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Quad-copter Self-positioning System for Precise Maneuvering during Landing Procedure

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Quad-copter Self-positioning System for Precise Maneuvering during Landing Procedure

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Abstract

UAVs are nowadays getting every year more practical applications as well as are a subject of interest of hobbyists. Multi-copters is a very interesting kind of UAVs offering for a reasonable price great maneuverability and expandability by additional sensors being a good platform for testing new solutions. The project is a trial of construction of a precise self-positioning quad-copter system for landing. Most of the nowadays positioning systems are based on GPS/GLONASS signal. Nevertheless such systems are not enough for precise landing procedure especially for small UAVs. Much better precision can be achieved using vision systems. Presented solution is based on an image processing system. Image of landing area is obtained from a camera fixed to the positioned UAV. The captured video image is transmitted over wireless connection to the ground station based on a PC. On the computer the image is processed, the special marker located at landing position is recognized and appropriate control signals are sent back to the UAV. Control and video transmissions are realized over separate wireless links. The pattern recognition needed for the system is performed using OpenCV library. The system needs only an appropriate marker placed on the ground.

The paper is a general analysis of the project emphasizing the most interesting observations. It shows the influence of the image processing on the positioning performance and accuracy.

Keywords: pattern recognition, computer vision, UAV, self-positioning, GPS, GNSS, image acquisition

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Introduction

As UAV (Unmanned Aircraft Vehicle) usage is wider every year autonomous navigation systems for such vehicles are being developed. Many of them base on GPS signal [1-4]. Such a solution though its many advantages has also limitations. One of them is accuracy. According to [4] GPS accuracy of around 3m CEP for a small UAV suitable receiver can be achieved (2.8 m for the specific tested device). GPS signal loss may also occur e.g. due to buildings interference. During a landing procedure where every loss of the signal or its inaccuracy may lead to UAV damage an alternative, more precise system is desired [5-7]. The system [5] requires an UAV equipped with an IMU and a camera. The camera is treated as a primary sensor and the IMU constituted of 3 low cost MEMS accelerometers, 3 angular rate sensors and 2 magnetometers is used to provide robust relative pose information and more generally allows autonomous navigation. In case of the system [6] the UAV has to be equipped with 2 cameras. The main reason of the second camera addition is measuring of a distance. It seems to be an interesting solution, but even using a single camera one can achieve very good results. The system [7] needs ultrasonic and barometric sensors. It is definitely better to have more sensors, but every additional sensor increases the system complexity and cost.

In our work we focused on development of a system which should be as simple and low cost as possible giving at the same time accuracy good enough for a precise landing of a quad-copter. The presented system uses directly only a camera. Other sensors are used for the UAV stabilization only and can be removed or replaced arbitrarily without any changes in the positioning system as long as it does not influence the UAV stability and maneuverability. As the whole control is realized by a software written in C/C++ the ground based station can be moved in future to the quad-copter itself using a low power ARM processor based system instead of a PC.

The paper is divided into a few sections. First the theoretical background is presented. It includes basic information about GNSS systems, PID controller which was used in the system as well as image processing and pattern recognition techniques needed. Then the experimental setup is presented. All the elements are described and their functions in the system are explained. In the next part obtained results are presented and discussed.

Theoretical Background

The section presents basic information about GNSS systems, theory of PID controller as well as employed image processing and pattern recognition techniques.

GNSS Systems

GNSS (Global Navigation Satellite System) systems provide geo-spatial positioning with global coverage. As for now two such systems (GPS and GLONASS) are operational.

GPS

GPS (Global Positioning System) is a United States -owned utility. It provides positioning, navigation, and timing (PNT) services. It is divided into three segments, where the U.S. Air Force is responsible for the first 2 ones:

- space segment consisting of a constellation of 24 satellites transmitting radio signal to users,
- control segment responsible for tracking and adjusting the satellites positions, their clocks as well as monitoring their health status,
- user segment consisting of user-owned GPS equipment receiving satellites' signals and using these data for calculating users 3D position and time.

Standard Accuracy

GPS is divided into a SPS (Standard Positioning Service) available for everyone and a military PPS (Precise Positioning Service). The SPS broadcasts at one frequency (L1 -1575.42Mhz) while the PPS on two (L1 -1575.42Mhz and L2 -1227.60MHz). It gives military users a possibility to perform ionospheric correction which is a technique reducing radio degradation caused by Earth's atmosphere thus improving accuracy.

According to the U.S. official government information a real-world Federal Aviation Administration (FAA) data shows that civilian GPS horizontal accuracy (without augmentation) for high-quality GPS receivers can be better than 3 meters.

GLONASS

GLONASS (Russian: ГЛОНАСС, Глобальная навигационная спутниковая система), acronym for Globalnaya navigatsionnaya sputnikovaya sistema or Global Navigation Satellite System. It is a Russian GNSS navigation system. It consists as GPS of 24 satellites. The accuracy of the system is comparable to the GPS one, but some breakdowns from time to time appear.

Other Systems

Two other GNSS systems are being developed:

- Galileo (European Union)
  The system will base on 27 satellites located on 3 orbits. The first two operational satellites were launched in October 2011. In contrast to GPS and GLONASS it will be controlled by a civil institution. It is not operational yet. An early service is planned for late 2014.

- BeiDou (China)
  It is a Chinese (as for now regional) navigation system. Global coverage is planned to be achieved by the year 2020.

Augmentations

Many different augmentation techniques intended for improvement of GNSS accuracy exist. Availability only for operational systems was pointed. The most important are:

- CORS (Continuously Operating Reference Stations)
  It is mainly used for post-processing allowing to set the GPS data to centimeters level. It is based on ground reference points and operated by the National Oceanic and Atmospheric Administration. It is available in the USA and supports only GPS.
- GBAS (Ground Based Augmentation System)
  It is an Australian service intended to provide precise data for aircraft landing in order to replace current Instrumental Landing Systems. It is available in Australia and supports only GPS.
- GDGPS (Global Differential GPS)
  A NASA Jet Propulsion Laboratory developed system giving a GPS decimeter positioning accuracy and sub-nanosecond time transfer accuracy all over the world independently of local infrastructure. The system is worldwide available supporting both GPS and GLONASS. However accuracy for GLONASS is worse. It is based on ground stations, but the information is transmitted to users using satellites.
- IGS (International GNSS Service)
  It is an international, worldwide available system consisting of a network of over 350 stations of over 200 organizations providing augmentation data. It supports both GPS and GLONASS.
- WAAS (Wide Area Augmentation System)
  It is a satellite-based system operated by FAA supporting aircraft navigation across the North America. Although designed for aviation it is available on many devices used for different purposes. It is available in the USA and supports only GPS.
- EGNOS (European Geostationary Navigation Overlay Service)
  It is an European satellite based augmentation system supporting both GPS and GLONASS. Its horizontal position accuracy in practice is in meter level.
- MSAS (Multi-functional Satellite Augmentation System)
  A similar system to WAAS and EGNOS, available in Japan and supporting only GPS.
- GAGAN (GPS And GEO-Augmented Navigation)
  A similar system to WAAS and EGNOS and MSAS, available in India and supporting only GPS.

In addition many recent devices can receive both GPS and GLONASS signals what improves accuracy. Using all those augmentation techniques one can achieve real-time positioning to within a few centimeters, and post-mission measurements at the millimeter level. However the study [4] shows that a standard small UAV suitable GPS receiver gives an accuracy of around 3m CEP (Circular Error Probability) (2.8m for the specific tested model).

PID Controller

In our work we used a PID controller. It was implemented in the control software operating on the ground station.

Transfer function of a PID controller:

$$G(s) = K_p + \frac{K_i}{s} + K_d s$$

where:
K_p –proportional controller gain
K_i –integral controller gain
K_d –derivative controller gain

A continuous PID algorithm:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt}$$

where:
u –control signal
e –control error

As we wanted to implement it as a part of the control software running on the ground based station which is a PC we used a discrete algorithm. It can be easily obtained from the continuous one using appropriate transforms.

A discrete PID algorithm:

$$u[k] = u[k-1] + K_1 e[k] + K_2 e[k-1] + K_3 e[k-2]$$

where:

$$K_1 = K_p + K_i + K_d$$
$$K_2 = -K_p - 2K_d$$
$$K_1 = K_d$$

Image Processing and Pattern Recognition

As the whole system is vision based the image processing and correct recognition of the marker position plays a crucial role.

HSV Color Space

For pattern recognition based on its color the HSV (Hue Saturation Value) color space is the most suitable. It represents color in the following way:

- Hue (0 -360º)

- Saturation -an amount of grey in the color (0 -100%)
- Value -describes the brightness of the color (0 -100%)

As the image is normally stored and transmitted in the RGB color space the image has to be converted to the HSV color space before thresholding.

Thresholding

The image is thresholded using the following condition:

$$\begin{cases} 1 \ if \ H \in < H_0, H_1 > and \ S \in < S_0, S_1 > and \ V \in < V_0, V_1 > \\ 0 \ otherwise \end{cases}$$

where:
H –Hue
S –Saturation
V –Value
H_0 –the lower bound of the hue
H_1 –the upper bound of the hue
S_0 –the lower bound of the saturation
S_1 –the upper bound of the saturation
V_0 –the lower bound of the value
V_1 –the upper bound of the value
Assumption: white = 1, black = 0

Marker Position Calculation

The marker position is calculated using the 1st order spatial moments around x and y axis and the 0th order central moments. It is done on the binary image.

Assuming f(x,y) being a binary image we can write the following equations.

Spatial moments' equation:

$$m_{i,j} = \sum_{x,y} x^j y^i * f(x,y)$$

Central moments' equation:

$$\mu_{i,j} = \sum_{x,y} (x - \bar{x})^j (y - \bar{y})^i * f(x,y)$$

where $(\overline{x}, \overline{y})$ is the mass center.

Smoothing

The image was smoothed before thresholding by a Gaussian filter. It is intended to remove the noise which appeared during the video capture, transmission and conversion.

The idea of the Gaussian filter is a weighted average. The closer the pixel is to the central one the more heavily it is weighted. The pixels are weighted according to the Gaussian function:

$$H(i,j) = e^{\frac{-(i^2+j^2)}{2\sigma^2}}$$

As the σ is small there is almost no effect of the filtering. As it gets large blurring appears. Commonly used values are $\sigma = \frac{w}{5}$ for w being the size of the kernel H.

OpenCV Library

We used the OpenCV (Open Source Computer Vision) library for the image processing and the pattern recognition. This open source library is released under a BSD license thereby being free for both academic and commercial use. It provides a great set of tools and is suitable for real-time applications. Many image filtering tools are provided.

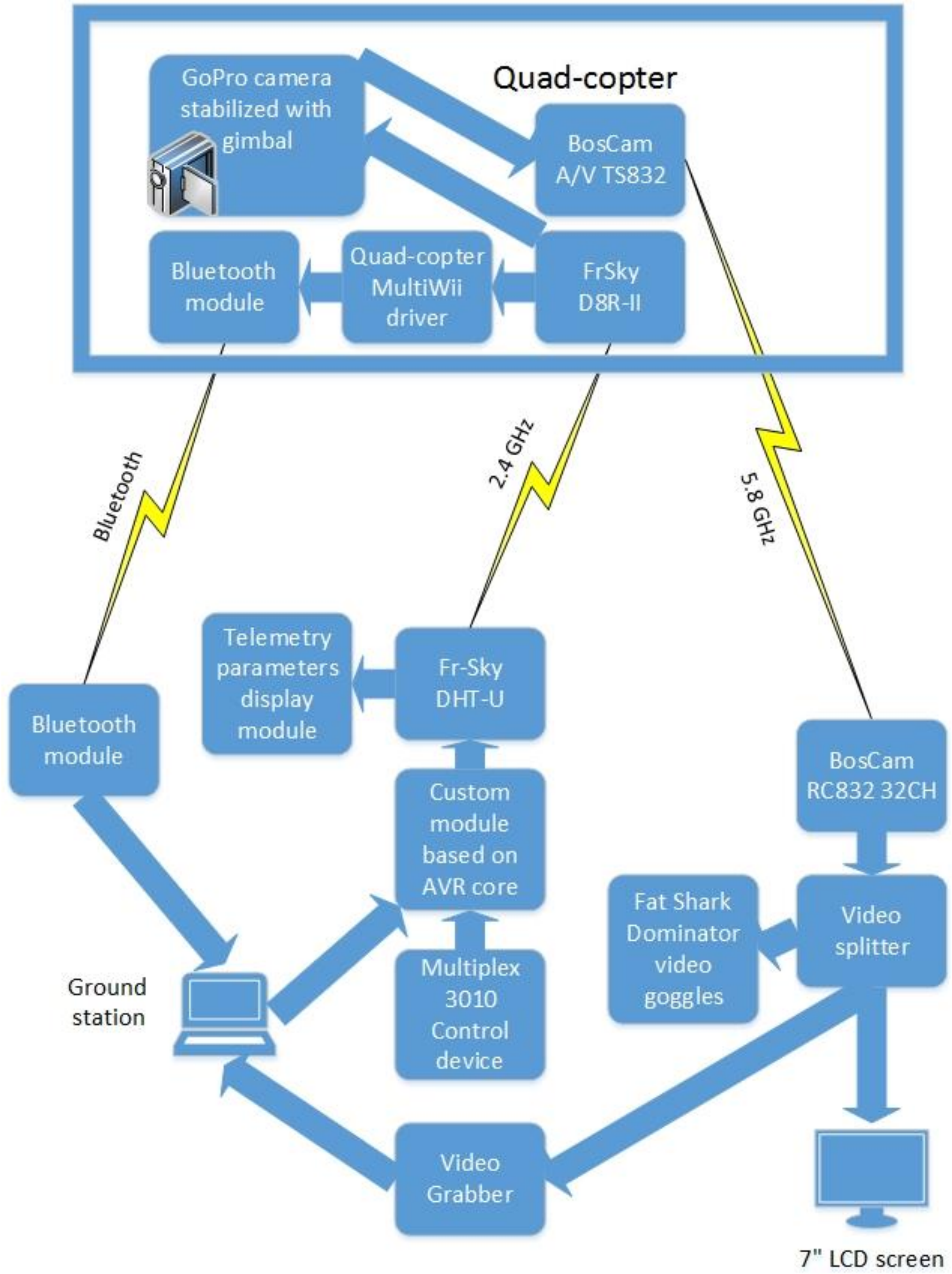
The HSV color space is represented in the OpenCV for a 24bit image in the following way:

- Hue (0 -179)
- Saturation (0 -255)
- Value (0 -255)

Experimental Setup

In this section the experimental setup is described. All the elements are presented and their role in the system is explained.

Figure 1. *Diagram Presenting the Experimental Setup*



Quad-copter

A medium-weight quad-copter frame was used:

- weight with motor mounts -460g,
- 254mm/16mm carbon arms.

Landing legs having the following parameters were used:

- weight -260g,
- 200mm clearance,

- materials: Fiberglass G10 2.00 mm thick, aluminum tubes 3-8x1mm.

E-MAX GT2215/10 engines with 10x4.7 propellers were used:

- weight -70g without propellers each,
- max thrust -1200g each.

Figure 2. *The Quad-copter*

Ground Station

As the ground station a PC equipped with an A/D converter and a Bluetooth module was used. Requirements of the control software meet most of recent PC's. A laptop equipped with Intel i5-2430 processor, 4GB DDR 3 RAM and NVIDIA GeForce GT540M graphics card was used.

Video Capture and Transmission

A GoPro Hero 3 Silver Edition camera was used. It is able to capture video in 1080p 60 fps and 720p 30 fps, but for our purposes only analog 640×480 px available at the Composite Video output was used.

It was stabilized using a gimbal which was also used to change the camera position from the *observation* position when it is directed horizontally to the *landing* position when it is directed vertically down.

The video signal was transmitted over an analog Composite Video link using Boscam 5.8GHz 600mW A/V TS832 + RC832 32CH edition modules. A/D conversion using an USB Video Grabber on the ground station was performed.

The video could be displayed on the screen of the ground station, Fat Shark Dominator video goggles as well as on a 7" additional display.

Control and Related Issues

A Multiplex 3010 remote control device with 2.4 GHz FrSky DHT-U and D8R-II wireless modules was used. In order to control the UAV from the ground station a custom module basing on an AVR core was designed. In the experiments a Bluetooth link for telemetry information transmission and MultiiWii WinGUI by Andras Schaffer for its visualization were used. We are currently working on transmitting this information to the ground station over a return channel of the FrSky modules.

Results and Discussion

The system needed to be tuned in laboratory conditions i.e. setting the image processing, pattern recognition and PID controller parameters. Then the flight tests were performed.

Image Smoothing

As noise appeared the image had to be smoothed in order to improve the marker detection. Without smoothing the position of the marker actually stable with respect to the UAV was recognized as slightly moving. The same effect appeared when the image was smoothed before and after thresholding. In case of smoothing only before thresholding the indications of the marker position were significantly more stable. In case of the presented system the smoothing was performed using a Gaussian kernel of size 9x9.

Lower and Upper Bound Choice for Thresholding

The choice of the bounds was a tradeoff between robustness to different light conditions and a problem of recognizing some environment elements as a part of the marker. A blue marker was used and the bounds set in the following way:

$H_0 = 105$

$H_1 = 130$

$S_0 = 160$

$S_1 = 255$

$V_0 = 70$

$V_1 = 255$

The system recognized the marker with such settings well as long as the lighting was good.

Control

The system needed a precise PID settings adjustment. The quad-copter faces very complicated effects connected with turbulences, wind and the air stream reflections from surrounding obstacles or the ground in case of landing procedure. For its stability the MultiWii driver was responsible. During maneuvers the UAV tilts what would cause shifting of the image and could be interpreted by the control software as a movement of the quad-copter itself.

Therefore the camera was stabilized by the gimbal what made possible to assume that the movement of the marker on the image was connected only with a movement of the quad-copter with respect to the ground. Taking into account such complicated environment the PID parameters had to be very precisely experimentally determined. There was a risk that providing too strong control signal could cause the UAV to lose stability. Therefore in the first phase the parameters were tuned in a simulated environment and the influence of the marker position changes on the control signals was examined. Then very careful flight tests could be performed. All the control system worked properly for the quad-copter positioning. Landing procedure tests are planned, but were not done yet.

Video Transmission and Acquisition

Video transmission over the analog link works well, but we faced a problem with its A/D conversion. The used converter was not recognized as an *Imaging device,* but appeared in the section *Sound, video and game controllers* of the Windows Device Manager. Using OpenCV we could not correctly recognize the incoming video stream. It resulted in fatal system errors. We were forced to use additional software for the video acquisition which created a virtual camera over which the stream was passed to the control software.

Final Remarks

As we could see a single camera is enough for a self-positioning of a quad-copter. The presented system although it is not very complicated, works fine. In order to improve the marker recognition one can add shape detection. It should eliminate the problem of recognizing some elements of the environment having similar color to the marker as elements of the marker itself allowing expansion of the bounds for thresholding what will make the system more robust to bad light conditions.

The system is planned to be expanded to a landing system and two cases are considered:

- The altitude before the landing procedure starts will have to be determined using another data source. In this case the size of the marker may vary. For every landing the marker size can be different as long as it will be enough visible for the camera. The system will determine the actual marker size taking into account the altitude obtained from the other source and its size on the image. Then during the landing procedure the altitude will be calculated using the algorithm basing on the marker size on the image.
- The altitude will be determined by the system. The marker size will have to be fixed in order to allow the system calculating the position basing on its size. The further procedure is the same as in the first case.

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