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A hybrid Radio-vision fault tolerant localization for mini UAV flying in swarm

Abstract: *This paper discuss the localization of one Unmanned Aerial Vehicle (UAV) when a failure of its GPS occurs and will propose a new solution based on the information collected by the swarm to localize it. we propose here an architecture for localization of a UAV with GPS signal failure in three dimensions based only on the estimation made by one Well Known Position UAV equipped with radio source and an Omni Directional Vision (ODV).*

Abstract: *W artykule opisano metodę lokalizacji bezzałogowego pojazdu powietrznego w przypadku gdy wystąpi bład system GPS. Zaproponowano metodę trójwymiarowej lokalizacji bazującą na sygnale radiowym i metodzie ODV. (**Metoda lokalizacji bezzałogowego pojazdu powietrznego przy możliwości błędu systemu GPS**)*

Keywords: Fault tolerance, Image motion analysis, Radio navigation, Unmanned aerial vehicles.
Słowa kluczowe: radionawigacja, pojazd bezzałogowy, analiza obrazu ruchomego

Introduction

To succeed forming a group of unmanned aerial vehicles (UAV) in a flying mission, the UAV localization is one of the most important factor. Based on INS/GPS only, the GPS signal is usually weak or cut off completely. In the case of GPS signal loss for one UAV equipped with INS/GPS system, its location is generally estimated by the INS only. This alternative will force the UAV to drift from its original path creating a dangerous situation for the group with risk of collision[17].

Many papers have discussed this issue and suggested solutions. Most of them attempt to correct the error and uncertainties caused by noises in INS with filtering and new statics and probabilistic methods. Recent literature debates the cooperation with the group of UAVs based on network communication when a fault occurs on one UAV's sensors.

The newest development in network communication allowed to achieve a information processing of the group of the UAVs in centralized or decentralized manner [6],[7] where, estimation of the whole flight is processed either by:

a) a hierarchical supervisor (master) collecting data from its slaves in centralized processing

b) or each UAV processes its states relatively to the group and shares it within the community to keep the desired distance and shape of the swarm.

This community will also share some other information helping the swarm during the mission as: obstacle avoidance, early warning, path planning, target tracking..etc.

In the same manner, we would like to use this community of UAVs to help one UAV having lost its GPS signal. A similar approach of a constellation concept (used in the GPS) may be applied also inside the group [4], [7]. Knowing the position of the rest of the swarm and finding out the relative position of the **F**aulty UAV (F-UAV) to the swarm will conduct to its absolute localization. However, the relative position of the F-UAV to the swarm is still unknown and becomes then the key of the present issue.

Among one of the most recent papers is [4] where the authors study the situation where one UAV loses its GPS signal. They suggest the use of radio localization to estimate the relative position of one UAV with three well known position UAVs **(**WKP-UAV) flying on the same altitude. This technique estimates the distance between each of the three WKP-UAVs and the F-UAV.

Based on this information the actual X,Y of the F-UAV can be determined assuming that the group flies at the same, previously known Z altitude in the earth frame [4].

Nevertheless, when the fault occurs at random Z altitude, the question becomes very difficult to achieve and the system equation finds more than one solution for the F-UAV's position.

Moreover, In natural shade or near buildings, we desire a position of the UAVs not all subject of GPS signal cut off. Collaboration with the operating UAV to be localized despite the GPS signal weakness may requires a positioning of the other UAVs at altitudes different of this operating UAV to avoid a total GPS cut off on the group.

In this present paper we propose a new concept of localization based on both visual and radio localization using just one known position UAV and no need for a constellation system. The technique works in three dimensions coordination and the constraint of flying on the same altitude is overcome.

The paper is organized in five sections as follow:

In the following section we summarize and discuss the radio localization method proposed in [4] using three UAV equations, section3 will advance the tracking principal with Omni Directional Vision **(**ODV) camera mounted on the most neighbor UAV. Then, in section 4 a mathematical development of the proposed technique to localize the F-UAV in the inertial frame in three dimensions based on the radio strength and the omnidirectional image processing will be carried out and we finish by a conclusion in section 5.

Radio Source Localization

Radio localization systems attempt to find the UAV by measuring the radio signals traveling between this UAV and a set of UAVs with at least three Well Known Positions UAVs (WKP-UAVs). The radio signal could provide the distance between the emitter and the receiver. This will not be enough to claim the precise position since the signal is propagating in spherical path. When flying on the same altitude, the Z-dimension is omitted and each sphere will be reduced to only a circle. We could then carried out a system of equation based on the intersection of these circles so as to provide the F-UAV position Figure(1).

In general, Radio localization technique could be implemented in one of two ways,

- Either the F-UAV transmits a signal which one or more UAVs react cooperatively to find the location of a radio emitter [15]
- Or the WKP-UAVs transmit signals that the F-UAV uses to estimate its own positions, in the same manner of the global positioning system (GPS) constellation [4].

The first method will be adopted in this study due to the simplicity of distance measurement on each receiver since the signals sent by more than one WKP-UAV to F-UAV in the second method could generate some interferences on the received signals and may require additional hardware to modulate each source on a channel to distinguish between them.

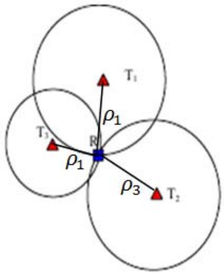

Fig. 1. Radio localization of one UAV using three receivers of the radio signal power in two dimensions XY. Intersection of circles provides the position of the faulty UAV

A. Swarm communication mode:

Once the fault in GPS is detected by the UAV two modes of signals are sent to the swarm:

- *The conventional communication* signal between the group to exchange the network information relative to the mission[19]. We would like that the transmitted data inside the group involves an additional string notifying the health state of the UAV. The first bit of this string is to activate the alarm whenever the fault occurs on any UAV of the swarm, the rest bits are to precise the source type of this fault (we assume here the Fault detection and isolation process FDI is embedded onboard). This string is similar to an S.O.S call to the community so as to start the rescuing algorithm.
- *The second signal* is dedicated to *"the radio localization"*. This signal will start to be considered by the group once the string of the fault alarm in the GPS wrapped in *"the communication signal"* is received. The swarm or a part of it respond by tracking the F-UAV and measured the relative distance. .

B. The distance measurement process based on radio strength signal:

There are several fundamental approaches for implementing a radio localization system including those based on *signal-strength* [8]–[9], *angle of arrival* (AoA) [10], and *Time Of Arrival* (ToA) [11], [12].

In this study let's assume that:

- The *signal-strength* radio localization is adopted
- A radio device previously installed on all the unmanned aerial vehicles.
- The communication between the whole UAVs group is established during the mission.
- The UAV with GPS failure is the *radio emitter* and the three other UAVs are *receivers*.
- A fault detection and isolation process is available on the UAV to trigger the Alarm.
- The radio signal is received by the whole swarm but the nearest three neighbors are subject of the distance measurement.

Let's denote e , r respectively the indices of the pair emitter (F-UAV) / receiver (the nearest WKP-UAV).

Next, consider *'M'* the radio emitter located at position $p_e = [x_e, y_e, z_e]$ on the F-UAV.

Given by statistical path-loss of radio propagation, the model of the power $P_{f\,(p_r)}$ received at a well known position $p_r = [x_r, y_r, z_r]$ from the emitter is:

(1) $$logP_f(p_r) = log\left(P_0.\left(\frac{d_0}{d}\right)^{\delta}\right) + v = k_0 - \delta.logd + v$$

where: p_0 and d_0 are reference power and distance respectively, and

(2) $$d = \sqrt{(x_r - x_e)^2 + (y_r - y_e)^2}$$

d :is the distance between the emitter and the receiver, and δ: the propagation decay exponent, varies between $\delta \in [2,\ 6]$. In Line-Of-Sight (LOS) case δ =2, in urban area close to 4. k_0 is lumps the constant parameters together, $k_0 = logP_0.d_0^{\delta}$ and: v: is Gaussian fast fading noise.

Figure(2) illustrates the decrease of the received $logP_f(p_r)$ with respect to the distance d between the emitter and the receiver with: $k_0 = 3822.0\,mW$, $\delta = 3.582$ and the fast fading noise standard deviation $\sigma = 1.96mW$.

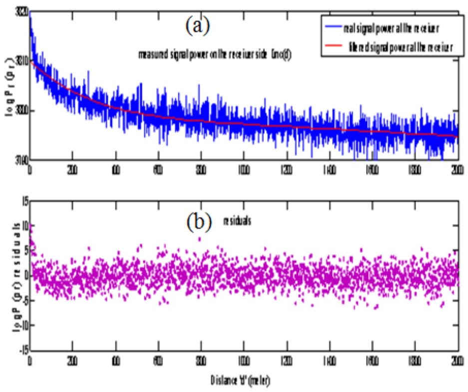

Fig.2 . Measured signal power on the receiver side with respect to the distance between two UAVs, b) Residual signal of the received signal power due to the noise interference when the standard deviation is σ = 1.96 mW

C. Localization in inertial coordinate of the F-UAV:

The received radio signals measure the distances between the set of three WKP UAVs, $(x,y)_{r1}, (x,y)_{r2}, (x,y)_{r3}$ and the F-UAV $(x_e, y_e)_e$.

These measured distances d_1, d_2, d_3 as well as the WKP-UAV coordinates in the inertial frame are then sent to the F-UAV by the communication channel path and fused with onboard INS to estimate the UAV position substituting the GPS signal.

To determine the inertial coordinates of the UAV in GPS fault the geometric relationship of '(3)' based on the known coordinates of the set of WKP UAVs is adopted:

(3) $$\begin{aligned} d_1 &= \sqrt{(x_{r1} - x_e)^2 + (y_{r1} - y_e)^2} \\ d_2 &= \sqrt{(x_{r2} - x_e)^2 + (y_{r2} - y_e)^2} \\ d_3 &= \sqrt{(x_{r3} - x_e)^2 + (y_{r3} - y_e)^2} \end{aligned}$$

D. Limitation of radio localization:

The main limitation to achieve a good position estimate of the F-UAV assumes the presence of direct line of sight (Line-Of-Sight, or LOS) between transmitter and receiver. However, especially in rural area, with the presence of several obstacles, This line of sight is not always, which detracts the measurement from the accurate location. The signal often experiences the phenomena of reflection, several versions of the signal attenuated and phase shifted are collected by the receiver which can add destructively or constructively the power of the received signal (we refer to the spread of the multipath signal). This profile of signal propagation by multipath in the internal environment and local blackouts of the transmitted signal greatly affect the localization accuracy. They might reach several dB over a distance less than the wavelength, and thus are difficult to model.

Fault-UAV tracking with Omnidirectional vision

Generally using an ODV (Omnidirectional Vision) on robots aims the localization of the robot itself. It is achieved by geometric computation on real-time processing. Dynamic Beacon tracker is very common to use to follow the marker in real time during the arbitrary movement of the vehicle.

The beacon recognition and tracking as well as landmarks are a key procedure for an omnivision guided mobile unit. This guidance technique would involves target recognition, vision tracking and object positioning as well as a path programming.

A beacon tracking-based method for robot localization has already been investigated in [13]. This method has utilized the color histogram, provided by a standard color camera system, in finding the spatial location of the robot carrying the camera with highest probability. The detection of the color markers represents the extraction of distinct colors in given images. An RGB color-based image processing procedure for four color markers detection by multi camera tracking multi indoor quadrotor was presented in [18]. Since each marker is distinguishable by their different features, precise position of the marker could be extracted.

In case of multiple UAV flight formation, colored markers are suggested to distinguish the different vehicles. However some problems may occur when color-based marker detection techniques are used. This is due to the fact that the number of distinguishable colors is limited[18].

A. Proposal Optic signal to claim the position:

to spot the F-UAV by the ODV as a target and avoid confusing with another UAV, we suggest an alarm marker concept where a third signal is added to the communication channel and radio localization signals previously advanced in section II.

The extra signal comes from an optic low power consumption beacon mounted on the UAV platform with light intensity enough to be detected by the neighbor camera. This solution would avoid the ODV to track the wrong UAV. We also suggest the blinking of this beacon at a specific frequency to keep the ODV away from any confusion with a same colored object existing by chance in the captured images.

In addition, assuming all the swarm own beacons, it is recommended to set up one UAV's beacon signal only when the fault alarm is triggered; this would help the neighbor UAV's ODV to spot it among the group and avoid using a specific color for each one.

B. Space decomposition process for an extract ODV image:

In radio localization the main drawback of the technique is the need of many sources to find the target. The radio signal is propagating in the space in spherical shape which ban one lonely source to determine the precise angle of incidence. Hence, even if the distance is estimated '(2)', the F-UAV may exist at any position of spherical space distant by 'd' and its absolute coordinates accept an infinite solutions fig.3.

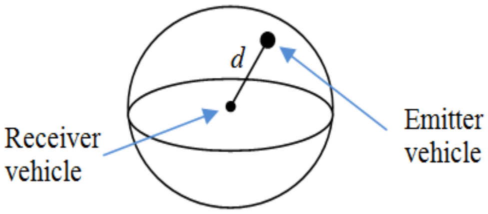

Fig.3. Spherical incidence of a radio signal from the transmitter to the receiver

We show in the following section how an ODV will help this issue when the distance is already estimated by the radio receiver.

Spherical angular extraction from the captured omnidirectional image

The ODV provides a scan of the space around the receiver. A detection of the colored blinking beacon in this image will be processed as a location in the captured and gridded image.

By dividing the space in eight main subspaces with respect to -/+180° in horizontal decomposition (-y y) and -/+90 in vertical decomposition(-z z) assuming that the camera is moving on Ox axe. With respect to the ODV camera frame $O_{camera}(0,0,0)$, the target UAV is on one of the eight subspaces.

Fig.4 shows an illustration of forming group of quad-rotors helicopters. The distance between each two of the group must be more or equal to the safety distance but also, less than a link distance to form the desired shape.

A panoramic view of 360° captured and processed by one UAV's ODV camera is shown on fig.6. The shadows on captured view caused by the UAV arms and rotors are not considered.

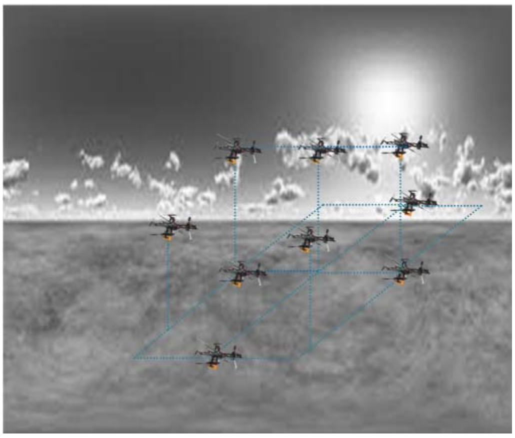

Fig.4 Quad-rotors flying in forming group with respect to a desired shape and inter-distance

The target UAV to localize is marked with four red marks on each rotor. According to its relative position to the vision camera, a preliminary localization could be done as a relative projection on the WKP-UAV frame (camera frame).

Using the spherical coordinates (Fig.5), the determination of the relative subspace is represented by the spherical coordinates intervals of (d, θ, φ),

where:

d: The Euclidean distance (from the origin *O* (Camera) to the UAV in fault) which is the measured distance already made by the radio localization process and also called the *radius* or *radial distance*,

θ: the *inclination* (or *polar angle*), which is the angle between the zenith direction and the line segment *OP*.

φ: the *azimuth* (or *azimuthal angle*): is the signed angle measured from the azimuth reference direction to the orthogonal projection of the line segment *OP* on the reference plane.

The spherical coordinates of a point P_e are then defined by a grid mesh of the captured and processed omnidirectional image (Fig.6).

Three layers are considered to describe the relative position of the UAV with respect to the omnidirectional camera installed on the leader UAV (WKP UAV) : *UP/ Down, Left/ Right, Front/Behind,* according to the angle interval of θ and φ *a) Cartesian transformations in Camera frame:*

The Cartesian coordinates with respect to the camera frame (fig.5)may be retrieved from the spherical coordinates (d, θ, φ), where $d \in [0, \infty)$, $\theta \in [0, \pi]$, $\varphi \in [0, 2\pi)$, by:

(4)
$$\begin{cases} {}^{ODV}x_e = d.\sin\vartheta\cos\varphi \\ {}^{ODV}y_e = d.\sin\vartheta\sin\varphi \\ {}^{ODV}z_e = d.\cos\vartheta \end{cases}$$

b) Localization in Inertial navigation frame:

$\boldsymbol{P_r} = [x_r, y_r, z_r, \alpha, \beta, \Psi]$ is the WKP-UAV (camera) current state of location and attitude. The orientation of the WKP UAV will be described as a parameterization of the transformation from the omnidirectional camera frame to the inertial frame. The Euler angles are widely used, since they have a very clear physical interpretation and are of minimum dimensionality. The minimum required dimensionality for describing an orientation in 3 dimensions is 3.

one Cartesian coordinate system, with respect to another, can always be described by three successive rotations. The orientation of a coordinate system can therefore be described by the z, y, x (also called 3-2-1) right-hand rotation sequence that is required to get from inertial frame into alignment with the Camera frame.

The rotations are denoted as follows:

• Right-hand rotation about the z-axis (positive ψ)
• Right-hand rotation about the new y-axis (positive α)
• Right-hand rotation about the new x-axis (positive β)

Matrices describing the rotations about the three axes are defined respectively with respect to the axis (OZ,OY OX) as :

(5.1)
$$C_z(\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & Cos(\beta) & Sin(\beta) \\ 0 & Sin(\beta) & Cos(\beta) \end{bmatrix}$$

(5.2)
$$C_y(\beta) = \begin{bmatrix} Cos(\alpha) & 0 & -Sin(\alpha) \\ 0 & 1 & 0 \\ Sin(\alpha) & 0 & Cos(\alpha) \end{bmatrix}$$

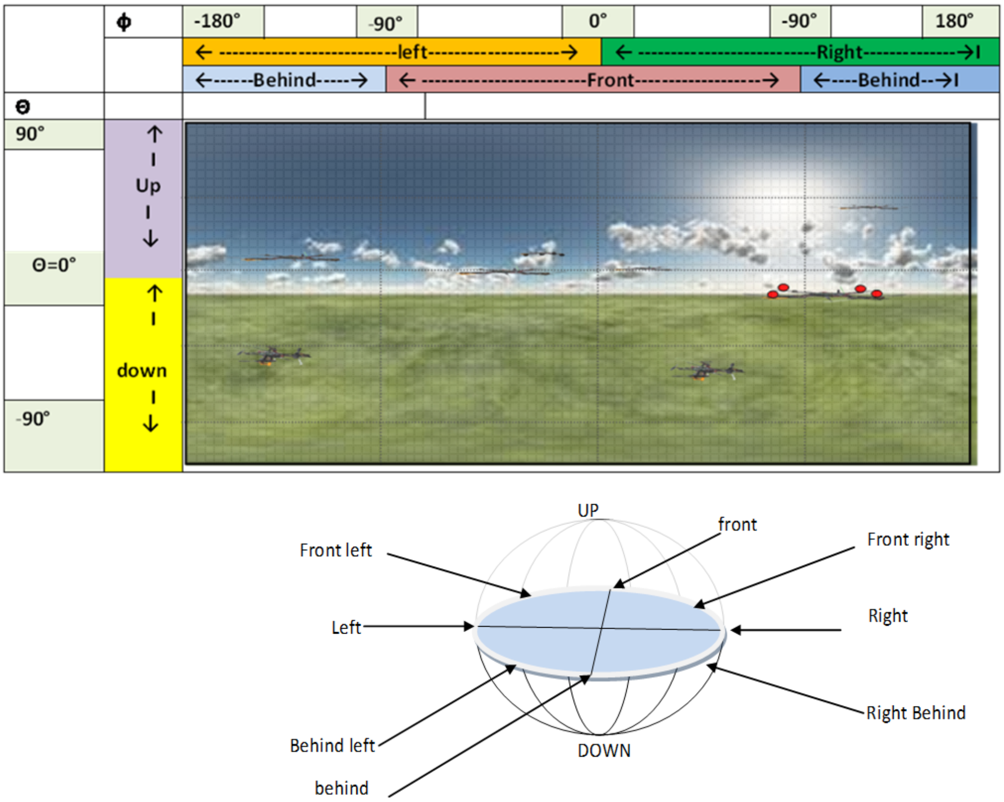

Fig.6. The captured and processed omnidirectional image to describe the relative position of the UAV with respect to the omnidirectional camera installed on the leader UAV (WKP UAV)

(5.3)
$$C_x(\beta) = \begin{bmatrix} Cos(\Psi) & Sin(\Psi) & 0 \\ -Sin(\Psi) & Cos(\Psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The successive rotations and the rotational matrix from inertial frame to camera frame is hereby defined as:

(6)
$${}^{ODV}C_{inertial}(\Xi) = C_x(\beta).C_y(\beta).C_z(\beta)$$

Because ${}^{ODV}C_{inertial}(\Xi)$ is orthonormal, the inverse transformation can be described at the transpose of ${}^{ODV}C_{inertial}(\Xi)$. we find:

(7)
$${}^{inertial}C_{ODV}(\Xi) = {}^{ODV}C_{inertial}(\Xi)^T$$

where $\Xi = [\alpha, \beta, \Psi]$ is the vector of Euler angles

The rotation from camera to inertial frame is given by:

(8)
$$\begin{bmatrix} C\alpha.C\Psi & (-C\beta.S\Psi + S\beta.S\alpha.S\Psi) & (S\beta.S\Psi + C\beta.S\alpha.C\Psi) \\ C\alpha.S\Psi & (C\beta.C\Psi + S\beta.S\alpha.S\Psi) & (-S\beta.C\Psi + C\beta.S\alpha.S\Psi) \\ -S\alpha & S\beta.C\alpha & C\beta.C\alpha \end{bmatrix}$$

where: C = cos and S = sin.

The position of the F-UAV is then seen in the inertial frame as:

(9)
$${}^{inertial}P_e = ({}^{inertial}C_{ODV}(\Xi) . {}^{ODV}P_e) + {}^{inertial}Pr$$

With:

(10)
$$\begin{cases} {}^{ODV}P_e = \begin{bmatrix} {}^{ODV}x_e \\ {}^{ODV}y_e \\ {}^{ODV}z_e \end{bmatrix} \\ {}^{inertial}P_e = \begin{bmatrix} {}^{inertial}x_e \\ {}^{inertial}y_e \\ {}^{inertial}z_e \end{bmatrix} \\ {}^{inertial}P_r = \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} \end{cases}$$

This description will substitute the need of a constellation of UAVs previously proposed where the position determination was in two dimensions only. Now, only one UAV equipped with an ODV and radio receiver would be enough since the distance and the orientation in three dimensions in the ODV frame and the inertial frame are already determined.

Conclusion

The position of a UAV flying in forming group and facing a fault in the onboard GPS was carried out. The proposed method is Based on the captured image done in 360° view by an omnidirectional camera and a radio localization mounted on a neighbor UAV with well known position. The technique of the localization laid basically on:

- the distance measured by the radio strength received by the WKP-UAV
- and the spherical angles extracted from the instantaneous captured image of the mounted omnidirectional camera.

The main limitation of the conventional radio localization was the number of UAVs used to estimate the position of the F-UAV. The accuracy of that alternative was very weak if the altitude of the F-UAV is uncertain and the solution of '(2)' accepted a unlimited solutions if the altitude is unknown. The uncertainty of direct Line-Of-Sight, (LOS) between transmitter and receiver, involving the phenomena of reflection due to multi path reflection when the obstacles interfere, may involve unconfident measurement of the distance.

With the proposed Omni-vision/radio-strength, all these issues are overcome where:

- The technique uses only one UAV instead of three UAVs (at least) in conventional radio localization,
- Thanks to the camera capturing in 360°, the localization is in three dimensions (x, y, z)
- The LOS condition in the received radio signal is confirmed since the F-UAV is visible on the captured image processed on the WKP-UAV and, as a result, the uncertainty in the distance measurement is removed.

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