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OPTIMIZING THE TRAJECTORY OF THE QUADCOPTER USING BUILT-IN SENSORS

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Abstract. *The task of optimizing the movement of a quadcopter using built-in sensors is considered. This is done using modern geolocation algorithms.*
Key words: *Algorithms, movement.*

I. INTRODUCTION

A quadcopter is an unmanned aerial vehicle with four main rotors that rotate diagonally in opposite directions. The rapid development of multicopters began in this century, but already as unmanned aerial vehicles.

Due to the simplicity of the design, multicopters have become very popular among modeling enthusiasts. Cameras and GPS modules are installed on them, which makes it possible to conduct high-quality video recording of the area from a height. Multicopters are small in size and weight, they are maneuverable, relatively cheap and easy to use. These possibilities are used not only for ordinary video recording, but also in many other places. Already today, multicopters can be seen in rescue services, research work, delivery of small cargo, and so on.

The compass serves so that the aircraft can orient itself in space, and has the ability to fly in "headless" mode. Additionally, a GPS module is attached to the aircraft. Usually, the compass is already built into the GPS module.

The accuracy of geolocation depends on a number of factors, including navigation satellite equipment errors, GPS receiver errors, and satellite signal propagation errors. In general, the geolocation accuracy for a household GPS receiver is about 15 meters. The sources of errors can be the following reasons:

- insufficient number of visible satellites;
- inaccuracy of ephemerides and errors of satellite clocks
- interference of the reflected signal to the antenna of the satellite receiver; obstacles associated with changes in the conditions for receiving signals from satellites (passing through a tunnel, densely built-up area, forest area);
- time delay in the receiver equipment;
- problems related to the power supply of the navigation device (power loss of the terminal or strong interference from the power grid to the terminal equipment);
- ionospheric delay;
- tropospheric delay.

At the current stage of technology development, mobile devices have become widely distributed. A large number of which have a built-in GPS receiver. Today, personal GPS monitoring is used in many areas of activity, so the problem of storing a large amount of recorded GPS data is relevant.

Reducing the amount of geolocation data can be achieved by applying various algorithms for processing received navigation data.

II. LITERATURE ANALYSIS

A GPS receiver is a radio receiving device designed to determine the geographic coordinates of one's current location using signals from artificial satellites of the corresponding GPS system.

The principle of operation consists in calculating the position based on the measurement data of the propagation time of radio signals emitted by artificial satellites to the receiver antenna and on the basis of information about the position of each satellite in orbit. In existing systems, data on the orbits of all satellites are transmitted periodically and stored in the receiver's memory. This is the so-called almanac.

2.1. Ramer-Douglas-Packer algorithm.

The Douglas-Packer algorithm is an algorithm that reduces the number of points on a curve approximated by a larger series of points. The algorithm is also known by the following names: the Ramer-Douglas-Packer algorithm, the iterative nearest point algorithm, and the split-and-merge algorithm.

The essence of the algorithm is to construct a kink with a smaller number of points from a given kink, approximating the curve. The algorithm determines the discrepancy, which is calculated by the maximum distance between the original and simplified curves. A simplified curve consists of a subset of points that are determined from the original curve.

The initial curve is an ordered set of points or lines, and a given distance $\varepsilon > 0$. The initial curve 0 and the simplified curve 4 are shown in Fig. 1.

The algorithm recursively divides the line. The input of the algorithm is the coordinates of all points between the first and the last. The first and last points are kept unchanged. After that, the algorithm finds the point furthest from the segment connecting the first and last points. If the point is at a distance smaller than ε, then all the points that have not yet been marked before saving can be thrown out of the set and the new straight line smooths the curve with an accuracy not lower than ε.

If the distance is greater than ε, then the algorithm recursively invokes itself on the set from the initial to the given and from the given to the final points (which means that the given point will be marked before saving).

At the end of all recursive calls, the output polygon is built only from those points that were marked before saving.

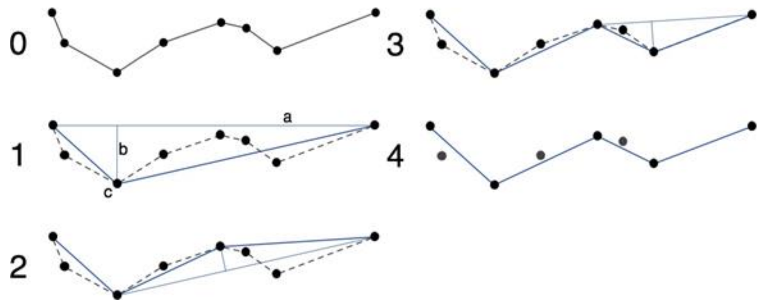

Fig. 1. Smoothing of the piecewise linear curve by the Douglas-Packer algorithm.

2.2. Kalman filter.

A Kalman filter is an algorithm that uses sequences of measurements over time that contain noise (random deviations) and other inaccuracies and produces estimates of unknown variables that are potentially more accurate than those based on measurements alone. More formally, the Kalman filter operates recursively on streams of noisy input data, and produces a statistically optimal estimate of the base state of the system. The filter is named after Rudolf Kalman, one of the main developers of its theory.

The Kalman filter has numerous applications in technology. Applications for guidance, navigation and control of vehicles, especially aircraft and spacecraft, are common. In addition, the Kalman filter is a widely used concept in time series analysis, used in fields such as signal processing and econometrics. Kalman filters are also a major topic in robotic motion planning and control, and are sometimes included in trajectory optimization.

This algorithm works as a two-step process. In the prediction step, the Kalman filter outputs estimates of the current state variables, along with their uncertainties. Once an observation of the output of the next measurement is obtained (surely distorted to some extent by deviation, including random noise), these estimates are refined using a weighted average, in which more weight is given to estimates with higher certainty. Due to the recursive nature of the algorithm, it can run in real time using only the available input measurements, the precomputed state, and its uncertainty matrix; no additional information is required.

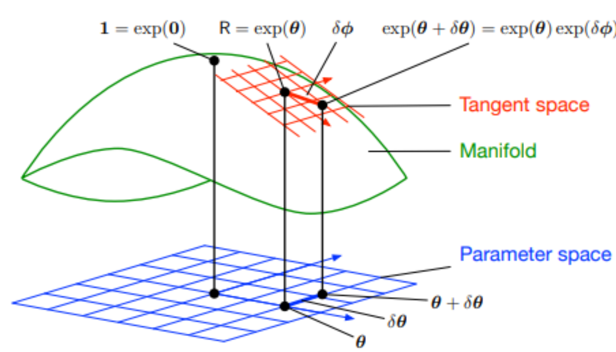

Fig. 2. Process of the Kalman filter

Application of EKF. The state area consists of 10 variables:

$$x_t := \left(x_t, y_t, z_t, \dot{x}_t, \dot{y}_t, \dot{z}_t, \Phi_t, \Theta_t, \Psi_t, \dot{\Psi}_t\right)^T \in \mathbb{R}^{10}; \quad (1)$$

where (x_t, y_t, z_t) denotes the current position of the quadcopter in meters and speed in meters per second in world coordinates, roll Φ_t, pitch Θ_t, search Ψ_t and angular velocity $\dot{\Psi}_t$ in degrees/s. In addition to each sensor, the observation function h (x_t), which describes how the vector of observations z_t is calculated from the output data of the sensors.

The quadcopter measures its horizontal $\hat{v}_{x,t}$ and $\hat{v}_{y,t}$ their local coordinates, which are transformed into global ones $\dot{x}_t$ and $\dot{y}_t$. Roll angle $\hat{\Phi}_t$ and pitch $\hat{\Theta}_t$, measured by the accelerometer, are direct measurements of Φ_t and Θ_t in accordance. To calculate the drift of the search, the differentiation of the height measurement is carried out $\hat{h}_t$ and rummaging $\hat{\Psi}_t$ and we consider them observations of the corresponding velocities. Therefore, the observation function and the measurement vector can be written as

$$h_I(x_t) := \begin{pmatrix} \dot{x}_t \cos\Psi_t - \dot{y}_t \sin\Psi_t \\ \dot{x}_t \sin\Psi_t - \dot{y}_t \cos\Psi_t \\ \dot{z}_t \\ \Phi_t \\ \Theta_t \\ \dot{\Psi}_t \end{pmatrix}; \quad (2)$$

$$z_{I,t} := \left(\hat{v}_{x,t}, \hat{v}_{y,t}, \frac{\hat{h}_t - \hat{h}_{t-1}}{\delta_{t-1}}, \hat{\Phi}_t, \hat{\Theta}_t, \frac{\hat{\Psi}_t - \hat{\Psi}_{t-1}}{\delta_{t-1}}\right)^T, \quad (3)$$

where δt denotes the time that has passed from the moment t to t + 1.

When the PTAM successfully tracks a video frame, the scale of the quadcopter's position in space is first determined through the scale factor λ * and converted to the quadcopter's local coordinate system using direct observations of the current position, which is given as

$$h_P(x_t) := (x_t, y_t, z_t, \Phi_t, \Theta_t, \Psi_t,)\ T; \quad (4)$$

$$z_{P,t} := f(E_{DC} E_{C,t}), \quad (5)$$

where $E_{C,t} \in SE(3)$ is calculated position cameras (scaled with λ); $E_{DC} \in SE(3)$ is static transformation with coordinate systems camera on coordinate system quadcopter, and f : SE (3) → Υ^6 transformation with of space SE (3) to presentation roll - pitch - yaw.

The prediction model shows how the state vector xt changes over time. In particular, the horizontal acceleration of the quadcopter is approximated. $\ddot{x}, \ddot{y}$, based on the current state of x^t – and the vertical acceleration is calculated $\ddot{z}$, acceleration of the rotation of the probe $\dot{\Psi}$ and roll speed $\dot{\Phi}$ and pitch $\dot{\Theta}$ based on the combination of the current ^{state} xt and the active control state u ^{t}.

The horizontal acceleration is proportional to the horizontal force acting on the quadcopter, which is given by

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \end{pmatrix} \propto f_{уск} - f_{сопр}, \quad (6)$$

where f $_{ref}$ denotes the braking force, and f the accelerating force. The drag force has a linear and quadratic part corresponding to laminar and turbulent flows - by setting the quadcopter at a relatively low speed, we can approximate a pure linear function to the current horizontal speed. Accelerating force f $_{usc}$ proportional to the projection of the z - axis of the quadcopter on the horizontal plane The above can be imagined as

$$\ddot{x}(x_t) = c_1 R(\Phi_t, \Theta_t, \Psi_t)_{1,3} - c_2 \dot{x}_t; \quad (7)$$

$$\ddot{x}(y_t) = c_1 R(\Phi_t, \Theta_t, \Psi_t)_{2,3} - c_2 \dot{x}_t, \quad (8)$$

where R (•) $_{i,j}$ means entries in the rotation matrix determined by roll, pitch, and yaw angles.

This model implies a constant thrust of all four rotors. The effect of outgoing control commands is also approximated. $u_t = (\bar{\Phi}_t, \bar{\Theta}_t, \bar{\dot{z}}_t, \bar{\dot{\Psi}}_t)$ using a linear model:

$$\dot{\Phi}(x_t, u_t) = c_3 \bar{\Phi}_t - c_4 \Phi_t; \quad (9)$$

$$\dot{\Theta}(x_t, u_t) = c_3 \bar{\Theta}_t - c_4 \Theta_t; \quad (10)$$

$$\ddot{\Psi}(x_t, u_t) = c_5 \bar{\dot{\Psi}}_t - c_6 \dot{\Psi}_t; \quad (11)$$

$$\ddot{z}(x_t, u_t) = c_7 \bar{\dot{z}}_t - c_8 \dot{z}_t. \quad (12)$$

Coefficients c $_3$ ... c $_8$ determined by test flights of the quadcopter. The general state of the system is given as

$$\begin{pmatrix} x_t+1 \\ y_t+1 \\ z_t+1 \\ \dot{x}_t+1 \\ \dot{y}_t+1 \\ \dot{z}_t+1 \\ \Phi_t+1 \\ \Theta_t+1 \\ \Psi_t+1 \\ \dot{\Psi}_t+1 \end{pmatrix} \leftarrow \begin{pmatrix} x_t \\ y_t \\ z_t \\ \dot{x}_t \\ \dot{y}_t \\ \dot{z}_t \\ \Phi_t \\ \Theta_t \\ \Psi_t \\ \dot{\Psi}_t \end{pmatrix} + \delta_t \begin{pmatrix} \dot{x}_t \\ \dot{y}_t \\ \dot{z}_t \\ \ddot{x}(x_t) \\ \ddot{y}(x_t) \\ \ddot{z}(x_t, u_t) \\ \dot{\Phi}(x_t, u_t) \\ \dot{\Theta}(x_t, u_t) \\ \dot{\Psi}_t \\ \ddot{\Psi}(x_t, u_t) \end{pmatrix}. \quad (13)$$

The model described in formulas (7)–(13) does not pretend to be physically correct due to numerous assumptions, but works very well in practice, mainly due to its completeness: the behavior of all state parameters and the action of all control commands are approximated, allowing "blind » forecast, that is. forecast without observations for a short period of time (~125 ms in practice).

A number of experiments were conducted to analyze the properties of the obtained system. They were conducted in different environments - in rooms of different sizes and appearance, as well as outdoors under the influence of sunlight and light wind.

2.3. Moving average.

Moving average or moving average is one of the analysis tools random processes and hours rows, what consists of in calculations average subsets values Sliding average not is scalar, and is random process Size subsets, from which is calculated average the value can be either constant or variable. A moving average can have weights, for example, to increase the impact of more recent data compared to older

Sliding average maybe to calculate from arbitrary data, however, most often him use in analysis hours rows for smoothing sudden fluctuations and emphasizing long-term trends or cycles. WITH mathematical points vision sliding average is variety convolutions and looks like on low pass filter in signal processing.

Simple sliding mean (SMA) — is alone with most simple ones and popular indicators in technical analysis SMA is ordinary average arithmetic from the values for a certain period. SMA refers to the class indicators that follow the trend, it helps to determine the beginning the new trend and its completion can be determined by its angle of inclination strength (speed movement), it same in quality foundations (or smoothing factor) is applied in big quantity others technical indicators.

2.4. Method of fast filtering of GPS data.

GPS receivers are devices that continuously calculate position, time and a number of other parameters. In its pure form, GPS data is inconvenient to use and often carries a lot of redundant information. Even if the receiver is in a stationary state, the position data is constantly changing, there is a kind of noise associated with the movement of satellites, processes in the atmosphere and radiation from the sun, which affect the signal. If you do not use filtering and take position data from a stationary receiver as is, you can observe a continuous change in its position, as shown in Fig. 3. As a result of such changes in half an hour of immobility, the calculated path of the observed object can reach several kilometers, which may be unacceptable for a number of systems.

In complex monitoring systems for collecting and storing GPS data from many objects, the use of filtering allows you to significantly reduce the volume of processed information without losing the quality of the latter. This filtering task consists in screening out data that do not provide fundamentally new information about the state of the object.

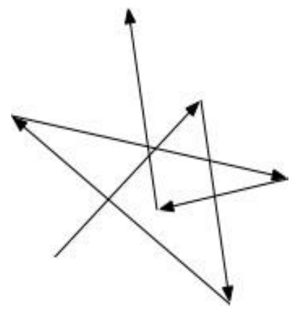

Fig. 3. An example of noise.

The proposed GPS data filter can be divided into two parts:

- pre-cleaning filter;
- redundant data filter.

Pre-filtering implements screening of samples that are erroneous, incomplete or do not correspond to the number of required parameters. For a number of systems, this stage of filtering can be useful. Additionally, depending on the data quality requirements, it is possible to screen out samples in which the accuracy values exceed the maximum permissible limits specified in the filter settings.

The redundant data filter uses the distance between two points as a criterion, which must be less than the sum of their positioning accuracies. For longitude and latitude, this is the radius of the circle (of the sphere, if the height is taken into account), which is taken equal to the precision value for the given point. New samples are filtered, provided that their circle does not intersect with the circle of the previous, filtered sample. If this type of filtering is not performed, then in addition to extra points without useful information, noise will be observed.

The main advantages of this method of filtering GPS data can be noted:

- the possibility of implementing the algorithm on a low-power device;
- significant reduction in data flow.

III. OBJECT, SUBJECT, AND METHODS OF RESEARCH

All quadcopters have a similar operating principle. Since they belong to aircraft, all the laws of aerodynamics also have their influence on their operation. In the theory of flight (aerodynamics), it is customary to distinguish three axes of rotation, which determine the orientation and direction of the aircraft's motion vector. These three axes are called roll, pitch, and yaw.

Roll is a turn of the device around its longitudinal axis (the axis that runs from the nose to the tail). Pitch is a turn around the transverse axis (tilts the nose, raises the tail). Yaw is a turn around a vertical axis, most similar to a turn in the "terrestrial" sense.

The quadcopter has another fourth indicator - Gas (Throttle). It determines the speed of movement along the vertical axis by increasing or decreasing the speed of the motors.

The design of the quadcopter provides it with the ability to fly due to the placement of the main propellers in the correct order. If you do not follow this order, take-off will be impossible. So, in order for the quadcopter to be able to take off, it is necessary to perform the following placement scheme:

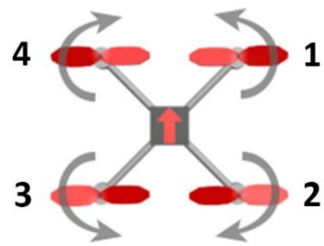

Fig. 4. Direction of rotation of all four screws

As you can see from the picture, each motor rotates in its own direction. For proper operation, motors 1 and 3 must rotate counterclockwise, and motors 2 and 4 must rotate clockwise. It is also possible to do the opposite, that is, 1 and 3 - clockwise, and 2 and 4 - counterclockwise.

To ensure rotation along each of the axes, the quadcopter must tilt in the required direction. Leaning forward, toward the nose, or vice versa, backward is pitch. A tilt to the left or right is a roll. If the quadcopter performs a turn around the vertical axis, then it will be a yaw.

To ensure tilting to one side, it is necessary to change the speed of the motors. When one of the motors starts rotating faster than the others, it starts to lift the aircraft up, but since the other motors are not spinning fast enough, it will tilt in the opposite direction to this motor. So, to create a forward pitch, motors 2 and 3 need to rotate faster than motors 1 and 4. In the case where a yaw is required, motors 1 and 3 need to rotate faster than 2 and 4 if it is a left rotation, and for rotation to the right, 2 and 4 should be faster than 1 and 3.

However, this is not enough to ensure stable movement. Unfortunately, the quadcopter is affected by many other factors that make its movement unstable. Such factors include: strong air, excess weight, asymmetric placement of components. This is where the GPS module comes to the rescue.

IV. RESULTS

After analyzing the work of implemented GPS data processing algorithms, they can be divided into two groups:

- algorithms that reduce the amount of data;
- algorithms that improve data accuracy.

The filters of the first group, which allow to reduce the amount of data, include the Douglas-Packer algorithm and the method of fast filtering of GPS data. The Kalman algorithm and the moving average belong to the filters of the second group, which allow improving the accuracy of navigation data.

As a result of the processing of GPS data by filters of the first group, the number of points is significantly reduced, but the accuracy of the route itself decreases. As a result of data processing with filters of the second group, the accuracy of the track improves, but the amount of data remains unchanged. Therefore, the use of several processing methods was proposed.

The GPS data was processed by various combinations of algorithms. Test GPS data was processed by different algorithms sequentially, while the order of algorithms and their number gives different results. Table 1 shows the processing data of two different sets of GPS data using different combinations of processing algorithms.

Table 1. Evaluation of the degree of similarity of objects

A combination of algorithms	**Data set #1**		**Data set #2**	
	Number of points	Average accuracy, m.	Number of points	Average accuracy, m.
—	66	6.05	128	5.97
Kalman Douglas-Packer	9	6.04	11	5.97
Douglas-Packer moving average	10	6,12	15	6.04
Quick filter. Kalman	44	6.35	80	6.33
Quick filter. Moving average	43	6.61	79	6.23
Quick filter. Kalman Douglas-Packer	6	6.98	11	6.75
Quick filter. Douglas-Packer moving average	7	6.28	8	6.92

Using a combination of the Kalman and Douglas-Packer algorithms showed the best result. This combination made it possible to increase the accuracy of the received GPS data and reduce their number.

V. CONCLUSIONS

Kalman, Douglas-Packer, moving algorithms are considered in the work average and fast filtering method of GPS data. For results GPS data processing, these algorithms can be divided into two groups. The first group algorithms, to which refers to algorithm Kalman and movable means allows to improve accuracy received navigational data The second group of algorithms, which includes the Douglas-Packer algorithm and method of fast filtering of GPS data, allows to reduce the number of GPS-data

It was conducted analysis work different combinations these algorithms, When GPS data are processed different algorithms successively. On based on the analysis of the received processing results, the best result has a combination of Kalman and Douglas-

Packer. Using this combination when processing GPS data, makes it possible to reduce the amount of data that necessary save, without reduction accuracy information about location which they contain

using this one combination algorithms, was developed module, which allows you to process GPS data for further use and storage.

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