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CHALLENGES OF UAV NAVIGATION BASED ON CELLULAR NETWORK

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ABSTRACT

Many approaches have been proposed to locate autonomous mobile platforms such as robotic trucks, aircrafts, and underwater vehicles. Relying on satellite navigation only is associated with permanent errors due to the passage of radio signals through the atmosphere. Furthermore, the use of satellite navigation is simply not enough in certain environments such as crowded or enclosed spaces. Therefore, it is essential to propose and implement another effective, simple, and flexible device to ascertain the actual situation. This device generally consists of a spatial sensor and an efficient processor that receives and processes signals from cellular network towers in the surrounding area. For this solution, it is crucial to determine the relative movement of the mobile platform based on new algorithms and models. This research paper outlines the problems and challenges of this solution, clarifying them for practical applications. Finally, it would be advantageous to easily equip this mechanism on a UAV platform based on its efficiency, features, and technologies.

KEYWORDS

UAV, Navigation, Cellular network, Positioning, Trajectory, Environment, Multipath.

1. INTRODUCTION

The automatic control of any mobile object relies heavily on accurately determining its position in space. It is impossible to ensure acceptable control for this object without knowing the exact coordinates. Furthermore, when there is a satellite signal, the accuracy is often inadequate for addressing cartographic and navigation issues (Al-Hsnawy, Thamer, et.al.,2024; Stateczny, A., et al., 2022; Ullah, Naveed, et al. 2021; Ueda, Kiyoshi, et al., 2019; Zeng, Yong, et al.,2019; Fotouhi, A., 2019). In practice, using real unmanned vehicles shows that their best models, even in open space, provide positioning accuracy within a few meters. This accuracy is insufficient to control a vehicle in a dense urban area, especially when tall buildings block the satellite signal and cause a complete loss of the vehicle orientation (Al-Hsnawy, Thamer, et.al.,2024; Ueda, Kiyoshi, et al.;2019; Zeng, Yong, et al.,2019; Fotouhi, A., 2019; Balamurugan, G., et al., 2016; Chang, Yingxiu, et al., 2023; Horri, N., et al., 2024). A new device can be equipped to expand the operating area of autonomous vehicles and ensure their safe navigation through unknown territory. This proposed device consists of a spatial sensor and an efficient embedded processor with memory unit, as illustrated in Fig. 1 below. Three important factors should exist: low cost, high processing, and high precision reliability under different environmental conditions. As a result, the spatial sensor technology depends on sending/receiving, and processing (detecting) signals. The other part includes processing algorithms to estimate location, speed, direction, and other variables that affect the vehicle's movement from one location to another safely.

With the advent of robots and UAVs, finding new navigational methods and algorithms has become challenging and important. These algorithms should be adapted to the types of UAVs and their size to increase the accuracy of calculating navigational variables that are affected by the components of the surrounding environment (Fotouhi, A., 2019; Balamurugan, G., et al. , 2016; Chang, Yingxiu, et al., 2023; Horri, N., et al., 2024). The navigation concept is the transportation from one point to another based on the known objects of the surrounding environment (Stateczny, A., et al., 2022; Ueda, Kiyoshi , et al., 2019; Yingxiu, et al., 2023). Therefore, this study investigates the following aspects:

The first aspect proposes cellular network towers (CNTs) as suitable objects for this application. CNTs are distributed in the urban environment, and their locations are usually known. CNT coverage angle is typically 360°, and the radius extends a few kilometers (Segun, Adewumi Adebayo, et al. ,2020).

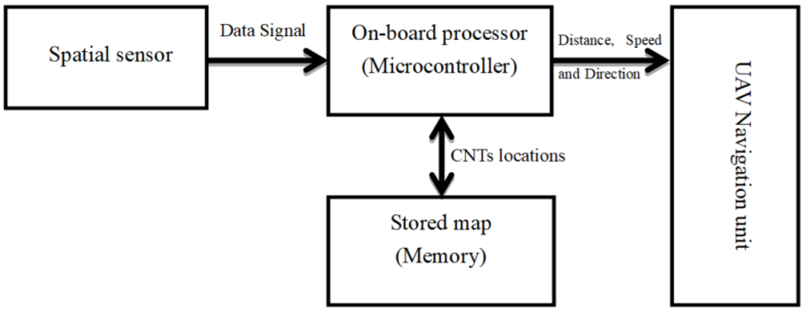

Fig. 1. The proposed system.

Suppose a vehicle is flying at a known altitude in an urban environment, then CNTs locations may help estimate the vehicle's navigation parameters. The proposed basic idea includes estimating the vehicle's position, direction, and trajectory based on the CNTs' locations by calculating distances and angles. The distance will be estimated, for example, depending on the power/energy (strength) of the CNTs signals or according to the stored map, which contains the pre-defined locations of CNTs. Fig.2 illustrates an example of public smartphone applications related to cellular networks that display the locations and distribution of towers within an area. The angles are defined as Azimuth and Elevation; the former refers to the tower's horizontal angle concerning the UAV direction, while the latter indicates the UAV's vertical angle for altitude (see Fig.3). Without a satellite signal, the vehicle will completely depend on CNT signals to move from point to point. Moreover, the positioning accuracy will increase if there is a satellite signal. GPS users typically need at least four satellites to estimate their location. Here we present the same idea: the vehicle needs at least 4 CNTs to estimate its location. Of course, implementing these operations can be difficult, so in this paper (the second aspect), we will explain the challenges and problems that need to be solved to estimate UAV coordinates based on cellular network towers only. Finally, the rest of the paper will cover the main idea and literature survey, challenges and discussion, and finally, the conclusions.

Fig. 2. One of the applications in smartphone about CNTs distribution.

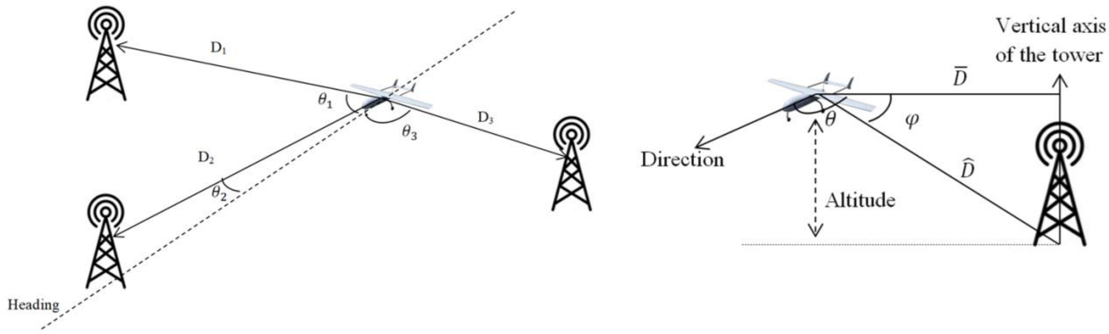

Fig. 3. Horizontal and vertical angles between UAV and CNTs.

2. THE MAIN IDEA AND LITERATURE SURVEY

As mentioned in the previous section, when satellite-based UAV positioning is not available or reliable, the cellular networks can used to provide the positioning (Andersson, Martin et al. ,2023; Ulmschneider, Markus, et al., 2016; Shamaei, Kimia, et al., 2018; Kamal, N. L. Mohd, 2019). Therefore, the main idea of developing navigation algorithms based on the presence of CNTs can be summarized as follows:

We assume that a group of cellular communications towers is distributed according to the geographical area and terrain, and these towers transmit communication signals according to established frequencies. We consider that a receiver is installed on the UAV platform. From this receiver, (a) the type of signal and its frequency will be determined, and (b) the received signal strength will be calculated. Two cases must be considered: in the first case, the locations of the towers are fixed and known to the UAV, while in the second case, the locations of these towers are unknown. The environments may also be known or unknown. In addition to being close in urban environments, cellular communications towers transmit on multiple frequencies and over multiple ranges depending on coverage requirements. Of course, the maximum altitude that the signal reaches from cellular communications towers must be known to determine the required altitude of UAV to fly.

The UAV positioning process will initially start when it is in “ON” mode, and its location will be (0, 0, 0) plus the location of the nearest tower detected with variation in distance and angles. The polar coordinates can be determined using trigonometric theories to calculate the distance between the UAV and the nearby tower. The horizontal and vertical distances between them vary according to the three-dimensional polar coordinates. When the UAV is flying at low altitudes and within the effective ranges of communication networks in the known environment, the location can be estimated simply by relying on the service provided by the cellular networks. Some of the requirements are the need for UAV operation to be at a minimal altitude and with the presence of reliable data-based coverage, as well as avoidance of collision with other flying vehicles (Kamal, N. L. Mohd, 2019). UAV trajectory estimation is also essential if the UAV operations are in indoor or outdoor environments (Khosiawan, Yohanes, et al., 2016). In case of indoor spaces, the environment may be unknown; for example, the authors of (Choi, Yeon Ji, et al., 2021) propose a cellular communications-based UAV navigation system to autonomously maneuver in previously unknown indoor environments using LiDAR sensors. The proposed scheme includes implementing LTE communication for drone navigation compared to Wi-Fi communication. This system is based on a combination of Robot Operating System-based Hector SLAM systems, a 2D-LiDAR sensor, and an LTE connection. As a result, the mapping efficiency of an LTE connection is greater than that of a Wi-Fi connection. We can note that the scenario of (Choi, Yeon Ji, et al., 2021) and other similar works, such as (Khosiawan, Yohanes, et al. ,2016), is suitable for application to other types of robots (i.e., not UAVs). However, almost all indoor environments are complex structures, and UAVs will be limited in operation.

In the case of outdoor spaces, UAV operation will be unlimited in range and space, but limited by the cellular network coverage and altitude. Additionally, the type of environment, such as desert, agricultural, or mountainous, will impact UAV navigation requirements. Some authors employ other techniques, such as machine and deep learning techniques, to solve side problems when working on UAV navigation. For example, the authors of (Afifi, Ghada, et al., 2021) propose 3D localization solutions for UAVs by utilizing the existing cellular infrastructure using the locations of four surrounding cellular network base stations. Localization solutions operate independently of the GPS or other detectable mobile signals transmitted by the UAV. The authors formulated the localization problem to reduce the error of the RSSI measurements from the surrounding cellular base stations. Furthermore, the problem is solved by using exact and heuristic optimization techniques to determine the optimal solution. The authors propose a deep supervised learning-based approach and a reinforcement learning-based approach to solve the problem in real-time. In (Afifi, Ghada, et al., 2022), the authors of (Afifi, Ghada, et al. ,2021) propose path-planning solutions independent of GPS and utilizing the existing cellular infrastructure to efficiently guide UAVs in complex environments under real-time conditions. They formulated the UAV path planning problems using optimization-based techniques to determine the optimal solution. They proposed two Machine Learning (ML)-based solutions and offered a detailed comparative analysis of each presented path planning technique. In the same vein, the authors of (Esrafilian, Omid, et al., 2020) investigate the problem of UAV trajectory design under cellular communications constraints to minimize its trajectory length between a pre-determined initial location and a given destination point in an urban environment. They proposed a novel approach to trajectory design that strikes a trade-off between performance (i.e., trajectory length reduction) and complexity by exploiting a 3D map of the environment and employing graph theory. They created a graph theory-based framework to evaluate the problem's feasibility and obtain a high-quality approximate solution to the UAV trajectory design problem. The performance of the proposed solutions was validated using a set of Monte-Carlo simulations. The authors of (Khalife, Joe, et al., 2018) introduce a software-defined receiver (SDR) for UAV navigation using cellular code-division multiple access (CDMA) signals. They provide a detailed description of the cellular forward link signal structure, with a development of the models for the transmitted and received signals. For positioning and timing purposes, the authors emphasize the extraction and utilization of relevant information as well as modeling the pseudorange and errors from the proposed receiver within an additive white Gaussian channel. Experimental results obtained from aerial and ground vehicles demonstrate a strong correlation between the variation in pseudoranges and the variation in actual ranges between the receiver and two cellular CDMA base transceiver stations (BTSs). The same authors of (Khalife, Joe, et al., 2018) have many publications on the subject of UAV navigation using CNTs and include simulations of the work. But, in the case of the multipath problem of CNT signals, the problem can be mitigated with increasingly dense network transmission and reception point deployments (TRPs). However, that is both impractical and costly (Andersson, Martin et al., 2023).

The issue of multipath is growing in urban areas, making it difficult to identify the correct signal to use. The traditional proposed solution relies on the power (strength) of the received signal. In this case, ensuring the receiving and processing of data obtained from the sensor is necessary. Firstly, reception of CNT signals must be performed using a device (e.g., a cell phone pad or a proposed receiving system). Next, we need to estimate the power/energy of the received signal and then convert that power/energy into a distance. Indeed, multiple signals are being received, so it is necessary to identify the line-of-sight (LoS) signal with the maximum strength. After that, we need to determine the direction of the signal. The final step is to estimate the UAV's position, and the results are sent to the onboard navigation system. Therefore, some authors are looking for solutions via simulation. For example, in (Andersson, Martin et al., 2023), the authors develop multipath-assisted tracking algorithms in an indoor environment and evaluate the performance in realistic simulations using 3rd Generation Partnership Project (3GPP) standardized positioning reference signals and measurements. Moreover, the authors of (Shamaei, Kimia, et al., 2018a) and (Shamaei, Kimia, et al., 2018b; X. Lin et al. (2018); Li, Y., et al., 2021) propose a design of an LTE receiver and discuss multipath analysis for navigation in urban environments.

Based on the above information and despite the good results obtained, the work scenario represents a tradeoff between the economic and computational costs. Second, designs are based on simulations to validate the results. Third, projects must be run and tested in real time. Fourth, optimization (improvement) and investigation are rationally absent. Finally, the expected size of the works may not be suitable for small-sized UAVs (i.e., mini size). However, the idea of UAV navigation is surrounded by many limitations and requires a low-cost, small-sized, and highly efficient system.

3. CHALLENGES AND DISCUSSION

The previous sections have described UAV navigation in indoor environments, and its scenario may be less complex; therefore, we will focus in this section on UAV coordinate estimation in the outdoor environment. However, designing and implementing a UAV navigation system requires deep thought and in-depth study to create an effective system that operates under various conditions.

In general, we have two main proposed cases for estimating UAV coordinates using CNTs in outdoor environments:

1. The first case involves reducing the error rate of the previously estimated coordinates obtained from external data sources like GPS. In this case, the estimated coordinates are combined with the base coordinates to reduce the error.

2. The second case involves the use of a new coordinate system that differs from the coordinates obtained through other systems used in UAV, such as GPS. This new system will serve two purposes:

a)It will help to reduce errors in the previously calculated coordinates (as mentioned in the previous point).

b) It will be relied upon when previous coordinates were inaccurately determined due to factors such as interference or noise.

Fig. 4 shows the UAV navigation scheme and illustrates how to generate a trajectory based on the positions of CNTs. The stored map of the known environment will be updated using information from various devices and techniques, such as SLAM or spatial cameras. The system will also generate a map for the unknown environment. Fig. 5 presents the data integration scheme within the UAV's navigation unit. It is important to note that the integrated parameters include coordinates, speed, heading, and others.

Assume that the positions of the base stations (x_i, y_i, z_i), $i = 1,2,3, \dots, k$ are known in the map stored; then the distance between CNT and UAV will be estimated via the well-known equation:

$$\widehat{D}_i = \sqrt{(x_i - x_{UAV})^2 + (y_i - y_{UAV})^2 + (z_i - z_{UAV})^2} \quad (1)$$

The relation between the received signal strength (RSS) and the distance between the CNT and UAV is:

$$RSS \propto \frac{1}{Distance}$$

This relationship is limited by several constraints, including the transmission angle of CNTs, the coverage area, and the type of generation.

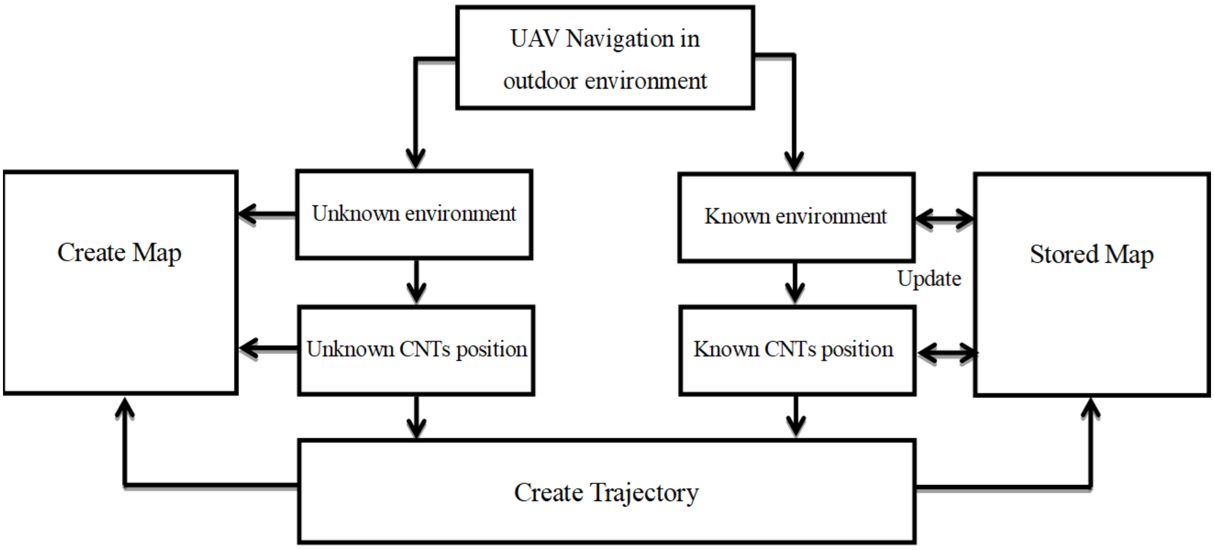

Fig. 4. UAV navigation scheme in the outdoor environment.

We can create a coordinate system that differs from the basic coordinate system, and it will be either a Cartesian coordinate system (3D or more) or a Polar Coordinate System (3D or more). Based on Fig.3, we suggest using the polar coordinates system $(\widehat{D}, \varphi, \theta)$, and it will be:

$$\varphi = cos^{-1} \frac{\overline{D}}{\widehat{D}}$$

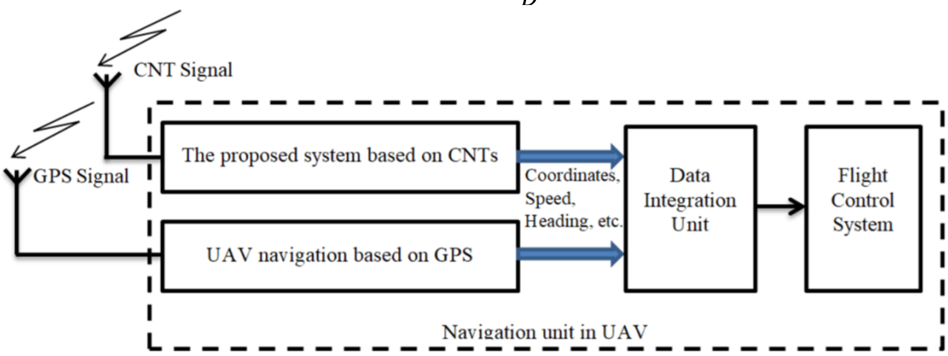

Fig. 5. Data integration of the proposed system with the other systems in UAV.

If the UAV is flying at a normal speed under normal conditions and movements of the UAV are submitted continuously to the time of flight $(t_i), i = 1,2,3, \ldots$in seconds, then:

$$\theta = tan^{-1} \frac{\Delta D_{t_i}}{\overline{D}}$$

The coordinates updated in the Cartesian form will be:

$$\left.\begin{aligned} x_{new} &= x_{old} + \Delta x \\ y_{new} &= y_{old} + \Delta y \\ z_{new} &= z_{old} + \Delta z \end{aligned}\right\} \tag{2}$$

while in polar form:

$$\left.\begin{aligned} \widehat{D}_{new} &= \widehat{D}_{old} + \Delta\widehat{D} \\ \varphi_{new} &= cos^{-1}\frac{\bar{D}+\Delta\bar{D}}{\bar{D}+\Delta\bar{D}} \\ \theta_{new} &= tan^{-1}\frac{\Delta D_{t_i}+\Delta D_{(t+1)_i}}{\bar{D}+\Delta\bar{D}} \end{aligned}\right\} \tag{3}$$

There are weaknesses and limitations in the application of the cellular network-based coordinate estimation technique. The most significant of them is the UAV's altitude, which will be restricted by the maximum range of the signal that reaches CNTs. Therefore, the UAV must descend to receive signals sent from the networks. As a result, it is a real challenge to use the coordinate estimation technique in areas with few CNTs, such as deserts, mountainous regions, and vast forests. Moreover, in an unknown environment, the presence of communication CNTs cannot simply be predicted. On the other hand, there are advantages; for instance, this technique can be utilized independently to reduce reliance on other techniques or to reduce the error rate in the calculations of those techniques. It is also highly reliable in indoor and outdoor urban environments, and its economic cost and actual system size are quite reasonable.

According to the next Figs. 6 and 7, there are several challenges associated with the design and implementation of the proposed system of CNTs for UAV navigation. Some of these challenges are as follows:

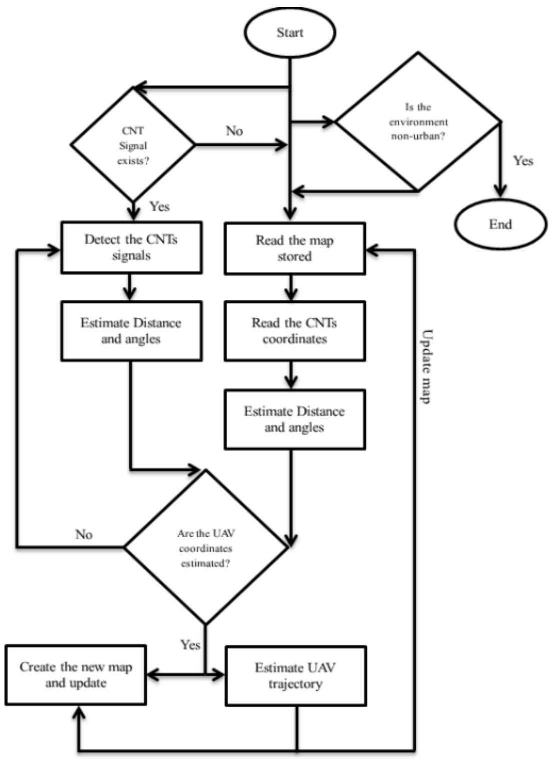

Fig. 6. Procedure of UAV coordinate estimation.

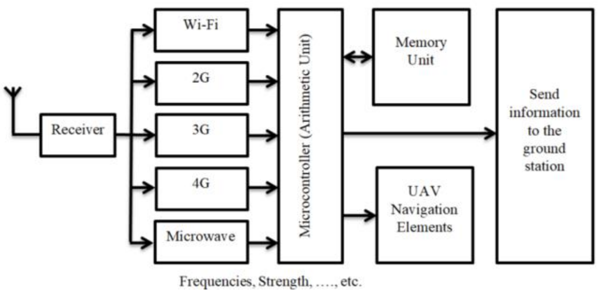

Fig. 7. Architecture of the proposed system system.

Fig. 8. One of the modern microcontrollers in the markets.

1. A specialized receiver integrated with an arithmetic unit must be designed to estimate the distance between the UAV and the available surrounding CNTs, and calculate the angle between them based on the received signal and its characteristics. The coordinates of the UAV, which assume the initial position as the center point, are determined relative to the CNTs. Note that the locations of the CNTs are assumed to be unknown. If the coordinates of CNTs are known and stored, the UAV's coordinate is estimated relative to those locations. The spatial sensor employed is a device for detecting the CNT signals. It is known that the CNT signals typically operate at frequencies of 900-910 MHz, 1800 MHz, and 2100 MHz. This means that the sensor should detect the signals and measure their power to estimate the distance using an arithmetic unit (microcontroller). Based on this fact, the sensor must be configured to read all signal power (strength) and estimate the distance. In other words, the sensor should have a table containing the signal order, frequency, power, and corresponding distances. We suggest utilizing a cell phone board with the appropriate adaptation condition to achieve this. We can employ multiple boards for the signals received from CNTs in the case of multiple signals. Multipath signals also pose a challenge and must be considered when designing the receiver. This issue represents the crux of estimating the range between the UAV and CNTs.

2. An arithmetic unit (Microcontroller) estimates the distance and direction of the received signal. Modern microcontrollers can be used for this purpose. Fig. 8 represents one of such device, which has the functions required to estimate the navigation parameters of a UAV.

3. The map stored in the memory unit represents a known environment that includes the locations of CNTs. The microcontroller will read these locations to estimate the distances between the UAV and CNTs. Consequently, the memory should consist of both static and dynamic data spaces. Additionally, modifications to the real data should also be taken into consideration.

4. The actual coordinates of the UAV must be calculated based on the locations of the CNTs, and the variable distances must be determined under changing weather conditions or when exposed to interference, etc. However, the trajectory estimated from these coordinates may be stored in memory for use, for example, in emergencies.

5. The area's terrain drastically affects the calculation of coordinates relative to the CNTs. While urban areas are filled with many high-rise buildings, CNTs are installed above them. Additionally, there are open areas such as agricultural lands, deserts, mountainous regions, and hills where the number of towers is often limited.

6. The UAV coordinates must be sent to the ground station, which requires a direct transmission process. The distance between the UAV and the ground station may vary.

7. The received signals must be classified based on the communication generation utilized. As a result, these signals will be used to minimize errors (i.e., correcting the navigation variable).
8. The properties and techniques of artificial intelligence should be incorporated into the design considerations to activate the decision-making factor. In modern applications, artificial intelligence significantly enhances UAV capabilities and performance, enabling the completion of tasks and missions across various fields with minimal errors.

4. CONCLUSIONS

This research paper describes and discusses the challenges of enhancing the accuracy of UAV coordinate determination based on the cellular communication network. This idea is based on considering the locations of cellular network towers as fixed objects, with coordinates calculated accordingly. The practical design and implementation of UAV navigation systems face several challenges, including the adaptation of the receiver/sensor under varying conditions and the estimation of navigation variables using an arithmetic unit based on cellular network calculations and locations. UAV navigation utilizing the cellular network is effective in urban areas and regions dense with tall buildings; however, it faces limitations in non-urban locations. The altitude of the UAV will not exceed the height of the tower, as the signal is limited in the direction of transmission (coverage). In unknown environments, the results of UAV coordinate calculations cannot be predicted. However, the practical results of calculating the location of a UAV based on cellular network locations require substantial time and effort cost.

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