Improved Heuristic Drift Elimination (iHDE) for Pedestrian Navigation in Complex Buildings

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***Abstract*—The main problem of Pedestrian Dead-Reckoning (PDR) using only a body-attached IMU is the accumulation of heading errors. The heading provided by magnetometers in indoor buildings is in general not reliable. Recently, a new method was proposed called *Heuristic Drift Elimination* (HDE) that minimizes the heading error when navigating in buildings. It assumes that the majority of buildings have their corridors parallel to each other, or they intersect at right angles, and consequently most of the time the person walks along a straight path with a heading constrained to one of four possible directions. In this paper we study the performance of HDE-based methods in complex buildings, i.e. with pathways also oriented at 45º, long curved corridors, and wide areas where non-oriented motion is possible. We explain how the performance of the original HDE method can be deteriorated in complex buildings. We also propose an improved HDE method called iHDE, that is implemented over a PDR framework that uses foot-mounted inertial navigation with an Extended Kalman Filter (EKF). The EKF is fed with the iHDE-estimated orientation error, as well as the confidence over that correction. We experimentally evaluated the performance of the proposed iHDE-based PDR method, comparing it with the original HDE implementation. Results show that both methods perform very well in ideal orthogonal narrow-corridor buildings, and iHDE outperforms HDE for non-ideal trajectories (e.g. curved paths).**

***Index Terms*—Indoor localization, IMU, INS, Drift elimination.**

I. Introduction

The main problem of Pedestrian Dead-Reckoning (PDR) using only a body-attached IMU (Inertial Measurement Unit) is the accumulation of heading errors. The heading provided by magnetometers in indoor buildings is in general not reliable. Recently, a new method was proposed by Borenstein and Ojeda [1] called *Heuristic Drift Elimination* (HDE) that minimizes the heading error when navigating in buildings. It assumes that the majority of buildings have dominant directions defined by the orientation of their corridors; consequently a person walks most of the time along straight-line paths parallel to these dominant directions. Abdulrahim et al. [2] exploit the same *building's dominant directions* assumption, but they implement the HDE idea in a totally different way.

The implementation in [1] uses a feedback control loop at the output of a vertically-aligned gyroscope. In the loop there is an integration stage to obtain the heading angle from the gyroscopic angular rate, and then this angle is compared to one of the main building orientations. The heading error is fed into a binary integral (I)-controller, whose output is an estimation of the slowing-changing bias of the gyroscope, which is subtracted from the measured gyroscopic angular rate to obtain an "unbiased" version of the gyro's angular rate. The I-controller has a gain proportional to the size of the step, so the gyro bias is computed preferably with long steps.

Fig. 1. Building with a complex layout: The Engineering School of the University of Alcalá-de-Henares (UAH) in Spain.

The implementation in [2] uses an inertial navigation or INS-based framework to directly integrate triads of accelerometer and gyroscopic signals. This INS mechanization is corrected by a complementary Kalman filter (see [3] and [4] for INS-based PDR implementation details). The heading difference between the dominant directions of the building and that of the user's stride (heading error) is fed as a measurement into the Kalman filter. When the Stride Length (SL) is shorter than 0.3 m, the heading correction is deactivated.

In this paper (section II) we analyze the limits of these HDE implementations, which can even damage the navigation solution when used in complex buildings, i.e. with curved corridors, pathways oriented other than 90º, or wide areas for non-oriented motion (e.g. the one in Fig. 1). We propose (section III) an improved HDE method, called iHDE, that although similar to the Abdulrahim et al. implementation [2] includes a motion analysis block to detect straight-line paths and an adaptive on-line confidence estimator for the heading corrections . Finally, the section IV presents some experimental results with curved paths in the test building.

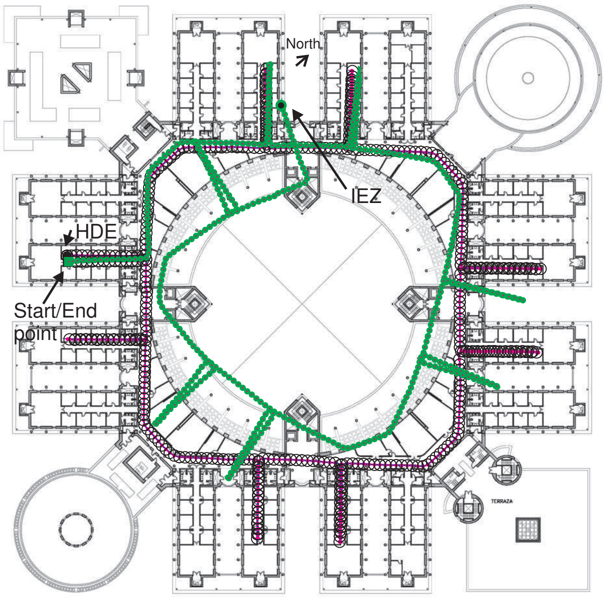


Fig. 2. PDR trajectory in the third floor of the building in Fig. 1 (an ideal floor for HDE navigation). In green color, the INS-based IEZ method (no magnetometers) [4]. The HDE solution (Δ =45º) is represented in magenta color, with black circles at the detected steps where the HDE correction is performed.

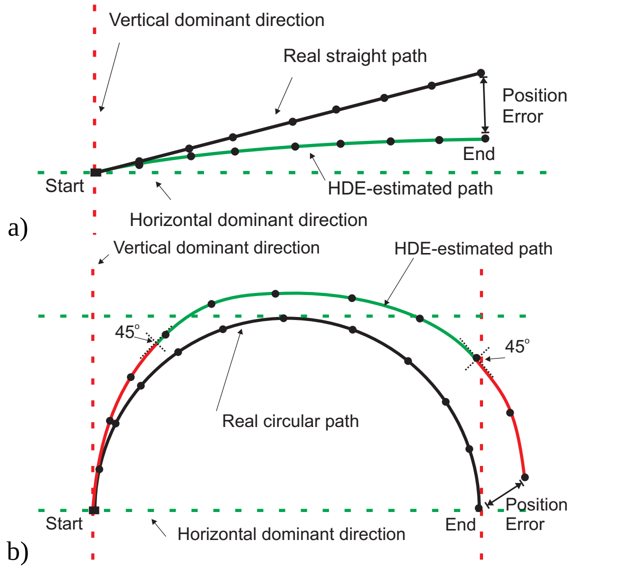


Fig. 3. Positioning error caused by the corrections of the original HDE method for: a) a straight path along a non-principal direction, and b) for a circular trajectory. This diagram only uses vertical and horizontal directions, i.e. Δ =90º. The color of the HDE-estimated path represents the building dominant direction to which the HDE correction is applied (red for vertical, and green for horizontal).

II. HDE: Benefits and Limitations

A. Benefits

HDE methods estimate the non-deterministic slow-variant bias of the gyro's angular rate. Therefore, they make the heading error to be observable. In fact the heading observability is almost as good as if a digital compass were used (assuming no magnetic disturbances). An HDE-based PDR solution basically eliminates the error in heading, and consequently, it reduces the positioning error. For example in [1] a 0.33% error of the Total Traveled Distance (TTD) is obtained, and in [2] the reported error is just 0.1% of the TTD.

Fig. 2 shows a PDR trajectory estimation example using HDE in an "ideal" floor that includes narrow long corridors at 0, 45º and 90º orientations. If the least angular difference between the dominant directions in a building is denoted by Δ, then this difference is 45º for the building under test in this paper (Δ =45º). In Fig. 2 is also included the non-HDE aided solution (IEZ) that is dominated by the uncorrected gyro drift in heading. As can be seen, HDE is an extraordinary method to navigate indoors.

B. Limitations

HDE uses a progressive correction of the gyro bias in order to obtain a robust operation even under temporal paths along non-ideal paths (curved or straight paths out of the dominant directions). If walking more than 30-60 seconds along non-ideal paths, then HDE can deteriorate the navigation solution as Borenstein states [1]. In Fig. 3 it is graphically shown the damaging actions of HDE for two non-ideal paths. The deformation of the true trajectory is progressive, not too severe, but causes a slight error in positioning and heading. This progressive error accumulation, could in principle cause the estimated trajectory to match a wrong dominant direction, although it is unlikely if $\Delta \geq$45º and the non-ideal paths are not too long.

III. The proposed iHDE method

A. The IEZ Framework for pedestrian navigation

We use the foot-mounted IMU-based PDR algorithm proposed by Foxlin [3] and later refined by Jiménez et al. [4], named IEZ. This approach uses Zero Velocity Update corrections (ZUPT) every time the foot is motion-less (stance phase), as well as, Zero Angular Rate Updates (ZARU), when the person does not walk (still). It uses an Extended Kalman Filter (EKF) that works with a 15-element error state vector: $\mathbf{X} = [\delta\mathrm{At}, \delta\omega^b, \delta\mathrm{Po}, \delta\mathrm{Ve}, \delta\mathrm{a}^b]$. This vector contains the estimated bias of accelerometers and gyroscopes ($\delta\mathrm{a}^b$ y $\delta\omega^b$, respectively), as well as, the 3D errors in attitude (δAt), position (δPo), and velocity (δVe).

Fig. 4 represents a block diagram of the complete IEZ PDR method (white color boxes), plus the proposed iHDE implementation (light-gray color blocks) that includes a *"movement analysis"* processing block, and an *"error in heading"* estimation block.

B. Movement Analysis in iHDE

Our movement analysis block, analyzes the stride direction of the person when walking, the length of this stride and decides if the trajectory is straight. This information is used to design some attenuators that will restrict the corrections of HDE to only some sections of the path. They are needed

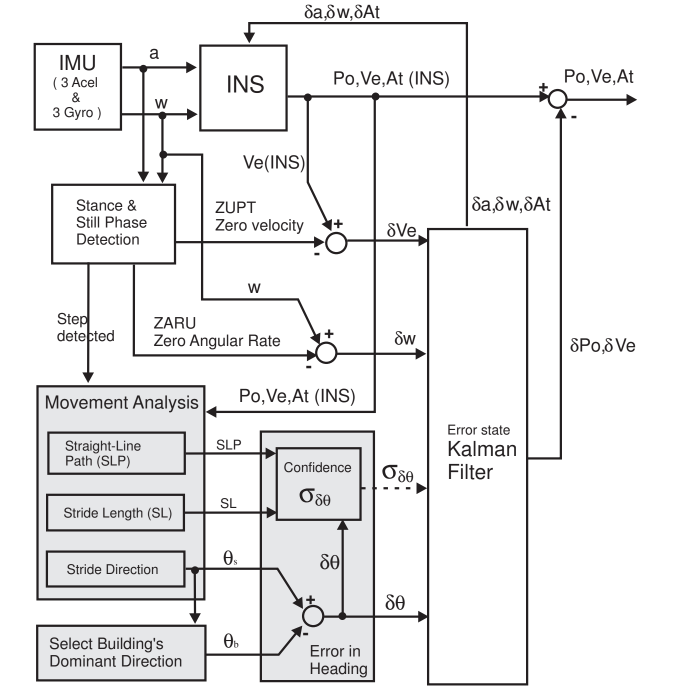


Fig. 4. The proposed iHDE method for improved heading error elimination. It is implemented over the IEZ PDR framework [4].

to estimate the heading error and the confidence on that estimation.

1) Stride Direction: The direction of movement of the pedestrian when walking is:

$$\theta_S(k) = \arctan\left(\frac{\mathrm{Po}_y^k - \mathrm{Po}_y^{k-1}}{\mathrm{Po}_x^k - \mathrm{Po}_x^{k-1}}\right), \tag{1}$$

where k is the index of the k-th step.

2) Stride Length (SL): Knowing the Stride Length (SL),

$$\mathrm{SL}(k) = \sqrt{(\mathrm{Po}_x^k - \mathrm{Po}_x^{k-1})^2 + (\mathrm{Po}_y^k - \mathrm{Po}_y^{k-1})^2}, \tag{2}$$

a Step Size (SS) binary attenuator is computed as:

$$\mathrm{SS}(k) = \begin{cases} 1 & \mathrm{SL}(k) > \mathrm{Th}_{\mathrm{SL}} \\ 0 & \text{Otherwise} \end{cases}, \tag{3}$$

which will be later used to reject HDE corrections when walking with short steps. A threshold for the SL of 1 meter ($\mathrm{Th}_{\mathrm{SL}}$=1 m) is used.

3) Straight Line Path (SLP): We decided to require at least five user strides with similar orientation in order to classify a trajectory as straight. We compute a binary *Straight-Line Path* (SLP) parameter as:

$$\mathrm{SLP}(k) = \begin{cases} 1 & \max(|\theta_S(j) - \mathrm{mean}(\theta_S(j))|) < \mathrm{Th}_\theta \\ & \text{for } j = k : k-4 \\ 0 & \text{Otherwise} \end{cases}, \tag{4}$$

where Th_θ is an angular threshold. SLP is used to deactivate the perturbing HDE corrections at curved paths.

C. *Estimating the error in heading in iHDE*

The error in heading is computed as a direct substraction between the stride direction $\theta_S(k)$ at step k, and the closest dominant direction of the building $\theta_b(k)$, as:

$$\delta\theta(k) = \theta_S(k) - \theta_b(k). \tag{5}$$

This is the error in heading that is fed into the EKF for a subsequent heading correction and an internal gyro bias estimation.

D. *Confidence of the error in heading*

We define the following expression for the standard deviation of the error in heading ($\sigma_{\delta\theta}$), so as to make the iHDE heading correction adaptive with each kind of motion:

$$\sigma_{\delta\theta}(k) = \frac{\sigma_{\mathrm{HDE}}}{\mathrm{SLP}\cdot\mathrm{SS}\cdot e^{-5|\delta\theta(k)|/\Delta}}. \tag{6}$$

The value of σ_{HDE} is 0.1 radians. The exponential term is used to limit the correction from straight paths not too aligned with the building's dominant directions. Note that only straight well-aligned paths are basically used in iHDE. This contrasts with the original HDE method that always applies corrections, even in curved trajectories, if steps are long enough.

IV. Experimental Evaluation

Several tests were performed using a foot-mounted IMU (XSens Inc.) at the building shown in Fig. 1 (Δ =45º).

A. *Wide slightly-curved corridors*

In the first floor of this building, there are wide curved corridors (see Fig.5a). We tested the HDE and the proposed iHDE algorithms in these challenging conditions. The positioning results for a closed 460-meters-long path is shown in Fig.5b and c. The damaging action of HDE is perceived mainly in the curved path in the east wing. iHDE basically does not apply corrections on curves and achieves a slightly lower positioning error than HDE.

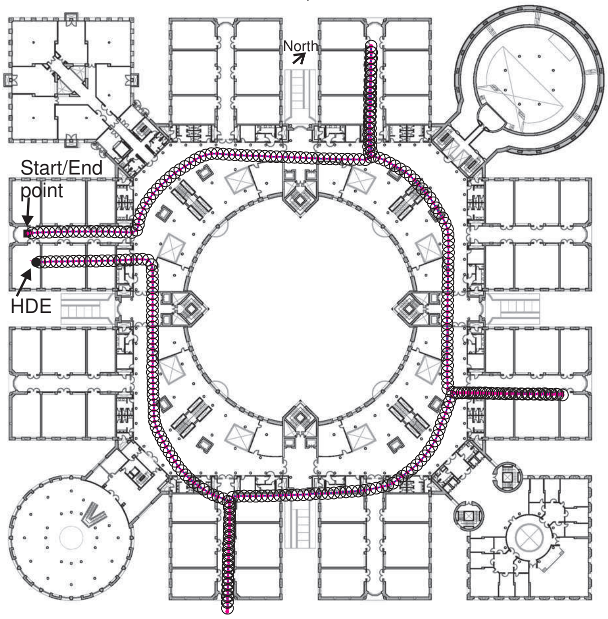
B. *Circular Paths*

Other results for circular paths are presented in Fig. 6. The damaging effect of HDE causes a position and orientation error when finishing the circular loops (e.g. after the 4 loops in Fig. 6 just before returning straight to the starting point). Other tests performed confirmed improvements of the iHDE method over the HDE for routes including difficult trajectories (improvements of about 0.2% of TTD). In more "ideal" floors having long narrow corridors (like the third floor in Fig.2), the performance of HDE and iHDE is quite similar, as expected.

V. Conclusion

We have analyzed the limitations of the HDE method, proposed a improved version (iHDE), and tested both in challenging buildings. We confirm that the heuristic that uses the dominant's directions of the building is an extraordinary method to implement practical PDR indoor navigation solutions (with none or a minimum infrastructure), and it is a great alternative to compass-based navigation when magnetic disturbances are significant.

a)



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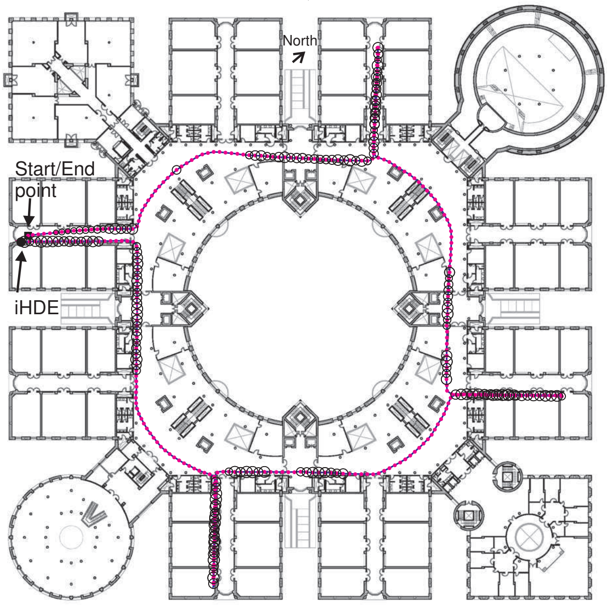
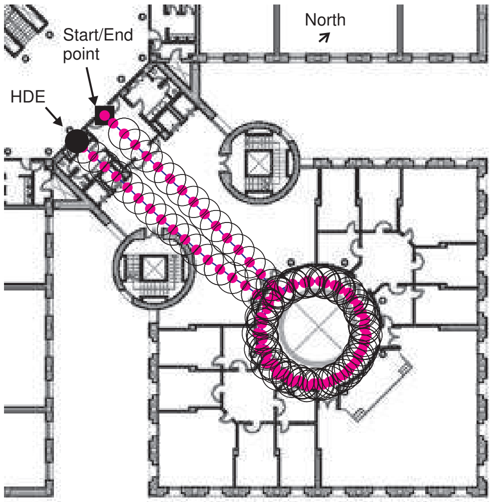


c)

Fig. 5. Tests in a floor with wide and curved corridors. a) Photo of the corridor, b) Estimation with HDE, c) Estimation with iHDE. The black small circles in the path mark the HDE or iHDE heading corrections. The size of these circles is inversely proportional to $\sigma_{\delta\theta}$. HDE is making corrections all the time with a constant $\sigma_{\delta\theta} = \sigma_{\text{HDE}}/\text{SS}$, however iHDE corrects adaptively, mainly at well-aligned straight-line segments, using eq. 6.



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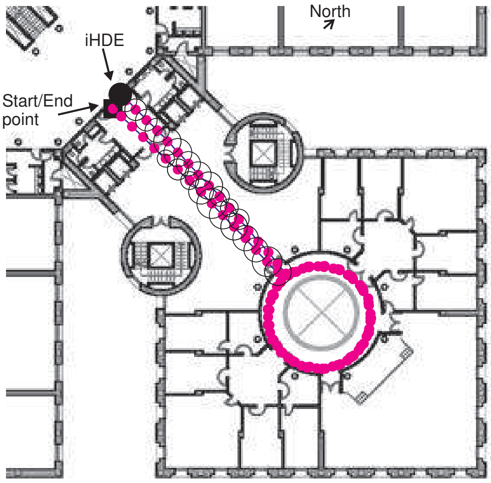

b)

Fig. 6. Test walking around a circular path 4 times (the starting and final path is straight at a 45$^{\text{o}}$ dominant direction). a) HDE estimation, b) iHDE estimation. The total route length is 146 m.

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