An Open-source Multi Inertial Measurement Unit (MIMU) Platform

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Abstract—An open-source low-cost multi inertial measurement unit (MIMU) systems platform is presented. First, the layout and system architecture of the platform, as well as the novel communication interface used to simultaneously communicate with the 18 IMUs in the platform are described. Thereafter, the potential gains of using a MIMU system are described and discussed. Finally, the error characteristics of the platform, when stationary, are illustrated using Allan variance plots.

I. INTRODUCTION

Micro-Electrical-Mechanical-System (MEMS) inertial sensors are fast becoming ubiquitous in just about any consumer electronics equipment, such as smartphones, tablet computers, video games, toys, power-tools, etc. Since these types of products have a short life-cycle and are manufactured in large volumes and under tight cost constraints, they are also the main driving force in the development of ultra-low-cost inertial sensors; constantly pushing the performance boundary of the MEMS inertial sensors technology.

As the technological development reduces the size, cost, and power consumption of the inertial measurement units (IMU), a natural approach to design sensors for systems requiring better performance than a single ultra-low-cost IMU may offer, is to fuse the measurements of multiple ultra-low-cost IMUs to create a single artificial high performance IMU. This "wisdom of the crowd" design approach also has, in addition to the increased measurement performance, the benefit of making it possible to detect and isolate sensor failures, thereby increasing the reliability and integrity of the sensor system.

In the literature, a handful of articles describing multi inertial sensor and multi IMU (MIMU) systems can be found, see e.g. [1,2,3,4]. These systems are generally constructed around high cost sensors and are thus quite costly. Further, the size of the sensors, the assembly complexity of the sensor array, and the communication solutions used, often limit the practical use of these systems; obstacles that need to be solved before MIMU systems can become more easily available to a wider range of researchers and research fields. To address these issues, we are presenting in this paper an open source low-cost MIMU system platform with an unprecedented number of IMUs. The platform is shown in Fig. 1. The key part of the platform design is a novel communication strategy that allows parallel communication with all IMUs. Further, the potential gains of a MIMU platform are categorized and discussed. Finally, basic Allan variance plots from the presented platform are given.

II. PARALLEL SOFTWARE DATA BUS

Today, single chip IMUs are readily available, and the PCB routing and assembly of a MIMU system of such ultra-low-
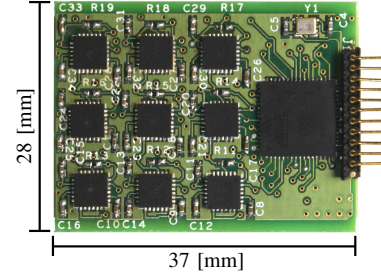

Fig. 1: The embedded MIMU platform displayed in actual size. The platform holds 18 MPU9150 IMUs (9 on the top side and 9 on the bottom side) and the AVR32UC3C2512 μC. The construction of the platform is made possible through a parallel software data bus enabling simultaneous communication with all the IMUs. Software as well as schematics and production files for the PCB are available open-source.

cost IMUs do not pose any fundamental problems. The key construction challenge is the communication interface. Previously presented systems have primarily relied on a common time-multiplexed data bus, which obviously does not scale well as the number of IMUs increases.

The solution is a *parallel software two- or three-wire data bus*. The key observation is that apart from different measurement values from the different IMUs, the communication with all the IMUs are identical. Consequently, by letting the IMUs share a common clock line and connecting the data lines from all IMUs to an I/O port of a microcontroller (μC), the communication can be handled in parallel in software (a.k.a. bit banging) by toggling the whole port to transmit bits, and by reading off the whole port to receive individual bits from all IMUs. This way, the μC can communicate in parallel with as many IMUs, as it has I/O pins. The solution is illustrated in Fig. 2. Reading off the I/O port gives one bit from each IMU at each time instant. To retrieve the measurements from individual IMUs, the bit matrix from the read-off operations has to be transposed. This is illustrated in Fig. 3.

III. MIMU SYSTEM IMPLEMENTATION

By exploiting single-chip ultra-low-cost IMUs and a parallel software data bus, we have built a low-cost embedded MIMU platform. The platform features an unprecedented small form factor (The circuit board area is about 2 times the size of the IMUs, plus an additional 2[cm^2] for processing and auxiliary components), and an unprecedented number of IMUs (including magnetometers). Consequently, we have come to refer to it as "massive-MIMU". Further, for algorithm development and implementation, the platform comes with an embedded floating-point-arithmetic-enabled processing frame-
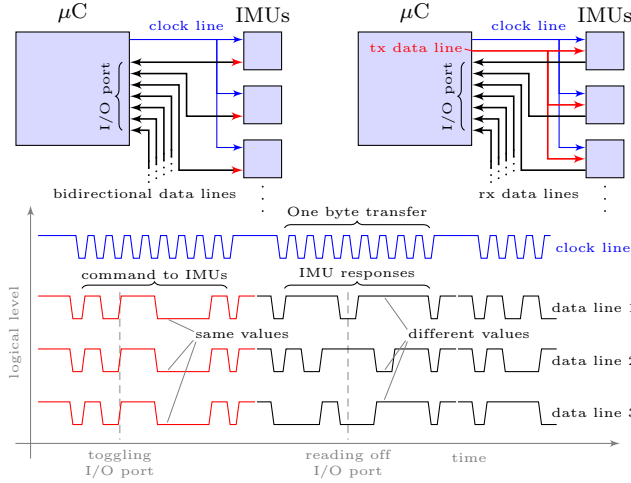
Fig. 2: The top diagrams illustrate the hardware architecture for the two- and three-wire interface data bus solutions. The IMUs have a common clock line, and tx data line in the case of a thee wire interface, and separate data lines connected to a port of the μC. The diagram below illustrates the related signaling. The clock line drives the signaling. For sending commands to the IMUs the whole I/O port is toggled. To read the responses of the IMUs, in parallel the whole I/O port is read off.

Fig. 3: The horizontal bit patterns correspond to the values/state read off from the I/O port at each time instant. The ith bit of consecutive values together contain the measurement values from the ith IMU. The measurement values (the bit string) have to be extracted by transposing this "bit-matrix", such that the bits can be read out in the right direction.

Fig. 4: The version of the MIMU platform where the IMUs are mounted on separate boards, which are connected in a daisy chain to the μC board.

work migrated from the OpenShoe project [5]. A rigid system version of the platform is shown in Fig.1 and a flexible version, to be used in motion tracking for example, is shown in Fig. 4. The platform is constructed around the Atmel μC AVR32UC3C2512C, which via the in-house built parallel software I2C bus can control and sample several Invensens MPU9150 IMUs in parallel at a rate of ~300 Hz; the limitation in the number of IMUs is set by the number of available pins on the μC's QFN64 package (larger packages are available). The current version of the system hosts 18 IMUs, 9 on the front side and 9 symmetrically mounted on the back side. The data is transferred to a PC via a USB interface. Each MPU9150 IMU holds: three orthogonal accelerometers, three gyroscopes, and three magnetometers. The schematics, PCBs, and software (both on the micro controller side and the PC side) for the MIMU platform are available under a permissive open source licence at www.openshoe.org.

IV. FUNDAMENTAL GAINS OF MIMU SYSTEMS

The cost and foot-print of the IMUs of a MIMU system increase linearly with the number of IMUs, so why is a MIMU system interesting? An alternative is to buy a more expensive (and probably better and larger) IMU. However, there are some fundamental differences/properties of MIMU systems which make them interesting. In summary they are the stochastic error diversity, the component redundancy and diversity, the spatial diversity, and the temporal diversity. All these properties relate, in one way or another, to how the inertial measurements should be combined and how the IMUs may/should be distributed. In the following subsections, we discuss and describe the corresponding fundamental gains.
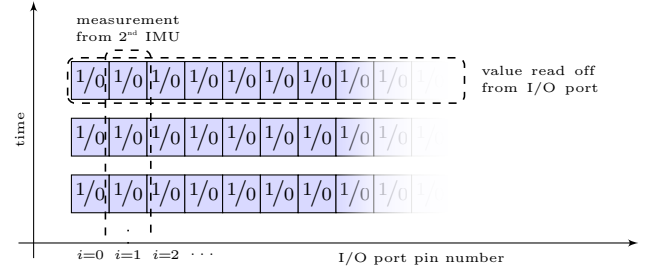
A. Stochastic error diversity and averaging

The first obvious gain of having multiple IMUs is the possibility to average out independent stochastic errors. Assume that the i:th IMU gives a measurement $\tilde{u}_k^i$ of the inertial quantities u_k with a zero-mean error v_k^i, i.e., $\tilde{u}_k^i = u_k + v_k^i$. Then by taking the mean of the measurements from all the IMUs, i.e.

$$\bar{u}_k = \sum_i \frac{1}{N} \tilde{u}_k^i = u_k^i + \sum_i \frac{1}{N} v_k^i. \tag{1}$$

The variance of the resulting estimate $\bar{u}_k$ of the inertial quantity is, under the assumption that the errors v^i are independent, given by $\mathrm{var}(\bar{u}_k) = \frac{1}{N}\mathrm{var}(\tilde{u}_k^i)$. The averaging and the error mitigation is illustrated in Fig. 5a. More refined combination strategies, where the weights $\frac{1}{N}$ are replaced with adapted values, as well as IMU constellation design strategies with different fixed gains have been studied in the literature [6,7,8,9]. However, the fundamental gain is the same, the suppression of the measurement errors.

B. Component redundancy and diversity

The second obvious gain of having multiple IMUs is the robustness against component failure. If one IMU fails, the system can continue operating using the remaining IMUs. In a system with two IMUs, a sensor failure can be detected while in a system with three or more IMUs, the failing IMU can be identified and isolated. This is illustrated in Fig. 5b. The fault detection and isolation has been thoroughly studied in the literature, see [3,4] and references therein.

In addition to component redundancy, one may with multiple IMUs exploit the benefits of using IMUs with complementary measurement characteristics. For example, IMUs with different dynamic ranges make it possible to measure

(a) With multiple IMUs, independent errors, e.g. bias and noise, can be averaged out.

(b) With multiple IMUs, a failing IMU can be detected and the system kept running.

(c) With non-collocated IMUs, the accelerometers picks up rotational info.

(d) Multiple non-rigidly connected IMUs will give dynamic diversity.

(e) Multiple non-collocated magnetometers give a finger print of the local magnetic field.

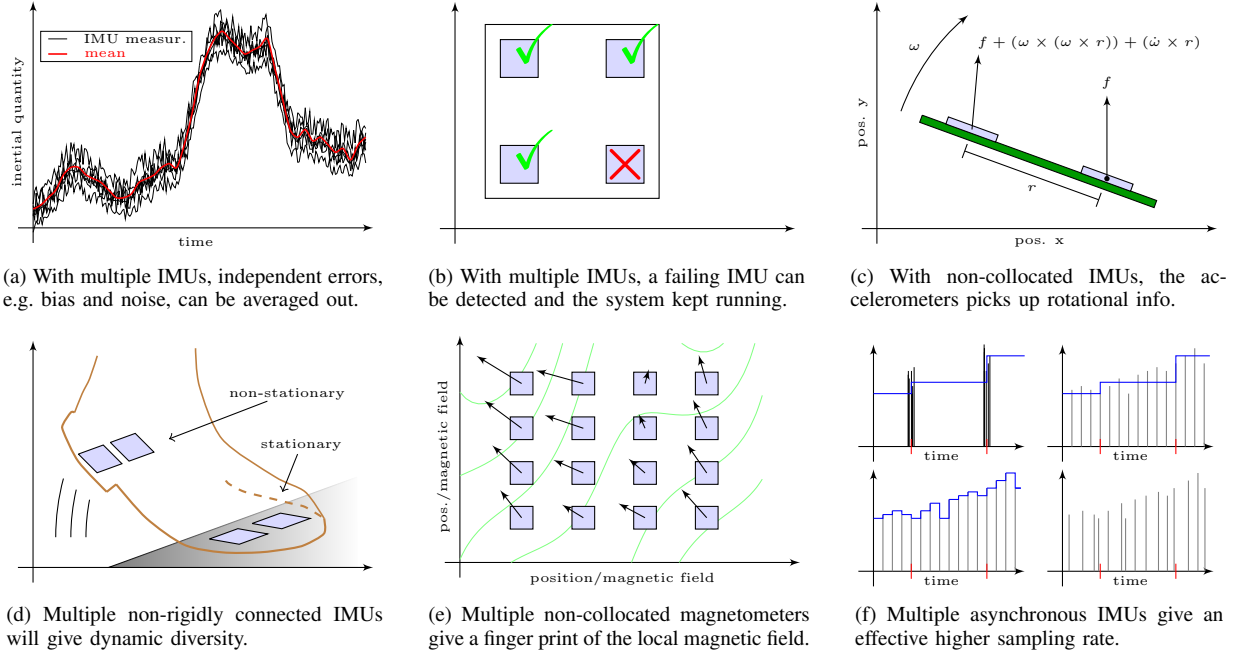(f) Multiple asynchronous IMUs give an effective higher sampling rate.

Fig. 5: The figures show gains and capabilities of MIMU systems. The capabilities cannot be attained by a single IMU system and therefore, they constitute the unique properties which can justify a MIMU system. The gains come from the stochastic, component, spatial, and temporal diversity provided by the multiple IMUs.

inertia over an extended dynamic range without introducing a significant amount of noise. This is commonly used in crash test dummies, for example [10].

C. Spatial and dynamics diversity

The spatial diversity refers to the fact that the IMUs are not collocated. While adding some difficulties in fusion of the measurement data, it also provides a number of fundamental gains relative to a single IMU. The gain of the spatial diversity takes on different shapes depending on, if the MIMU system is rigid (fixed relations between IMUs) or non-rigid.

In the rigid case, all gyroscopes sense the same rotation. However, the separation of the accelerometer triads makes them pick up rotational information. Given the specific force f_k^i at the i:th IMU, the specific force f_k^j at j:th IMU, under the assumption that their sensitivity axes are aligned, is given by $f_k^j = f_k^i + (\omega_k \times (\omega_k \times r)) + (\dot{\omega}_k \times r)$, where ω_k is the angular rate of the platform and r is the separation of the IMUs [6]. The two additional terms are the added information provided by the spatial diversity. Sensing rotational information with the accelerometers is beneficial since normally the gyroscopes are primarily limiting the performance of inertial navigation systems. The gain is illustrated in Fig. 5c.

In the non-rigid case, the measurements of the different IMUs cannot directly be related to each other. However, the processed data, such as the position estimates from the different IMUs, can often be related to each other, and therefore the stochastic errors can still be reduced; see e.g. [11]. Further, since many errors are dependent upon the dynamics of the system, the dynamics diversity obtained by having the IMUs at separate locations, can potentially improve the

system performance beyond that obtained by fusing the IMU measurements in the rigid system configuration. Also, with IMUs on each segment of a rigid linkage body, information about mechanical constraints can be introduced in the system. The gain is illustrated in Fig. 5d.

Finally, in both the rigid and non-rigid case, there is a last gain of the spatial diversity related to the prevailing magnetometers included in the IMUs. The spatial diversity means that a snapshot from the magnetometers gives a rich fingerprint of the magnetic field over an area rather than just a measurement in a single point. Further, the spatial separation means that curved field-lines (magnetic disturbances) could be detected without introducing feedback in the system. The magnetic fingerprint is illustrated in Fig. 5e.

D. Temporal diversity and the effective sampling rate

The temporal diversity arises if the internal sampling of the IMUs is interleaved (asynchronous). The potential gain is most easily understood through the example illustrated in 5f. In an synchronous system (top left plot), all IMUs sample their measured inertial quantities at the same time instant. Then, after averaging and assuming a zero-order-hold signal reconstruction, the integration differential in the inertial navigation system becomes

$$dt\, \bar{u}_k = dt \sum_i \frac{1}{N} \tilde{u}_k^i, \qquad (2)$$

where dt is the time difference between the sampling instants. However, since we are assuming the signal to be constant (over the sampling period), we would have an equivalent result if we would introduce a slight delay in the internal
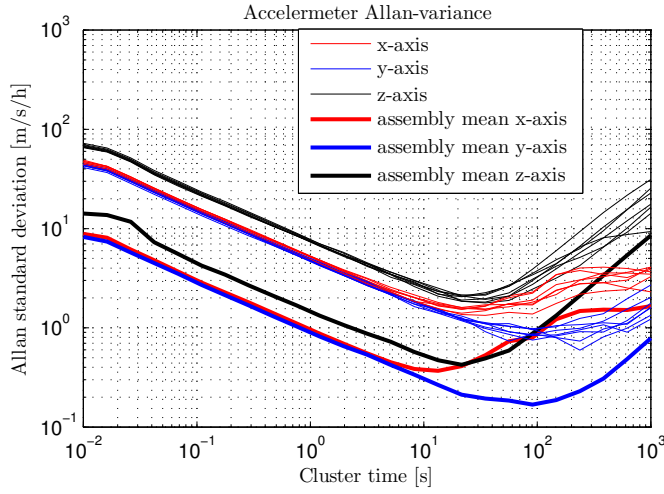
Fig. 6: Allan-variance of the raw accelerometer outputs and Allan-variance when taking the ensemble mean of the outputs from 14 IMUs.
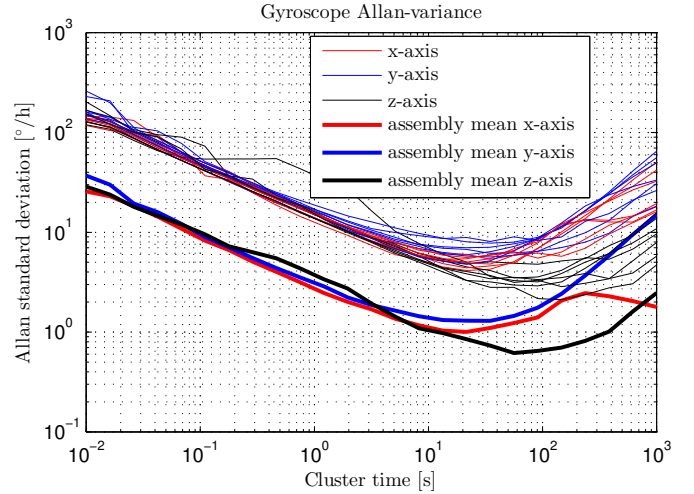

Fig. 7: Allan-variance of the raw gyroscope outputs and Allan-variance when taking the ensemble mean of the outputs from 14 IMUs.

sample clocks of the IMUs, so that their sampling time instants become interleaved (top right plot). But then, we may as well just drop the zero-order-hold assumption and sum up smaller time differentials $\frac{dt}{N}$ (lower left plot). If the zero-order-hold assumption holds, then this gives no difference; but if it does not hold, then we have achieved an N times higher effective sampling rate. Now, in practice, realizing the small inter-IMU delays is cumbersome. Fortunately, since the order in the sum does not matter and if the delays between the IMUs are uniformly distributed over the sampling period, then the difference is small (lower right plot), and we may use the mean differential $\frac{dt}{N}$. A uniformly distributed sampling can be achieved by letting the internal clocks of the IMUs run without synchronization.

V. System characteristics

The most basic fundamental gain is the reduction of the stochastic errors through averaging, see (1). If the measurement errors were independent, we would expect a drop in the standard deviation of $N^{1/2}$. This and the performance of the sensor combination can be quantified by the Allan variance plots, shown in Fig. 6-7 [12]. As expected, the standard deviation is reduced by roughly a factor of $14^{1/2} \approx 3.7$ (in the current version only 14 IMUs are working). This shows that the dominating errors when the platform is stationary are independent. Unfortunately, our experience from using the MIMU platform for inertial navigation is that the dynamics dependent errors, e.g. non-linearities, g-sensitivity, and scale-errors, are significant [13]. Consequently, using simple averaging does not let us harvest the full apparent gain indicated by the Allan variance plots, and further research will be required to efficiently exploit the multiple IMUs.

VI. Conclusion

We have presented a low-level communication solution in the parallel software data bus, which makes massive-MIMU systems feasible. Based on this idea, an open-source embedded massive-MIMU platform has been constructed. Together, this will facilitate the research on MIMU systems. Further, we have qualitatively categorized the different fundamental gains of a MIMU system, giving directions to future research. Finally, the expected noise reduction achieved has been experimentally demonstrated.

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