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AUTONOMOUS UAV NAVIGATION: TECHNOLOGIES FOR ORIENTATION AND LOCALIZATION

Navigation of autonomous vehicles and particularly unmanned aerial vehicles (UAV) remains one of the core challenges in achieving full autonomy. Autonomous vehicles must independently analyze an environment, react on the dynamic change of surroundings, create optimal trajectories, and perform mission-critical tasks independently. That is why drones need to precisely understand their pose (position and orientation). While in case of error, ground and marine drones might stop the performance, the error of UAV has significant consequences due to the high working speed and heights. It may lead both to losing UAV and harming infrastructure, nature, and civilian houses in accordance to the area, where the UAV is operating.

Localization and orientation issues require information from both the state of the drone and information from the environment, as the vehicle's position in relativeness with other objects is necessary for path planning tasks. This article analyzes the sensors and navigation systems that might give convenient data about both inertial parameters and surroundings. Solutions for both known, partially known, and unknown environments are described. Special attention is paid to Visual SLAM (Simultaneous Localization and Mapping) and Visual-Inertial Odometry, which are key for map creation and relative movement estimation in unknown environments. These approaches enable drones to navigate in GPS-denied or dynamic environments by fusing visual data with inertial measurements.

This article also gives a comprehensive review of the map-based sensors, which greatly simplify the UAV performance in pre-known environments. Map-based sensors are applicable for both indoor and outdoor scenarios.

The final section of the article introduces the sensor fusion technics, which are necessary for all kinds of UAVs to reduce drifting error and improve navigation accuracy. It enables the comparison of measurements from different sensors or navigation systems with two levels of filtering. Selecting an observer must be done with consideration of the nonlinear nature of autonomous vehicles.

***Key words:** unmanned aerial vehicle, orientation, navigation, localization, sensor fusion, odometry.*

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АВТОНОМНА НАВІГАЦІЯ БПЛА: ТЕХНОЛОГІЇ ОРІЄНТАЦІЇ ТА ЛОКАЛІЗАЦІЇ

Навігація автономних транспортних засобів, зокрема й безпілотних літальних апаратів (БПЛА) залишається однією з основних проблем у досягненні цілковитої автономності. Автономні механізми повинні самостійно аналізувати навколишнє середовище, реагувати на динамічні зміни умов навколишнього середовища, створювати оптимальні траєкторії руху та самостійно виконувати критично важливі завдання. Отже, дронам необхідно чітко розуміти свої положення та орієнтацію у просторі. Якщо за несправності наземні та морські дрони можуть припинити роботу, похибка безпілотних літальних апаратів має значні наслідки через високу робочу швидкість і висоту польоту. Це може призвести як до втрати безпілотних літальних апаратів, так і до завдання шкоди інфраструктурі, природі та цивільним будинкам, відповідно до місцевості, де працюють безпілотні літальні апарати.

Питання локалізації та орієнтації потребують інформації про стан дрона, а також із навколишнього середовища, оскільки відомості про розташування транспортного засобу щодо інших об'єктів є необхідним для планування траєкторії подальшого руху. У статті проаналізовані датчики та навігаційні системи, які можуть надавати необхідні дані як про інерційні параметри, так і про навколишнє середовище. Описані рішення як для відомих, частково відомих, так і для невідомих середовищ. Особлива увага приділяється Visual SLAM (Simultaneous Localization and Mapping) та Visual-Inertial Odometry, які є ключовими технологіями для створення карти й оцінювання відносного руху в невідомих середовищах. Ці підходи дозволяють безпілотним літальним апаратам орієнтуватися в динамічних середовищах без використання GPS, за поєднання візуальних даних з інерційними вимірюваннями.

У роботі подано вичерпний огляд датчиків, що працюють на основі карт місцевості. Вони значно спрощують роботу безпілотних літальних апаратів у заздалегідь відомих середовищах. Датчики на основі карт місцевості можна застосовувати як усередині будівель, так і на відкритому просторі.

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Останній розділ статті представляє техніку синтезу датчиків, яка необхідна для всіх типів безпілотних літальних апаратів, щоб зменшити вплив дрейфу вимірювань і підвищити точність навігації. Це дозволяє порівнювати вимірювання від різних датчиків або навігаційних систем із використанням двох рівнів фільтрації. Вибір методу фільтрування даних повинен здійснюватися з урахуванням нелінійної природи автономних транспортних засобів.
Ключові слова: *безпілотний літальний апарат, орієнтація, навігація, локалізація, злиття датчиків, одометрія.*

Introduction

One of the technological trends of 2020s is the integration of autonomous vehicles into various sectors to optimize operations and minimize risks to human life and health. They became widely adopted in agriculture and military tasks and are increasingly being employed in rescue operations, disasters response and logistics of critical supplies. The most promising area is unmanned aerial vehicles (UAV), as their operation in air usually does not require additional infrastructure, allows to avoid traffic and reach remote or inaccessible regions.

The global goal of UAV's development might be formulated as increasing the autonomy of the UAV to the level, in which human operator is not required for the successful mission completion. One of the most critical and enduring challenges in achieving this goal is reliable navigation. It remains the complex problem through decades, as real-world scenarios vary in the observability of environments, external disturbances and used sensors features. Errors in UAV navigation are particularly crucial as they can influence system stability and lead to potential loss of control.

Analysis of the latest research and problem statement

The highest of the defined levels of aircraft autonomy implies the independent completion of tasks in observed, partially observed, and unknown environments [1]. Advancement in autonomy is achieved by various types of sensors and cameras, some of which aim to provide accurate navigation. To be more precise, the most common navigation systems used are inertial navigation systems and the Global Positioning System (GPS) [2].

The navigation problem can be divided into 4 parts:

– localization (defining accurate position and orientation of the drone on the exciting or created map of the environment);

– estimation of various inertial parameters of flight (the parameters of the aircraft, that influence the flight);

– mapping of surroundings (it can be used for localization purposes and/or for environment exploration);

– path planning.

Successful implementation of these issues leads to autonomous flight [3]. However, considering possible bias and fairness in physical sensors, the main issue remains the attitude estimation and sensor fusion. One of the common biases eliminating technics is using nonlinear observers, that are using feedback loops to get rid of random values and noise [4; 5].

Since there is no sensor, that can directly measure the attitude of a three-dimensional rigid body, the fusion of different technics is used [6; 7].

The aim and objectives of the research

This paper is intended to give a comprehensive review and comparison of the sensors used for navigation purposes in different environments. Moreover, the work studied multi-sensor fusion technics, that are used for increasing the efficiency of location and orientation estimation algorithms.

Research results

Measurement of inertial parameters

Considering that UAVs operate in 3-dimentional space, controlling the rotation with respect to three axis x, y and z is crucial. Losing balance for the tiniest period of time might led to the undesirable

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movements or even loss of control. Orientation is difficult to be controlled by human operator, as it requires smooth movement and quick reaction. Drones, that unable to estimate orientation on their own requires complex training for human operators before flying.

The majority of drones are equipped with at least one inertial measurement unit (IMU), which consists of accelerometer, gyroscope and, optionally, magnetometer. Relatively new MEMS technologies allows to equip even the smallest drone with IMU.

The orientation parameters are extracted from IMU accelerometer measurements as follows:

$$\phi = arctan\left(\frac{a_y}{a_z}\right), \tag{1}$$

$$\theta = arctan\left(\frac{-a_x}{\sqrt{{a_y}^2 + {a_z}^2}}\right), \tag{2}$$

where ϕ – roll, θ – pitch, a_x, a_y, a_z – measured accelerations with respect to axis x, y and z.

Euler angles are also extracted from gyroscope measurements as follows:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}, \tag{3}$$

where ψ – yaw, and $\omega_x, \omega_y, \omega_z$ – measured angular velocities with respect to axis x, y and z.

From magnetometer measurements only yaw may be extracted:

$$\psi = arctan2\left(m_x^I, m_y^I\right), \tag{4}$$

where m_x^I, m_y^I – magnetometer measurements calculated for inertial frame [8].

IMU is the only system that may give information about rotations with respect to all three axes. That is why sensor fusion technics between accelerometer, gyroscope and magnetometer are used to make the obtained data more accurate. The most popular technics are complementary filter [8] and nonlinear filters such as Extended Kalman Filter and observers [9].

In addition to orientation the information about drone localization is also required. When the premade map is not available, the start point is considered as (0; 0; 0) coordinate, from which UAV is preforming a desired, usually, pre-programmed trajectory. To understand the movement with respect the axis *x* and *y* optical flow sensors are widely used. Its output is displacement in position, which is relative. For scaling the measurements from Optical Flow to the real-world units, the altitude is required.

Altitude, or the height of the flight, might be obtained from barometer or distance sensors, such as sonar or LiDAR, which are located at the bottom of drone. The selection of the sensor depends on the estimated height of flight and characteristics of environment.

The described set of sensors might be considered as an inertial navigation system for small UAVs, when the environment is known.

Localization and mapping

Distance sensor are essential for localization tasks when the map of environment is unavailable. These sensors are crucial for constructing a map of unknown surroundings, which can subsequently be used for both environmental analysis and localization purposes. The widely used approach is SLAM (Simultaneous Localization and Mapping).

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As SLAM does not rely on any pre-made landmarks and does not correct measurements with map-based sensors, exploration of the environment might lead to the drifting bias. This issue is resolved by revisiting previous locations. UAVs match new data with previously observed landmarks, creating a closed loop of exploration. Moreover, Kalman-based filters are applied.

Instead of distance sensors, cameras might be used for exploring the environment, which is applied in Visual SLAM. The key feature of this algorithm is that it is working with video or image data, what requires high computational resources, but might lower the cost of onboard equipment. The most commonly used are stereo, monocular, and RGB-D cameras. Visual SLAM is also sensitive to environment changes, as landmarks might not be identified if the light or visibility conditions differ.

Moreover, integrating Artificial Intelligence (AI) technologies allows to identify and classify objects, observed by UAV`s cameras.

In scenarios where the drone operates repeatedly in a known environment, the map can be generated during the initial deployment and later updated if changes are detected. This reduces computational load and improves localization performance over time.

Cameras might also be used for Visual Inertial Odometry (VIO), which combines the visual data with the measurements from IMU. Odometry algorithms are used when the map of environment is not required, and knowledge or relative position is enough to complete the task.

VIO requires pre-made visual landmarks, which will be further identified in image and video frames. From media data features like the position and size of landmark, angle of observability, gradient, etc.) are extracted. Comparing the features movement in different frames allows to understand the relative position and orientation of the UAV.

Map-based sensors

When it comes to the large territories of operation and limited available time, which are usually connected with delivery, optimal path planning tasks, or disaster response, the pre-existed map is required. Map-based sensors are developed both for outdoor and indoor operation. The most commonly used is Global Navigation Satellite System (GNSS), which can provide geo-spatial position. The main issue of this system is the existence of GNSS – denied environments, and the possibility to block signal in desired regions.

Indoor solutions are working on the same principle as the GNSS. Instead of satellites, space is equipped with based stations, precise positions of which are known. The position is relative and user can select the initial point as it will be optimal for task completion. Operating in this space, UAV's onboard systems calculate the distance to each anchor and defines its location in defined space. The minimum required number of anchors is 3, while the recommended one is 6.

Commonly used indoor solutions are:

– Lighthouse Positioning System – is made using technologies of Steam VR Positioning;

– Motion Capture System – allows to get position and orientation of the rigid body, works using infrared light, requires markers to be installed on the drone;

– Ultra-Wideband (UWB) Positioning System – uses radio frequency waves to determine the position and send information to UAV;

– Bluetooth Navigation System – uses Bluetooth Low Energy (BLE) Beacons, which can work on distances up to 30 meters.

The most precise and costly solution is Motion Capture System, which usually considered as ground-truth. It allows also to consider obstacle for path planning algorithms. More low-cost solutions, that are working on radio waves, have a high level of uncertainties.

Access to the pre-existed map also simplifies the task of path planning, as it enables finding an optimal trajectory.

Sensor fusion

Considering advantages and disadvantages of internal and external navigation systems, which are mentioned in [2], sensor fusion technics are required. As sensors may differ according to the objective, the main idea of sensor fusion technic remains the same. It is demonstrated in Figure 1.

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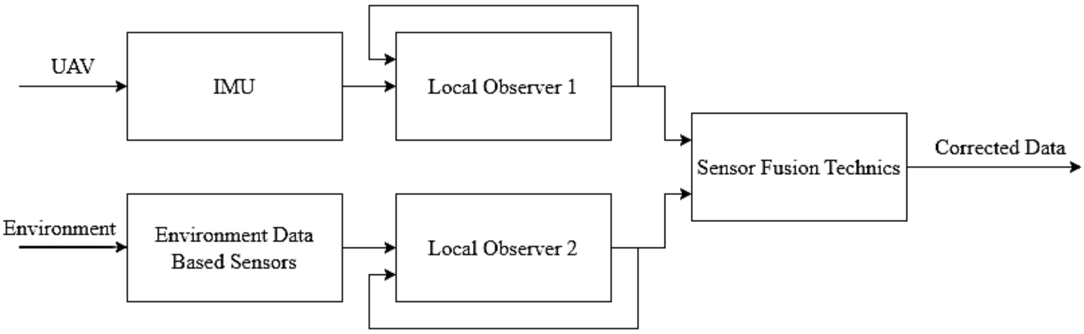

Fig. 1. Multi-sensor fusion architecture

In Figure 1 Environment Data Based Sensors (EDBS) stands to all devices, that are interacting with an environment to get measurements: distance sensors, cameras, map-based sensors, and the IMU represents the internal navigation system, which does not receive any information from surroundings and measures only inertial parameters of the drone.

Both IMU and EDBS must have local observers, which are usually Kalman-based filters. These filters are eliminating random values and noise, as they are comparing current values with previous. Even though some of Kalman-based filters are made for nonlinear systems (such as Extended Kalman Filter or Unscented Kalman Filter), they require linearization for computation, what can lead to inconsistent results. Moreover, these observers cannot identify measurement drift over time. That is why the comparison of outputs from different sources is done.

Sensor Fusion Technics may be performed with Kalman-based filters as well. However, in modern applications the nonlinear observer design is usually required. Nonlinear observers compare the current measured state of the UAV with the estimated one, what allows them to correct bias and undesired drift of measurements. Considering the high frequency of IMU outputs and low work frequencies for other devices, sensor fusion is performed not on each step, but with the specific period. Which is why, while using sensor fusion technics, the timing of outputs from each sensor should be considered. If the UAV is working on high speeds, asynchronous measurements might lead to huge errors in final results. This issue is resolved by defining the specific frequency for taken outputs, in which data from all existed on board sensors can be taken.

Working frequencies for the sensors, described in this paper are as follows:

– IMU – 200–1 000 Hz;
– Optical Flow Sensor – 50–100 Hz;
– GNSS – 5–10 Hz;
– LiDAR – 100–500 Hz;
– Sonar – 100–500 Hz;
– Lighthouse Positioning System – 300–750 Hz;
– Motion Capture System – 30–500 Hz;
– Ultra-Wideband (UWB) Positioning System – 10–40 Hz;
– Cameras – 1–5 Hz.

Considering the complexity of the nonlinear observers designs, attitude estimation algorithm might be also created with Reinforcement Learning usage. This method does not require the mathematical model of the UAV and can adapt to dynamic environments. However, the required time, resources for training and reliability of the model must be considered before implementation.

Conclusions

Localization and orientation technologies might be divided into two groups in accordance to the perception of the environment:

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– Sensors and systems that are giving relative position;

– Sensors and systems that are giving global position.

Type of localization may vary in accordance with the task features and the observability of working environment. In some cases, measuring only inertial parameters of UAV will be enough for successful performance. However, we must consider that the environment is pre-known, stable and feedback filters are implemented.

However, in most of the cases we expect to have multiple disturbances and partially observable or unknown environments. In that case the analysis of environment is required, what allows to estimate the position and orientation of the drone.

While there is no exact sensor, which directly measures UAV's pose, the growing error in measurements is expected. To decrease the error sensor fusion technics are used. One system, that works based on sensor fusion, must have a set of sensors, that measures inertial parameters (usually IMU) and environment state.

Considering, that the majority of modern filtering technics requiring linearization of the system before estimation, design of the nonlinear observers remains open.

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