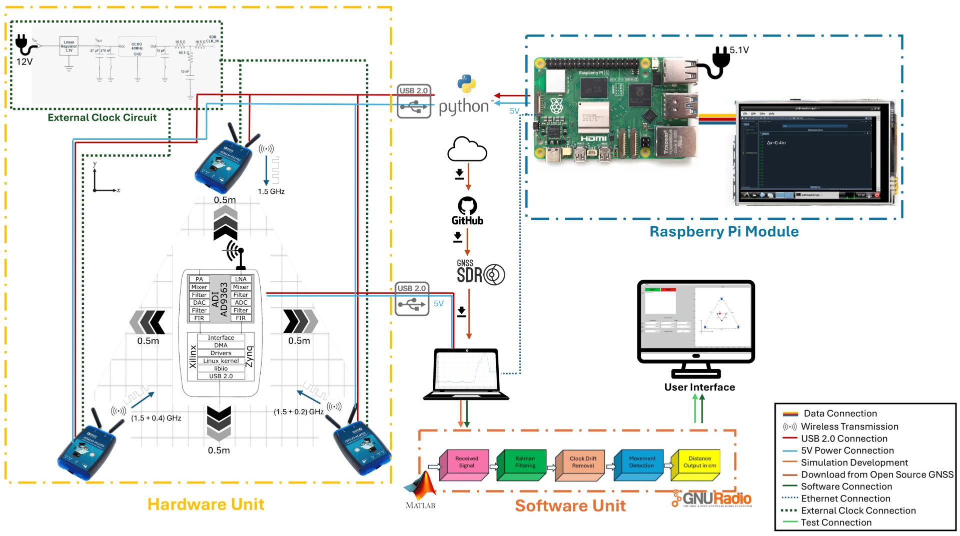

FIGURE 1. Big Picture of the Project

MILESTONES

- **Algorithm Development**

  Description: Implementation of the Phase-Locked Loop, Delay-Locked Loop and Signal Acquisition algorithms

  Success Criteria: Successful completion of the development, implementation, and validation of the DLL, PLL, and signal acquisition algorithms with a single SDR and a multi-SDR setup.
- **1D Δ-Position Calculation**

  Description: Achieving 1D positioning (Phase 1) using three SDRs to compute linear delta-position estimates

  Success Criteria: Achieving a positioning accuracy within ±5 cm
- **Synchronization**

  Description: Implementing synchronization between multiple SDRs to mitigate clock and phase differences that hinder accurate delta-positioning.

  Success Criteria: Successful synchronization of multiple SDRs, verified through the elimination of clock and phase offsets

- **Implementation of the Monitoring System**
  Description: Implementing a monitoring system to display 1D and 2D positioning results for both Phase-1 and Phase-2 of the project.
  Success Criteria: Displaying accurate distance measurements with minimal error on both the monitor and the Raspberry Pi–connected LCD screen.

DESIGN DESCRIPTION

Our project consists of two phases which aim to measure the distance in 1D and 2D. The setups for each phase can be seen in Figures 2 and 3 respectively.

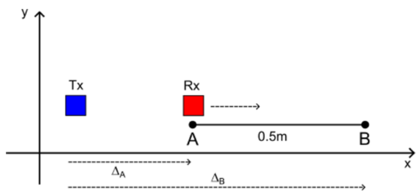

FIGURE 2. Phase 1 Setup

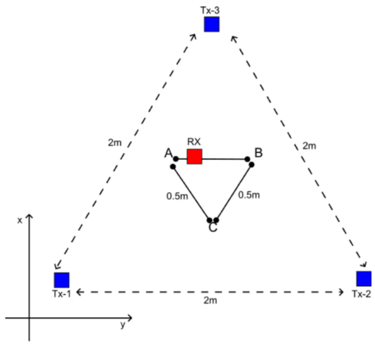

FIGURE 3. Phase 2 Setup

First Phase: Our solution strategy was to use phase tracking algorithms to measure the distance. Phase tracking was done with Kalman filtering, which constitutes the basis of our first milestone among signal acquisition algorithms [5]. Kalman Filter estimates two state variables from the measured complex phase of the received IQ signal: the phase and the frequency. The filter also tracks the windowed average phase error of the signal and determines a threshold value to detect skips between signal samples. Among these estimations, phase estimate and integral of the frequency are used to calculate the distance traveled. During the initial phases of the project, frequency drift estimation was also an output of the Kalman Filter and was used to determine the behavior of the clock.

Through multiple tests, it is realized that, after the initial movement of the SDR, there is a sudden and drastic change in clock drift; thus the clock frequency starts to follow a different polynomial trend immediately after acceleration. Moreover, during the first 10 seconds of operation, higher order change occurs compared to the steady-state and static operation of the SDRs. Firstly, methods like polynomial fit to this clock drift was proposed to overcome this problem, but that method was far away from the specified resolution criteria due to the instability of the internal clocks of the SDRs. Hence, to overcome this problem, external clocks with higher frequency stabilization were utilized. With these external clocks, the clock drift became much more stable. hence the drifts caused by the SDRs can be overcome, and thus the synchronization milestone is achieved. The only remaining problem regarding the phase tracking became the lost samples.

During some intervals, the receiver SDR lost some of the samples. These losses are not periodic and result in a drastic change in the phase and frequency estimations of the Kalman Filter. To overcome this problem, a Huber-Loss style method is implemented together with the Kalman Filter. The working principle of this filter depends on the error which the skipped samples create. Phase and frequency changes due to the movement are gradual, compared to the phase and frequency changes caused by the skipped samples. Hence, by determining an error threshold by averaging the Kalman phase error; and modifying the parameters like the measurement and process noise powers before and after the movement, the filter alleviates the effects of skipped signals by disregarding most of these occurrences.

Since phase 1 also includes two transmitter SDRs, Frequency Division Multiple Access has been utilized. Two signals with different center frequencies were transmitted and at the receiver side the signals were filtered using the appropriate low-pass filters. With this method the signals were differentiated easily.

After this step, using the Kalman filter, phase and frequency estimates of both signals are calculated. Then, using the difference of these estimations leaves us with only the shift caused by the movement, eliminating most of the clock drift caused by the receiver. To get rid of the remaining clock drift, the frequency offset is calculated. This offset is calculated by taking the mean of the frequency difference during the motionless interval at the beginning of the reception duration. When this offset is subtracted by the difference of the frequency difference between the signals and divided by two, the doppler shift is obtained. After scaling the doppler shift to obtain the velocity, the displacement can be found by integrating the velocity over the entire reception duration and dividing by the sampling rate to obtain the result in cms. This marks the success of the second milestone of our project, which is 1D position calculation. The overall flow chart of the signal processing part can be seen in Figure 4.

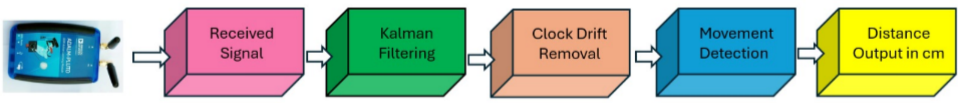

FIGURE 4. Flow Chart of Signal Processing and Distance Measurement

For this setup the required hardware tools are three SDRs, one for signal reception and two for signal transmission, a linear track on which the receiver SDR can move linearly, a sledge to put the SDR on the track and a computer to perform the signal processing steps. The signal processing steps were executed on MATLAB.

Second Phase: For the second phase of our project, we needed to calculate the distance traveled in a 2D setup. The distance calculation will be done using the same phase tracking method as described in the first phase. Additionally, to determine the direction of the motion, frequency division multiple access is utilized. The only difference between the methods used in first and second phases are the calculation of the distance. In the second phase a more advanced geometric distance calculation is used whereas in the first phase, only a scaled differential phase estimate was enough.

In addition to these algorithms, a monitoring interface is implemented. Moreover, a Raspberry-pi module with an LCD connected to it will be programmed to enhance the portability of the the receiver SDR. The LCD screen will display the distance traveled as well. Other than the Raspberry-pi module and the LCD screen, second phase of the project does not require any additional tools.

RESULTS AND PERFORMANCE EVALUATION

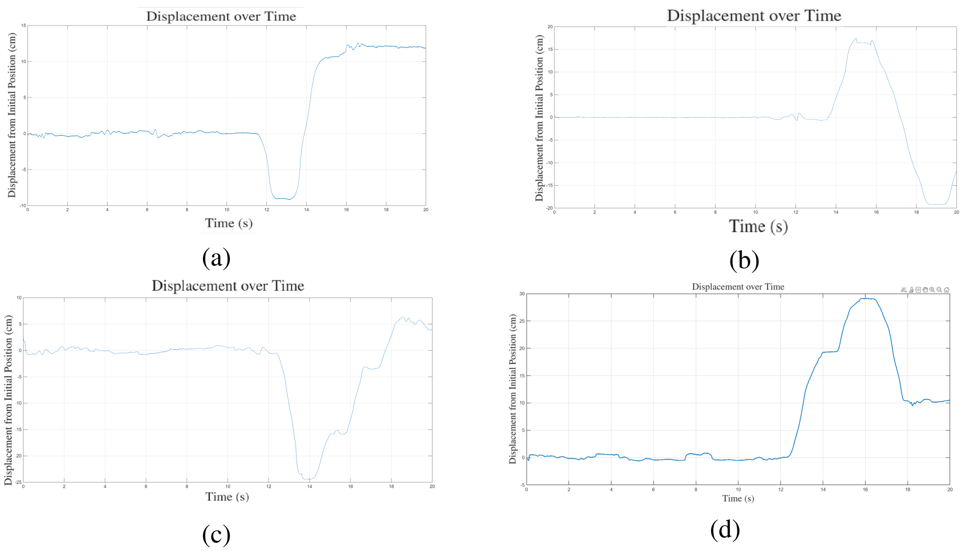

FIGURE 5. Distances from Initial Positions in 20 Seconds for Different Paths.

In the Figures 5(a) to 5(d), the plots of the disposition estimations are shown. In Figure 5(a), the receiver SDR is moved -10 cm, then +20 cm; in Figure 5(b), the receiver SDR is moved by +20 cm, then -40 cm; in Figure 5(c), the receiver SDR is moved by -25 cm, then +10 cm, +10 cm, +10 cm; finally in the figure 5(d), the receiver SDR is moved by +20 cm, then +10 cm, -20 cm. All these measurements are taken in the phase 1 configuration with 2 transmitter SDRs with a common oscillator and 1 receiver SDR which is moved in a 1D path. The receiver SDR is driven by its internal oscillator, and it records both of the signals using the FDMA approach. During the first 12 seconds of the transmission, the SDRs have been kept stationary to allow the internal oscillators to settle after power-up and to detect the constant frequency offset between the transmitters. The phase estimates of the received signals are fed to Kalman filter. Later, by subtracting the phase estimate outputs of the Kalman filter, we isolate the Doppler frequency shift of the movement and calculate the corresponding displacement.

Small fluctuations in displacement in the figures above are caused by noise and are limited to 1-2 cm. The sudden jumps are caused by the missed signal samples, which are the main sources of error. These missed samples result in an error of up to 5 cm of displacement. When all sources of errors are considered, algorithms precision is in the desired bounds for phase 1.

CONCLUSIONS AND FUTURE DIRECTIONS

This project successfully demonstrated that RF signals can be used to calculate delta-position without relying on GNSS infrastructure. In Phase 1, one-dimensional displacement estimation was achieved by processing the phase and frequency differences between two transmitted signals. Kalman filtering, DLL, PLL, and doppler-based velocity extraction were applied, and the integration of external clocks significantly improved system stability. While challenges such as sample loss and SDR oscillator behavior were encountered, parameter tuning and signal preprocessing helped maintain accuracy close to the ±5cm target.

In Phase 2, the system was extended to two-dimensional movement estimation using three transmitters. The system estimated delta-position by separating transmitter signals using FDMA and calculating movement through advanced geometric methods. The portable hardware setup—including a Raspberry Pi and LCD—enabled real-time monitoring and operation.

Future work will focus on making the system more reliable and fully independent. Improving Kalman filtering and frequency tracking will help handle movement-related issues better. Moving all processing to a Raspberry Pi or similar device will allow the system to run in real time without needing a computer.

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BEHIND THE SCENES