Indoor Localization Using Inertial Sensors and Ultrasonic Rangefinder

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***Abstract*—This paper presents a simple, novel inertial sensor based indoor localization system which utilizes distance information between the top of the foot and the ground measured from ultrasonic rangefinder to detect the still-phase of the Zero Velocity Update (ZUPT) method. In this way, the computational consumption of the gyro-based ZUPT detection is avoided and one inertial sensor module is enough to extend the useful range of ZUPT method (both low- and high-speed human movements), thus the complexity of the system can be efficiently reduced.**

***Index Terms*—IMU, indoor localization and navigation, inertial sensor, still-phase detection, ultrasonic, ZUPT,**

I. Introduction

Although localization is becoming available to the general public and businesses via widespread use of GPS receivers, GPS signal can be blocked by high buildings, canyons or forests among others. It can be a significant problem in certain situations for emergency responders such as fire fighters.

Inertial sensor based localization systems provide a solution for personal navigation and localization by using inertial sensors such as accelerometers and gyroscopes which do not depend on the environment where pedestrians are located. However, the calculated velocity and position after the integration suffer from the accumulative drift error when using low cost inertial sensors. In order to overcome the drift error when operating integration, ZUPT algorithm which resets the foot speed at every step when the still-phase is detected was introduced in [1]. In this approach, the gyro-based still-phase detection required data recording and average/mean calculation [1], [2], which added more burdens to the hardware. Beside, although the drift problem of normal pedestrian movements with small velocity like walking can be solved, the same algorithm setting fails when operating high-speed movement, since steps can not be detected by using the same threshold value. Foxlin suggested enlarging the step detection threshold when experiencing high-speed movements [3], however no further details were given. Even if the correct threshold value for detecting high-speed movements can be determined, how to switch the threshold value between activities with different velocities is still a problem. Zhang presented an idea to use two inertial measurement units (IMU). The foot mounted IMU was used to implement the ZUPT detection based on the classification result provided by chest attached IMU, which was used to classify different movements and determine the proper ZUPT thresholds [4]. However, large computation of data processing, synchronization and communication between two IMUs increase the difficulty of system implementation. A shoe-embedded radar for ZUPT still-phase identification was proposed in [5], [6]. The radar embedded in heel is able to sense the position relative to the reflection surface. Unfortunately, the required hardware specification for antenna design is not easy to fulfill. Besides, no results were given on the high-speed movements.

Based on previous works, a simple indoor localization system using an ultrasonic rangefinder, which lowers the complexity of the system and meanwhile is capable of tracking both low- and high-speed human movements, is presented in this study.

II. Software Design

The following subsections will demonstrate two main sections of the software design: Inertial sensor based positioning calculates the orientation, velocity and position information from output of inertial sensors; Zero Velocity Update corrects the velocity and position information by resetting the velocity during still-phase.

A. Inertial Sensor Based Positioning

The orientation of the IMU module with respect to a body-fixed frame of axes, which is a frame or a Cartesian coordinates system fixed with respect to the sensor module body, is defined by three Euler angles named roll ϕ, pitch θ and yaw ψ. The IMU is assumed to be oriented parallel to this fixed reference frame of axes. The relationship between the angular rates of roll, pitch and yaw p, q, r, measured by gyroscopes inside IMU, the Euler angles and their rates, is given by

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}. \quad (1)$$

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Thus, the Euler angles can be derived by integration of the above equations using initial conditions of a known orientation data at a given time. However, since tangent tends to infinity when pitch angles are around $\pm 90°$, the error becomes unbounded. This problem can be solved by applying Quaternion algebra which uses four Euler parameters instead of three Euler angles to present the orientation and calculate the orientation of next time step. Details can be found in [7].

As the readings from the acceleration sensors inside IMU module, a_x, a_y and a_z, contain the gravity of earth g, the accelerations only generated from the human movement, i.e. the rates of the velocities V_X, V_Y, V_Z, in body-fixed frame, need to be calculated. The equations are given by

$$\dot{V}_X = a_x + V_Y \cdot r - V_Z \cdot q + g \cdot \sin\theta, \tag{2}$$

$$\dot{V}_Y = a_y - V_X \cdot r + V_Z \cdot p - g \cdot \cos\theta \sin\phi, \tag{3}$$

$$\dot{V}_Z = a_z + V_X \cdot q - V_Y \cdot p - g \cdot \cos\theta \cos\phi. \tag{4}$$

After the first time integration the obtained velocity components (V_X, V_Y and V_Z), are then transformed using the Direction Cosine Matrix (**DCM**) to give velocity along North (V_N), velocity along East (V_E) and downward velocity (V_D) in the earth-fixed frame, which is a frame fixed with respect to the earth.

$$\begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} = \mathbf{DCM}^{-1} \cdot \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix}, \tag{5}$$

where **DCM** is the matrix, which transforms data from earth-fixed frame to the body-fixed frame. Additional details can be found in [7]. V_N, V_E and V_D are then integrated the second time to give position information.

B. Zero Velocity Update

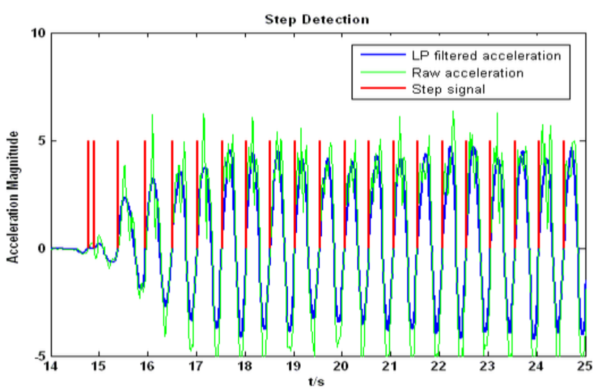

Fig. 1. Step detection

Conventionally, PDR is simply the estimation of a step length (or walking speed) and the direction of walking. The position information is able to be determined if the step length, direction and number of steps are obtained. Each step can be detected by acceleration signals and step boundaries are defined by the positive-going zero crossings of a low-pass filtered version of acceleration [8] as shown in Fig. 1. In this study, the 2^{nd} order Butterworth low-pass filtered acceleration signals of x-axis in body-fixed frame are used to detect each step. performance of this system depends on the accuracy of determining the stride length, which can be obtained by GPS or artificial neural network. However, constant stride-length condition may not always be met, since emergency responders may run, climb over debris, or may alter their stride length as a function of the weight of their gear.

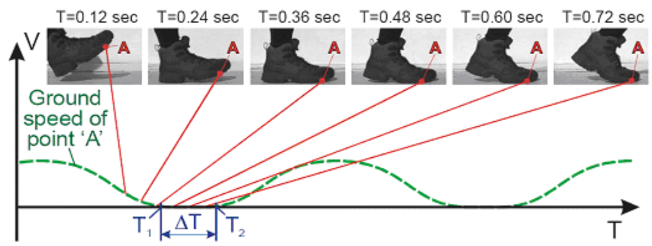

Fig. 2. Key phases in a stride [1]

According to [1], in the whole phases of a stride during normal walking, point A on the bottom of the sole was in contact with the ground for a short period of time, called 'still-phase' as shown in Fig. 2. During that time, 'A' was not moving relative to the ground and the velocity vector of 'A' was zero. The readings of the three velocities as well as accelerations were expected to show the result of zero during this time. If the reading was not zero, then the difference between zero and the momentary reading was assumed to be the accumulated errors during the step interval. As a result, the velocity error should be reset when still-phase is detected. In this way the accumulated errors from the accelerometer output could be effectively removed, at least for a few seconds. This method is called 'Zero Velocity Update'. The accuracy of the ZUPT based solution relies on the accuracy of the still-phase detection.

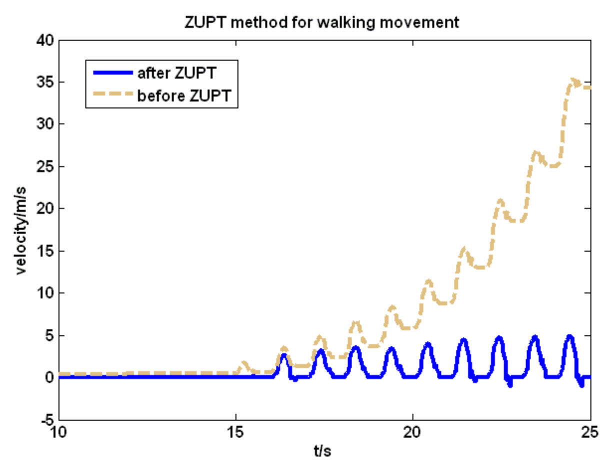

Fig. 3. Comparison between ZUPT applied and not applied velocity determinations

Since the distance between the top of the foot and ground is shortest within still-phase during a stride, this information can be used as indication for ΔT. In this study an ultrasonic rangefinder is mounted on the foot to measure the distance. When the measured value is lower than predefined threshold, we assume that the foot is within still-phase and thus the velocities and accelerations can be reset.

III. Hardware Design

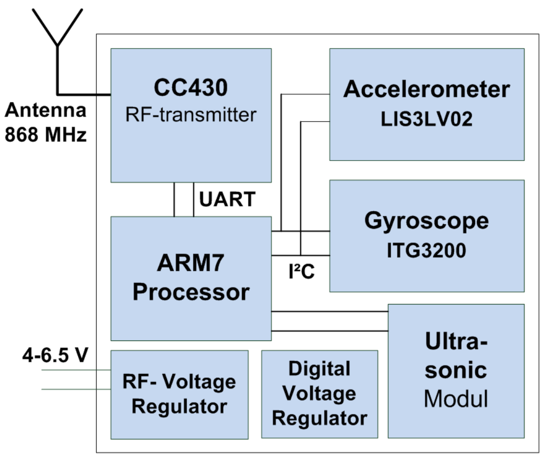

Fig. 4. System structure

A presented indoor localization system prototype was built, consisting of four parts: inertial sensors, ultrasonic rangefinder, microcontroller and wireless communication, which are shown in Fig. 4. The sensor signals and distance signal are firstly obtained from inertial sensors and rangefinder. Then, the demanded results are calculated from the obtained signals by microcontroller. At last, the controller outputs are transmitted and received via wireless communication.

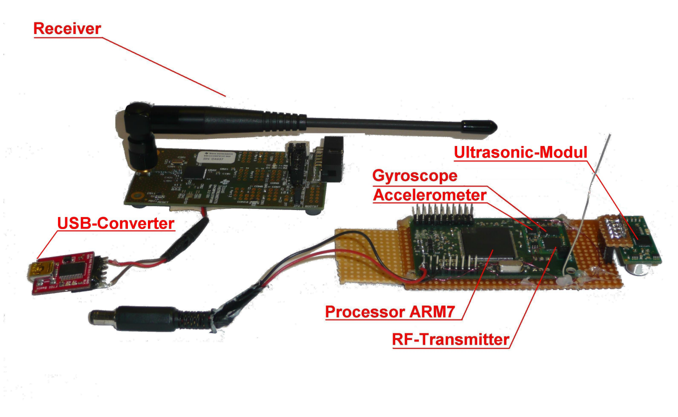

Fig. 5. System components

The 3-axis accelerometer LIS3LV02 from STmicroelectronics and 3-axis gyroscope ITG-3200 from InvenSense are used to provide inertial sensor data. SRF10 ultrasonic rangefinder from Robot Electronics is used to measure the distance between the foot and ground for still-phase detection. Each of them has digital output and can be communicated via I^{2}C bus interface. Microcontroller TMS470, microcontroller CC430 and its wireless development tool EM430F6137RF900 from Texas Instruments are used for algorithm implementation and RF communication. All the sensed data is sampled at $36Hz$.

IV. Experimental Results

The purpose of the experiments was to investigate the capability and accuracy of the distance based ZUPT detection when operating both low- and high-speed human movements. The system accuracy was assessed by comparing still-phase and velocity with ones obtained by gyro-based ZUPT detection. The system is mounted on the foot front as shown in Fig. 6.

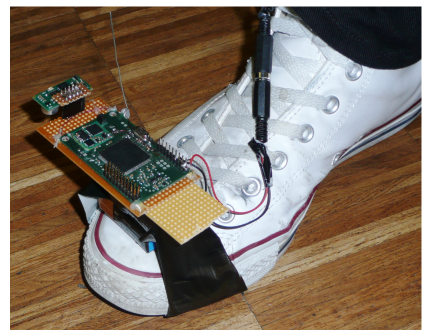

Fig. 6. System mounted on the foot

Since the raw data of the rangefinder can not be used directly, a 2^{nd} order Butterworth Low-pass filter is implemented before the detection procedure. As the system requires on-line processing, smaller cut-off frequency is chosen in this study so as to keep the window length short. The comparison of raw and filtered ultrasonic rangefinder data when walking and running are shown in Fig. 7 and Fig. 8, where thin green (light colour) line stands for raw data, and thick blue (dark colour) line for filtered date. Straight red line is the predefined threshold.

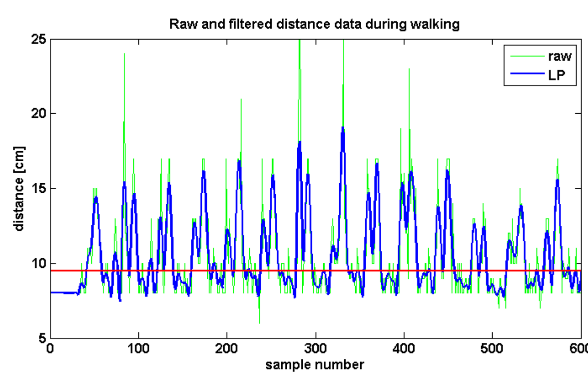

Fig. 7. Raw and filtered distance information when walking

In order to compare the still-phase detection accuracy using ultrasonic rangefinder with the conventional gyro-based

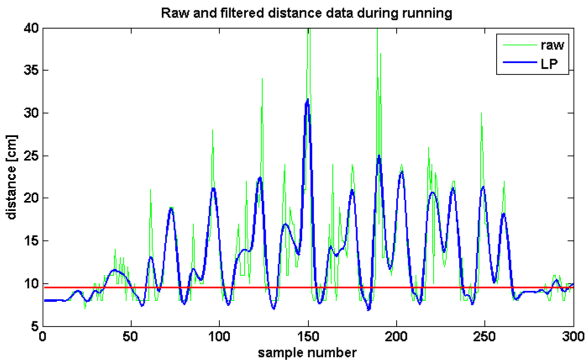

Fig. 8. Raw and filtered distance information when running

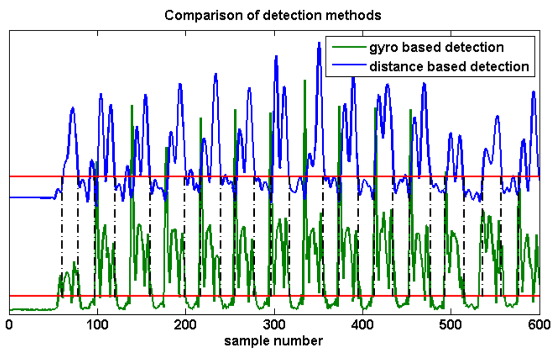

Fig. 9. Still-phase comparison of gyro- and distance-based detection when walking

method, the norm values of three gyroscopes for both walking and running cases are calculated.

As shown in Fig. 9 and Fig. 10, the upper blue signal stands for the changes of distance measured by rangefinder during walking. The lower green signal represents the changes of gyros' norm value. Two red straight lines are predefined thresholds for these two methods.

We can see clearly that in the walking case of both methods the start and end points of still-phases are almost identical. Although there are some ripples close to the start points, the experimental result only shows little changes which can be seen later from comparison of velocities. Note that in the walking case the threshold for gyro-based detection is $1rad/s$ and for distance-based detection it is about $9.5cm$.

In running case, the similarity remains strong especially after the speed increasing stage. The mismatch in the first step is due to the wrong threshold for gyro-based detection. According to [4], the threshold should be chosen differently when the movement speed changes. Actually, the constant threshold for gyro-based threshold shown in Fig. 10 is only for comparison. In fact, the threshold should be lower during the first step due to the lower velocity, yielding the start points of the first step being closer. Note that in running case the threshold for gyro-based detection is now chosen as $3rad/s$, while the threshold for distance-based detection remains the same. Therefore, no threshold adjustment needs to be made

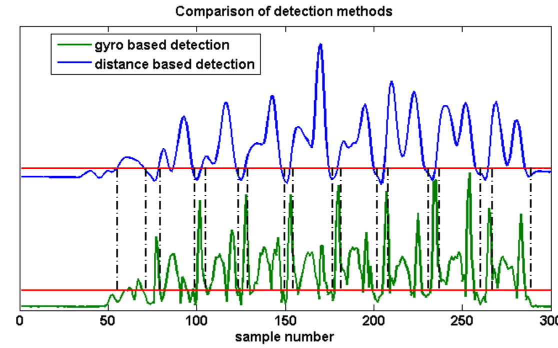

Fig. 10. Still-phase comparison of gyro- and distance-based detection when running

when velocity changes by using distance based still-phase detection.

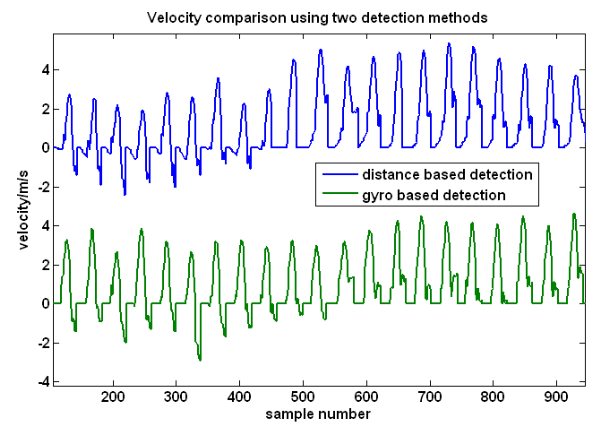

Fig. 11. Velocity comparison using gyro- and distance-based detection when walking

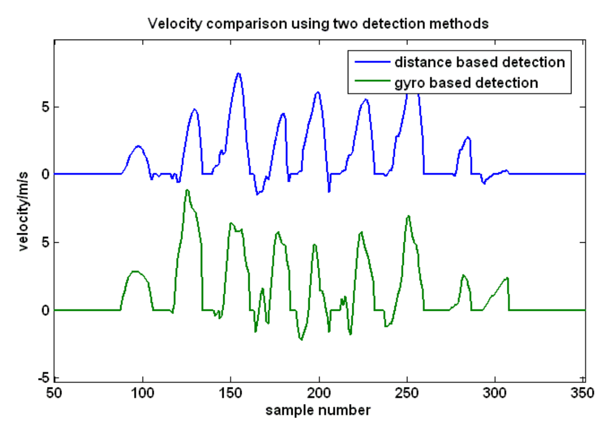

Fig. 12. Velocity comparison using gyro- and distance-based detection when running

As a result, the velocity data in body-fixed frame shows strong similarity by using both ZUPT detection methods in both walking and running case, which can be seen in Fig. 11

and Fig. 12. Setting the gyro-based one as the reference, the mean over time of RMSE after 20 Monto-Carlo runs is less than $0.5m/s$ in the walking case and about $1m/s$ in running case. Note that in the running case the performance of distance base detection is even better than gyro based detection.

The trajectories in the walking case in Fig. 13 are very close. The mean over time of RMSE after 20 Monto-Carlo runs is about $0.5m$ when setting the gyro-based detection as a reference.

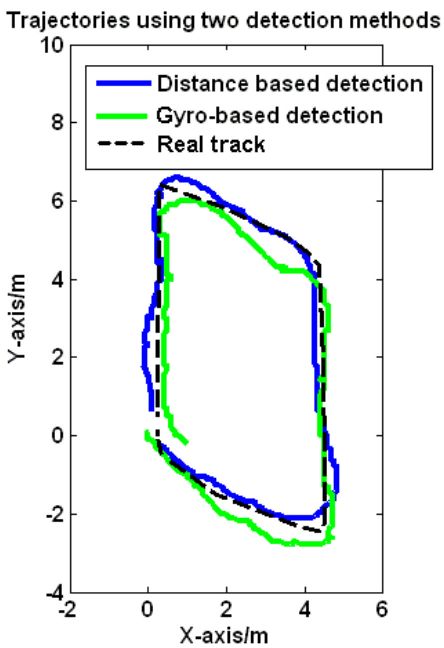

Fig. 13. Position comparison using gyro- and distance-based detection when walking

No trajectory information for running case is given, since the orientation determination during high-speed movement can not only rely on inertial sensors. Reference sensors (e.g. a magnetic sensor) need to be fused with inertial sensors through the Kalman filter by Attitude and Heading Reference System (AHRS), in order to provide a long tern stable solution. Unfortunately, due to memory size limit of the controller, additional functions, e.g. Kalman filter, can not be implemented in this prototype system. Since there is no reference information, e.g. magnetic field, available for correction in this case, the orientation data of next time step are calculated only based on the one of previous time step, which results accumulated error. Therefore, at the moment this prototype system is only suitable for movements in small area with short time duration (e.g. moving in the room).

V. Conclusion

This paper presented a simple, novel indoor localization system utilizing inertial sensors and ultrasonic rangefinder to obtain position information. All the components are low-cost commercial products with digital output and can be easily purchased. All the experimental results showed that within small areas, both low- and high-speed movements were able to be tracked without human motion classification and threshold adjustment, which significantly reduced the computational consumption and simplifies the whole system. The achieved velocity and position information using distance-based detection were very close to ones using gyro-based detection. However, due to the hardware limit, AHRS could not be implemented in the prototype. Thus, the orientation, velocity and position information would become incorrect when tracking movements within a large area. Future work is to update the hardware so as to implement the Kalman filter to fuse inertial sensor data and magnetic sensor date. Thus, a long term stable orientation solution can be achieved and position information within large area can be further improved.

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