neMEMSi: One Step Forward in Wireless Attitude and Heading Reference Systems

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Abstract— **This work presents neMEMSi, a novel MEMS based inertial and magnetic system-on-board with embedded processing and wireless communication capabilities, providing an ultra low-power and easy to use Attitude and Heading Reference System (AHRS). Main target applications are navigation systems and inertial based motion tracking technologies. The paper describes the architecture of neMEMSi and provides an evaluation of the performance in terms of key features of state-of-the-art AHRS.**

I. INTRODUCTION

Inertial Measurement Units (IMUs) and Attitude and Heading Reference Systems (AHRS) based on MEMS sensors are spreading over in consumer electronics, navigation systems and motion capture technologies, thanks to their small dimensions, low power consumption and low cost. Along with these features, advanced embedded processing capability and wireless communication represent additional desirable characteristics for easy to use and portable applications. However, on-board integration of both a microcontroller and a wireless communication module can significantly increase the area occupancy and the power consumption as well, requiring a very accurate and aggressive AHRS design.

This paper presents neMEMSi, a novel system-on-board designed to definitely address some of key issues of state-of-the-art IMUs and AHRS based on MEMS sensors, such as area occupancy, overhead due to on-board processing, wireless communication capabilities and power consumption. neMEMSi is the evolution of the work reported in [1], where an attractive AHRS, suitable for inertial based motion tracking applications, has been presented.

This paper aims to describe the hardware architecture, the building blocks of the system and the state machine managing the sensors acquisition, the on-board processing and the wireless communication. Moreover, measurement results of the power consumption together with the embedded sensor fusion algorithm computing real-time 3D orientation at different update rates will be presented, and a comparison in terms of orientation estimation with respect to a state-of-the-art AHRS [2] will be carried out.

II. SYSTEM ARCHITECTURE

neMEMSi is the result of an advanced AHRS design aimed to provide a wireless low-power system-on-board with inertial and magnetic based processing capabilities and a small form factor. As shown in Fig. 1, the wireless AHRS is enhanced with additional sensing units for a large variety of applications. In this section, an overview of the building blocks providing the AHRS together with the wireless protocol and the additional peripheral units will be described.

CPU

The processing unit of neMEMSi is the STM32L1, an ultralow-power 32 bit microcontroller provided by STMicroelectronics, with the outstanding 33.3 DMIPS peak computation capability and an extremely low power consumption scalable down to 233uA/MHz. The Cortex™ M3

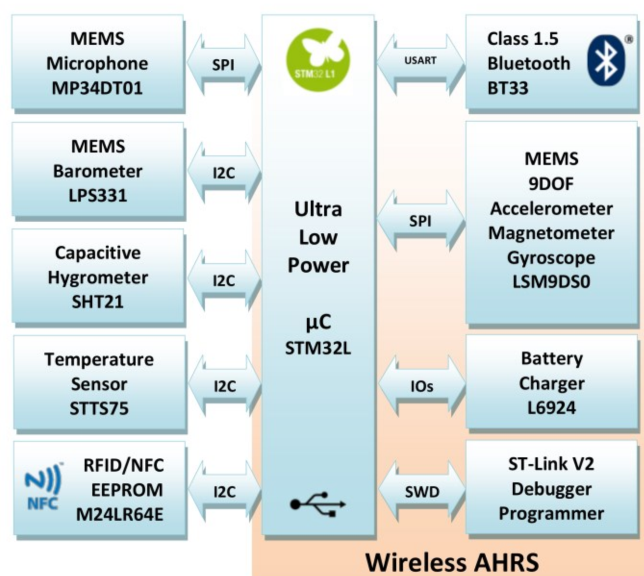

Figure 1. Block diagram of neMEMSi. The wireless AHRS consists of the STM32L1 microcontroller, the inertial and magnetic MEMS sensor and the Bluetooth module.

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architecture along with the 32 MHz clock frequency make this microcontroller suitable advanced and low-power embedded computations. Finally, the low-power AHRS is achieved by means of the same embedded sensor fusion algorithm presented in [1], which can operate between the 25 Hz and the 200 Hz update frequencies.

Geomagnetic and Inertial Module

neMEMSi is one of the first platforms integrating the new System-in-Package (SiP) LSM9DS0 [3] manufactured by STMicroelectronics, with the nine degrees of freedom of an inertial and magnetic measurement unit in a single package. The LSM9DS0 integrates a ±16 g (g-force) 3D accelerometer, a ±12 Gauss 3D magnetometer and a ±2000 dps 3D gyroscope in a 4x4 mm^2 Land Grid Array package. The sample frequencies are programmed according to the selected update rates of the sensor fusion algorithm. The full scales have been set to ±2 g, ±2 Gauss and ±2000 dps for the accelerometer, magnetometer and gyroscope respectively, in order to cover the widest angular rate range and provide at the same time the highest resolution for the steady state operation.

Connectivity

Both wired and wireless communication are supported by neMEMSi. Indeed, the USB 2.0 full-speed interface is provided by microcontroller and is also used for battery recharge. As far as the wireless communication is concerned, the standard Bluetooth technology for short distances data communication has been chosen. The BT33 [4] class 1.5 micro-sized (11.6 × 13.5 mm^2) Bluetooth V3.0 module provided by Amp'ed RF/STMicroelectronics is a highly integrated solution for Bluetooth applications using the Serial Port Profile (SPP), simplifying the development of Body Sensor Networks (BSN). It also ensures communication interoperability with any kind of Bluetooth enabled platforms and Windows, Linux, MacOS or Android based devices. Finally the STMicroelectronics M24LR64E RFID/NFC EEPROM provides an interface for an instant pairing between the platform and any NFC-ready device, thus ensuring an immediate and easy configuration of neMEMSi.

Environmental Sensors

Beside the AHRS, neMEMSi comes with additional sensing units making it suitable for a wide range of applications without compromising the power consumption:

- The temperature sensor is the STTS75 provided by STMicroelectronics, with a programmable resolution up to 0.0625°C and a typical accuracy of about ±3°C.
- The igrometer sensor is the Sensirion SHT21, with a fully calibrated low-power relative humidity (RH) CMOS sensor chip. It ensures an accuracy of ±2 % RH and a typical resolution of 0.04 % RH.
- The high accuracy pressure sensor LPS331AP provided by STMicroelectronics, ensures a resolution of 0.020mbar RMS, thus enabling neMEMSi to detect vertical variation of about 10 cm and making it suitable for indoor inertial navigation.

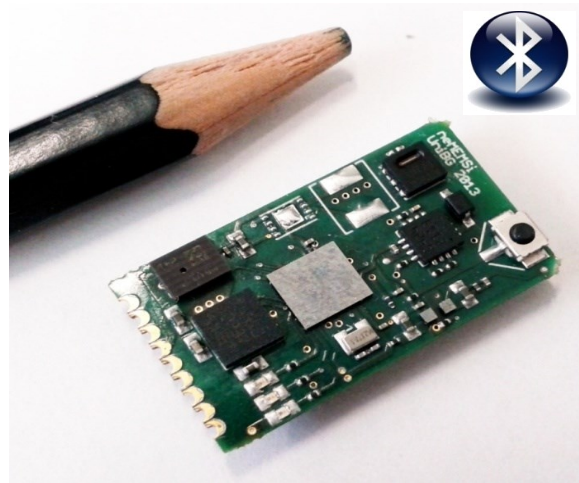

Figure 2. The neMEMSi device (25 × 14 mm^2). The battery can be placed depending on the application.

PCB Fabrication and Power Supply

A 6 layers High Density Interconnect (HDI) PCB technology has been adopted in order to minimize the area occupancy. As depicted in Fig. 2, the outstanding form factor of 25 × 14 mm^2 has been achieved.

The power can be supplied by either a battery or a wired connection. The input voltage can range between 3.0 V and 5.5 V and additional LDOs and filters ensure a high PSRR (power supply rejection ratio) for sensors and Bluetooth module supply. neMEMSi is associated to a 3.8 V 90 mAh lithium polymer battery providing up to 5 hours of continuous data stream without compromising the overall form factor. By placing the battery aside, the form factor is 25 × 25 mm^2.

Firmware

The firmware has been developed taking into account the low-power specifications of wearable devices. As depicted in the state machine of Fig. 3, a set of commands sent through the Bluetooth interface allows the user to easily and remotely configure and communicate with the platform.

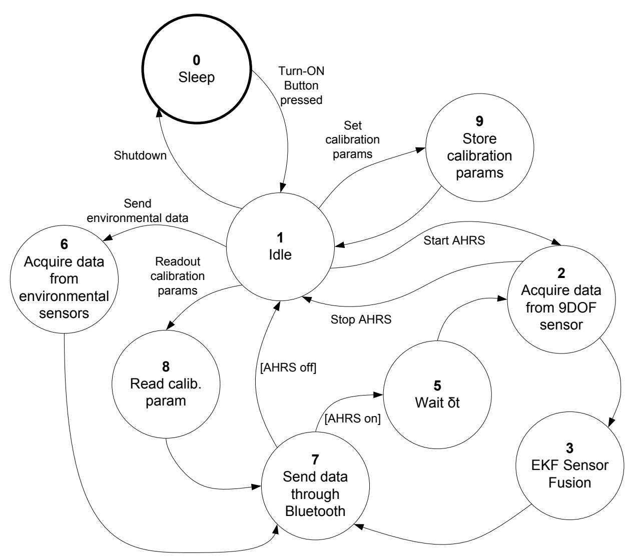

Figure 3. State machine of the embedded firmware.

The power-on button placed on the top side of the platform brings the system in the idle state. From this state, the operation is controlled by means of specific commands sent over the Bluetooth interface:

- The sensor fusion algorithm can be enabled at different update rates by means of a set of start communication commands. The inertial and magnetic raw data will be sampled at the given period and the output of the Extended Kalman Filter (EKF) based sensor fusion algorithm, which is the quaternion representing the orientation, will be sent together with the raw data, resulting in a data stream at the given frequency. A stop command will bring the system back to the idle state. The same operation is available for a quaternion data stream only.
- Single shot data from the environmental sensors can be achieved by means of a specific command which will make neMEMSi to sample and send the data.
- The calibration parameters of the magnetometer [1] can be set by sending a specific command followed by the nine values representing the symmetric gain matrix (6 values) and the offset vector (3 values) which will be stored in the ROM memory of the microcontroller and used by the sensor fusion algorithm. The same parameters can be retrieved with a single shot transmission by means of another command.

III. Performance

neMEMSi has been primarily developed as AHRS for biomedical and rehabilitation purposes, where the form factor and the low-power consumption are key features for more comfortable and easier to use applications.

In this section, a comparison in terms of power consumption with respect to the specifications of state-of-the-art devices will be described. Moreover, the orientation estimated on board will be compared to the one provided by a state-of-the-art AHRS.

A. Power Consumption

As described in Section II, neMEMSi provides several update rates of the sensor fusion. Table I summarizes the power consumption at different Output Data Rates (ODR), whereas Table II compares main features of state-of-the-art devices [2, 5-8] taken from datasheet with respect to the one of neMEMSi. It has to be noted that the dimensions refer to the package enclosing the platform. As can be noticed, the performance of the presented AHRS are the highest even at the maximum update rate of 150 Hz and even with respect to devices which do not provide wireless communication capabilities. Moreover, the lowest form factor of neMEMSi makes it suitable for very comfortable and ease to use motion tracking applications.

TABLE I. Overall Power Consumption of neMEMSi

ODR[a] [Hz]	*Radio Mode*	*Current Drawn* [mA]	*Power Cons. @ 3.8V* [mW]
0	WAIT	14.8	56.2
25	ON	26.5	100.7
50	ON	29.0	110.2
100	ON	34.0	129.0
150	ON	38.5	146.3

a. Output Data Rate of the sensor fusion algorithm.

TABLE II. Main feautres of neMEMSi with respect to state-of-the-art devices

Device	*Power Cons.*	*Max ODR* [Hz]	*Size* [mm3]	*Wireless*
MTi 30 [2]	160 mA @ 3.3V	100	57 × 42 × 23	no
MTi 300 [5]	245 mA @ 3.3 V	100	57 × 42 × 23	no
Mtw [6]	n.a.	120	35 × 58 × 15	802.15.4
X-IMU [7]	100 mA @ 3.6 V	512	57 × 38 × 21	BT Class 1
VN100 [8]	70 mA @ 5.0 V	300	36 × 33 × 9	no
neMEMSi	**38.5 mA @ 3.8 V**	**150**	**30 × 30 × 8**	**BT Class 1**

B. 3D Real-Time Orientation

In order to evaluate the 3D orientation estimated on-board, neMEMSi has been compared to a state-of-the-art device, the MTi-30 module provided by Xsens [4]. The analysis has been performed by means of a robotic system provided by the Italian Institute of Technology (IIT). Both neMEMSi and the MTi-30 module have been mounted on the head of the robot, as shown in Fig. 2, and a set of single rotations around each axis have been performed. Such experiments are not intended to provide an accurate characterization of the platforms, since the robot itself introduces some errors. Moreover, it has also to be noticed that the maximum orientation accuracy of the MTi-30 ranges between 0.5 degrees and 1 degree depending on the specific rotation. Therefore, these preliminary tests aim to provide an evaluation of the reliability and the reproducibility of the orientation provided by neMEMSi.

Fig. 5 depicts three samples of single rotations around the x (roll), y (pitch) and z (yaw) axes together with the relative difference, ε. These tests have been repeated several times and Table III summarizes the results according to data statistics on the absolute value of the difference. As can be noticed, the relative difference, ε, for the roll and pitch components is lower than 1 degree, showing very promising results. As far as the yaw component is concerned, higher values have been achieved, as expected. Indeed, since the heading estimation is based on the magnetometer only, a very accurate and continuous calibration of both the sensors should be needed in order to take into account possible local distortions of the magnetic field. This is the main issue leading to a worse accuracy on the heading of AHRSs.

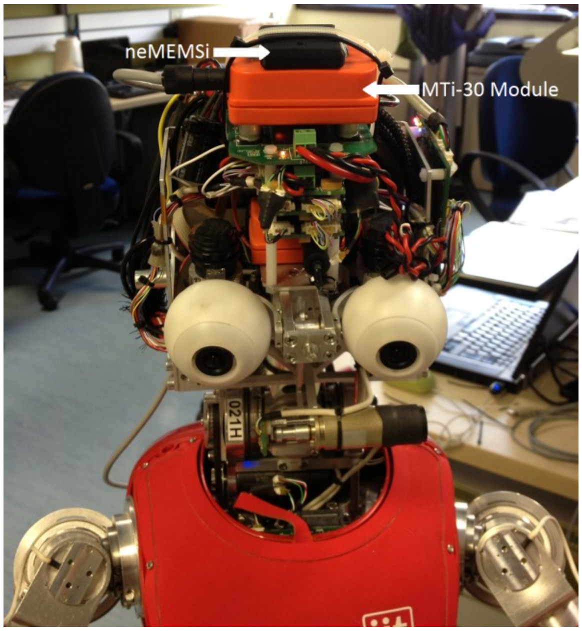

Figure 4. Test setup used for the comparison of neMEMSi with respect to the MTi-30 module.

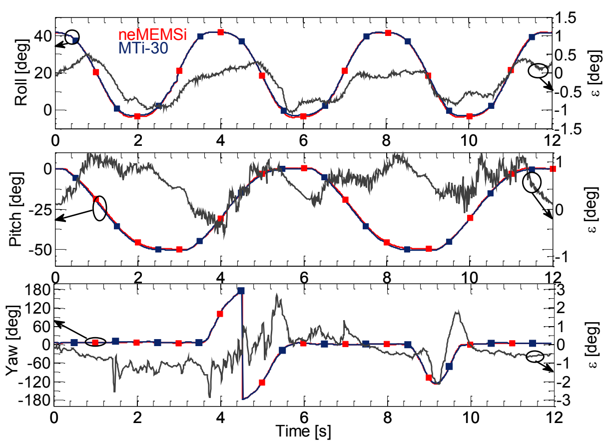

Figure 5. Sample results of single rotations around the x (roll), y (pitch) and z (yaw) axis, together with the relative difference.

TABLE III. **AVARAGES AND STANDARD DEVIATIONS OF THE ABSOLUTE VALUE OF THE DIFFERENCE ON THE ROLL, PITCH AND YAW ANGLES**

$\|\varepsilon\|$	***Rotation***		
	Roll	**Pitch**	**Yaw**
Avg [deg]	**0.37**	**0.54**	**0.75**
σ [deg]	**0.29**	**0.30**	**0.52**

The orientation resolution has been evaluated in terms of standard deviation (σ) of the noise affecting each component of the Euler angles at the steady state after single rotations around each axis. As summarized in Table IV, the values achieved are always lower than 0.1 degrees and are comparable for all the Euler angles components.

TABLE IV. NOISE STANDARD DEVIATION IN STATIC CONDITIONS AFTER SINGLE ROTATIONS AROUND EACH AXIS

Device	***σ [mdeg]***		
	Roll	Pitch	Yaw
neMEMSi	49	62	59
MTi-30	59	64	55

IV. CONCLUSIONS

In this work, neMEMSi, a wireless AHRS designed for navigation systems and motion tracking applications, has been presented. The advanced PCB fabrication process together with the newest SiP LSM9DS0 and the low-power microcontroller integrated on-board, feature neMEMSi the smallest wireless AHRS up to the present. The power consumption is the lowest of its category, thanks to the combination of the innovative design, last generation components and the embedded sensor fusion algorithm. Preliminary results of a comparison with respect to a state-of-the-art device have demonstrated the suitability of neMEMSi as AHRS for accurate navigation systems and body motion tracking applications. These features lead neMEMSi one step forward in wireless AHRS.

Ongoing activities are focused on a further characterization of the orientation by means of an optical systems, which provides a reliable and very accurate orientation reference. Moreover, a network of seven neMEMSi have been demonstrated for motion tracking applications and is being used for rehabilitation of Parkinson's disease patients.

ACKNOWLEDGMENT

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