Selection and Pathways to Next Generation Innovations of Speed Over Ground (SOG) Measurement Technologies to Overcome Harsh Conditions and Technological Limitations: A Review

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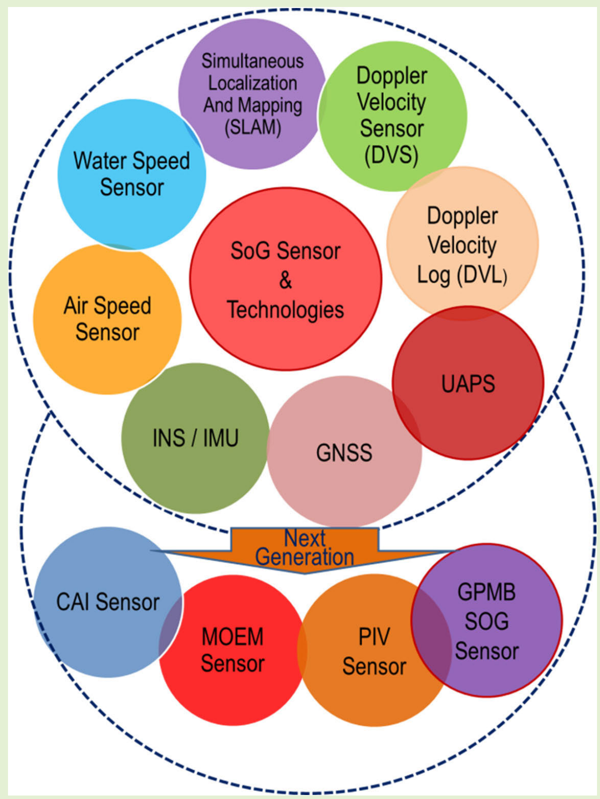
***Abstract*—Determining speed over ground (SOG) with high precision is a critical challenge for marine and aerial vehicles due to various harsh conditions and technological limitations. Here, we review and evaluate current SOG measurement technologies, such as water speed sensor, air speed sensor, global navigation satellite system (GNSS), underwater acoustic positioning system (UAPS), Doppler velocity log (DVL), Doppler navigation system (DNS), simultaneous localization and mapping (SLAM), conventional inertial navigation system (INS), and their performance amidst harsh condition and technological limitations. It reveals the vulnerabilities, and noting their limitations when faced with stressors and technological challenges, thus highlighting the urgent need for resilient and innovative SOG measurement solutions. A substantial focus is placed on emerging sensor technologies, including cold atom inertial sensor (CAIS), micro-opto-electro-mechanical systems (MOEMS) inertial sensor, and particle imaging velocimetry (PIV) inertial sensor. Each of them presents a new frontier in navigational sciences, offering the potential for improved precision and robustness against harsh conditions that traditionally hamper SOG measurement accuracy. However, they still suffer from technological limitations like integration error over time. The Galilean projectile model-based SOG Sensor is spotlighted for its potential to provide a contactless, environment-independent SOG measurement, which is less prone to both harsh conditions and technological limitations like integration error over time. As such, this article outlines a pathway toward selecting the best SOG sensor based on harsh conditions and technological limitations for particular applications, as well as future research direction that could significantly enhance the reliability and accuracy of SOG measurements, ensuring safer and efficient navigation.**



***Index Terms*—Accelerometer, air speed, ground speed, inertial measurement unit (IMU), inertial navigation system (INS), speed over ground (SOG), speed through water (STW), speedometer.**

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I. INTRODUCTION

THE term speed over ground (SOG) is indispensablefor water and air vehicles, determining their horizontal speed in relation to the Earth's surface—a vital metric for navigation, safety, and operational efficiency [1], [2]. Unlike ground vehicles that traverse relatively predictable paths, water and air vehicles must contend with a more complex set of variables that make direct SOG measurement a multifaceted challenge.

Historically marine vessels, used to calculate their SOG by combining the vessel's speed through water (STW) from water speed sensor with the vectorial impact of ocean currents [1]. Envision a ship is sailing in a region where there is no current. In this case, the speed from the water speed sensor and the actual SOG is same. However, if the ship sails in a region where a powerful current is flowing in the same direction, the ship's water speed sensor may register at ten knots, but with the help of the current the ship's actual SOG will be 15 knots. Here, if no other sensors are used to measure the ocean current, it is not possible for the ship's Captain to know the actual SOG, which enables the ship to arrive at the destination sooner than anticipated. Alternatively, if the ship sails against the current, the actual SOG would be lower than the water speed sensor reading. Hence, water speed sensors are prevalent for measuring the vessel's velocity but fall short of providing SOG due to their technological limitation. In the same way, it is critical for the air speed sensors to measure the SOG of aircrafts without the support from other assisting sensors and systems in the presence of wind [2]. To overcome these limitations, an array of sensors and systems are employed to measure SOG, including but not limited to global navigation satellite systems (GNSS), underwater acoustic positioning system (UAPS), Doppler velocity log (DVL), Doppler navigation system (DNS), simultaneous localization and mapping (SLAM), and conventional inertial navigation system (INS). GNSS provides global coverage and precise positioning by leveraging satellites orbiting the Earth, offering a foundational layer for broad-scale navigation [3]. UAPS, employing acoustic signals for underwater positioning, bridges the gap where satellite signals cannot penetrate [4]. DVLs utilize the Doppler effect of sound to measure velocities relative to the seafloor, essential for underwater navigation accuracy [5]. DNS, similar in principle to DVL, extends this functionality to aerial vehicles, using the Doppler effect of electromagnetic wave to calculate velocity relative to the ground [6]. SLAM combines real-time data from various sensors to build a map of an unknown environment while simultaneously tracking the system's location within it, offering a dynamic solution for navigation without reliance on external [7].

Particularly, conventional INSs are relying on accelerometers and gyroscopes, provides self-contained navigational data by calculating an object's position and velocity independently of external signals [8]. Except INS, all these technologies are often highly vulnerable to the deleterious effects of harsh conditions like absorption, scattering, deflection and jamming of transmitted signals, temperature, pressure, density, vibration, shock, and magnetic field which can lead to significant performance degradation in SOG measurement. Amongst these systems, conventional INS stands as a singularly robust technology capable of providing reliable SOG measurements across all these harsh conditions. Though INS is less affected by harsh conditions, it suffers significantly from technological limitation; the inherent accelerometer bias error leads to an accumulation of SOG measurement errors over time.

Addressing the challenge of measuring SOG under harsh conditions and technological limitations is a critical concern for enhancing navigational accuracy in marine and aerial vehicles. This introductory exploration is set against the backdrop of existing technologies and their limitations, pointing toward the necessity for advancements in SOG measurement techniques. Emerging sensor technologies, including cold atom inertial sensor (CAIS), micro-opto-electro-mechanical system (MOEMS) inertial sensor, and particle imaging velocimetry (PIV) inertial sensor, are at the forefront of this technological evolution [9], [10], [11], [12], [13]. These sensors offer enhanced precision and adaptability by employing cutting-edge approaches such as manipulating ultra-cold atoms, integrating micro-mechanics with optics and electronics, analyzing fluid particle motion. These innovative approaches represent significant strides toward overcoming the limitations imposed by harsh conditions on the accuracy of SOG measurements. Despite their advancements, these technologies are not immune to technical challenges, including cumulative integration errors over time. Another promising technology is the Galilean projectile model-based SOG sensor is highlighted for its unique approach to measuring SOG in a manner that minimizes susceptibility to both harsh conditions and common technological hurdles, particularly those associated with long-term integration inaccuracies [14].

This article undertakes a comprehensive review of the current landscape of SOG measurement technologies, focusing particularly on their performance under various harsh conditions and technological limitations that can degrade accuracy and reliability. It delves into an anticipatory analysis of sensor technology trends, spotlighting innovations that have the potential to redefine the standards for SOG measurement accuracy and reliability.

A critical aspect of this investigation is the analysis of the harsh conditions, technological limitations, and their impact on sensor performance. Understanding these dynamics informs the development of a decision matrix and is essential for advancing navigational technologies. This matrix is a strategic tool designed to assist in selecting the most suitable SOG sensor for specific applications and environments, based on a thorough comparative analysis of technology options. It aims to illuminate the path toward optimized sensor selection by integrating theoretical insights with practical considerations.

Acknowledging the importance of pinpointing strategic directions for future research in SOG measurement technologies, thorough review is needed to evaluate the current limitations of state-of-the-art systems and to identify the potential of new sensor technologies. The study will serve as a decisive factor for shaping future research endeavors. It will also cast a spotlight on the existing technologies highlighting their susceptibility to harsh conditions and shall advocate for the exploration of innovative sensor. The insights gleaned from this comprehensive review will aid in steering the future research toward enhancing precision, cost-effectiveness, and environmental resilience, crucial for advancing navigation in both marine and aerial domains.

Fig. 1. EM log with flow sensor and display, from NASA Marine Instruments, from [17].

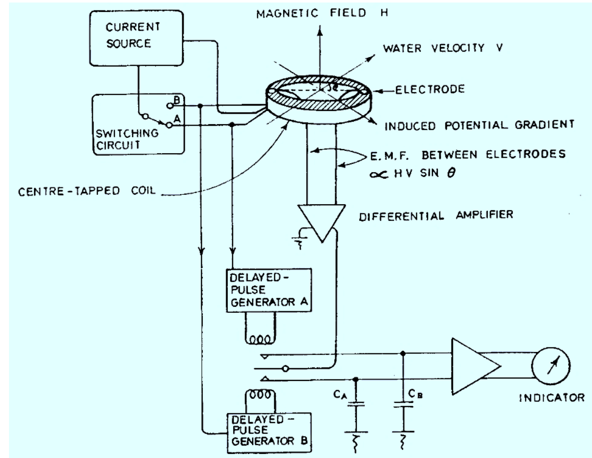

Fig. 2. Principle of operation of EM logs, from [18].

II. State of the Art SOG Measurement Technologies

A. Water Speed Sensor

At present, the state-of-the-art and most commonly used water speed sensor for measuring the relative speed of water is the electromagnetic log, also known as the EM log [15], [16]. The EM log operates by utilizing a solenoid that is enclosed in a casing known as a flow sensor or rod meter. This casing is positioned vertically downward from the hull of the vessel to ensure that the magnetic lines of force run vertically downward along the rod. As the vessel moves through the water, the seawater flows in the opposite direction, creating a relative motion. This moving seawater acts as a conductor for the electromagnetic speed log. The flow sensor is equipped with two electrodes positioned at the athwartship on opposite sides. The distance between these electrodes represents the length of the conductor, which is the strip of water between them. As the water flows through this position, cutting through the electromagnetic lines of force, an electromotive force (EMF) is induced in the strip of water between the electrodes. This induced EMF is then measured by electrodes located outside of the rod meter. The measured EMF is then applied to drive a servo meter, which displays the speed on an indicator in the wheelhouse of the vessel. This allows the vessel's speed through the water to be accurately determined using the EM log [13], [14], [15], [16], [17], [18], [19], [20]. Fig. 1 shows a basic EM log with a flow sensor and display [17].

Fig. 2 shows the operating principle of an EM log [18]. If there is no ocean current, SOG is equal to the speed through the water. As a result, when there is no ocean current, EM log data can be used for SOG calculation with good accuracy. However, SOG calculation becomes difficult with the presence of an ocean current, because it adds a velocity component to the vehicle which is not detected by the EM log. Thus, when there is tide or current, only EM log data are not enough for calculating SOG. For example, if a ship is anchored at sea under a strong current, the EM log shall show that it is moving at high speed, though, in reality, the ship's SOG is zero. In the presence of ocean currents, besides EM log data, other information like ocean current's speed and ocean current's direction are also required for measuring SOG. However, this method provides large errors in measuring SOG as the ocean current's speed and ocean current direction are derived from the prepublished tide table book, which is often inaccurate. Therefore, the EM log is frequently used in conjunction with other navigation systems, such as GPS or INS for better SOG calculation.

Water speed sensors have reached a pinnacle in their development, with minimal prospects for further advancements. These instruments have been refined to near-optimal performance within their current technological framework, indicating that significant breakthroughs in this field are less likely. Consequently, future development may pivot toward enhancing their integration and reliability in multimodal sensing systems rather than seeking major functional improvements.

B. Air Speed Sensor

A Pitot tube, also known as a pilot tube, is currently the most advanced and widely used air speed sensor for determining the relative speed of air [21]. A pitot tube measures the difference in pressure between the stagnation pressure of the fluid and the static pressure of the surrounding air to determine the velocity of the fluid. The pitot tube consists of a small open-ended tube that is aligned with the direction of airflow. When air flows into the tube, it creates a pressure difference between the inside and outside of the tube. The pressure inside the tube is higher than the pressure outside, which is known as the stagnation pressure. The pitot tube measures the stagnation pressure and converts it to an airspeed reading using a mechanical or electronic instrument. To do this, the pitot tube is often combined with another device called a static port, which measures the static pressure of the surrounding air. By comparing the stagnation pressure from the pitot tube with the static pressure from the static port, the airspeed of the aircraft can be calculated [22], [23]. Fig. 3 shows the schematic of an aeronautic pilot tube [23].

In theory, if the true wind speed is zero, SOG is equal to the airspeed measured by the pitot tube. As a result, when the true wind speed is zero, the pitot tube data can be directly used for SOG calculation with good accuracy. However, SOG calculation becomes difficult when true wind speed is greater

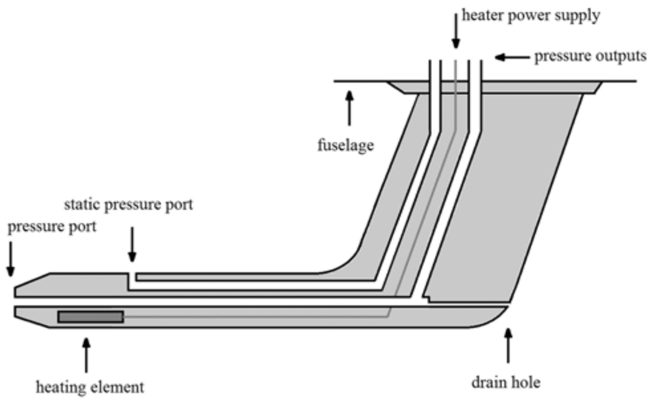

Fig. 3. Schematic of an aeronautic Pilot Tube, from [23].

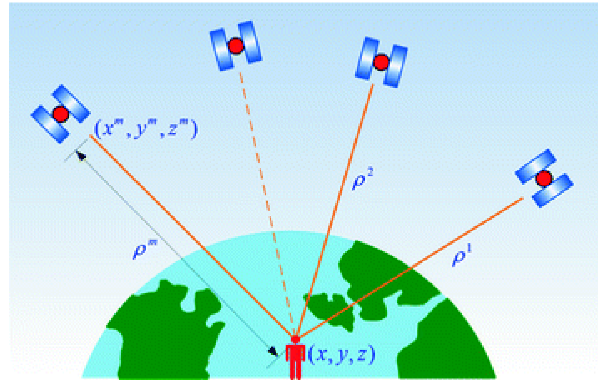

Fig. 4. GNSS position estimation requires range measurements of three satellites to calculate the position of the receiver. A fourth satellite is needed to estimate the clock bias in the receiver common to all pseudorange measurements, from [8].

than zero because it adds a velocity component to the vehicle which is not detected by the pitot tube. Thus, when true wind speed is greater than zero, only pitot tube data are not enough for calculating SOG. For example, if a helicopter remains stationary under strong wind, the pitot tube shall show that the helicopter is moving at high speed, though in reality, the helicopter's SOG is zero. If true wind speed is greater than zero, besides pitot tube data, other information like true wind speed and direction are also required for measuring SOG. However, without the help of other navigation systems like GNSS or INS, it is difficult to calculate true wind speed and direction. Therefore, the accuracy of SOG measurement goes down if the pitot tube is not used in conjunction with GNSS or INS.

For air speed sensors, the state of development has progressed significantly, leading to highly refined technologies. However, the potential for groundbreaking advancements appears to be narrowing as these sensors have been optimized within the constraints of current methods and materials. Thus, future improvements may largely revolve around enhancing system integration and leveraging synergies with other navigational aids to enrich overall performance and reliability in diverse operational contexts.

C. Global Navigation Satellite System

GNSS is a widely used system for SOG measurement in water and air vehicles [3]. GNSS provides accurate SOG measurement for a very long period. Navigation satellites transmit radio signals in predetermined timing and pattern. When GNSS receivers receive these radio signals from at least three satellites, they calculate the timing of the radio signals and find out the SOG of the vehicle [8]. Fig. 4 shows the operating principle of GNSS [8].

However, GNSS is vulnerable to interference, jamming, and spoofing [24], [25], [26], [27], which can result in significant errors in SOG measurement. Moreover, GNSS does not work underwater, which limits its applicability for SOG measurement in underwater environments. Despite these limitations, GNSS remains a valuable tool for SOG measurement in favorable environmental conditions.

The GNSS technology has reached a pinnacle of precision and efficiency, leaving relatively little room for drastic improvements. Future advancements are likely to focus on incremental enhancements in signal processing and integration with complementary technologies rather than fundamental changes to the GNSS infrastructure itself. This maturity in GNSS development underscores its reliability and the sophistication of current satellite navigation systems.

D. Underwater Acoustic Positioning System

UAPS is used for measuring the speed of underwater vehicles. In a UAPS, typically one or more transmitters are used to send acoustic signals into the water. These transmitters could be positioned on the surface of the water, on buoys, on underwater vehicles, or other fixed or mobile platforms. The transmitted signals, which are usually in the form of sound waves, propagate through the water and interact with objects or devices in the water. Objects or devices in the water, such as underwater vehicles, sensors, or other equipment, can have receivers that are capable of detecting and measuring the characteristics of the transmitted acoustic signals. The receivers may be located on the objects or devices themselves or on other platforms, such as buoys or fixed structures in the water.

The receivers capture the transmitted signals that are reflected or scattered back from the objects or devices and the characteristics of these returned signals, such as time delay, frequency shift, or amplitude, are used to calculate the position and location of the objects or devices in the water. This information can then be used for various purposes, such as navigation, tracking, mapping, or monitoring in underwater environments [4]. Fig. 5 shows various types of acoustic localization systems [4].

In a wide range of underwater tasks, such as oil and gas exploration, ocean sciences, salvage operations, marine archeology, law enforcement, and military operations, UAPS is frequently utilized. UAPS are generally categorized into three broad types or classes long-baseline systems, short-baseline systems, and ultra-short-baseline systems. The major limitation of the system is, that when vehicles go a few kilometers away from the UAPS system, the system does not work [28], [29], [30], [31], [32], [33].

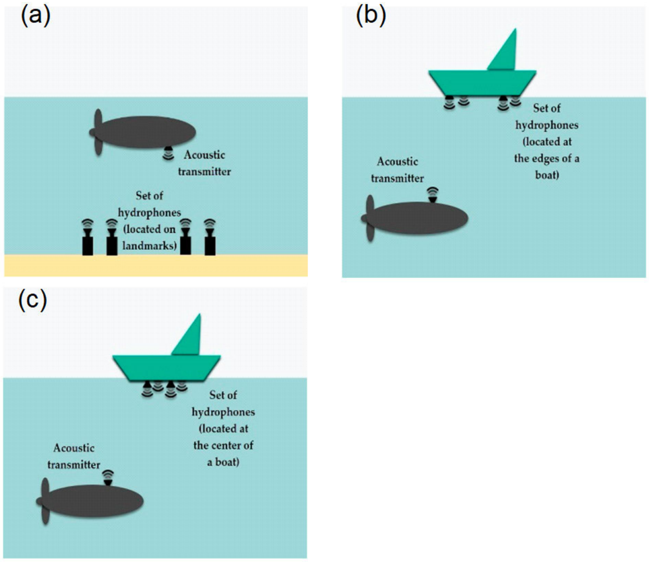

Fig. 5. Acoustic localization systems. (a) Long baseline, (b) short baseline, and (c) ultra-short baseline, from [4].

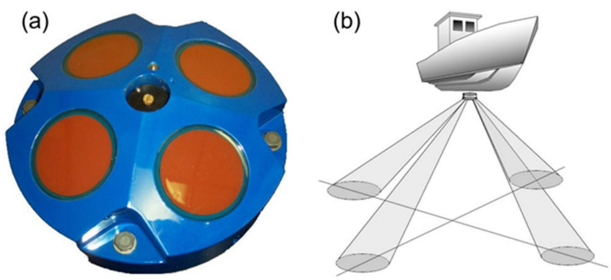

Fig. 6. Four transducer DVL heads and their beam configuration. (a) Four transducer DVL heads, from the National Oceanic and Atmospheric Administration (NOAA) [35]. (b) Four transducer DVL beam configurations, from [5].

UAPSs have reached a high degree of maturity, with current systems offering robust and accurate positioning capabilities. Given the sophisticated nature of these systems and the constraints of underwater signal transmission, significant breakthroughs may be limited. Future progress is likely to hone in on refining system interoperability, user interface, and energy consumption to maximize operational endurance and ease of use within the existing framework of underwater acoustic technology.

E. Doppler Velocity Log

DVL is used for measuring the SOG of water vehicles [5], [34], [35], [36], [37], [38]. It is also referred to as bottom tracking. The procedure consists of two steps: first, using the acoustic echo to determine the position of the bottom; second, determining the velocity using a window centered on the bottom position. When a sonar-like hydroacoustic current meter is put aboard a moving ship, the observed water velocity can be reduced by the bottom track velocity. The net current profile is the outcome. Fig. 6 shows a four-transducer DVL head and its beam configuration [5], [35].

The bottom tracking function can be employed as a crucial part of the navigational systems for underwater vehicles. In deep water, where acoustic signals cannot reach the bottom, the ship's velocity is calculated using a more intricate mix of heading and velocity data from GPS, gyro, and other sources [40]. In this scenario, data from the accelerometer is merged with the vehicle's velocity, an initial position fix, and a compass or gyro heading. To estimate the SOG of the vehicle, the sensor array is merged (usually with the use of a Kalman filter) [41]. The major limitation of DLV is, that if the water is too deep, the acoustic signal does not reach the bottom and the DVL cannot measure SOG [42].

The advancement of DVLs has led them to a level of refinement where significant technological breakthroughs may be limited. As essential tools for subsea navigation, DVLs have reached a plateau in development, achieving remarkable accuracy in velocity measurements against the seafloor. Future progress is expected to be incremental, focusing on improvements in areas such as power efficiency, data integration, and miniaturization to fit a broader array of subsea vehicles. The primary trajectory for DVLs may lie in enhancing compatibility with other underwater positioning and mapping systems to support more complex applications.

F. Doppler Navigation System

DNS is used for measuring the SOG of air vehicles. In DNS, a specialized Doppler radar is used for measuring air vehicle's velocity components with respect to the ground [6], [39].

DNS can execute stand-alone dead reckoning navigation computations as a Doppler navigation set when the aircraft's true heading, pitch, and roll are provided. A Doppler radar antenna is made to emit a minimum of three noncoplanar microwave electromagnetic beams at the earth's surface in order to measure the SOG of an air vehicle. The earth's surface scatters some of the radiation back to the radar. The components of aircraft velocity are produced by combining three or more beam-doppler frequencies with the knowledge of the beam angles. Fig. 7(a) two-beam, (b) shows three-beam lamda, (c) shows three-beam tee, and (d) shows four-beam DNS configuration [6].

DNS measurements can be affected by various factors that may reduce their accuracy. For example, reflections, scattering, or interference from objects in the beam's path, such as buildings, trees, or other obstacles, can result in inaccurate SOG measurements. Signal attenuation due to atmospheric conditions or other environmental factors can also impact the accuracy.

DNSs have reached a high level of refinement, where the potential for significant technological breakthroughs seems increasingly limited. These systems, fundamental in enhancing the accuracy of airspeed and drift measurements, have been optimized within the constraints of current aerodynamic and electronic technologies. Future enhancements are likely to focus on incremental improvements, such as integration with other avionic systems, slight increases in measurement precision, and enhancements in user interface and data processing capabilities. The core functionality and performance of DNS have thus matured to a point where the scope for radical improvement is minimal, signaling a shift toward optimizing

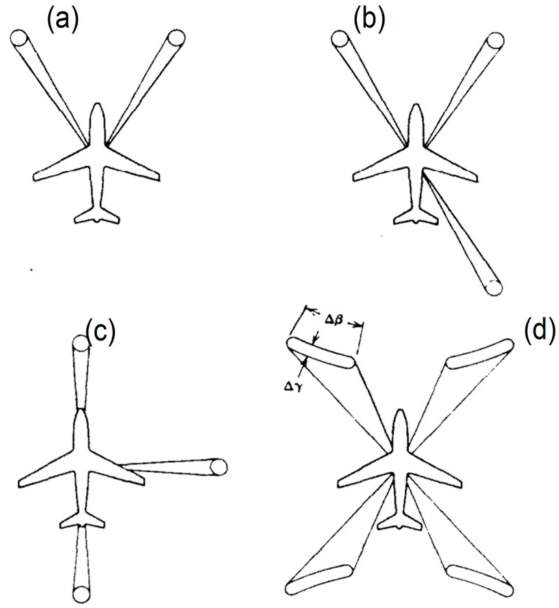

Fig. 7. Various types of DNS beam configurations (a) two-beam, (b) three-beam lamda, (c) three-beam tee, and (d) four-beam, from [6].

and refining the existing capabilities rather than pioneering new frontiers.

G. Simultaneous Localization and Mapping

SLAM is used for measuring the SOG of both air and water vehicles. It is based on the concept of building a map of an unknown environment by incrementally adding landmarks while estimating the position of the robot with respect to these landmarks. SLAM operates by using a range of sensors such as cameras, lidar, radar, and sonar to capture data about the environment and then processes this data to create a map [7], [40], [41], [42], [43], [44], [45], [46].

The SLAM algorithm uses these sensor measurements to create a feature-based map of the environment, where each feature represents a landmark, such as a corner or edge. SLAM also estimates the vehicle's pose, which is its position and orientation in the environment. This is done by using the sensor measurements to calculate the vehicle's movement and then using this information to update the vehicle's position estimate. As the vehicle moves through the environment, SLAM continuously updates the map and the vehicle's position estimate. This allows the vehicle to navigate through the environment, avoiding obstacles and reaching its destination. Fig. 8 shows the basics of SLAM operation [7].

SLAM technology has significantly evolved, particularly in its application to autonomous navigation and mapping in unknown environments. The advancements in computational power, sensor technology, and algorithms have brought SLAM to a level of sophistication where further substantial breakthroughs may be limited. The focus is now shifting toward refining existing frameworks, improving the efficiency of algorithms in terms of power consumption and processing time, and enhancing the integration of SLAM with other systems for more comprehensive environmental understanding. As SLAM matures, the emphasis will likely

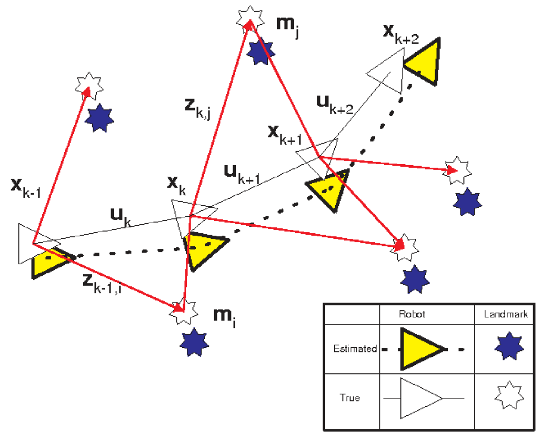

Fig. 8. Essential SLAM problem. A simultaneous estimate of both robot and landmark locations is required. The true locations are never known or measured directly. Observations are made between true robot and landmark locations, from [7].

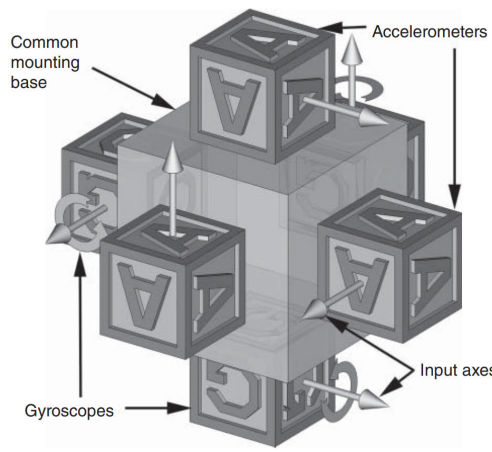

Fig. 9. ISA components, from [8].

be on application-specific optimizations and the robustness of systems in diverse conditions rather than on fundamental changes to the underlying technology.

H. Conventional INS/Inertial Measurement Unit (IMU)

INS is widely used in aviation, marine, and military applications where GPS signals may not be available or reliable and where high accuracy and reliability are required. It is a standalone navigation device used to provide position, orientation, and velocity information for water and air vehicles [8], [47], [48], [49], [50], [51], [52]. INS works on the principle of measuring the acceleration and rotation of a vehicle in three axes (roll, pitch, and yaw) and using this data to calculate its change in position and velocity. The sensor package of the INS is called IMU which consists of gyros and accelerometers [8]. Fig. 9 shows inertial sensor assembly (ISA) components [8].

IMUs are typically classified into five categories based on their performance: strategic, navigation, short-term navigation, tactical, and industrial. These categories are ranked according to their level of accuracy, with strategic IMUs being the highest grade and industrial IMUs being the lowest grade (see Table I).

TABLE I
SOG ERROR GROWTH OF IMUS OVER TIME

Parameters		INS/ IMU Class				
		Strategic	Navigation	Short Term Nav	Tactical	Industrial
Application		ubmarine, War Ship, Inter Continental Ballistic Missile (ICBM)	Commercial aviation, UAV, AUV	UAV	UAV, Short range missile	ROV, AUV, UAV
Maximum suitable duration for speed measurement		few days	few hours	few minutes	few seconds	stabilization only
Cost of IMU		1,000, 000 USD	100,000 USD	50,000 USD	2,000 USD	1,000 USD
Accelerometer bias (mg)		0.001 mg	0.1 mg	1 mg	10 mg	20 mg
Maximum uncertainty in SOG measurement	1 sec	0.000001 m/s or 0.0000036 km/h	0.0001 m/s or 0.00036 km/h	0.001 m/s or 0.0036 km/h	0.01 m/s or 0.036 km/h	0.02 m/s or 0.072 km/h
	1 min	0.00006 m/s or 0.000216 km/h	0.006 m/s or 0.0216 km/h	0.06 m/s or 0.216 km/h	0.6 m/s or 2.16 km/h	1.2 m/s or 4.32 km/h
	1 hr	0.0036 m/s or 0.01296 km/h	0.36 m/s or 1.296 km/h	3.6 m/s or 12.96 km/h	36 m/s or 129.6 km/h	72 m/s or 259.2 km/h
	12 hr	0.0432 m/s or 0.15552 km/h	4.32 m/s or 15.552 km/h	43.2 m/s or 155.52 km/h	432 m/s or 1555.2 km/h	864 m/s or 3110.4 km /h
	24 hr	0.0864 m/s or 3.1104 km/h	8.64 m/s or 311.04 km/h	86.4 m/s or 3110.4 km/h	864 m/s or 31104 km/h	1728 m/s or 62208 km/h

The major IMU sensor responsible for measuring the SOG of water and air vehicles is an accelerometer. The major types of accelerometers used in IMU are mechanical accelerometers, optical and surface acoustic wave accelerometers, fluid-based accelerometers, and micro-electro-mechanical system (MEMS) accelerometers [53]. All IMUs suffer from integration drift. Small errors in the measurement of IMU's accelerometer sensor are integrated into progressively larger errors in speed. Accurate SOG is also essential for the accurate positioning of water and air vehicles. The impact of accelerometer error on positioning has an even more severe effect than on SOG measurement [54]. For example, if an accelerometer has bias error a, s is positional error due to accelerometer bias, and v is speed error due to accelerometer bias, then after time t, the positional error and speed error of the IMU should be

$$s = 1/2at^2 \tag{1}$$

$$v = at. \tag{2}$$

From the above equations, we can see that due to accelerometer error, the positional error increases squarely over time. For example, after 10, 100, and 1000 s, the positional error shall be 102, 1002, and 10 002 times, respectively, in comparison to the first second. Whereas after 10, 100, and 1000 s, the SOG error shall be 10, 100, and 1000 times, respectively, compared to first second. Table I shows the SOG error growth of various grade IMUs over time. From Table I, we can see that, in the absence of external sources, only the strategic grade IMUs can provide usable SOG measurement for more than a day. Other grade IMUs can provide usable SOG measurement for a few hours or less. As a result, strategic-grade IMUs are suitable for long-operating vehicles like warships and submarines. However, due to their high cost (around one million USD), strategic-grade IMUs are not used by merchant ships.

INS are at the forefront of navigational technology, providing pivotal data for a variety of applications ranging from marine navigation to aerospace engineering. While conventional INS/IMUs have significantly evolved, there remains substantial scope for advancement, particularly in enhancing sensitivity, reducing cost, and mitigating issues associated with long operational durations.

Advancements in CAISs, with their cutting-edge precision in inertial force measurement, offer promising avenues for the future, potentially redefining accuracy standards for strategic applications. Similarly, MOEMS inertial sensors continue to push the boundaries in miniaturization and cost-effectiveness, indicating a shift toward more compact and versatile navigational tools.

Moreover, particle image velocimetry (PIV) inertial sensors present an innovative approach to flow measurement, leveraging optical methods to track flow dynamics with high accuracy. The integration of such diverse technologies suggests a trend toward multifaceted sensor systems, capable of delivering comprehensive data even in the most challenging environments.

Future trends may likely see these advanced technologies converge, perhaps leading to hybrid systems that incorporate the stability and precision of cold atom sensors with the cost-efficiency and agility of MOEMS and the detailed flow analysis provided by PIV sensors. Such integration could pave the way for breakthroughs in fields like autonomous navigation and complex geospatial analysis, aligning closely with the ongoing development of Galilean projectile-based SOG sensors. These are engineered to not only offer robust SOG measurements but also to withstand the rigors of extreme environments, embodying the next leap in sensor technology evolution.

III. Performance, Harsh Conditions, and Technological Limitations of State of the Art SOG Measurement Technologies

A. Water Speed Sensor

In favorable environmental conditions, the SOG error of these sensors remains within 1% of the actual SOG [15], [16], [17], [18], [19], [20], [55]. Harsh conditions for water speed sensors are changes in temperature, density, salinity, speed, the direction of seawater, and collision with external objects. In harsh conditions, the water speed sensor's performance is affected severely. These sensors completely fail to measure SOG at fresh water and when the ships are at anchor.

B. Air Speed Sensor

In favorable environmental conditions, the error of these sensors remain within 1% of the actual SOG [21], [22], [23], [56]. Harsh conditions for airspeed sensors are changes in air density, pressure, temperature, speed, and direction of true wind and collision with external objects. In harsh conditions, the airspeed sensor's performance is affected severely. These sensors completely fail to measure SOG when the vehicle stands still in the presence of wind.

C. Global Navigation Satellite System

In favorable environmental conditions, they show an error of 0.0216 km/h in SOG measurement [3], [8], [24], [25], [26], [27], [57], [58], [59]. Harsh conditions for GNSS are underwater environment, jamming, atmospheric interference, solar flares, and radio frequency interference. In harsh conditions like underwater environment and jamming, GNSS completely fails to measure SOG.

D. Underwater Acoustic Positioning System

In favorable environmental conditions, the SOG error of these sensors remains within 1% of the actual SOG [4], [28], [29], [30], [31], [32], [33], [60]. Harsh conditions for UAPS are noise, water currents, water temperature changes, and collision with external objects. UPAS is a localized system and in comparison to vast sea area, it covers only a distance from a few hundred meters to several kilometers. As a result, when vehicles go out of the UAPS range, they completely fail to measure SOG.

E. Doppler Velocity Log

In favorable environmental conditions, the SOG error of these sensors remains within 1% of the actual SOG [5], [34], [35], [36], [37], [38], [61], [62]. Harsh conditions for DVL are depth of water, bottom absorption, bottom scattering, water currents, and collision with external objects. In harsh conditions like depths below 500 m, DVL completely fails to perform. Thus, in the context of measuring SOG, DLV is highly vulnerable to harsh conditions.

F. Doppler Navigation System

In favorable environmental conditions, the SOG error of these sensors remains within 0.15% of the actual SOG [6], [39], [63], [64], [65], [66], [67]. Harsh conditions for DNS are electromagnetic interference, scattering, attenuation, vibration, temperature, and collision with external objects. In harsh conditions, DNS's performance is affected severely.

G. Simultaneous Localization and Mapping

Harsh conditions for SLAM are absorption, scattering, large distance, electromagnetic interference, vibration, temperature, and collision with external objects [7], [40], [41], [42], [43], [44], [45], [46]. In harsh conditions, SLAM's performance is affected severely. For example, in favorable environmental conditions, DVL used in SLAM shows a SOG error of 1% of the actual SOG. As a result in harsh conditions like depths below 500 m, SLAM completely fails to measure SOG [68], [69].

H. Conventional INS/IMU

Conventional INS/IMU suffer very little from harsh conditions, rather they suffer much from technological limitation like increment of SOG measurement error over time due to accelerometer bias [8], [47], [48], [49], [50], [51], [52], [53], [54]. As a result, long operating hours affect the performance of these sensors severely. For example, after 1 s, these sensors show a small error of 0.0000036 km/h in SOG measurement. However, after 1 day, they show a huge error of 3.1104 km/h in SOG measurement [70], [71].

IV. Future Trends in SOG Measurement Technologies

At present, a large number of researches are going on to advance inertial sensor technologies for improving INS/IMU performance [53]. Amongst them, CAISs, MOEMS inertial sensors, and PIV inertial sensors are mentionable [53]. As well as for direct SOG measurement and to sustain both harsh conditions and integration error over time another sensor is in development named, Galilean projectile model-based SOG sensor.

A. Cold Atom Inertial Sensor

The working principle of a CAIS involves the manipulation of a cloud of atoms using lasers and magnetic fields. The sensor typically consists of a vacuum chamber containing a source of ultra-cold atoms, such as rubidium or cesium, which are cooled to temperatures close to absolute zero (−273 °C) using lasers and magnetic fields. The cloud of cold atoms is then manipulated by applying external forces such as acceleration or rotation using additional lasers and magnetic fields. These external forces cause the cloud of atoms to move or shift relative to each other, which can be measured using a variety of techniques such as interferometry or absorption spectroscopy. By precisely measuring the changes in the position or velocity of the cloud of atoms, the sensor can accurately determine the inertial forces acting on the sensor. These measurements can then be used to determine parameters such as acceleration, rotation rate, and gravity, with high accuracy and precision [9], [72], [73], [74]. Fig. 10 shows sensing fields by use of atoms [9].

B. MOEMS Inertial Sensor

The working principle of MOEMS inertial sensors involves the integration of micro-optics, micro-electronics, and micro-mechanics in a single chip. These sensors typically use a suspended micro-mirror, which is actuated by electrostatic forces to detect the inertial forces acting on the sensor. When an inertial force is applied to the sensor, the micro-mirror undergoes a displacement, which causes a change in the reflection angle of a laser beam directed toward the mirror. The change in reflection angle can be measured using a position-sensitive detector, which provides an output proportional to the inertial force [10], [11], [75], [76]. Fig. 11 shows a graphical representation of MOEMS [11].

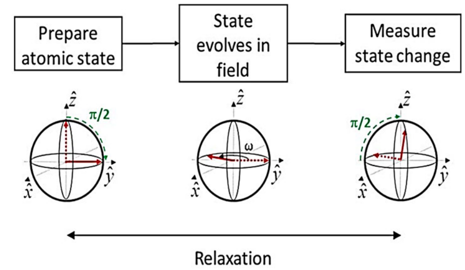

Fig. 10. Sensing fields by use of atoms, from [9].

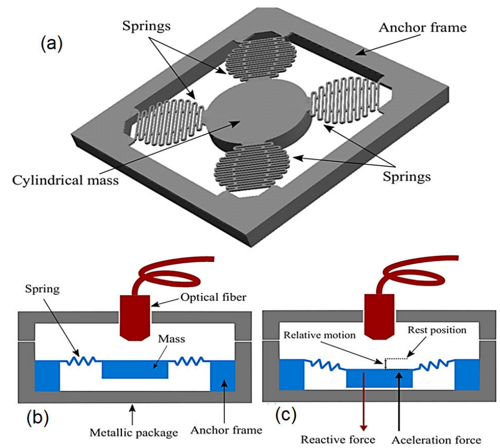

Fig. 11. Graphical representation of MOEMS (a) MEMS device, (b) metallic package coupling the MEMS structure with an optical fiber, and (c) sensor's reaction to exerted acceleration, from [11].

C. PIV Inertial Sensor

PIV is a technique used to measure fluid velocity by analyzing the motion of particles suspended in the fluid. PIV inertial sensors use this technique

to determine the motion of the sensor in a fluid. The working principle of PIV inertial sensors involves the release of particles into the fluid surrounding the sensor. A laser is then used to illuminate the particles and a camera is used to capture images of the particles as they move. The motion of the particles is analyzed to determine the velocity of the fluid, which is proportional to the inertial force acting on the sensor [12], [13], [77]. Fig. 12 shows a schematic of a PIV gyroscope structure [12].

D. Galilean Projectile Model-Based SOG Sensor

Galilean projectile model-based SOG sensor has been reported to be an environment-independent and contactless

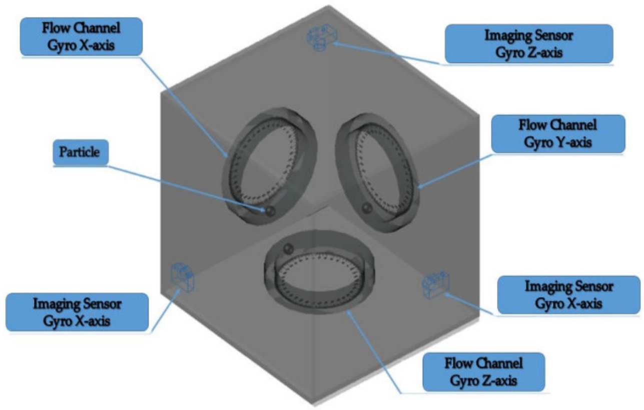

Fig. 12. Schematic of a PIV gyroscope structure, from [12].

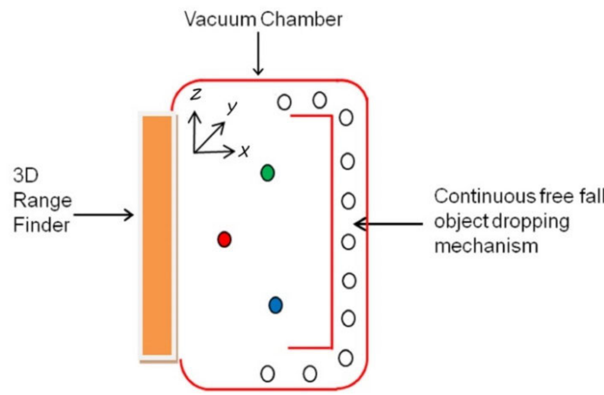

Fig. 13. Basic configuration of Galilean projectile model-based SOG sensor, from [14].

sensor capable of measuring the SOG of water and air vehicles directly [14], [78]. In this sensor, a continuous object-dropping mechanism is configured to release small objects inside a vacuum chamber. These continuous falling objects are used as a reference for measuring SOG. A depth sensor is used to detect the position of the falling objects and generate a corresponding signal. Upon receiving the signal, a computer processor connected to the depth sensor calculates the SOG. Fig. 13 shows the basic configuration of a falling object-based SOG sensor [14].

Previously, it was discussed that errors in the measurement of IMU's accelerometer sensor are integrated into progressively larger errors in speed [54]. So, instead of an accelerometer if this environment-independent and contactless SOG sensor is used in IMUs, it may provide better SOG measurement for a long time by eliminating the integration error of the accelerometer. Also, no accelerometer means, no incremental positional error in square fashion over time. As a result, instead of an accelerometer if this sensor is used in IMUs, it shall not only increase the SOG accuracy but also increase the accuracy in position measurement.

V. Performance, Harsh Conditions, and Technological Limitations of Future Trend SOG Measurement Technologies

A. Cold Atom Inertial Sensor

These types of sensors are graded as upper strategic class INS According to their performance. CAISs are almost insensitive to harsh conditions [9], [72], [73], [74], [79], [80]. However, cold-atom inertial sensors still they suffer from technological limitation like increment of SOG measurement error over time due to accelerometer bias. For example, after 1 s, these sensors show an error of 0.00000036 km/h in SOG measurement and after 1 day, they show an error of 0.31104 km/h in SOG measurement. Unlike other inertial sensors, due to long operating time, the CAIS's performance is affected little. However, they are the most expensive sensor amongst all.

B. MOEMS Inertial Sensor

According to their performance, these sensors are graded as navigation class INS. MOEMS inertial sensors are less sensitive to harsh conditions [10], [11], [75], [76], [81], [82]. They also suffer from technological limitation like increment of SOG measurement error over time due to accelerometer bias. For example, after 1 s, these sensors show a small error of 0.0036 km/h in SOG measurement. However, after 1 day, they show a huge error of 3110.4 km/h in SOG measurement.

C. PIV Inertial Sensor

These sensors can be graded as tactical class INS considering their performance. Particularly, PIV inertial sensors are insensitive to harsh conditions [12], [13], [77]. However, they also suffer from technological limitation like increment of SOG measurement error over time due to accelerometer bias. For example, after 1 s, these sensors show a small error of 0.036 km/h in SOG measurement. However, after 1 day, they show a huge error of 31 104 km/h in SOG measurement.

D. Galilean Projectile Model-Based SOG Sensor

The experimental Galilean projectile model-based SOG sensor has the potential to operate in extreme temperature, pressure, vibration, shock, radiation, interference, and humidity as they do not rely on any physical contact with the environment [14], [78]. As well as, unlike inertial sensors, as no accelerometer is used, this sensor does not suffer from the problem of integration error over time. This capability is beyond the scope of all other currently available state-of-the-art and future-trend inertial sensors. As well as their expense is comparatively lower than other sensors.

VI. Selection Matrix of SOG Measurement Technologies

To facilitate informed decision-making when selecting the optimal SOG sensor for a given application, it is very important to know each SOG technology's performance in favorable environmental conditions, their cost and their maximum uncertainty in SOG measurement due to harsh conditions, and technological limitations. Table II serves as a selection matrix, offering a comprehensive overview of SOG measurement technologies tailored to various applications, aiding in the selection of the most appropriate sensor.

TABLE II

SELECTION MATRIX FOR CHOOSING SOG MEASUREMENT TECHNOLOGY BASED ON HARSH CONDITIONS AND TECHNOLOGICAL LIMITATIONS, FROM [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105]

Sensor /System	Application	Harsh Conditions and Technological Limitations	Performance in Favorable Environmental Conditions	Maximum Uncertainty in SOG Measurement under Certain Harsh Conditions and Technological Limitations	Cost	Advantage	Disadvantage
Water Speed Sensor	Surface and subsurface vessel	Changes in temperature, density, salinity, speed, and direction of seawater	Shows upto 1% error of actual speed through water	100% at fresh water and when vehicle speed is 0 m/s (at anchor) and ocean current speed is more than 0 m/s	15,000 USD	Provides good SOG measurement in the absence of ocean current	SOG measurement is highly affected in the presence of ocean currents and sensor has the risk of collision with external objects
Air Speed Sensor	Air vessel	Changes in air density, pressure, temperature, speed, and direction of wind	Shows upto 1% error of actual speed through air	100% when vehicle speed is 0 m/s (hovering) and wind speed is more than 0 m/s	10,000 USD	Provides good SOG measurement in the absence of wind	SOG measurement is highly affected in the presence of wind and sensor has a risk of collision with external objects
GNSS	Air and surface vessel	Underwater environment, jamming, atmospheric interference, solar flares, and radio frequency interference	Shows an error of 0.0216 km/hr	100% in jamming and underwater environment	100,000,000 USD (Total system)	Receiving device is cheap and provides precise SOG measurement for a long time	Total system extremely expensive, Controlling country can stop service, does not work in jamming and underwater environment
UAPS	Surface and subsurface vessel	Noise, water currents, water temperature changes, and if the transponder distance is more	Shows upto 0.2% error of the measured distance	100% at a distance over 10 kilomeetrs or depth over 2km	1,000,000 USD	Provides precise SOG measurement at short-range	Very expensive, localized system, short area coverage and risk of collision with external objects
DVL	Surface and subsurface vessel	Depth of water, bottom absorption, bottom scattering, and water currents	Shows upto 1% error of actual SOG	100% at a depth over 500 meters	20,000 USD	Provides direct SOG measurement	Limited range and risk of collision with external objects
DNS	Air vessel	Electromagnetic interference, scattering, attenuation, vibration and temperature	Shows upto 0.15% error of actual SOG	>0.15%	100,000 USD	Provides direct SOG measurement	SOG error increases with aircraft speed and risk of collision with external objects
SLAM	Air, surface and subsurface vessel	Absorption, scattering, large distance, signal interference, vibration and temperature	Shows upto 1% error of actual SOG	100% at a depth over 500 meters	100,000 USD	Can provide redundant SOG measurement if multiple sensors are used	Multiple sensors are required and risk of collision with external objects
Conventional INS/IMU	Air, surface and subsurface vessel	SOG measurement error increases over time due to accelerometer bias	Shows an error of 0.0000036 km/hr after 1 second	3.1104 km/hr after 1 day	1,000,000 USD	Can be placed inside the vehicle and is not affected by harsh conditions	Very expensive, SOG error increases over time
Cold Atom Inertial Sensor	Air, surface and subsurface vessel	SOG measurement error increases over time due to accelerometer bias	Shows an error of 0.00000036 km/hr after 1 second	0.31104 km/hr after 1 day	2,000,000 USD	High end strategic grade INS, extremely high precision, can be placed inside the vehicle and is not affected by harsh conditions	Very costly, SOG error increases over time
MOEMS Inertial Sensor	Air, surface and subsurface vessel	SOG measurement error increases over time due to accelerometer bias	Shows an error of 0.0036 km/hr after 1 second	3110.4 km/hr after 1 day	5,000 USD	Can be placed inside the vehicle, small size, lightweight, low power consumption, low cost and is not affected by harsh conditions	Short Term Navigation grade INS, SOG error increases over time
PIV Inertial Sensor	Air, surface and subsurface vessel	SOG measurement error increases over time due to accelerometer bias	Shows an error of 0.036 km/hr after 1 second	31104 km/hr after 1 day	20,000 USD	Can be placed inside the vehicle and is not affected by harsh conditions	Navigation grade INS, SOG error increases over time
Galilean Projectile Model-Based SOG Sensor	Air, surface and subsurface vessel	Experimentation is going on	Experimentation is going on	Experimentation is going on	1,000 USD	Only sensor which is not affected by harsh conditions and accelerometer integration error over time, can be placed inside the vehicle	Experimentation is going on

VII. PATHWAYS TO NEXT GENERATION INNOVATIONS

In the evolving landscape of SOG measurement technologies, the pursuit of precision, reliability, and resilience in the face of harsh conditions and technological limitations is paramount. This journey is marked by a clear delineation between state-of-the-art technologies, which are currently at the forefront of navigational aids, and emerging trends that promise to redefine the standards of accuracy and robustness in SOG measurement. As we navigate toward the future, the ambition that fuels the development of these emerging technologies is not just to surpass their predecessors in performance but to create a new paradigm in navigational accuracy and resilience. Through dedicated research and innovation, the goal is to usher in a new era of navigational technology that is both precise and impervious to the adversities of the natural world.

A. State-of-the-Art SOG Measurement Technologies

Current technologies such as water speed sensors, air speed sensors, GNSS, UAPS, DVL, DNS, SLAM, and conventional INS constitute the backbone of today's navigational and positioning systems. However, despite their invaluable contributions, these technologies have reached a maturity stage where significant advancements are becoming increasingly challenging. The performance of these systems is notably compromised under various harsh conditions, including deep-water pressures, electromagnetic interference, atmospheric anomalies, and temperature extremes. Consequently, there appears to be a diminishing scope for substantial improvement in their fundamental operation, steering the focus toward the exploration of new horizons in SOG measurement technologies.

B. Future Trend SOG Measurement Technologies

As we venture into the future of navigational technology, a new generation of SOG measurement systems emerges, promising not only to enhance accuracy and reliability but also to overcome the limitations imposed by harsh conditions and technological challenges.

1) Cold Atom Inertial Sensor: Future research in this domain could be principally focus on diminishing the expenses and dimensions of these sensors, rendering them more viable and accessible for a wider array of uses outside upscale tactical installations.

2) MOEMS Inertial Sensor: The focal point of upcoming research could be on enhancing their accuracy to reach navigation-grade INS levels while simultaneously working on reducing their price, thus bridging the gap between high performance and economic viability.

3) PIV Inertial Sensor: The research direction for PIV inertial sensors can be concentrated on improving their accuracy to match that of short-term navigation-grade INS and on efforts to minimize both cost and physical dimensions, thereby expanding their utility across a diverse range of navigational challenges.

4) Galilean Projectile Model-Based SOG Sensor: Standing out with the unique zero integration error capability with contactless and environment-independent measurement technique, this sensor is on the brink of revolutionizing SOG measurement. The Galilean projectile model-based SOG Sensor will focus on refining its accuracy to approach upper navigation-grade INS standards while also aiming to reduce both its cost and size. This sensor, with its innovative design and promising potential, is poised to offer a robust solution for accurate SOG measurement across both harsh conditions and technological limitation like increment of SOG measurement error over time due to accelerometer bias.

VIII. Conclusion and Remark

This review has systematically examined the prevailing SOG measurement technologies, highlighting their operational characteristics, strengths, and weaknesses within harsh conditions and technological limitations. Our analysis underscores that while state-of-the-art SOG sensors—such as water speed sensors, air speed sensors, GNSS, UAPS, DVL, DNS, SLAM, and conventional INS—have been instrumental in advancing navigational capabilities, their susceptibility to harsh conditions and technological limitations casts a shadow on their reliability and, consequently, on the safety and efficiency of marine and aerial navigation. We noted that existing technologies, despite their sophistication, exhibit diminishing returns in terms of potential improvements. In many cases, they face a near-impassable threshold of enhancement, largely due to the fundamental constraints imposed by their operating principles and the harsh realities of dynamic and unpredictable environments.

Turning to future trends, we observed a shift in focus to emerging technologies which suffer a little from harsh conditions, like the CAIS, MOEMS inertial sensor, and PIV inertial sensor. Each presents unique avenues for future research and development like, reducing costs and sizes for cold atom and PIV sensors, improving accuracy for MOEMS sensors. However, due to their technological limitation, it will never be possible to completely eliminate their integration error over time.

The Galilean projectile model-based SOG sensor, in particular, exhibits a remarkable potential to revolutionize SOG measurements by offering a robust, contactless, and environmentally independent method. Its unique zero integration error capability and relative insensitivity to harsh conditions make it a promising candidate for future navigational technologies that are both precise and impervious to harsh conditions. Further research might upgrade their precision to upper navigation-grade INS standards.

As the demand for accurate SOG measurement in harsh conditions continues to grow, so too must efforts in innovating and refining the sensors relied upon. The path forward is not without challenges, but with continued research, interdisciplinary collaboration, and a steadfast commitment to innovation, there is a poised stance to enter a new epoch of navigational science—one marked by resilience, precision, and an unyielding assurance in the face of the planet's harshest conditions.

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References

[1] Ø. Ø. Dalheim and S. Steen, "Uncertainty in the real-time estimation of ship speed through water," *Ocean Eng.*, vol. 235, Sep. 2021, Art. no. 109423, doi: 10.1016/j.oceaneng.2021.109423.

[2] M. Kayton and W. Fried, *Avionics Navigation Systems*, 2nd ed., Hoboken, NJ, USA: Wiley, 1997.

[3] A. El-Rabbany, *Introduction to GPS: The Global Positioning System*. Norwood, MA, USA: Artech House, 2002.

[4] J. González-García, A. Gómez-Espinosa, E. Cuan-Urquizo, L. G. García-Valdovinos, T. Salgado-Jiménez, and J. A. E. Cabello, "Autonomous underwater vehicles: Localization, navigation, and communication for collaborative missions," *Appl. Sci.*, vol. 10, no. 4, p. 1256, Feb. 2020, doi: 10.3390/app10041256.

[5] D. Rudolph and T. A. Wilson, "Doppler velocity log theory and preliminary considerations for design and construction," in *Proc. IEEE Southeastcon*, Mar. 2012, pp. 1–7, doi: 10.1109/SECON.2012.6196918.

[6] W. R. Fried, "History of Doppler radar navigation," *Navigation*, vol. 40, no. 2, pp. 121–136, Jun. 1993, doi: 10.1002/j.2161-4296.1993.tb02299.x.

[7] H. Durrant-Whyte and T. Bailey, "Simultaneous localization and mapping: Part I," *IEEE Robot. Autom. Mag.*, vol. 13, no. 2, pp. 99–110, Jun. 2006, doi: 10.1109/MRA.2006.1638022.

[8] A. Noureldin, T. B. Karamat, and J. Georgy, *Fundamentals of Inertial Navigation, Satellite-Based Positioning, and Their Integration*, 1st ed., Berlin, Germany: Springer, 2013.

[9] J. Kitching, S. Knappe, and E. A. Donley, "Atomic sensors—A review," *IEEE Sensors J.*, vol. 11, no. 9, pp. 1749–1758, Sep. 2011.

[10] J. Mireles, Á. Sauceda, A. Jiménez, M. Ramos, and R. Gonzalez-Landaeta, "Design and development of a MOEMS accelerometer using SOI technology," *Micromachines*, vol. 14, no. 1, p. 231, Jan. 2023, doi: 10.3390/mi14010231.

[11] S.-X. Lu, S.-F. Chen, and Y. Zhao, "MOEMS Gyroscope based on acoustooptic mode coupling," *Proc. SPIE*, vol. 7990, Jan. 2010, Art. no. 79900I.

[12] A. A. Youssef and N. El-Sheimy, "Particle imaging velocimetry gyroscope," *Sensors*, vol. 19, no. 21, p. 4734, Oct. 2019, doi: 10.3390/s19214734.

[13] A. Youssef and N. El-Sheimy, "Particle based accelerometer," U.S. Patent 62 796 266, Jan. 1, 2019.

[14] J. M. Imam, M. A. Islam, N. Mokhtar, S. F. W. M. Hatta, and H. Rajagopal, "Modeling of an environmentally independent and contactless speed sensor for measuring the speed of ships, submarines, and aircraft in relation to the ground development of image," in *Proc. Int. Conf. Artif. Life Robot. (ICAROB)*, Oita, Japan, Feb. 2023, pp. 749–758, doi: 10.5954/ICAROB.2023.OS29-4.

[15] W. L. Griswold, "Underwater logs," *Navigat., J. Inst. Navigat.*, vol. 15, no. 2, pp. 127–135, 1968, doi: 10.1002/j.2161-4296.1968.tb01596.x.

[16] C. G. Smith and J. Slepian, "Electromagnetic ship's log," U.S. Patent 1 249 530 A, Dec. 11, 1917.

[17] *Clipper Electromagnetic 2 Speed Log*. Accessed: Apr. 18, 2023. [Online]. Available: https://www.nasamarine.com/product/clipper-electromagnetic-speed-log/

[18] M. J. Tucker, N. D. Smith, and E. P. Collins, "Two-component electromagnetic ship's log," *Nature*, vol. 217, no. 5135, pp. 1244–1245, Mar. 1968, doi: 10.1038/2171244a0.

[19] J. T. Hertel, "Investigating the implemented mathematics curriculum of New England navigation cyphering books," *Learn. Math.*, vol. 36, no. 3, pp. 4–10, 2016.

[20] S. Lehuta, R. Girardin, S. Mahévas, M. Travers-Trolet, and Y. Vermard, "Reconciling complex system models and fisheries advice: Practical examples and leads," *Aquatic Living Resour.*, vol. 29, no. 2, pp. 210–217, Apr. 2016, doi: 10.1051/alr/2016022.

[21] J. Mcorlly, "Pilot tube," U.S. Patent 2 399 370, Apr. 5, 1946.

[22] R. Klopfenstein Jr., "Air velocity and flow measurement using a Pitot tube," *ISA Trans.*, vol. 37, no. 4, pp. 257–263, Sep. 1998, doi: 10.1016/s0019-0578(98)00036-6.

[23] R. Jäckel, G. Gutiérrez-Urueta, and F. Tapia, "A review on Pitot tube icing in aeronautics: Research- design and characterization—Future trends," *Flow Meas. Instrum.*, vol. 81, Oct. 2021, Art. no. 102033, doi: 10.1016/j.flowmeasinst.2021.102033.

[24] H. Jiang, C. Shi, T. Li, Y. Dong, Y. Li, and G. Jing, "Low-cost GPS/INS integration with accurate measurement modeling using an extended state observer," *GPS Solutions*, vol. 25, no. 1, pp. 1–15, Jan. 2021, doi: 10.1007/s10291-020-01053-3.

[25] R. Babu and J. Wang, "Ultra-tight GPS/INS/PL integration: A system concept and performance analysis," *GPS Solutions*, vol. 13, no. 1, pp. 75–82, Jan. 2009, doi: 10.1007/s10291-008-0097-9.

[26] R. Zajdel, K. Kazmierski, and K. Sośnica, "Orbital artifacts in multi-GNSS precise point positioning time series," *J. Geophys. Res., Solid Earth*, vol. 127, no. 2, Feb. 2022, Art. no. e2021JB022994, doi: 10.1029/2021jb022994.

[27] S. S. Leroy, A. E. McVey, S. M. Leidner, H. Zhang, and H. Gleisner, "GNSS radio occultation data in the AWS cloud," *Earth Space Sci.*, vol. 11, no. 2, Feb. 2024, Art. no. e2023EA003021, doi: 10.1029/2023ea003021.

[28] A. Färm, S. Boij, R. Glav, and O. Dazel, "Absorption of sound at a surface exposed to flow and temperature gradients," *Appl. Acoust.*, vol. 110, pp. 33–42, Sep. 2016, doi: 10.1016/j.apacoust.2016.03.017.

[29] S. M. Smith and D. Kronen, "Experimental results of an inexpensive short baseline acoustic positioning system for AUV navigation," in *Proc. Oceans Conf. Rec.*, Oct. 1997, pp. 714–720, doi: 10.1109/OCEANS.1997.634454.

[30] J. Reis, M. Morgado, P. Batista, P. Oliveira, and C. Silvestre, "Design and experimental validation of a USBL underwater acoustic positioning system," *Sensors*, vol. 16, no. 9, p. 1491, Sep. 2016, doi: 10.3390/s16091491.

[31] Z. Yuyi, G. Zhenbang, W. Lei, Z. Ruiyong, and L. Huanxin, "Study of underwater positioning based on short baseline sonar system," in *Proc. Int. Conf. Artif. Intell. Comput. Intell.*, vol. 2, Nov. 2009, pp. 343–346, doi: 10.1109/AICI.2009.83.

[32] Y. Han, C. Zheng, and D. Sun, "Accurate underwater localization using LBL positioning system," in *Proc. OCEANS-MTS/IEEE Washington*, Oct. 2015, pp. 1–4, doi: 10.23919/OCEANS.2015.7401893.

[33] A. Bahr, J. J. Leonard, and M. F. Fallon, "Cooperative localization for autonomous underwater vehicles," *Int. J. Robot. Res.*, vol. 28, no. 6, pp. 714–728, Jun. 2009, doi: 10.1177/0278364908100561.

[34] G. Xu, Y. Zhao, K. Xu, H. Xu, and Z. Cheng, "A speed measurement method for underwater vehicle based on pulse speedometer and accelerometer," in *Proc. 23rd Int. Offshore Polar Eng. Conf.*, Jun. 2013, Paper ISOPE-I-13-262.

[35] *Acoustic Doppler Current Profiler*. Accessed: Apr. 18, 2023. [Online]. Available: https://oceanexplorer.noaa.gov/technology/acoust-doppler/acoust-doppler.html

[36] P. Liu, B. Wang, Z. Deng, and M. Fu, "INS/DVL/PS tightly coupled underwater navigation method with limited DVL measurements," *IEEE Sensors J.*, vol. 18, no. 7, pp. 2994–3002, Apr. 2018, doi: 10.1109/JSEN.2018.2800165.

[37] W. Gao, J. Li, G. Zhou, and Q. Li, "Adaptive Kalman filtering with recursive noise estimator for integrated SINS/DVL systems," *J. Navigat.*, vol. 68, no. 1, pp. 142–161, 2015, doi: 10.1017/S0373463314000484.

[38] M. García-Méndez, A. B. Calle, R. R. Segura, and V. Coello, "WITHDRAWN: Investigation of the optical and structural properties of RF-sputtered ZnO thin-film submitted to an annealing regime at various temperatures," *Optik Int. J. Light Electron Opt.*, pp. 3872–3876, Aug. 2015, doi: 10.1016/j.ijleo.2015.08.062.

[39] A. Nekrasov, A. Khachaturian, V. Veremyev, and M. Bogachev, "Doppler navigation system with a non-stabilized antenna as a sea-surface wind sensor," *Sensors*, vol. 17, no. 6, p. 1340, Jun. 2017, doi: 10.3390/s17061340.

[40] Y. Lu and D. Song, "Visual navigation using heterogeneous landmarks and unsupervised geometric constraints," *IEEE Trans. Robot.*, vol. 31, no. 3, pp. 736–749, Jun. 2015, doi: 10.1109/TRO.2015.2424032. https://doi.org/10.1109/TRO.2015.2432428.

[41] H. Carrillo, P. Dames, V. Kumar, and J. A. Castellanos, "Autonomous robotic exploration using occupancy grid maps and graph SLAM based on Shannon and Rényi entropy," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2015, pp. 487–494, doi: 10.1109/ICRA.2015.7139224.

[42] M. Pizzoli, C. Forster, and D. Scaramuzza, "REMODE: Probabilistic, monocular dense reconstruction in real time," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2014, pp. 2609–2616, doi: 10.1109/ICRA.2014.6907233.

[43] C. Brand, M. J. Schuster, H. Hirschmüller, and M. Suppa, "Stereo-vision based obstacle mapping for indoor/outdoor SLAM," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2014, pp. 1846–1853, doi: 10.1109/IROS.2014.6942805.

[44] Y. R. Petillot, G. Antonelli, G. Casalino, and F. Ferreira, "Underwater robots: From remotely operated vehicles to intervention-autonomous underwater vehicles," *IEEE Robot. Autom. Mag.*, vol. 26, no. 2, pp. 94–101, Jun. 2019, doi: 10.1109/MRA.2019.2908063.

[45] S. Calinon, F. Guenter, and A. Billard, "On learning the statistical representation of a task and generalizing it to various contexts," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2006, pp. 2078–2084, doi: 10.1109/ROBOT.2006.1642154.

[46] M. F. Fallon, M. Kaess, H. Johannsson, and J. J. Leonard, "Efficient AUV navigation fusing acoustic ranging and side-scan sonar," in *Proc. IEEE Int. Conf. Robot. Autom.*, Shanghai, China, May 2011, pp. 2398–2405, doi: 10.1109/ICRA.2011.5980302.

[47] P. D. Groves, "Navigation using inertial sensors [tutorial]," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 30, no. 2, pp. 42–69, Feb. 2015, doi: 10.1109/MAES.2014.130191.

[48] D. Titterton and J. L. Weston, *Strapdown Inertial Navigation Technology*, vol. 17. London, U.K.: IET, 2011.

[49] M. Perlmutter and L. Robin, "High-performance, low cost inertial MEMS: A market in motion!" in *Proc. IEEE/ION Position, Location Navigat. Symp.*, Apr. 2012, pp. 225–229, doi: 10.1109/PLANS.2012.6236884.

[50] C. Jekeli, "Precision free-inertial navigation with gravity compensation by an onboard gradiometer," *J. Guidance, Control, Dyn.*, vol. 30, no. 4, pp. 1214–1215, 2007, doi: 10.2514/1.15368.

[51] K. Borodacz, C. Szczepański, and S. Popowski, "Review and selection of commercially available IMU for a short time inertial navigation," *Aircr. Eng. Aerosp. Technol.*, vol. 94, no. 1, pp. 45–59, Jan. 2022, doi: 10.1108/aeat-12-2020-0308.

[52] Y. Li et al., "IMU/magnetometer/barometer/mass-flow sensor integrated indoor quadrotor UAV localization with robust velocity updates," *Remote Sens.*, vol. 11, no. 7, p. 838, Apr. 2019, doi: 10.3390/rs11070838.

[53] N. El-Sheimy and A. Youssef, "Inertial sensors technologies for navigation applications, state of the art, and future trends," *Satell. Navigat.*, vol. 1, no. 1, p. 2, 2020, doi: 10.1186/s43020-019-0001-5.

[54] A. Lawrence, "Gyro and accelerometer errors and their consequences," in *Modern Inertial Technology*. New York, NY, USA: Springer, 1998, pp. 25–42, doi: 10.1007/978-1-4612-1734-3_3.

[55] A. S. Voronov and M. I. Evstifeev, "Influence of structural parameters on instrumental error of electromagnetic log sensor," *J. Phys., Conf. Ser.*, vol. 1536, no. 1, May 2020, Art. no. 012010, doi: 10.1088/1742-6596/1536/1/012010.

[56] F. Sklenář and J. Matějů, "Indicated airspeed error due to gradual blocking of Pitot tube with drain hole," *Aviation*, vol. 26, no. 1, pp. 64–71, Apr. 2022, doi: 10.3846/aviation.2022.15963.

[57] K. De Jong, "Minimal detectable biases of cross-correlated GPS observations," *GPS Solutions*, vol. 3, no. 3, pp. 12–18, Jan. 2000, doi: 10.1007/pl00012798.

[58] A. Grant, P. Williams, N. Ward, and S. Basker, "GPS jamming and the impact on maritime navigation," *J. Navigat.*, vol. 62, no. 2, pp. 173–187, 2009, doi: 10.1017/S0373463308005213.

[59] G. Taraldsen, T. A. Reinen, and T. Berg, "The underwater GPS problem," in *Proc. OCEANS IEEE*, Jun. 2011, pp. 1–8, doi: 10.1109/Oceans-Spain.2011.6003649.

[60] B. Xu, S. Li, A. A. Razzaqi, and J. Zhang, "Cooperative localization in harsh underwater environment based on the MC-ANFIS," *IEEE Access*, vol. 7, pp. 55407–55421, 2019.

[61] H. Qin, Y. Wang, G. Wang, X. Qin, and Y. Bian, "GSCV-XGBoost based information reconstruction and fusion method for SINS/DVL integrated navigation system," *Meas. Sci. Technol.*, vol. 34, no. 3, Mar. 2023, Art. no. 035105.

[62] Z. Wang, X. Liu, X. Wu, G. Sheng, and Y. Huang, "A virtual velocity-based integrated navigation method for strapdown inertial navigation system and Doppler velocity log coupled with unknown current," *Rev. Sci. Instrum.*, vol. 93, no. 6, Jun. 2022, Art. no. 065112.

[63] J. Testud, P. H. Hildebrand, and W.-C. Lee, "A procedure to correct airborne Doppler radar data for navigation errors using the echo returned from the Earth's surface," *J. Atmos. Ocean. Technol.*, vol. 12, no. 4, pp. 800–820, Aug. 1995.

[64] H. Cai, W.-C. Lee, M. M. Bell, C. A. Wolff, X. Tang, and F. Roux, "A generalized navigation correction method for airborne Doppler radar data," *J. Atmos. Ocean. Technol.*, vol. 35, no. 10, pp. 1999–2017, Oct. 2018.

[65] M. Kayton and W. R. Fried, *Avionics Navigation Systems*. New York, NY, USA: Wiley, 1969, ch. 6.

[66] W. R. Fried, "An FM-CW radar for simultaneous three-dimensional velocity and altitude measurement," *IEEE Trans. Aerosp. Navigational Electron.*, vol. ANE-11, no. 1, pp. 45–57, Mar. 1964.

[67] S. K. Benjamin, "The AN/APN-153 (V) Doppler navigation equipment," *IEEE Trans. Aerosp.*, vol. AS-1, no. 2, pp. 265–271, Aug. 1963.

[68] P. Fritsche, S. Kueppers, G. Briese, and B. Wagner, "Fusing LiDAR and radar data to perform SLAM in harsh environments," in *Proc. 13th Int. Conf. Informat. Control, Autom. Robot. (ICINCO)*, Lisbon, Portugal. Cham, Switzerland: Springer, Jul. 2018, pp. 29–31.

[69] J. M. Santos, M. S. Couceiro, D. Portugal, and R. P. Rocha, "A sensor fusion layer to cope with reduced visibility in SLAM," *J. Intell. Robotic Syst.*, vol. 80, nos. 3–4, pp. 401–422, Dec. 2015.

[70] Y. Zhi-Yong, W. Jiang-Feng, C. Guo-Dong, and X. Jian-Ping, "Effects of harsh electromagnetic environment on inertial measurement unit of a flight vehicle," in *Proc. Int. Symp. Electromagn. Compat.*, Nov. 2007, pp. 307–310.

[71] G. T. Schmidt, *Low-Cost Navigation Sensors and Integration Technology*, document RTO-EN-SET-116-2011, INS/GPS Technol. Trends (NATO RTO), 2011, doi: 10.14339/RTO-EN-SET-116-2011.

[72] S. De Silva, "A 2D atom interferometer accelerometer in the horizontal plane," Ph.D. dissertation, Dept. Phys., Imperial College London, London, U.K. [Online]. Available: https://spiral.imperial.ac.uk/bitstream/10044/1/93374/1/de-Silva-S-2021-PhD-Thesis.pdf

[73] X. Cheng, "Building a sensitive atom interferometer for navigation," Ph.D. dissertation, Dept. Phys., Imperial College London, London, U.K., 2020. [Online]. Available: https://spiral.imperial.ac.uk/bitstream/10044/1/79347/1/Cheng-X-2020-PhD-Thesis.pdf

[74] J. Stammers, "An atom interferometer for measuring horizontal accelerations," Ph.D. dissertation, Dept. Phys., Imperial College London, London, U.K., 2019. [Online]. Available: https://spiral.imperial. ac.uk/handle/10044/1/68008

[75] C. Trigona, B. Andò, and S. Baglio, "Fabrication and characterization of an MOEMS gyroscope based on photonic bandgap materials," *IEEE Trans. Instrum. Meas.*, vol. 65, no. 12, pp. 2840–2852, Dec. 2016.

[76] B. Zhang and W. F. Li, "Development of a micro accelerometer based MOEMS," in *Proc. Int. Conf. Manipulation, Manuf. Meas. Nanosc. (3M-NANO)*, Aug. 2012, pp. 250–253.

[77] A. Youssef and N. El-Sheimy, "Gyroscope using torus shaped channels and image processing," U.S. Patent 62 796 231, Jan. 13, 2019.

[78] J. M. Imam and M. A. Islam, "Environmentally independent and contactless onboard speed sensor for measuring the speed of water and air vehicles with respect to the ground directly," PBD Patent 2 023 000 107, Apr. 1, 2023.

[79] R. Geiger, A. Landragin, S. Merlet, and F. P. dos Santos, "High-accuracy inertial measurements with cold-atom sensors," *AVS Quantum Sci.*, vol. 2, no. 2, Jun. 2020, Art. no. 024702, doi: 10.1116/5.0009093.

[80] A. Gauguet, B. Canuel, T. Lévèque, W. Chaibi, and A. Landragin, "Characterization and limits of a cold-atom Sagnac interferometer," *Phys. Rev. A, Gen. Phys.*, vol. 80, no. 6, Dec. 2009, Art. no. 063604.

[81] J. Kähler, A. Stranz, A. Waag, and E. Peiner, "Packaging of MEMS and MOEMS for harsh environments," *J. Micro/Nanolithography, MEMS, MOEMS*, vol. 11, no. 2, May 2012, Art. no. 0212021.

[82] P. M. Nieva, "New trends on MEMS sensor technology for harsh environment applications," *Sensors Transducers J.*, vol. 2, pp. 10–20, Oct. 2007.

[83] Atos. *LMN5 Electromagnetic Speed Log*. Accessed: Mar. 31, 2024. [Online]. Available: https://atos.net/wp-content/uploads/2019/08/atos-ben-marine-lmn5-electromagnetic-speed-log.pdf

[84] AMI Mar. *Walker 7070 Mk2*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.amimarine.com/wp-content/uploads/2021/02/AMI-7070-Mk-Speed-Log-Data-Sheet.pdf

[85] B. Marine. *CLETA Electromagnetic Speed Log*. Accessed: Mar. 31, 2024. [Online]. Available: https://atos.net/wp-content/uploads/2020/09/ben-marine-cleta-factsheet.pdf

[86] Yokogawa. *EML500 Series Electromagnetic Speed Log*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.codar.com.sg/wp-content/uploads/2019/01/ELECTRO-MAGNETIC-LOG-EML-500-SERIES.pdf

[87] YDK Technologies. *EML900 Series Electromagnetic Log*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.ydktechs.co.jp/en/product/pdf/EML900series_catalog.E.pdf

[88] Omega. *An Introduction to Pitot Tubes and Probes*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.omega.com/en-us/resources/pitot-tube#section3

[89] Omega. *FTP 3000 Series Pitot Tube*. Accessed: Mar. 31, 2024. [Online]. Available: https://assets.omega.com/pdf/test-and-measurement-equipment/flow/vortex-flow-meters/FPT-3000.pdf

[90] (Mar. 3, 2022). *GPS Accuracy*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.gps.gov/systems/gps/performance/accuracy/
[91] iXblue. *Underwater Acoustic Positioning Solutions*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.ixblue.com/defense/naval-navigation/underwater-acoustic-positioning-solutions/
[92] MIT Deep Water Archaeology Research Group. *Precision Navigation for Deep Water Archaeology*. Accessed: Mar. 31, 2024. [Online]. Available: https://web.mit.edu/deeparch/www/research/precisionnav.html
[93] Water Linked. *Underwater GPS G2*. Accessed: Mar. 31, 2024. [Online]. Available: https://waterlinked.com/web/content/7539?unique=0e0957583b670554b27abb667a70927bcf35c6a7
[94] iXblue. (2023). *Gaps M5*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.ixblue.com/wp-content/uploads/2023/03/datasheetgaps-m5exail.pdf
[95] Tema Systems. (2024). *EVOLOGICS S2CR 18/34H USBL Underwater Acoustic Positioning System*. Accessed: Mar. 31, 2024. [Online]. Available: https://stema-systems.nl/equipment/evologics-s2cr-18-34h-usbl-underwater-acoustic-positioning-system/
[96] Water Linked. (2022). *DVL A50*. Accessed: Mar. 31, 2024. [Online]. Available: https://neotek-web.com/wp-content/uploads/2022/04/wl-21035-3_DVL_A50.pdf
[97] Water Linked. (2022). *DVL A125*. Accessed: Mar. 31, 2024. [Online]. Available: https://waterlinked.com/web/content/7525?unique=5c826d6027d39482ee721494bacf8677c77bd950
[98] NORTEK. (2022). *DVL1000—4000 M*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.uniquegroup.com/wp-content/uploads/2022/10/Nortek_DVL1000_4000-m.pdf
[99] BAE Systems. (2017). *Doppler/GPS Navigation Set AN/ASN-157*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.baesystems.com/en-media/uploadFile/20210404063505/1434592267344.pdf
[100] BAE Systems. (2020). *Doppler/GPS Navigation Set AN/ASN-128D*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.baesystems.com/en-media/uploadFile/20210404064438/1434657336105.pdf
[101] BAE Systems. (2020). *Doppler/GPS Navigation Set AN/ASN-128E*. Accessed: Mar. 31, 2024. [Online]. Available: https://www.baesystems.com/en-media/uploadFile/20210404064435/1434657335904.pdf
[102] Honeywell. (2024). *Compare Our Inertial Measurement Units*. Accessed: Mar. 31, 2024. [Online]. Available: https://aerospace.honeywell.com/us/en/products-and-services/product/hardware-and-systems/sensors/inertial-measurement-units
[103] Honeywell. (2018). *HG9900 Inertial Measurement Unit*. Accessed: Mar. 31, 2024. [Online]. Available: https://aerospace.honeywell.com/content/dam/aerobt/en/documents/learn/products/sensors/brochures/N61-1638-000-000-hg9900inertialmeasurementunit-bro.pdf
[104] Safran. (2017). *The European Leader in Aerospace Navigation*. Accessed: Mar. 31, 2024. [Online]. Available: https://safran-navigation-timing.com/wp-content/uploads/2023/02/aerospace_navigation.pdf
[105] Safran. *Naval Navigation Systems*. Accessed: Mar. 31, 2024. [Online]. Available: https://pardot.oroliads.com/datasheet/naval-ins

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