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ON-BOARD APPLICABILITY OF MEMS-BASED AUTONOMOUS NAVIGATION SYSTEM ON AGRICULTURAL AIRCRAFTS

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In practical terms of agricultural flights, the success of the mission has been largely determined by the airmanship, experience and visual reference of the pilot. By using microelectro-mechanical system (MEMS) devices, a complex on-board system can be designed which increases flight safety and improves the efficiency of pest control. With the help of dead reckoning navigation system using MEMS accelerometers and gyroscopes, the spatial attitude and geographic location of the aircraft can be obtained. By measuring the surrounding local air pressure and applying the mathematical model of particular aircraft types´ vortex and stream systems and the properties of the pesticides deployed the accuracy of the crop spraying can be improved while the spraying device can be operated automatically in a control loop. With real-time data processing the pesticide coverage is more uniform, the overlap spraying of the fields can be avoided, and the lateral distance limit between fields and urban built-up areas can be better controlled. It follows that the environmental load can be decreased and the usage of chemicals and pesticides can be optimized.

Keywords: agricultural flight, pest control, on-board systems, dead reckoning navigation, MEMS devices

There are a lot of applications of MEMS-based devices in automotive and defence industries. Now it is about to become common in the commercial aerospace industry, as new perspectives are opening up in general aviation. This paper focuses especially on their deployment on-board agricultural aircrafts, where pest control and crop spraying efficiency can be dramatically improved, thus the environmental load can be minimized.

General overview

The early commercial deployment of microelectro-mechanical system (MEMS)-based accelerometers and gyroscopes were in the automotive industry in the late 1980´s in airbag systems. Today they are widely used in active restraint systems, dynamic stability control, suspensions and in several on-board electronic devices. In the aerospace industry the laser-gyros provided the best performance for a very long time but now the MEMS-based devices can be constructed with the same accuracy yet with better resolution and long term stability. MEMS-based inertial measurement units (IMU) are now certified for primary navigation equipment on-board of general aviation aircrafts.

According to Yazdi et al. [1] the accuracy of MEMS devices has doubled every second year since 1991. This could help compete with the accuracy of the Navstar GPS system which is now used for secondary navigation equipment only. The main reason not to use Navstar GPS as a primary source is its availability. Its operation is not independent (operated by US Department of Defense), can be jammed, sensitive to interferences and requires continuous view of at least three satellites for a 2D fix. On the other hand the MEMS-based IMU system is a self contained, low cost, easy-to-integrate solution and can be deployed on-board of every vehicle even on those which have no sky view (e.g. subways, trains in tunnel, submarines, etc). The inertial grade MEMS gyros *(Table 1)* and the navigation grade accelerometers *(Table 2)* are now providing the required accuracy and performance for the construction of a high-end airborne navigation system. The original specification of navigational grade accelerometer in Table 2 has been altered from ±1g to ±10g to conform to the general aviation requirements. Most utility category aircrafts – like the agricultural aircrafts which are now in our focus – are designed for -1,8g to +4,5g load. For aerobatics or military usage a ±15g range would be a reasonable choice.

Agricultural aspect

A generic agricultural flight profile is executed at 5–30 m above ground level with a 120–160 km/h velocity according to the visual flight rules (VFR). The pilot relies mostly on his perceptions and the senses transmitted by his vestibular system. During the crop spraying fly-bys the standard cockpit instruments are mostly used for crosschecks only. They are the most important contributing factors which influence the efficiency of the crop spraying. That is why the success still depends mostly on the flight experience and airmanship of the pilot. According to the national regulations, crop spraying cannot be executed when the actual wind component exceeds 6 m/s and at least a 500–2500 m boundary strip shall be kept between fields subject to different chemicals and between fields and built-up areas. As a consequence, significant sizes of fields may be left out of treatment and the efficiency of the spraying is not uniform or optimal. That is why the pilot should be supported during his mission.

The utilization of the MEMS devices on-board of agricultural aircrafts is now in an early stage. Our main goal in this article is to provide a concept for the deployment of MEMS-based IMU navigation systems which could improve the flight safety as well as the efficiency of the crop spraying and pest control.

MEMS IMU on board

The aircraft flies relative to the wind which is expressed with the value of the True Airspeed (TAS). From the actual Wind Component (WC) and the TAS the aircraft's relative speed over the ground (Ground Speed, GS) can be obtained.

$$TAS \pm WC = GS \qquad (1)$$

Usually the airspeed indicator in the cockpit indicates the so called Indicated Airspeed (IAS) which is subject to position, compression, instrument and density errors. The pilot has mostly inadequate information on the actual wind vector (wind speed and wind direction, WC) which as a matter of fact has the highest impact on the dispersion and coverage of crop spraying. Moreover it is an important factor in general navigation, as well.

In a MEMS IMU device the accelerometers measure the linear acceleration referred to the inertial reference frame and the gyroscopes measure the angular velocity. The accelerometers provide the direction and the gyroscopes the orientation about the X-Y-Z axis. By integrating the inertial accelerations with an initial condition set to the original velocity – practically zero, since IMU setup in the aircraft shall be performed on ground prior block off – the system yields the inertial velocities which is considered as the ground speed (GS). Integrating again yields the system's inertial position. If the initial inertial position has been entered to the IMU then the actual inertial position can be calculated any time and can be provided for other system components for further processing. The kind of determination of the position without external reference is known as dead-reckoning. It is useful to enter WGS-84 compatible initial position by latitude and longitude – which can be obtained by a stable GPS measurement – to preserve compatibility with ICAO standards[1] and Navstar GPS. In this way the MEMS IMU can be used to provide ground speed, position, spatial referenced attitude and heading information and g-load. Based on those data further key air navigation information can be obtained especially if external sources (map and performance database, magnetometer, air data computer, etc.) are linked.

To obtain the TAS value it is practical to use a digital Air Data Computer (ADC) which provides the static and dynamic air pressure and outside air temperature via standard digital interface (ARINC[2] 421). The Sandia Aerospace Type SAC 7-35 ADC [2] could be a cost-effective choice. Some of the pressure-sensing parts of the unit are also MEMS devices.

If the IMU is extended with an ADC equation 1 can be solved. The wind vector (WC) can be gained by the vector difference of the corresponding heading and track information provided. The angle between the two vectors is called drift angle and it has high importance in navigation as well as in the dispersion-calculation of the pesticide particles.

Adding a geo-referenced navigational database (NAVDATA) to the system would be beneficial for both purposes, general navigation and pest control, crop spraying. NAVDATA should comprise of the waypoints, airspace fixes, navigational aids, terrain objects, towns, roads and should provide additional space for user defined fixes such as lateral extension of a field to be sprayed. Referred to this database and the data obtained from IMU+ADC; bearing, distance and ETA (estimated time to arrival) information can be calculated.

In this way, the IMU+ADC+NAVDATA system provides an optimal and cost-effective solution compared to a simple GPS receiver or a high-end laser-gyro based platform. The average refresh rate of this system is about 300 Hz, while a precision grade GPS is able to give position information maximal 5 times per second. Extending the system's capability by installing an angle-of-attack vane opens more safety feature for the operator. Wind shear warning and stall indication can be released to the pilot. This could dramatically improve the situation awareness and therefore the flight safety and absolute necessary for proper dispersion calculations of crop spraying.

Design concept

Every component of the designed system is permitted for civil use without restrictions and available in commercial retail stores off-the-shelf. Due to the strict certification rules in aviation, the system is designed for experimental, supplementary use only, but it is capable for redundant, airborne usage and ready by design for airworthiness certification.

The Control Display Unit (CDU) is located in the cockpit at the dashboard in the pilot's field of view. The design of the CDU shall accommodate the latest human-machine interface requirements. It is extremely important to design the CDU in cooperation with the pilots and

[1] International Civil Aviation Organization (ICAO) establishes standards which are mandatory for all contracting countries. ICAO is the organization of the United Nations dedicated to increasing the safety and security of international civil aviation.

[2] ARINC is a major provider of transport communications and system engineering in aviation industry. In its 400 series standards numerous design foundations and guidelines for databuses and databases has been developed.

operators to achieve the best 'user-experience' and the highest level of ergonomics on board. The main goal is to support the pilot and not to increase his workload. The central processing unit can be a single board computer (SBC) running real-time Linux based operating system. Inertial unit based on Analog Devices ADIS16405 iSensor IMU [3], ADC is the above introduced Sandia SAC 7-35 [2]. The ADIS16405 IMU is a triaxial inertial sensor with magnetometer which is capable of autonomous operation and data collection. Its gyroscopes are inertial grade and accelerometers are well over the navigation grade. The dynamic range of the angular rate sensor can be reconfigured in-flight which improves the scale factor accuracy during lower roll-rate turns (e.g. enroute flights). The angle of attack vane is optional for inertial navigation purpose, but mandatory for agricultural deployment. The angle of attack value is used among others in the calculation of the drift of the pesticide particles in the slipstream and vortex system of the aircraft in actual atmospheric conditions.

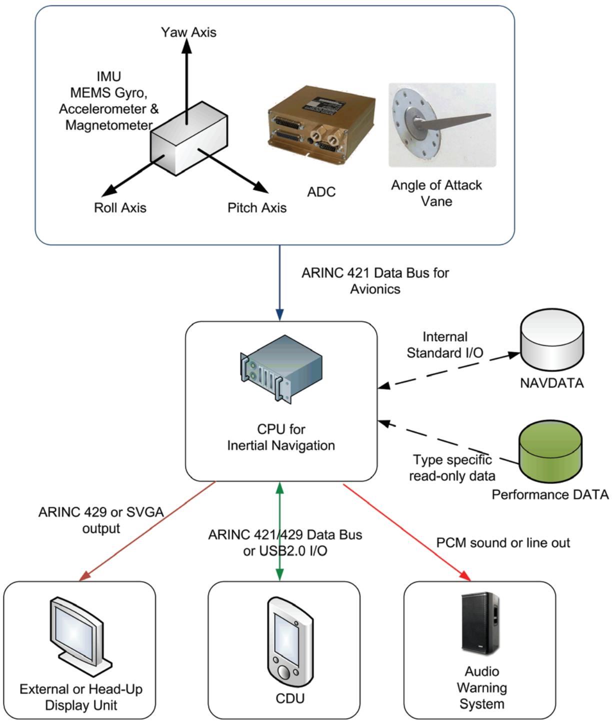

Figure 1: Block diagram of the MEMS IMU based system on-board agricultural aircraft

The optional audio warning system and head-up display contributes to situation awareness and flight safety.

NAVDATA and Performance DATA are solid-state databases stored in the SBC. The NAVDATA is based on standard AIRAC (Aeronautical Information Regulation and Control) circulars and updated in every 28 days. The update can be done through memory cards or USB. The Performance DATA database stores the specific parameters related to the particular aircraft type. These parameters include the local slipstream and vortex system of the aircraft in different speed versus angle of attack ranges, moreover the dispersion and spreading of the pesticide chemicals at different mixture ratio. They come mostly from wind tunnel measurements and mathematical models and field experiments. In the 1980´s significant research [4] was also performed in Hungary, where the most frequently used agricultural aircrafts (e.g. AN-2, Ka-26, Z-37) were involved in this experiment.

To improve the accuracy and efficiency of the spraying, the location of the field and the aircraft's position and ground speed must be known as well as the trajectory of the sprayed particles in the air.

NAVDATA provides the coordinates of the field to be treated. IMU is used to determine the aircraft's actual position and ground speed. The performance database stores the model of the aircraft and the pesticide chemical's physical dispersion properties. Based on IMU and ADC data the atmospheric condition with wind vectors, pressure surfaces and temperature lapse rates can be obtained.

The calculation of the pesticide particles dispersed over the field can be formulated as a complex ballistic problem; the motion of the particle under the influence of wind, gravity, drag and lift forces while it suffers from elastic form changes and evaporates too. Kármán-Biot [5] offers a simplified solution for the ballistic problem, Derevjanko [6] calculated and proved the motion trajectory for some typical droplet sizes. Using them helps to create a computer based model which can be used for real-time calculation of the approximate dispersion of the pesticide particles from the particular aircraft under the actual atmospheric conditions.

The CPU is responsible for the soft real-time calculation of the differential equations belonging to the ballistic problem. This way it is possible to calculate the pseudo-waypoints where the pilot shall commence the spraying and where it shall be terminated near the end of each row and the point where the turn for the new fly-by shall be initiated, etc. Their representation on the Head-up Display and CDU device is also the task of the CPU. The visualization can be similar like the bomb sights on military aircrafts however the aiming is more peaceful. If the spray nozzles can be inserted in a control loop then their operation can also be controlled by the signals provided by the CPU or the autopilot. This would highly contribute to the efficiency of the crop spraying, the dispersion could be more uniform and accurate. Moreover it would significantly decrease the environmental load caused by over-dosing or unintentional spread off the fields caused by wind and the aircraft's slipstream.

The cabin of the agricultural aircrafts is usually neither pressurized nor hermetically isolated. Therefore it has a notable risk of harmful chemicals entering into the cabin which have adverse effects on the health of the pilot. By numerical tracking of the particle cloud sprayed before an aural and/or visual warning could be released to the pilot if his intended track coincides with an earlier sprayed and supposedly not yet properly dispersed pesticide cloud. This threat is very serious on older agricultural aircrafts with open cabins like Kamov Ka-26 helicopter and Zlin Z-37 Cmelak or Piper Pawney.

According to local regulations, the crop spraying cannot take place in updrafts. With the convective updrafts the pesticide particles are not dispersing on the ground onto the plants but they may rise up to high altitude. If they reach the condensation level then they would be mixed in the precipitation which could affect areas which were not intended to be treated by the pesticide included in the precipitation. Usually updrafts build over light colour fields on sunny days which are also typical and ideal for the agricultural mission. With the help of IMU and ADC the updrafts can be detected or even predicted so if the spraying device is being controlled by the CPU, then the spray nozzles can be closed and the pesticide can be cut off before flying into the updrafts.

The track of the flights over the fields can be recorded and with the spraying together a virtual coverage map can be constructed. The areas which were not involved adequately in the crop-spraying can be displayed or visualized on the HUD or CDU. This can provide essential information for the pilot for a proper crop spraying technique. The virtual coverage map can be utilized at a later stage for evaluation and further analysis on the efficiency and profitability of the procedure. Furthermore the operator of the agricultural aircraft and the pilot will be accountable for the flight time, duty time, fuel and pesticide usage and the treated areas.

Conclusion

The outlined MEMS-based inertial navigation system can contribute to the improvement of the efficiency of the agricultural crop spraying missions. Moreover, it could improve flight safety even in general aviation. It provides a proper platform for further development and deployment on various aircraft types. The feasibility and the economical manufacturing of the designed structure are assured by the cost-effective availability of all necessary components. The later certification of the system may open wider range of further usage.

The industrial utilization of this system is open for all countries where aerial agricultural activities are still in progress. The benefit of deploying this advanced solution would be enormous both for environmental protection and from an economical point of view. The possible operators may come from USA, Ukraine, Russia and China where huge amount of agricultural aircrafts are still in service and the agricultural flights are widely used for pest control over large areas.

Table 1: Performance requirements for different classes of gyroscopes by Yazdi et al [1]

Parameter	Grade	Tactical	Inertial
angle random walk, $^\circ/\sqrt{h}$	>0.5	0.5–0.05	<0.001
Bias drift, °/h	10–1000	0.1–10	<0.01
Scale factor accuracy, %	0.1–1	0.01–0.1	<0.001
Full scale range, °/sec	50–1000	>500	>400

Table 2: Typical specifications of accelerometers for automotive and inertial navigation applications by Yazdi et al [1]

Parameter	Automotive	Navigation
Range	±50 g (airbag) ±2 g (stability system)	±10 g
Resolution	<100 mg (airbag) <10 mg (stability sytem)	<4 µg
Off-axis sensitivity	<5%	<0.1%
Nonlinearity	<2%	<0.1%

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