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Innovative navigation strategies based on multiple signals for performance improvement of drone-based operations

Verdiana Bottino[1,a *]

[1]Department of Industrial Engineering, University of Naples Federico II, Italy

[a]verdiana.bottino@unina.it

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Abstract. The growing employment of Unmanned Aerial Systems (UASs, commonly referred to as drones) in civilian and military environments, along with the increasing accuracy of avionics components, has led to the definition of more stringent drone-based mission requirements. In this sense, the following work summarizes a series of Ph.D. research activities aimed at improving UAS performance under different aspects, in order to enhance their use in a variety of application contexts and environmental conditions while ensuring a satisfactory level of accuracy.

The last decade experienced a rapid expansion of the UASs market thanks to the significant cost reduction of new technologies. Indeed, compared to fixed-wing aircraft or helicopters, drones are characterized by much lower dimensions and weight, and the substantial performance improvement reached by avionic components made them a cost-effective and versatile solution capable of meeting various mission needs. As a result, the use of drones is no longer limited to military operations but is spreading to a wide range of application domains, such as precision agriculture, monitoring, surveillance, communication, and goods delivery. Moreover, the autonomy and flexibility of drones make their employment highly beneficial for emergency operations, cinematography, and infrastructure inspection, which often require costly equipment, repetitive procedures, and a high level of technical experience [1–5].

The general improvement of UAS performances is also owed to their capability to integrate more sensors at the same time, with the aim of allowing simultaneous data collection from different sources, including electronic devices, high-resolution cameras, thermal cameras, and Micro-electro Mechanical Sensors (MEMS). The latter, in particular, play a fundamental role in the development of aerial vehicles and platforms: in fact, compared to the traditional heavy and expensive navigation units, the inertial units manufactured using MEMS benefit from miniaturized electronic components (such as microphones, gyroscopes, accelerometers, and pressure sensors) that are lighter, more compact, and definitely cheaper than other sensors. Also, their most advanced releases are becoming comparable in terms of accuracy with the bulky and costly fiber-optic technology, which is why MEMS are being massively employed also in the aerospace and defense field [1,6–10].

Despite the increased reliability and ease of integration, the use of MEMS is associated with a series of issues (such as the inertial sensors bias drift with time) whose resolution is still the object of numerous studies. Navigation-related issues must be adequately considered, with the aim of proposing suitable and cost-effective solutions capable of meeting both accuracy and reliability requirements; for this reason, the Ph.D. project outlined in the present work was aimed at improving UAS navigation performances to enhance drone employment in different mission types, also developing innovative navigation solutions to successfully use drones in challenging environments.

Since UAS-based operations require accurate and autonomous navigation capabilities exploited in the estimate of attitude parameters, the initial part of the research activities has been focused on the heading angle computation. An innovative gyrocompassing procedure based on the integration of a tactical-grade MEMS Inertial Measurement Unit (IMU), composed of an accelerometer and a gyroscope, and a low-cost MEMS magnetometer was proposed [11]: particularly, a Matlab^{TM} tool was implemented to acquire the IMU data, and the magnetometric measurements allowed to compute the three components of the Earth magnetic field which were used to initialize the gyrocompassing procedure. A Kalman Filtering algorithm composed of a prediction stage and a correction stage was implemented to perform data fusion, and the estimated heading angle was compared with a reference value obtained by means of a certified Attitude and Heading Reference System (AHRS). The results reported in Table 1 showed that the heading angle computed by the proposed system was compliant with the certified value, with a difference of 0.76 deg in Root Mean Square Error, proving that the magnetometer measurements integration allows the designed system to reach remarkable performances in terms of heading estimate.

Table 1: Difference in heading angle (Δθ) between the reference and the proposed system in terms of Mean, Root Mean Square Error (RMSE), and Standard Deviation (STD).

	Mean	**RMSE**	**STD**
Δθ [°]	0.76	0.76	0.04

The same goal was reached through an innovative methodology exploiting the Sun polarization properties and designed to support GNSS/IMU integrated solutions [12]. A polarimetric camera was embarked on a commercial drone to acquire different images, which were processed to deduce the Sun Meridian/anti-meridian position in the local reference frame and, subsequently, the heading angle. Ground and flight tests were performed using an 8mm focal length lens, and these measurements were integrated with the ones obtained by the IMU in the filtering phase. Then, the computed attitude parameters were compared with the ones obtained by a certified AHRS for ground tests and by drone telemetry for flight tests: in both cases, an RMSE error of about 1 deg was shown, proving that the use of a polarimetric camera permits adequate compensation of IMU-related bias drift and that the proposed system represents a suitable solution to adopt when traditional GNSS/IMU cannot be employed. An example of the results obtained in a flight test is shown in Table 2.

Table 2: Average values of roll (ϕ), pitch (θ), and heading (ψ) angles computed by the drone telemetry during a flight test along a straight path, using an 8mm focal length lens. The average error is computed as the difference between the heading angle obtained by the drone telemetry and the one measured by the proposed system. The reported values refer to a single group of images acquired at different drone locations.

Parameter	**Value**
Average ϕ [°]	-1
Average θ [°]	-1.2
Average ψ [°]	199.5
Average ε_{ψ} [°]	-0.2

Present studies are aimed at the elimination of magnetometric measurements to perform the gyrocompassing procedure, despite a Kalman Filter-based algorithm still representing the best option to adopt for data fusion; regarding the visual-based UAS navigation, further studies based on polarimetric camera measurements are being conducted, with particular focus on fisheye lenses.

During the last year, research activities have also been carried out to perform accurate UAS heading estimation in unstructured environments where GNSS satellite positioning is problematic. Indeed, despite working well outdoors, GNSS signal easily suffers from blockage or degradation in urban areas with tall buildings, indoor settings, deserts, and under bridges, having large errors affecting the drone attitude and position estimates consequently [13]. Different options were investigated but, eventually, the most suitable solution was found in exploiting 5G technology, because of the numerous advantages associated with this type of connection (including higher carrier frequencies, insensitivity to magnetic interference, and the capability to ensure a positioning service with sub-meter accuracy) [14–16]. So, a preliminary system architecture for UASs operating in GNSS-challenging scenarios based on an integrated IMU/GNSS solution was proposed [13]: as shown in Figure 1, the possibility to switch to a 5G/GNSS integrated configuration in case of GPS signal unavailability or degradation was included.

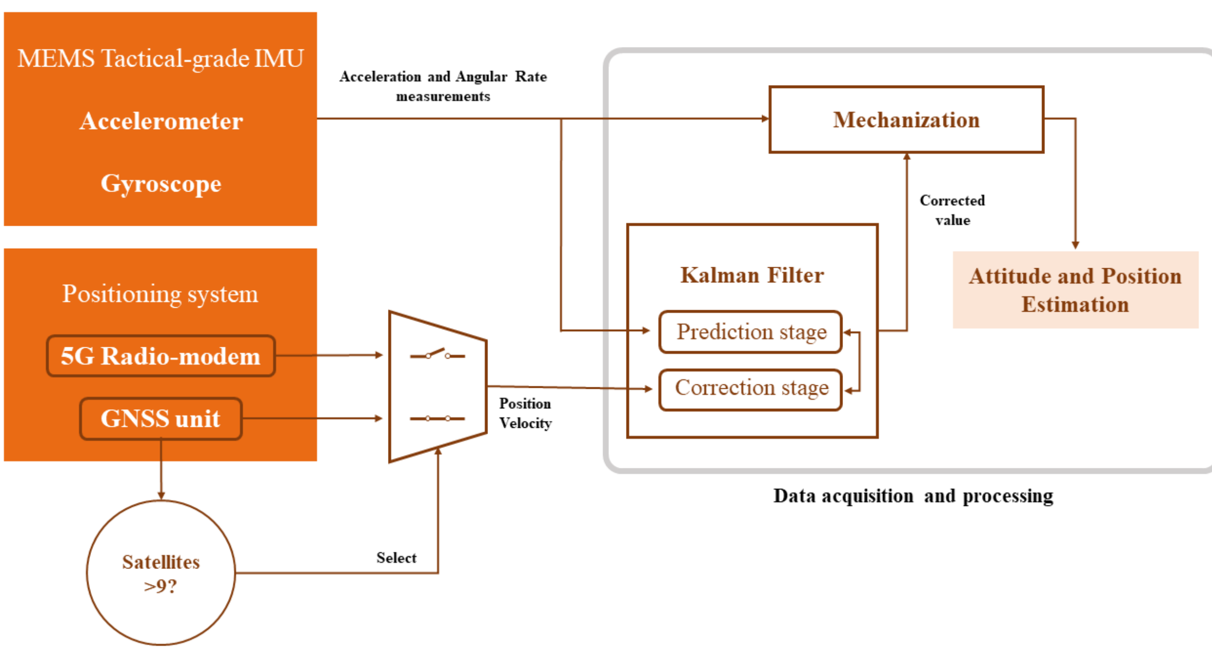

Figure 1: Proposed 5G-GNSS RTK/IMU system architecture. The 5G Radio-modem is integrated onboard the drone to replace the GNSS service during its outage periods or in case the GNSS positioning service doesn't provide sufficiently accurate results. The navigation process is divided into two main steps: a mechanization process that allows to obtain the navigation solutions in their continuous form, and a Kalman Filtering stage that provides position, velocity, attitude, and bias corrected values.

Currently, Ph.D. research activities concerning this topic are proceeding with the elaboration of a Matlab™ tool aimed at simulating 5G communication and computing the drone position using trilateration techniques so that, in the near future, flight tests will be performed embarking a 5G radio modem on a commercial drone with a flying platform composed by a MEMS-based IMU and a GNSS receiver. The results will be compared with the ones obtained through Matlab™

simulations, while data fusion will be performed by means of a Kalman Filter algorithm. During the experiment planning and trajectory design phases, particular attention will be paid to the application UASs for automated cinematography, which frequently operates in GNSS-denied or GPS-challenging environments.

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