Gait & Posture 54 (2017) 1–7

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Inertial and time-of-arrival ranging sensor fusion

Paul Vasilyev[a], Sean Pearson[a], Mahmoud El-Gohary[a,*], Mateo Aboy[a], James McNames[a,b]

[a] APDM, Inc., 2828 SW Corbett Avenue, Portland, OR, USA
[b] Department of Electrical and Computer Engineering, Portland State University, Portland, OR, USA

ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form 11 February 2017
Accepted 16 February 2017

Keywords:
Bayesian estimation
Indoor positioning
Ultra wideband (UWB)

ABSTRACT

Wearable devices with embedded kinematic sensors including triaxial accelerometers, gyroscopes, and magnetometers are becoming widely used in applications for tracking human movement in domains that include sports, motion gaming, medicine, and wellness. The kinematic sensors can be used to estimate orientation, but can only estimate changes in position over short periods of time. We developed a prototype sensor that includes ultra wideband ranging sensors and kinematic sensors to determine the feasibility of fusing the two sensor technologies to estimate both orientation and position. We used a state space model and applied the unscented Kalman filter to fuse the sensor information. Our results demonstrate that it is possible to estimate orientation and position with less error than is possible with either sensor technology alone. In our experiment we obtained a position root mean square error of 5.2 cm and orientation error of 4.8° over a 15 min recording.

1. Introduction

There is a growing interest in wearable sensor systems for quantifying human activity and movement. Applications of this technology range from measuring gross activity throughout the day to monitoring specific symptoms of a disease or injury [1–6]. The underlying sensor technologies for these applications have advanced greatly over the last decade due to advances in low power integrated circuits that enable sample rates well above the Nyquist rate of most human movement (roughly 30 Hz) [7].

A common goal in the processing of this sensor data is to estimate the sensor orientation and position, known as pose, continuously during normal daily activities. Many early efforts focused on the use of wearable inertial sensors, which were mostly limited to orientation estimation [8–15]. Because the inertial sensors lack an absolute reference for orientation and position, the accumulated error from using the gyroscopes to estimate orientation grows linearly with time, *othtruein*(n). The orientation error results in an error in the estimated gravitational force when estimating the acceleration in the Earth frame. This error is compounded by integrating the estimated Earth frame acceleration twice to obtain an estimate of position. The combined effects of these errors causes the position error from inertial sensors alone to grow cubicly with time, *othtruein*(n^3).

Recently low-cost and low-power sensors have become available that are capable of measuring the time of flight between a transmitter and receiver based on ultra wideband (UWB). This makes use of very short pulses to achieve high spatial resolution. The two sensor technologies have advantages that are complementary. One can infer position from ranging sensors with an accuracy that does not degrade over time. However, it is not feasible to estimate the orientation from ranging sensors alone. This is due to the infinite number of orientation possibilities that can be inferred from the same ranging measurements when the sensor is stationary. The accuracy of position estimates is diminished when multipath is present or when the sensors are not within the line of sight of one another.

Inertial sensors are frequently combined with magnetometers to estimate the full sensor orientation (elevation, bank, and heading) [16,14,15]. These algorithms use gravity during periods of slow movement to improve estimates of the elevation and bank angles and use Earth's magnetic field to improve estimates of the heading. In many applications the sensor is in continuous motion for long periods of time and gravity cannot be used to improve the orientation estimate. Similarly, in many indoor environments the magnetic field is distorted and cannot be used to improve heading estimates. This limits the range of applications in which accelerometers and magnetometers can aid the gyroscopes in estimating orientation. Similarly, due to the rapid accumulation of error when integrating acceleration twice to estimate position, inertial sensors alone are unable to estimate position accurately except over brief periods from a known starting position. We propose to

* Corresponding author.
E-mail address: mahmoud@apdm.com (M. El-Gohary).

http://dx.doi.org/10.1016/j.gaitpost.2017.02.011
0966-6362/

fuse inertial and ranging technologies in a state space model to estimate pose with greater accuracy than could be attained with either technology alone. This technology can accurately estimate the orientation even during continuous movement and in environments with magnetic disturbances.

Several other groups have also investigated the possibility of fusing these two sensor technologies. Their approaches can be generally categorized based on loosely coupled and tightly coupled models. The loosely coupled models preprocess the UWB range measurements to obtain a position solution through trilateration [17–20]. This position estimate is then used as a measurement for the UWB-inertial fusion. This has the advantage of simplifying the model because the measurements are linearly related to the position estimates. However, trilateration requires a minimum of four simultaneous range measurements to unambiguously estimate the 3-D position of a tag and does not take advantage of the information provided by the inertial sensors. Tightly coupled models use the range measurements directly in the fusion framework [21,22]. Although the models are nonlinear, they are potentially more accurate than loosely coupled models and provide some advantages. For example, it is easier to detect outliers in range estimates due to multipath or occlusion. The tightly coupled approach is more scalable and can continuously provide estimates even when there are not enough range sensors to estimate position directly. We use a tightly coupled model.

Hol [21] and Asher [22] both use an unsynchronized wearable transmitter to transmit a message to a set of synchronized receivers. Since the transmitter is unsynchronized with the receivers, the time delay between transmission and reception is unknown and must be estimated. This approach to estimating position is called Time Difference of Arrival (TDOA), and it relies on a precise synchronization of the receivers. This can often be difficult to accomplish wirelessly. Since the distance is measured by the amount of time it takes an electromagnetic pulse to travel from the transmitter to the receiver at the speed of light, it takes only 3.34 ns of timing error to accumulate a 1 m range error. Therefore such precise synchronization is usually achieved through a physical wired connection of the receivers. This may be cumbersome or impractical.

Our approach uses a different fundamental UWB technology that does not require precise synchronization of receivers or transmitters. Each device acts as both a receiver and transmitter. Each device is equipped with a precise clock which can time-stamp transmit and receive events with nanosecond resolution. To measure the range a series of transmit and receive events are performed between two UWB devices in order to collect a set of precise time-stamps, which are then used to compute the range between them. To minimize the effects of clock drift, we use a ranging protocol called Symmetric Double-Sided Two-Way Ranging (Fig. 1).

This requires more power consumption and results in a slower sampling rate than a simpler two-way ranging, but it is considerably less sensitive to the mismatch between the frequencies of the clocks in the two devices. Our UWB radio network is comprised of stationary (anchors) and mobile (tags) devices. The tag sends a poll message to a specific anchor and records the transmit time T_{tx1}. The tag then listens for a response message. When the anchor receives a poll, it records the receive time A_{rx1}, sends a response back to the tag, and records its send time A_{tx1}. When the tag receives the response, it records the receive time T_{rx1}, and sends a second poll message recording the transmit time T_{tx2}. The tag then listens for the final response message from the anchor. The anchor listens for the second poll message. When the anchor receives the second poll it records the receive time A_{rx2} and sends the final response to the tag. When the tag receives the final response message it has all the time-stamps necessary to computethe range between the tag and anchor devices.

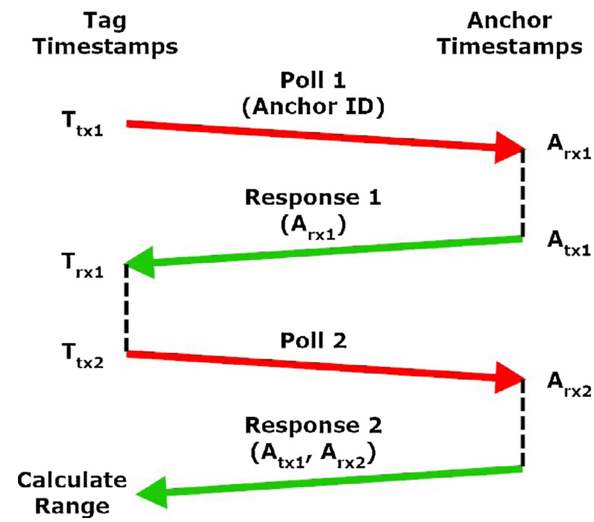

Fig. 1. Ranging protocol between tag and anchor.

$$d = \frac{(T_{rx1} - T_{tx1}) - (A_{tx1} - A_{rx1}) + (A_{rx2} - A_{tx1}) - (T_{tx2} - T_{rx1})}{4 * c} \quad (1)$$

Our unsynchronized UWB approach has many distinct advantages over the synchronized anchors approach based on time difference of arrival. For example, it does not require carefully synchronized transmitters or receivers. Eliminating the need to physically interconnect the transmitters or receivers enables this technology to estimate ranges between multiple wearable sensors that are not physically connected with one another. A consequence of our unsynchronized approach is that the ranging can only be done between one pair of devices at a time, and therefore the sample rate is inversely proportional to the number of device pairs in the network.

Our proposed tightly coupled state space model includes both a nonlinear process model and a nonlinear measurement model, both with additive noise. There are a variety of algorithms available for state estimation with nonlinear state space models. The extended Kalman filter (EKF) is one of the most common for tracking pose from fused UWB and inertial sensor data. The EKF is based on linearizing the process and observation models with a first-order Taylor series expansion. If the model is highly nonlinear, then the linearization may lead to poor performance. The EKF also requires calculation of Jacobian matrices for the process and measurement models, which can be tedious and error prone.

Sequential Monte Carlo methods, also known as particle filters, can overcome the performance limitations of the EKF [23], but they have computational requirements that are orders of magnitude larger than the EKF [24,25]. Unlike earlier approaches that used an extended Kalman filter [21] or an iterative Kalman filter [22], we use the Unscented Kalman Filter (UKF) [26] to fuse the inertial and ranging inertial sensors. Like the EKF, it relies on a linearization of the process and measurement models, but the linearization is done statistically with sigma points, which accounts for the effects of the variability in the state estimate. The computation required by the UKF is approximately the same as the EKF, but the accuracy is typically higher. LaViola [27] has shown the UKF to be more accurate than the EKF for orientation tracking, which is a key component of pose estimation.

Previous work has not precisely quantified the accuracy of the performance in this type of applications. Consequently, it is difficult to determine from the existing literature what level of position and orientation accuracy is achievable from the fusion of