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ARIANNA: a Two-stage Autonomous Localisation and Tracking System

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Abstract— **ARIANNA is a small-size system, wearable by an operator for his localisation and tracking. Its design stems from the following assumptions: no need of infrastructure for localisation; low cost, no need of warm-up time (e.g. training phases); seamless switch between GPS-denied/available conditions; computational requirements relaxed enough to be hosted in a commercial smartphone. ARIANNA meets these objectives by adopting a novel two-stage approach: the former stage is a conventional tracking process based on Extended Kalman Filter and step detection; the latter is a post-processing in which the errors due to the sensor drifts are estimated and compensated. The system has been extensively tested with various sensors, different operators, in clear and polluted magnetic environments, with good and poor/intermittent GPS, with paths ranging from 300 m to 3 km, each walked with mixed speeds. The results systematically show good and repeatable performance.**

Keywords- ***IMU, PDR, compass, GPS, tracking, calibration, localisation, pedestrian, indoor positioning, multi-sensor navigation, human motion models***

I. INTRODUCTION

Substantial efforts and resources have been steered in the past decade toward INSs (Inertial Navigation System) for human tracking and localization based on IMUs (Inertial Measurement Unit) based on MEMS (Micro Electro-Mechanical Systems) technology [1], [2]. The major attractive is that these devices might provide low-cost, low-power, miniaturized, lightweight and infrastructure-less solutions for the accurate navigation in GPS-denied scenarios. However they suffer significant bias, noise, scale factors, temperature drifts and limited dynamic range, resulting into position deviation and magnification of the angular Abbe error. These drawbacks *de-facto* prevent the use of MEMS IMUs for long-range localisation. As a consequence, it is not surprising that most of the efforts in the recent years address a widespread ensemble of techniques to improve the localization capabilities of MEMS-based INS for pedestrians. Most of the techniques rely on the PDR (Pedestrian Dead Reckoning) [1], where the walking behavior is exploited to reset the INS errors by adopting an ECKF (Extended Complementary Kalman Filter). Other approaches achieve better performance by exploiting the presence of ancillary sensors, such compass [3], or by visual-inertial odometry [4]. Also independent, pre-existing sources of information are exploited, such as or RFID tags [5] or “map matching” techniques [6]. The recent trends jointly exploit multiple-sensors readings (e.g. compass, barometer, RFID tags) into UKF (Unscented Kalman Filter) structure [7].

However, scrutinizing the current state of the art, it can be highlighted that a common factor shared by all the approaches is the adoption of a unique, powerful, sophisticated processing, fusing multiple input data coming from heterogeneous sensors, usually sampled at different rates and with different relative delays, trying to provide the best possible output. This pushes up the HW complexity and poses a constraint on the battery drain of a wearable system, as well as on its cost, weight and size. In addition, some sensors need a mandatory calibration phase before the operations: gyroscopes biases and scale factors drift with temperature and magnetometers need the Hard-Iron Calibration (HIC) and Soft-Iron Calibration (SIC). The lack of gyro calibration introduces an amplification of the Abbe error and uncalibrated magnetometers can significantly magnify the position errors, when they are exploited to reduce the inertial angular drifts. Despite the plethora of calibration methods for gyros and magnetometers [8], [9], some MEMS-based IMUs and compasses also suffer a long-term obsolescence of the calibration (e.g. a few months for gyros and even 1-2 weeks for magnetometers HIC). This would imply a re-calibration performed on a regular basis: an unacceptable task from the end-user perspective.

In this paper we describe ARIANNA, a novel comprehensive system for the tracking of pedestrian operators. The key assumptions and requirements of ARIANNA stem from a long phase of analysis performed with the collaboration of end-users (e.g. firefightes, army, speleologists).

- Low cost, small-size and lightweight system, smoothly wearable by an operator, with at least 4 hours of battery life with no recharge.
- Unavailability of any ancillary infrastructure for localisation, either pre-existing or to be deployed during the operations.
- Zero-touch interaction with the operator, no need of warm-up times, training phases or constraints on the initial path to be walked.
- No calibration tasks to be performed by the end-users.

- Performance independent of the number of operators.
- Computational requirements relaxed enough to be hosted (as option) in a commercial smartphone.

These objectives are met by adopting a novel two-stage approach: the former is a conventional PDR based on ECKF; the latter is a post-processing in which sensor drifts are estimated and compensated. The data coming from the GPS (when available) and from the compass (when reliable) can be exploited in both stages.

This paper is organized as follows: the proposed ARIANNA system and its post-processing are illustrated in Section II, whereas its performance is assessed in Section III. Finally, in Section IV some conclusions are provided.

II. ARIANNA SYSTEM

ARIANNA is a light, smoothly wearable and highly customizable localization and tracking system for the remote tracking of pedestrians, seamlessly managing presence/absence of the GPS signal. Its basic components are:

- miniaturized IMU+Compass shoe-fastened unit, small enough to be also sealed into the heel;
- wearable computing and transmission unit, also equipped with GPS, where PDR processing is performed (it can range from a Smartphone to a dedicated pocket-size HW, depending on the end-user's needs);
- remote receiving and visualisation unit (e.g. a commercial, mid-level PC) where the ARIANNA proprietary post-processing is performed.

As illustrated in Fig.1, the raw sensor data from a shoe-mounted unit can be linked to the processing unit by a wireless (e.g. BT) link or by a waterproof cable (e.g. when the operators walk in partially flooded environments). In the wireless version, the sensor unit comes with a battery insuring 4 hours of continuous operations and the recharging can be done with a proprietary RF device (working at 150 kHz), avoiding the need of accessible plugs (e.g. when the sensor is sealed inside the heel). The position data are computed by the processing unit (power consumption 1.2 W); these data are transmitted to the remote command and control center (C2), where the ARIANNA post processing for the drift compensation is performed and the tracking data are displayed in 3D. The bandwidth needed for each operator on the user-C2 link is so small (~50 bps) that a commercial digital radio modem (260-485MHz band, 38-57 kbps) can in principle accommodate hundreds of simultaneous transmissions. So far 3G/4G cellular links and commercial radio-modem have been employed over virtually unlimited and 2-3 km ranges, respectively.

A schematic block diagram of the whole processing chain of ARIANNA is depicted in Fig. 2. A purely inertial tracking is computed in the wearable processing unit; this PDR is performed at the sensors sample rate (e.g. 400 Hz) and is expected to be affected by significant drifts, as no information coming from the ancillary sensors (compass, GPS) is exploited. The uncompensated tracking data (along with the raw compass and GPS data, if available), transmitted to the C2 at a much lower rate (e.g. 1-2 Hz), are subsequently employed in a joint scheme to estimate the HIC of the compass. The normalized GPS data (if and when reliable) and the compensated compass data are subsequently employed to estimate the positioning drift parameters, so to compensate them in the last processing step.

It should be highlighted that the compass data, even if corrupted by local polarization and interference, are always available, whereas GPS data can appear and disappear in an unpredictable way: the ARIANNA post-processing automatically handles this, avoiding the inclusion of any special logic, thus insuring seamless indoor/outdoor operations (e.g. continuous walk inside and outside buildings).

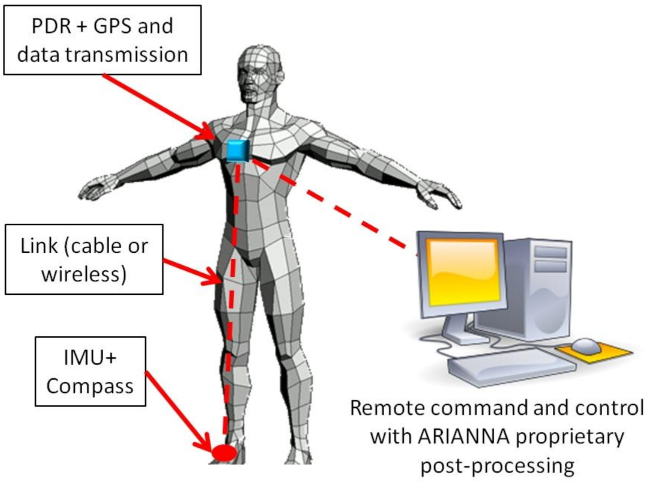

Figure 1. Basic elements of ARIANNA system.

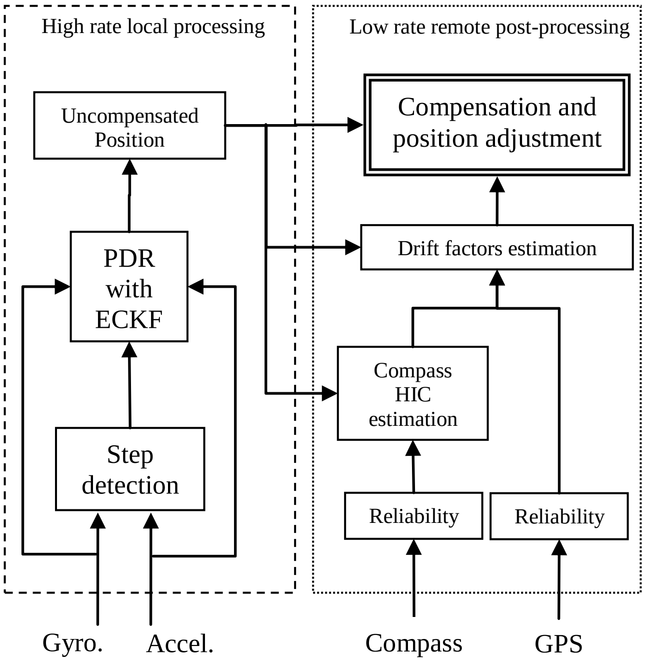

Figure 2. Functional block diagram of ARIANNA processing chain.

Beyond the performance improvement expected by the joint exploitation of the independent information coming from the GPS and compass, ARIANNA comes with some additional advantages at system level. The processing performed at higher data rate is a PDR based on ECKF with a minimal complexity configuration, as no attempt of further correction/compensation is performed at this stage: this minimises the hosting HW complexity, cost and the associated battery drain. In addition, the uncompensated position data are transmitted at rates as low as 1-2 Hz (enough to insure an effective post-processing) and this slow transmission rate further shrinks the requirements on the power needed for the data delivery and the relevant bandwidth to be allocated. On the post-processing side, the low data rate and the absence of complex algorithms are the key factors to let the proprietary estimation/compensation algorithms run on any commercial mid-level PC. From the operational point of view, usually the gyro biases are estimated by requiring the operator to stand still a few tens of seconds before moving; the HIC and SIC parameters can be roughly estimated by requiring the operator to walk a circle or an 8-shaped path. ARIANNA does not have such requirements: the operator's interaction with the system in basically zero-touch, so to let him/her focus on the mission, also considering that constraints such as the still periods and/or constrained paths sound as unacceptable by some classes of end-users (e.g. soldiers, firefighters). As a last consideration, looking at the ARIANNA system as a whole, the mitigated requirements on calibration, power, bandwidth and hardware leave a significant room for customisation.

III. EXPERIMENTAL RESULTS

ARIANNA has been widely and extensively tested with various sensors, different operators, in clear and very polluted magnetic environments, with straight and random paths ranging from 300 m to 3 km, each walked with mixed speeds, ranging from 0 km/h (long still periods), up to 8 km/h. Usually the performance are measured by walking closed paths and adopting the metric $PE = \|\mathbf{r}_0 - \mathbf{r}_e\|/L$, i.e. the distance between the starting and final positions ($\mathbf{r}_0$ and $\mathbf{r}_e$, respectively) as a percentage of the walked distance L. However this metric could be somewhat misleading, as it does not account for the departure of the estimated path from the ground truth: e.g. two distinct angular errors might compensate each other, so to lead to a small *PE* score, despite the poor similarity of the path with the ground truth. In the absence of a calibrated testbed, enabling point-by-point differential measures, we introduce also the (subjective) *SFI* index (Shaping Fidelity Index) roughly ranking the similarity between the estimated path and what we know to be the ground truth (0=no similarity, 10=excellent match).

The following Table I summarises the mean values and the SD of the *PE* and *SFI* metrics, estimated over 36 heterogeneous experiments. From the table, the significant boost of ARIANNA w.r.t. the PDR and PDR+MAG (i.e. PDR with magnetic drift reduction) is apparent, both for *PE* metric and *SFI* index. It should be also considered that PDR also benefits of a calibrated compass and an initial still period (gyro biases estimation), whereas ARIANNA does not.

In the following, the results of three experiments are provided. In Fig. 3 no GPS is employed and ARIANNA solely relies on *uncalibrated* compass to compensate drifts. The experiment is a 2.53 km path walked back and forth on a long straight road, then entering a large building and finally back to the starting point. The *PE* metric in this case is 0.51%. In vertical plane (not reported here) PDR is affected by a constant drift, leading to a final vertical position error of 45 m, whereas ARIANNA never exceeds 1.5 m of vertical position error along the whole experiment, with an error at the end point of 1 cm.

TABLE I. MEAN AND S.D. OF THE PERFORMANCE METRICS

	No GPS		***GPS (urban/suburban)***	
	PE %	**SFI (0-10)**	**PE %**	**SFI (0-10)**
PDR	9.6±12.4	3.8±2.8	-	-
PDR+MAG	7.0±6.0	4.1±3.0	-	-
ARIANNA	1.75±2.3	8.4±1.4	0.8±1.1	9.1±0.5

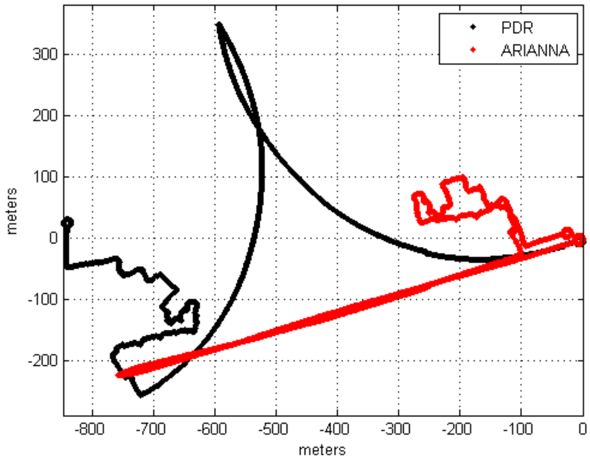

Figure 3. Estimated paths by PDR (black) and ARIANNA exploiting only compass data (red); walked distance: 2.53 km.

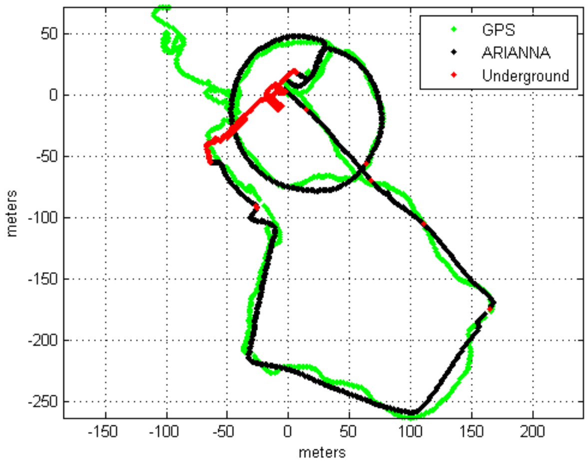

Figure 4. GPS (green) and ARIANNA exploiting both GPS and compass data (black) and only compass (red); walked distance: 1.4 km.

The experiment in Fig. 4 has been performed in a typical dense urban environment. Both GPS and compass are employed in ARIANNA. The path length is 1.40 km, with a long section walked in the underground metro station, where the GPS, although still available, is definitely unreliable. This underground path estimated by ARIANNA is reported in red in Fig. 4 and a detail is provided in Fig. 5. The *PE* metric for this experiment is 0.71% (for GPS is 0.4 %). In Fig. 4, large fluctuations can be noticed for GPS: they are mainly due to the typical multipath effects in urban environments; on the opposite ARIANNA preserves a better resemblance with the ground truth. Also in this case (not reported in the figures) the vertical drift of the PDR leads to a final vertical position error of 24 m, whereas the ARIANNA vertical error at the final point of 0.2 m (the corresponding GPS error is 5 m, but with fluctuation as large as 20 m along the whole experiment).

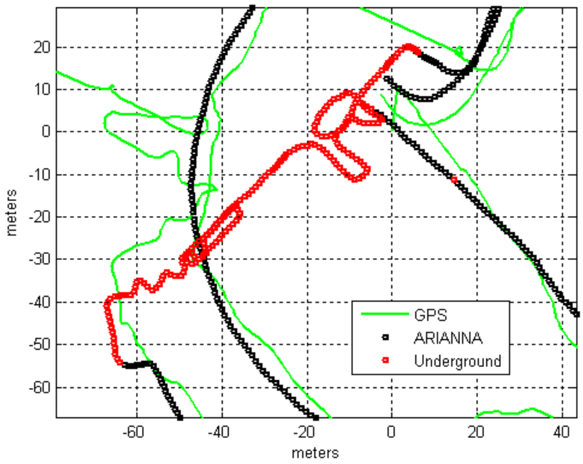

Figure 5. Detail of Fig. 4, relevant to the underground metro station.

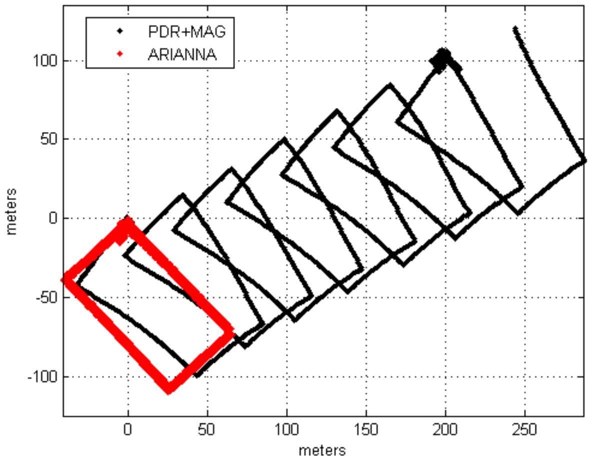

Figure 6. PDR with compass aiding (black) and ARIANNA (red), both exploiting the same uncalibrated compass data; walked distance: 2.32 km.

The experiment in Fig. 6 consists of 6 rounds (plus some random walk at the beginning and at the 5th round) of a soccer pitch for a total walked length of 2.32 km. In this case the *uncalibrated* compass data have been employed to correct the PDR estimation, an operation resulting in an effective improvement when the compass is properly calibrated, but in this case, the lack of calibration results in a dramatic loss of performance for PDR+MAG. On the opposite, ARIANNA, although exploiting the same uncalibrated compass, performs well, giving a final *PE*=0.31%. In addition, the final vertical error is 3 m for PDR and only 1 cm for ARIANNA.

IV. CONCLUSIONS

In this paper, ARIANNA, a customizable, novel pedestrian positioning and tracking system specifically designed for low-cost MEMS-based IMUs, is presented. It splits the path estimation and the drift compensation in two separate processing structures: the former, hosted on the wearable computing unit of the operator, operates at higher rate; the latter, hosted on the remote receiver side, operates at much slower rate. An extensive validation campaign, performed with a wide range of experimental conditions, has systematically demonstrated a superior performance of ARIANNA w.r.t. PDR and, more important, a good repeatability. The current work for its further improvement is focused on configurations with IMUs mounted on both shoes and the management of lifts and elevators. In conclusion, ARIANNA is a mature system in which electronic, logistic, recharging, processing and visualization have not been designed just for demonstration, but for the use in real-operations.

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