Inertial Sensor Arrays – A Literature Review

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***Abstract*—Inertial sensor arrays present the possibility of improved and extended sensing capabilities as compared to customary inertial sensor setups. Inertial sensor arrays have been studied since the 1960s and have recently received a renewed interest, mainly thanks to the ubiquitous micro-electro-mechanical (MEMS) inertial sensors. However, the number of variants and features of inertial sensor arrays and their disparate applications makes the literature spread out. Therefore, in this paper we provide a brief summary and literature review on the topic of inertial sensor arrays. Publications are categorized and presented in a structured way; references to +300 publications are provide. Finally, an outlook on the main research challenges and opportunities related to inertial sensor arrays is given.**

I. INTRODUCTION

An inertial sensor arrays is the concept of combining redundant accelerometer and gyroscope sensing elements. The interest in such arrays comes from their ability to provide properties and capabilities not attainable from conventional, non-redundant sensor assemblies, i.e. inertial measurement units (IMUs) made out of three accelerometers and three gyroscopes. In short, the attainable capabilities are:

- Higher accuracy
- Higher reliability and uncertainties estimation
- Higher dynamic measurement range
- Estimation of angular motion from accelerometer data
- Direct estimation of angular acceleration

Owing to these desirable properties and capabilities, inertial sensor arrays have been an active research topic since the 1960s and the research literature consists of some +300 publications and +10 PhD theses; publications that are covering different aspects related to the design and development of inertial sensor arrays, such as measurement fusion, calibration and geometry optimization. The application areas range from inertial navigation for aerospace to vehicle crash test systems. The disparate topics of the publications and varying application areas mean that the publications are dispersed out over a wide range of research fields and *many results are reproduced over and over again*. The aim of this paper is therefore to provide a brief review of the literature and summarize the key findings. It is the authors' hope that this will provide the interested reader with an overview of the topic and inspire further research in an area where the rapid development of sensor and computational technologies provides many new opportunities.

Fault detection and identification is an important capability of inertial sensor arrays, but rather separated from the other capabilities. Therefore, we have chosen to omit it from this literature review. The interested reader is referred to [26], [317], [134] and the references therein. The review has further been limited to English literature. The references are numbered in alphabetical order.

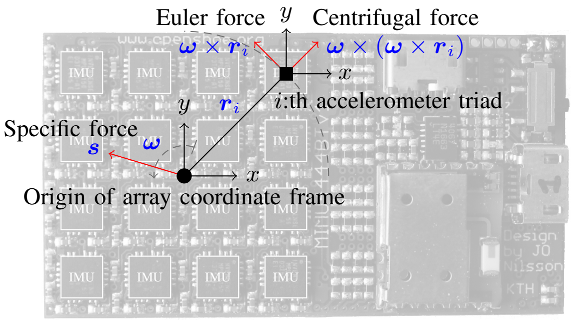

Fig. 1. An illustration of the forces sensed by the accelerometers in an inertial sensor array, overlaid on a picture of an inertial sensor array constructed from 32 IMUs [270]. The specific force sensed by the i:th accelerometer triad is the sum of the specific force at the origin of the array coordinate frame, the centrifugal force, and the Euler force.

II. INERTIAL SENSOR ARRAYS

The properties and capabilities of an inertial array are best understood with a basic array signal model. For simplicity, assume an array consisting of N_s accelerometer and N_ω gyroscope triads. Further, assume that the sensors are identical, their sensitivity axes aligned, and that they have an additive measurement error. The measurements of the i:th accelerometer triad and j:th gyroscope triad can then be modelled as

$$\mathbf{y}_s^{(i)} = \mathbf{s} + \underbrace{\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}^{(i)})}_{\text{Centrifugal force}} + \underbrace{\dot{\boldsymbol{\omega}} \times \mathbf{r}^{(i)}}_{\text{Euler force}} + \mathbf{n}_s^{(i)} \tag{1}$$

and

$$\mathbf{y}_\omega^{(j)} = \boldsymbol{\omega} + \mathbf{n}_\omega^{(j)} \tag{2}$$

respectively. Here $\mathbf{s}$ is the specific force at the origin of the array coordinate system and $\mathbf{r}^{(i)}$ is the location of the i:th accelerometer triad. $\boldsymbol{\omega}$ and $\dot{\boldsymbol{\omega}}$ are the array's angular velocity and angular acceleration, respectively. $\mathbf{n}_s^{(i)}$ and $\mathbf{n}_\omega^{(j)}$ are the measurement errors of the accelerometer triads and gyroscope triads, respectively. See Fig. 1. for an illustration of the accelerometer measurement components and the geometry. From the measurement models it can be observed that: (i) the accelerometers provide information both about the linear motion and the rotational motion (angular velocity and angular acceleration), whereas the gyroscopes only provide rotation information; (ii) the rotation information gained from the accelerometers depends on the geometry and scale of the array; and (iii) there is a sign ambiguity in the angular velocity information provided by the accelerometers, i.e., $\boldsymbol{\omega} \times \boldsymbol{\omega} = (-\boldsymbol{\omega}) \times (-\boldsymbol{\omega})$.

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A. Capabilities

From the listed observations it follows that with an array of inertial sensors the following capabilities can be obtained[1]:

- *Higher accuracy*: By simply averaging the accelerometer and gyroscope measurements the specific force and angular velocity error covariance can be reduced by a factor N_s and N_ω, respectively[2]. However, since the accelerometers also provide rotational information, the angular velocity estimation accuracy can be improved further by fusing the information from both the accelerometers and gyroscopes. The additional information[3] (accuracy) gained is proportional to the square of the angular speed. Refer to [273] for details about the information gain and a lower bound for the estimation accuracy. Further, with asynchronous sensors an effective higher sampling rate than that of individual sensors can be achieved [270].
- *Extended sensing*: The possibility of extracting rotational information from the accelerometers implies that it is possible to construct an array of only accelerometers and still be able to estimate both the linear and the rotational motions. Further, in the case of an array consisting of both accelerometers and gyroscopes, this possibility also implies that the angular velocity can be estimated, even though the gyroscopes are saturated, i.e., the angular velocity dynamic range is increased [273]. Moreover, since the accelerometers also provide information regarding the angular acceleration, this can be directly estimated, and the noise amplifying differentiation of gyroscope measurements avoided [258]. Finally, in principle (though not seen from the basic signal model), accelerometer arrays can separate gravity from platform acceleration [203], [334]. However, the required hardware is not and will not be practical for this type of navigation in the near future.
- *Uncertainty assessment*: Since the same quantities are measured by multiple sensors in the array, the consistency between the measurements can be checked and used for sensor fault detection and isolation, increasing the reliability of the inertial sensor array [26], [317]. Further, the redundant measurements can also be used to estimate the uncertainty of the same, and by introducing a (low parameterized) model for the measurement uncertainties, the measurement fusion algorithm can be designed to adapt to the error characteristics of the sensors [5], [300]. The uncertainty in the estimated linear and angular motion parameters can also be calculated.

B. Fundamental requirements and limitations

To be able to achieve the listed capabilities there are certain requirements the array must fulfill, and there are also fundamental limits to what can be achieved with certain types of arrays. These requirements and limitations are:

- *Geometry requirements*: To be able extract 3 degrees-of-freedom rotational motion information from the accelerometers in the array, it is necessary that the array holds at least 6 (single axis) accelerometers whose locations span a 3 dimensional space or or at least 9 (single axis) accelerometers whose locations span a 2 dimensional space [258], [273]. The rotational motion information gained is proportional to the square of the scale of the distance between the accelerometers [273] and, depending on the number of sensors and their geometry, the complexity of calculating the rotational motion information varies (see Sec. III-B for details.).

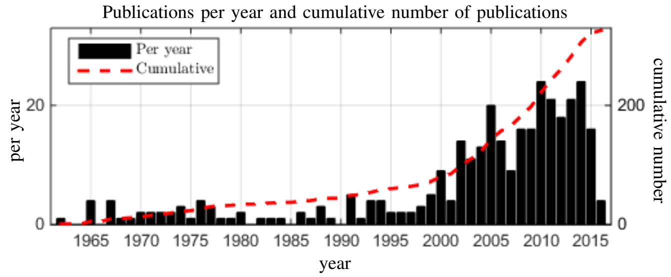

Fig. 2. Publications per year and the cumulative number of publications in the field of inertial sensor arrays from 1962 to the spring of 2016.

- *Identifiability and accuracy limitations*: In arrays made out of only accelerometers, the sign of the angular velocity cannot be determined from the measurements taken at a single time instant since the Coriolis force is quadratic in the angular velocity. Further, even if sign of the angular velocity where known, the variance of any unbiased (accelerometer measurement based) estimator of the angular velocity tends to infinity as the angular velocity goes towards zero [273].

C. Practical problems

Beyond the fundamental limitations of the inertial sensor arrays, there are several practical problems related to the design and use of the arrays. For reliable rotational motion information to be extractable from accelerometers, their placement within the array must be known with very high degree of precision[4]. Further, the mutual orientation of the sensitivity axes of the sensors must also be well known. Calibration of these parameters along with standard parameters such as sensor biases and scale factor errors are essential to obtain the full capability of an inertial sensor array. Finally, the sampling of the sensors needs to be well (time) synchronized.

III. LITERATURE REVIEW

There are some +300 publications in the field of inertial sensor arrays, excluding work on fault detection. Inertial sensor arrays, and special cases thereof, go under several different names in the literature, such as *gyro-free/non-gyro/all-accelerometer/accelerometer-only/(6-/9-/12-) axis accelerometer IMU/INS, multi-/redundant IMU systems, gyroscope array, accelerometer array*. The temporal distribution of the publications can be seen in Fig. 2. Of note is the strong increase in publications around the year 2000 which coincides with the appearance of MEMS-accelerometers on the market. There is

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[1] To simplify the discussion we will assume that the origin of the array is defined so that $\sum \mathbf{r}^{(i)} = \mathbf{0}$ and that the triads are independent.

[2] The assumption that $\sum \mathbf{r}^{(i)} = \mathbf{0}$ implies that the effects of the centrifugal and the Euler force cancel out when averaging the measurements.

[3] Information in the terms of Fisher information.

[4] To the first order the angular velocity error is proportional to angular speed times the relative position error of the sensor.

a similar trend, not shown in the graph, for an emphasis from around year 2010 on systems based on complete IMUs, which coincides with an increasing availability of complete MEMS-IMUs. In addition to the categorized literature, 10 PhD theses have been published on inertial sensor arrays [3], [17], [37], [53], [88], [127], [212], [215], [238], [325]. Further, 2 old PhD theses have also been cited in the literature [113], [262], but their titles are rather unspecific and we have not been able to verify their content. We also wish to point out some seemingly relavant early work which we have not been able to access [63], [75], [105], [106], [140], [192].

The publications are categorized in Tables I and II based on their objectives and their applications areas, as described in the following subsections. A few publications also deal with attributes of inertial sensor arrays which fall outside the listed categories [14], [32], [42], [62], [294].

A. Objectives

The objectives of the publications in the literature are categorized as follows:

- *Measurement fusion*: Publications dealing with how to process and combine the inertial measurements (and possible other information) to attain estimates of s, $\boldsymbol{\omega}$ and $\dot{\boldsymbol{\omega}}$ or higher level information such as attitude or position.
- *Calibration and error analysis*: Publications dealing with how to model, estimate and compensate for array imperfections and how errors affect the system.
- *Sensor constellation optimization*: Publications dealing with the constellation geometry and number of sensors to be used.
- *Experimental platforms*: Publications including experimental platforms and evaluations of inertial sensor arrays.

B. Array types

The array types in the literature are categorized as follows:

- *Accelerometers-only* arrays, with subcategories:
    - *≤8 axis*: The minimum number of accelerometers needed to extract 3 degrees-of-freedom rotational information is 6. However, with 9 unknowns (s, $\boldsymbol{\omega}$ and $\dot{\boldsymbol{\omega}}$) and less than 9 measurements, one has to exploit the temporal dependence between $\boldsymbol{\omega}$ and $\dot{\boldsymbol{\omega}}$ to attain estimates for the same [309]. This creates an additional integration for the inertial mechanization, increasing the error growth rate [191], [232]. The 6 sensor configuration requires a non-coplanar array geometry.
    - *9–11 axis*: With 9 or more accelerometers it is possible to estimate s, $\boldsymbol{\omega}$ (with sign ambiguity) and $\dot{\boldsymbol{\omega}}$ directly. This eliminates the hard dependence on the extra integration, except for resolving the sign of $\boldsymbol{\omega}$. The 9 sensor configuration enables the use of a coplanar array geometry.
    - *≥12 axis*: With 12 or more accelerometers, a linear relaxation can be introduced, enabling a least-squares framework to be used for estimating s, $\boldsymbol{\omega}$ (with sign ambiguity) and $\dot{\boldsymbol{\omega}}$. This is convenient, but requires a non-coplanar array and gives a suboptimal performance [273]. Not all methods dealing with 12 or more accelerometers exploit this relaxation, see e.g. [39], [43], [273], but for simplicity they are all classified in the same category.
- *Accelerometers and gyroscopes*: In arrays made out of both accelerometers and gyroscopes the number and the configuration of accelerometers is of less significance. The sign ambiguity of $\boldsymbol{\omega}$ disappears but the challenge is in how to combine the angular motion information from the accelerometers and the gyroscopes measurements.

The listed categories make up the vast majority of the presented systems. However, there also exist publications on several other array setups. *Gyroscopes only arrays*, which only have the capability to quantify and mitigate the effect of the measurement errors [19], [20], [22], [45], [46], [71], [104], [119], [154], [181], [189], [265], [314], [315], [323]. Arrays made out of *identical accelerometers (and gyroscopes) integrated on a chip level*, in which case the distances between the accelerometers are negligible and one may only quantify and mitigate the effect of the measurement errors [25], [163], [199], [330]. Arrays constructed out of *accelerometers with different dynamic range*, but with insignificant spatial separation. This enables an increased specific force dynamic measurement range and measurement accuracy, but no other capabilities [24], [143], [200], [256]. Distributed (semi-rigid) *inertial networks* [9], [157], [162]. There also exist publications on dynamic accelerometer and other more complex inertial sensors [11], [44], [47], [66], [67], [74], [95], [100], [145], [168], [197], [205], [207], [219], [279].

C. Application areas

The actual/suggested applications are classified as follows:

- *Biomechanics*: This is the most common application area for accelerometer-only arrays, which are especially used for crash and impact tests for vehicle safety and sport medicine. In these fields, short highly dynamic motions and forces resulting in linear and angular accelerations are studied, which is suitably done with accelerometer arrays. For a general review on so called accelerometry, see [110].
- *Navigation*: This is the most common application for combined accelerometer and gyroscope arrays. Previously, general navigation with arrays of only accelerometers has been suggested, often motivated by the high cost of gyroscopes. But due to the poor performance of accelerometer-only arrays at low angular velocities and the availability of low-cost gyroscopes, these type of systems are today only motivated in certain niche-applications.
- *Ballistic platform guidance*: This may be viewed as navigation with very special requirements. Munition is often subject to very high acceleration making usage of gyroscopes difficult. However, the motion is highly dynamic, short and constrained, facilitating the usage of accelerometer-only systems.
- *Platform control*: Platform control and especially stabilization benefits from the capability to directly estimate angular acceleration. This enables acceleration mode control, which can significantly increase the servo bandwidth, as compared to angular velocity mode control.

- *Other*: Application areas such as gravity gradiometry, vibration sensing, and gesture detection.

IV. KEY REFERENCES

The field exhibits a large degree of redundancy, also in the publications. Many results have been reproduced over and over again. However, the key results and a good overview of the field can be attained from a small number of key references which we would like to point out:

- *A. Schuler et al.* (1967) [263], an early account of the theory for handling 6 and 9 axis accelerometer-only arrays.
- *A. Padgaonkar et al.* (1975) [231], an account of the theory and experimental data for a 9 axis accelerometer-only array.
- *J. Angeles et al.* (1987) [13], contains the first account of the linear relaxation enabling a least squares solution for $\mathbf{s}$, $\boldsymbol{\omega}$ and $\dot{\boldsymbol{\omega}}$ for a general (non-coplanar) accelerometers array.
- *P. Cardou et al.* (2008) [39], an account of methods to solve the nonlinear estimation for an accelerometer-only array.
- *M. Pachter et al.* (2013) [230], inertial navigation, mechanization, and error analysis of accelerometer-only arrays.
- *I. Skog et al.* (2016) [273], estimation-theoretical formulation of inertial arrays containing accelerometers and gyroscopes.

V. OUTLOOK

Motion sensing is a fundamental property and inertial sensor cost, size, power consumption, and performance are steadily improving. Inertial sensors are already present in large numbers, in everything from gadgets to industrial systems, and will be present in even larger numbers in more and more systems. Already today, inertial sensors are packaged with microcontrollers; high-end tactical and navigation grade sensors are reaching price levels where new applications are within reach; and novel high-end technologies such as atom interferometry-based accelerometers are emerging. This will create numerous opportunities for applying inertial sensor array techniques. However, still lacking are solid and mature methods such as:

- Combined adaptive statistical tools for estimation, fault-detection, and uncertainty assessment.
- Robust automatic online array calibration tools including time synchronization of different inertial signals.
- Methods for combining asynchronous inertial sensors with different dynamic range, bandwidth, error/stability characteristics and sampling frequency.

These are among the current and future challenges for researchers involved in the field of inertial sensor arrays and a prerequisite for capitalizing upon the new opportunities that comes with new inertial sensor hardware and systems.

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TABLE I

PUBLICATION SORTED BY ARRAY TYPE AND CONTENT. PAPERS MAY BE LISTED AT MULTIPLE ENTRIES IF COVERING MULTIPLE OBJECTIVES. REFERENCES ARE NUMBERED AND LISTED IN ALPHABETICAL ORDER.

	Array type			
Content	Accelerometers only			Accelerometers & gyroscopes
Measurement fusion	$\leq$ 8 axis	9-11 axis	$\geq$ 12 axis	[15], [16], [18], [28], [30], [48], [60], [68], [89], [90], [91], [98], [99], [107], [108], [109], [114], [116], [117], [118], [120], [121], [122], [123], [125], [148], [159], [160], [170], [184], [185], [186], [198], [200], [204], [221], [226], [233], [247], [253], [271], [278], [286], [291], [293], [300], [305], [308], [312], [316], [322], [326], [327]
	[1], [12], [18], [49], [51], [58], [73], [84], [93], [96], [103], [135], [161], [164], [172], [173], [174], [175], [178], [179], [209], [210], [214], [217], [225], [227], [228], [231], [234], [236], [263], [277], [280], [282], [285], [283], [284], [302], [304], [311], [320], [324]	[2], [4], [5], [6], [18], [34], [36], [38], [51], [56], [64], [65], [76], [78], [79], [80], [81], [96], [103], [132], [133], [141], [142], [144], [155], [156], [159], [164], [172], [173], [176], [180], [182], [183], [190], [201], [206], [213], [218], [223], [224], [231], [237], [250], [251], [258], [263], [266], [269], [281], [296], [297], [298], [299], [303], [311], [331], [332]	[2], [7], [13], [29], [34], [35], [38], [39], [36], [40], [41], [43], [50], [57], [61], [64], [65], [70], [85], [86], [87], [92], [111], [112], [126], [136], [138], [139], [158], [166], [171], [172], [173], [187], [188], [194], [196], [202], [220], [230], [235], [239], [241], [242], [243], [246], [252], [259], [260], [261], [289], [291], [311], [313], [319], [328], [333], [334]	
Calibration and error analysis	[1], [33], [70], [77], [82], [126], [131], [141], [142], [146], [147], [165], [196], [217], [222], [228], [237], [239], [240], [242], [248], [257], [259], [261], [267], [284], [285], [296], [306], [324]			[8], [10], [27], [54], [55], [72], [137], [149], [167], [249], [329]
Optimization of sensor constellation	[52], [101], [129], [130], [139], [175], [188], [196], [211], [252], [260], [258], [285], [307], [309], [310], [318], [328]			[125], [134], [150], [151], [152], [244], [245], [253], [268], [274], [276]
Experimental platform	[1], [5], [6], [29], [31], [33], [35], [43], [52], [56], [73], [76], [77], [80], [82], [102], [111], [138], [139], [146], [156], [158], [164], [166], [169], [174], [175], [194], [196], [201], [202], [209], [213], [214], [217], [218], [223], [227], [228], [231], [243], [246], [251], [258], [261], [264], [277], [282], [292], [302], [319], [321], [295]			[15], [16], [48], [55], [59], [61], [90], [91], [98], [99], [107], [108], [109], [114], [115], [120], [124], [160], [176], [186], [198], [200], [204], [221], [226], [229], [233], [242], [270], [272], [278], [286], [288], [291], [301], [300]

TABLE II

PUBLICATION SORTED BY ARRAY TYPE AND INTENDED APPLICATION AREA. PAPERS NOT STATING AN EXPLICIT APPLICATION AREA ARE NOT LISTED. REFERENCES ARE NUMBERED AND LISTED IN ALPHABETICAL ORDER.

	Array type	
Application area	Accelerometers only	Accelerometers & gyroscopes
Biomechanical/crash tests	[21], [23], [31], [34], [35], [56], [69], [83], [97], [102], [103], [111], [128], [135], [136], [141], [156], [158], [159], [196], [202], [213], [214], [223], [231], [255], [264], [275], [281], [295], [321]	[24], [30], [159], [160], [226], [301]
Navigation	[29], [38], [70], [79], [81], [87], [92], [178], [180], [183], [220], [230], [236], [246], [251], [280], [285], [289], [308], [331]	[15], [16], [59], [68], [107], [108], [109], [124], [134], [198], [221], [229], [253], [254], [271], [276], [278], [286], [287], [327]
Ballistic platform guidance	[58], [64], [65], [66], [101], [112], [132], [133], [176], [195], [208], [225], [234]	[193], [312]
Platform stabilization and control	[5], [6], [4], [174], [177]	[98], [99], [291], [290]
Other	[2], [12], [33], [73], [74], [93], [94], [96], [153], [161], [201], [209], [216], [227], [277], [298], [304], [320], [333], [334]	[115], [185]

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