"Sugar-Cube": Pedestrian Hardware Platform that Fits in the Sole of a Shoe

Austin R. Parrish, Chi-Shih Jao, Danmeng Wang, Andrei M. Shkel
Department of Mechanical and Aerospace Engineering
University of California, Irvine
Irvine, USA
Email: {aparrish, chishihj, danmenw, andrei.shkel}@uci.edu

***Abstract*—We report on the design, implementation, and demonstration of a miniaturized Inertial Navigation platform. The platform, with a total volume of 7.1 cm^3 (excluding battery and case), includes the Inertial Measurement Unit (IMU), chip-scale barometer, magnetometer, as well as a powerful computational engine for signal processing and execution of the navigation algorithm. The sensors are integrated using separate PCBs with castellated edges forming the connections with the main board allowing some flexibility in sensor selection. The platform is small enough for integration in the sole of a shoe, which is an optimal location for implementation of Zero Velocity Update (ZUPT) algorithms for prolonged self-contained navigation. The navigation solution is performed using an Extended Kalman Filter (EKF) framework with an update rate of 500 Hz. A series of indoor walking experiments were conducted to verify the navigation accuracy of the platform which showed error 0.53% of the trajectory length for a 125 m, 2.75-minute duration walk including flat planes, stairs, and an elevator ride.**

***Index Terms*—Indoor navigation, Pedestrian Navigation, Inertial Navigation Platform, Foot-mounted IMU, Zero Velocity Update, Altimeter**

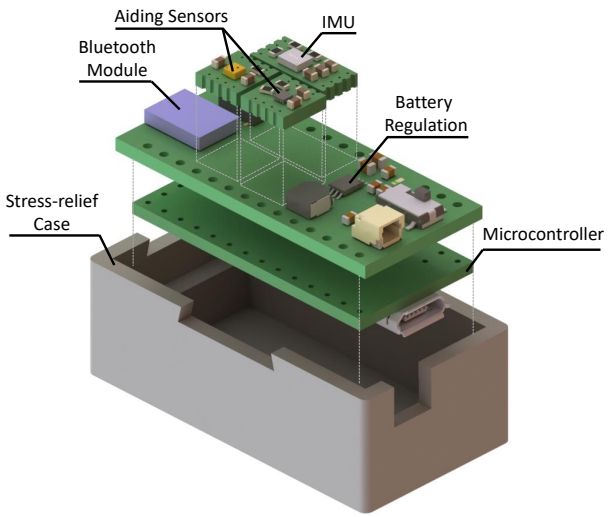

Fig. 1. "Sugar Cube" conceptual architecture including a microcontroller, separate sensor PCBs, a Bluetooth module, battery regulation, and a 3D printed case for stress relief and environmental protection.

I. Introduction

Over the past decade, the performance of microfabricated inertial sensors has greatly improved prolonged self-contained inertial navigation. Inertial measurement units (IMUs) contain multi-axis accelerometers and gyroscopes, which can be mechanized to perform navigation via integration of angular velocity and double integration of acceleration - referred to as dead reckoning. However, the navigation performance suffers from stochastic time-varying biases of accelerometers and gyroscopes. Despite this, low cost ($\sim \$10$) inertial measurement units are approaching performance levels capable of 1 m accuracy after several minutes of pedestrian navigation under ideal conditions with Zero velocity UPdaTe (ZUPT) aiding (e.g. [1]–[3]). ZUPT-based inertial navigation algorithm makes the assumption that the foot is briefly stationary when in contact with the ground during the walking gait cycle and resets the velocity error [4]. Integrating ZUPT with an optimal estimation filter, such as the Extended Kalman Filter (EKF), enables estimation of IMU biases, further constraining error accumulation.

Many navigation modalities exist, such as global navigation satellite system (GNSS), or other external signals, such as long-term evolution (LTE), AM/FM radio signals, or radar [5]. However, these Radio Frequency (RF) signals are not as effective when underground or indoors due to signal attenuation and multi-path effects. RF Beacons have also been employed to improve navigation accuracy in indoor environments using phenomena such as Wireless Local Area Network (WLAN), ultra-Wide Band (UWB), or radio-frequency identification (RFID) [6]. While these methods have been shown to demonstrate accuracy on the order of 1 meter, all reported RF methods depend on prior infrastructure and many are susceptible to jamming, and/or spoofing [7]. The update rate of these methods also may not be fast enough to capture dynamic motion of highly maneuverable platforms or human motion. Inertial navigation systems (INS) have the advantage of providing fast update rate (typically limited by computation power), self-contained, continuous navigation solutions. In an ideal scenario, external signals will be used to enhance the navigation solution, if available, but a self-contained, continuous navigation component is essential. Some applications of indoor/underground navigation, where prior infrastructure may not be available, include urban warfare, law enforcement searching various facilities, firefighters performing smoke-diving in buildings, and emergency response operations during humanitarian crises [8].

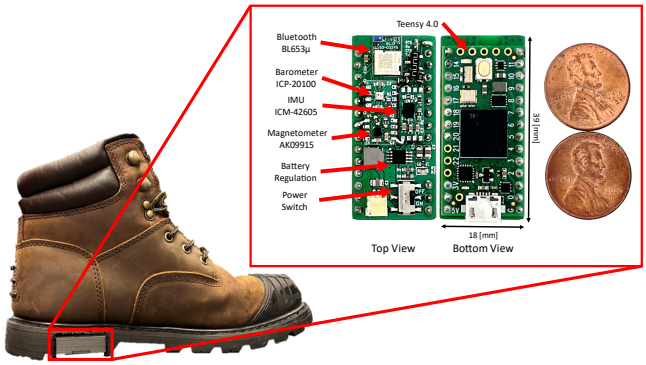

Fig. 2. Illustration of "Sugar-Cube" architecture platform integrated in the sole of a shoe.

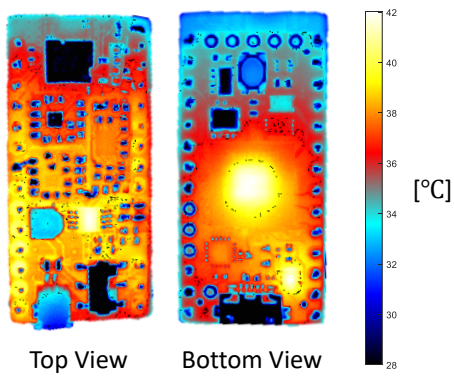

Fig. 3. The thermal profile of the "Sugar-Cube" after one hour of operation is shown with the corresponding color map.

Prior inertial navigation platforms have been reported, notably the OpenShoe platform [9], as well as commercial implementations [10]. These platforms implemented a nine-state EKF, omitting estimation of IMU biases in order to reduce computational cost and enable high update rate navigation solutions with a ∼64MHz microcontroller clock rate. Flexible navigation systems optimized to rapidly integrate additional sensors (e.g. ultrasonic, UWB ranging) have been reported [11], [12], but generally significantly add to the size and cannot be considered for integration in the sole of the shoe. This paper introduces an inertial navigation platform that is architecturally different from the previously reported implementations. The main attributes of the proposed platform are low-cost (∼$61 for PCBs and components), small form factor, multi-sensor fusion architecture, flexibility in sensor selection, increased computational power, and, as a result, increased navigation accuracy. The reported navigation platform enables rapid re-programming of on-board processing units via Arduino IDE, allowing flexibility in the real-time navigation algorithm. This platform was designed for insertion in the sole of the shoe, fully immersing in the footwear.

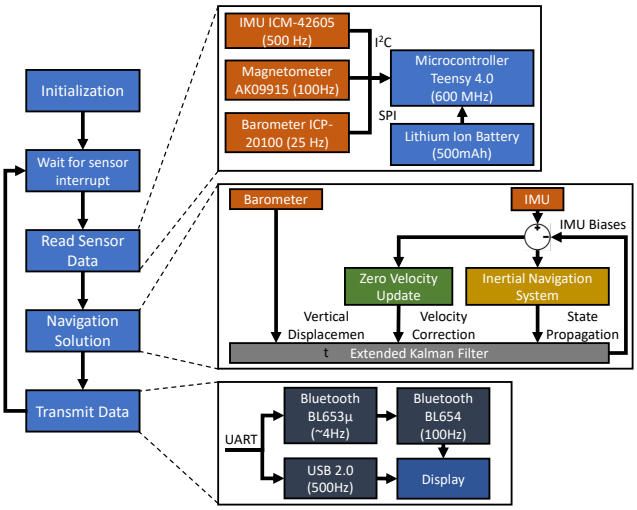

Fig. 4. Flowchart of the runtime framework. The framework runs in a real-time loop as new sensor data is collected.

II. Hardware Architecture

The "Sugar-Cube" embedded INS consists of an IMU as well as desired aiding sensors (e.g. barometer), a processing unit that reads data from external sensors and performs navigation filtering computation, a method of communicating the navigation solution to an external display, and finally a method of mounting the system. The following sections describe the implementation in detail.

A. Navigation Algorithm

The "Sugar-Cube" Board was programmed with C/C++ using the Teensyduino library in the Arduino Integrated Development Environment (IDE). The barometer enhanced ZUPT-aided INS was implemented using an EKF framework, the details of which are described in [13], [14]. The run-time framework of the platform is described in Fig. 4. During the initialization process, sensor and Bluetooth communication is established while the IMU biases are estimated by averaging over a 10-second interval in which the "Sugar-Cube" is assumed to be stationary. The heading angle of "Sugar-Cube" could also be determined via the magnetometer during the initialization step of the algorithm. In the present implementation, two sources of aiding for the INS are included. ZUPT was employed to correct for IMU velocity drift while walking, using the Stance Hypothesis Optimal Detector (SHOE) to detect stance phase [15]. Barometer aiding was also employed to constrain the vertical drift of the INS [14]. In this initial demonstration, the magnetometer was not included in the navigation algorithm.

Due to the high computational power of Teensy 4.0, the platform is capable of including accelerometer and gyroscope biases in the EKF states, in addition to the position, velocity, and attitude, at an update rate of 500 Hz. In prior implementations, these states were omitted in order to improve the navigation update rate [16]. The navigation update rate is limited by

TABLE I
SPECIFICATIONS OF SENSORS AND OTHER COMPONENTS USED ON THE "SUGAR-CUBE" NAVIGATION BOARD.

Component	Specifications	Samp. Rate [Hz]	Power Consumption [mW]
IMU ICM-42605	Gyro: noise floor 0.0035 dps/$\sqrt{Hz}$, bias instability 5.15 deg/hr, range 2000 dps Accel: noise floor 0.07 mg/ $\sqrt{Hz}$, bias instability 0.041 mg/hr, range 16g	500 (max 8,000)	8.5
Barometer ICP-20100	30-110 kPa range, 1 Pa resolution, 0.5 Pa-RMS	25	10.5
Magnetometer AK-09915	0.15 μT resolution, 49.1 mT range	100	6.5
Microcontroller Teensy 4.0	600 MHz clock rate (1GHz overclock), 1024kB RAM	-	490
Bluetooth BL653μ	Bluetooth 5.0, up to 1 MBps	-	26
Lithium Ion Battery	500mAh capacity (30 x 20 x 9.5 mm size)	-	-

computation of the state transition matrix exponential, which is approximated by a seven-term power-series. In one update, it takes 0.58 ms to compute the matrix exponential, 0.46 ms for the remaining EKF calculations, and 0.2 ms to receive the next IMU sample. Currently, the update rate is constrained to 500 Hz in order to eliminate issues with timing of IMU samples. An update rate of $\sim$760 Hz is possible without this limitation and even 1 kHz could be achieved if the Teensy 4.0 were overclocked to 816 MHz; however, a significant overclocking would require active cooling. The "Sugar-Cube" module can also be used purely for data collection, which can output sensor data at significantly higher data rates via USB (e.g. 2,000 Hz for IMU).

B. Hardware Implementation

A prototype of the "Sugar-Cube" Navigation Board is shown in Fig. 2 - the system PCB is $39 \times 18 \times 10$ mm. The reported system integrates off-the-shelf components including a Teensy 4.0 microcontroller with Invensense ICM-42605 IMU, Invensense ICP-20100 Barometer, and Asahi Kasei Microdevices (AKM) AK-09915 Magnetometer. A summary of these components is provided in Table I. The sensors selected for this module are consumer grade ($< \$10$) and tailored for foot-mounted navigation. The utilized barometer and magnetometer are designed to operate in ambient atmospheric conditions. The IMU selection is critical to the navigation performance. The selected IMU had sufficient bandwidth, sampling rate, and full-scale range to capture the dynamics of walking with sufficient accuracy, particularly the shock when the foot contacts the ground [17]. For the same reason, it is critical to have a powerful computation engine capable of processing these measurements in real-time. In this implementation, all sensors are soldered on separate PCBs, with relevant pull-up resistors and filtering capacitors, while castellated edges provide the connection to the main PCB; this provides some margin of flexibility for the platform. For example, if a custom IMU is used, only the IMU PCB needs to be replaced.

Sensor communication is performed using SPI for the barometer with a 25 Hz sampling rate, while I^2C was used for the IMU/magnetometer at sampling rates of 500/10 Hz, respectively. In order to minimize the time the microcontroller takes to receive each sample, each of the sensors are configured to provide continuous measurements at a specific data rate. When new data is available, a data ready bit triggers the corresponding interrupt service routine on the microcontroller. The sensor firmware was developed based on existing libraries (ICM-42605 [18] / AKM09915 [19]) or custom developed (ICP-20100). The data is transmitted via USB 2.0 connection at 500 Hz or via the Bluetooth module (BL653μ) at $\sim$4 Hz to an external display. Only two bytes of the navigation solution are sent to the BL653μ per navigation update, which uses its internal buffer to handle Bluetooth communication - this minimizes the impact of Bluetooth communication on the navigation update rate. The Laird BL654 Bluetooth USB Adapter acts as a Virtual Serial Port (VSP) in order to facilitate communication with an external display - any computer with Serial communication can receive the results. However, it is possible to circumvent the use of the BL654 with the development of a customized communication protocol.

The "Sugar-Cube" Board integrates a 3.7 V Lithium-Ion battery as the power source, which is connected to a voltage boosting module (PAM2401) for 5 V output. This system consumes roughly 550 mW during operation, with the majority of the power drawn from the Teensy 4.0 operating at 600 MHz (490 mW). The sensors and Bluetooth module only consume roughly 50 mW of power in total, and the efficiency of the voltage boosting module will marginally decrease as the battery voltage decreases, increasing the overall power consumption. The thermal profile of the "Sugar-Cube" is also shown in Fig. 3 after one hour of operation. The hottest parts are the ARM Cortex M7 microprocessor of the Teensy 4.0, which reached a temperature of 48.4°C, the 3.3 V voltage regulator on Teensy, and the battery boosting circuit (42°C). The temperature of the IMU was $\sim$38°C, which will likely cause sensor bias shift during the initial operation of the platform as it reaches steady state temperature. The battery used in this demonstration is of dimension $30 \times 20 \times 9.5$ mm with 3.7 V output and 500 mA-hr capacity rendering $\sim$ 3 hours of operation.

III. PERFORMANCE EVALUATION

The navigation performance of the platform was evaluated in a real-world scenario, summarized in Fig. 5. The scenario was repeated 10 times spanning flat planes, stairs, and an elevator ride for one floor. The platform was mounted in the sole of the shoe near the heel, as shown in Fig. 2 - however, it can be mounted anywhere on the shoe or the body. A 3D printed case was designed to minimize the stress exerted on the sensors due to mounting of the system in the sole of the

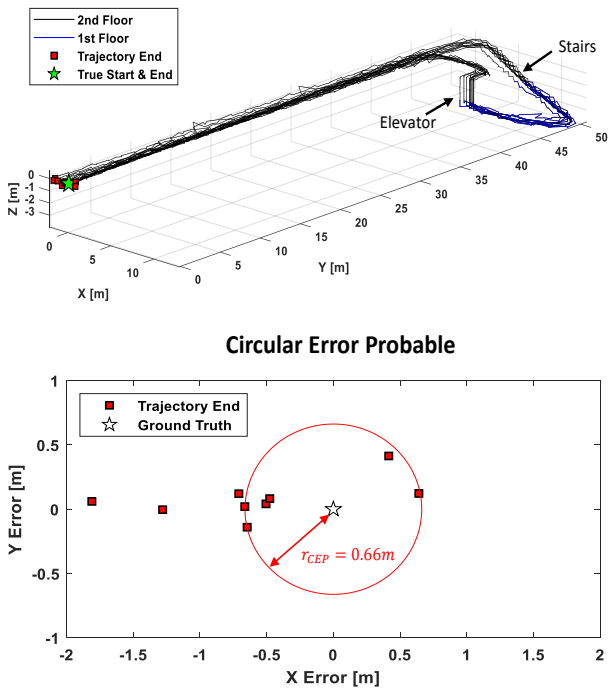

Fig. 5. Navigation Solution and Circular Error Probable for the "Sugar-Cube" board over a 125 m trajectory spanning flat planes, an elevator, and stairs. The experiment was performed 10 times.

shoe. In this implementation, a slot was drilled into the sole of a shoe in order to house the relevant battery and "Sugar-Cube" board.

The accuracy was evaluated using the circular error probable (CEP), which is the median error in the North-East plane as well as the root mean squared error (RMSE) in the vertical direction. The total distance traveled in the experiments was 125 m and the duration was 2.75 minutes. The CEP was 0.66 m, which is 0.53% of the trajectory length, and the vertical RMSE was 0.16 m. The navigation solution appears to drift towards the left, this is hypothesized to be due to stress on the IMU from compression of the shoe during the stance phase.

IV. Conclusion

This study reports the design, implementation, and demonstration of the "Sugar-Cube" board integrating an IMU, barometer, magnetometer, and a computational engine with a total volume of 7.1 cm^3 (excluding battery and case). The platform was integrated into the sole of the shoe for initial demonstration with ZUPT-aided INS implmeted in an EKF framework with an update rate of 500Hz. A series of indoor walking experiments were conducted to verify the navigation accuracy of the platform which showed an error 0.53% of the trajectory length for a 125 m, 2.75-minute duration walk including flat planes, stairs, and an elevator ride.

Acknowledgment

This work was performed under the following financial assistance awards: 70NANB17H192 and 70NANB21H154 from U.S. Department of Commerce, National Institute of Standards and Technology. The authors would like to thank Ben Dolan of IDMI at UC Irvine for his help with 3D printing the case. The first author would also like to acknowledge the support of the Holmes Endowed Fellowship and Rose-Hill Fellowship. All work was conducted in the MicroSystems Laboratory at the University of California, Irvine.

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