Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 31, 2019, Sofia

DOI: https://doi.org/10.3897/arb.v31.e07

QUATERNION-BASED AUTOPILOT FOR DODECACOPTERS - PART II

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Keywords: *Unmanned Aerial Vehicle (UAV), Autopilot, Dodecacopter.*

Abstract

"Quaternion-based Autopilot for Dodecacopters - Part I" was published in Aerospace Research in Bulgaria journal, book 28/2016. The theoretical model at that time, evolved into a prototype autopilot system during the last two years. This small as per its dimensions, but large according to its capabilities, autopilot is now presented herein.

The autopilot is given the nomenclature identification "Z-Pilot Nano" and is currently at version 1.0 of its development. The device is scrutinized from the point of view of its major application platform – micro-drones weighing not more than 250 g. Furthermore, Z-Pilot Nano has been installed in Bulgarian Knight UAV and elaboration on this implementation is disclosed in the current article.

The autopilot is also applicable to other aircraft, as well as land and sea unmanned vehicles, due to its versatility and high performance parameters.

Introduction

The development of an autopilot for dodecacopters based on quaternion mathematical model began three years ago. The author published the Part I of this article series back in 2016 in Aerospace Research in Bulgaria journal, book 28. Further, the work continued and two years later resulted in the creation of a 12-rotor helicopter autopilot with miniature dimensions and weight. There were two motivations for creating the prototype such small in size and also versatile in capabilities:

1. The modern trend of using very small UAVs for various purposes [1–4].
2. The application of the autopilot to both dodecacopters and larger, by the number of rotors, drones.

The proposed autopilot is also suitable for land and sea unmanned vehicles. The autopilot prototype was named "Z-Pilot Nano" and has been mounted on a micro-dodecacopter model Bulgarian Knight (see Fig. 1).

The recently raised interest in micro unmanned aerial vehicles (micro-UAVs) is by no means random. Micro-drones are hard to detect and track by any means of physics or any technical instruments [5]. The manifested benefits of micro-drones are the driving force behind their extraordinary popularity during the last few years. There doesn't exist a single specific threshold of the total weight that, being below, a drone will be considered a micro-drone. Different scales of measure have been elaborated, but law changes, from not long ago, in some countries have established the 250 g total weight upper limit as the most often recognized criterion for classification of micro-drones. A similar upper limit of 25 g would generally classify a drone as a nano-drone.

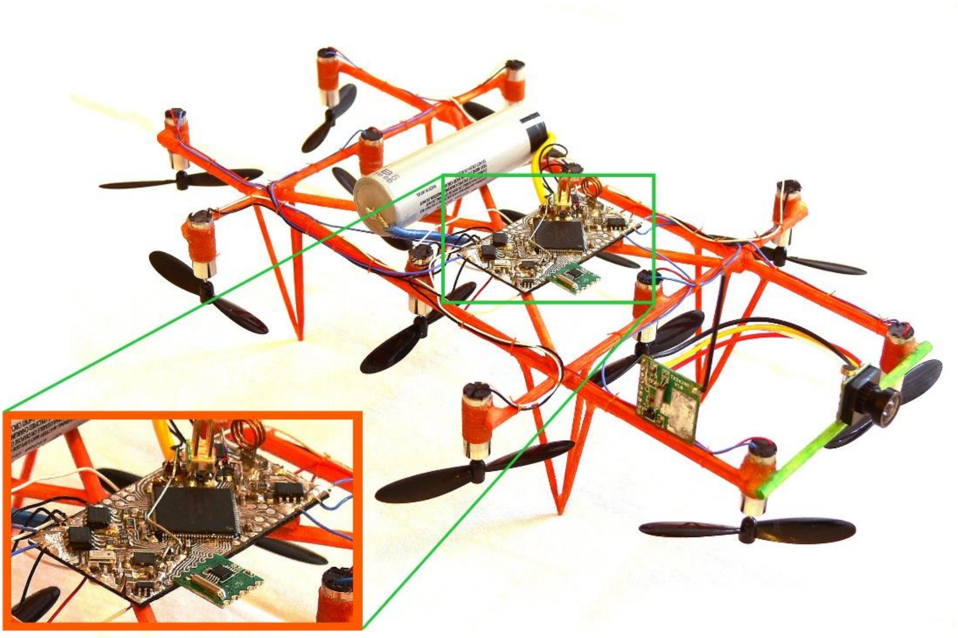

Fig. 1. Autopilot Z-Pilot Nano on board of Bulgarian Knight dodecacopter micro-drone. The aircraft total weight is 121 g and has dimensions: 280 × 185 × 40 mm.

Z-Pilot Nano prototype design

In Fig. 2, a block diagram of the Z-Pilot Nano design is presented. The heart of the system is a modern microcontroller with DSP capabilities from semiconductor division of Philips – NXP. Such devices are called Digital Signal Controllers (DSCs). The chip has a processor with ARM 32-bit architecture – Cortex-M4. The core of the processor is ARMv7-M. The processor is working at 120 MHz clock speed. Cortex-M4 architecture offers 3-stage pipeline with branch prediction and internal data and code cache memory. The RAM of the chip is 128 kiB (kibibyte) and the flash memory is 1 MiB (mebibyte). The chip is supplied with a single precision IEEE 754 compliant math coprocessor that executes most 32-bit floating point operations with 1 clock cycle latency.

The DSP capabilities offered by the device are:

- Single cycle 16/32-bit MAC (multiply-accumulate operation).
- Single cycle dual 16-bit MAC (multiply-accumulate operation).
- 8/16-bit SIMD arithmetic.
- Hardware Divide (2–12 Cycles).

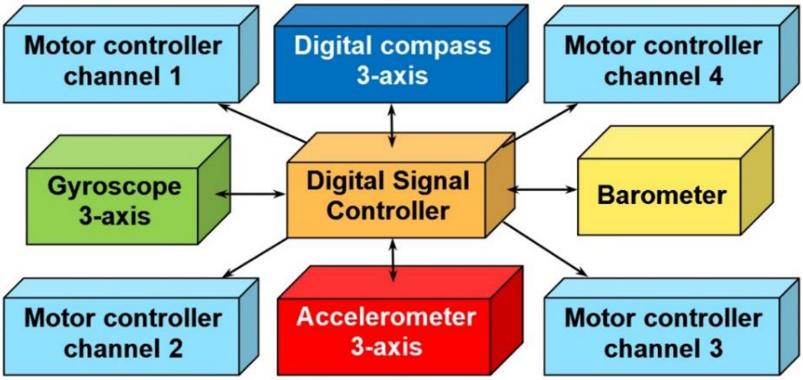

Fig. 2. Z-Pilot Nano principal block diagram

The employed digital signal controller offers a number of timers, analogue to digital converters, digital to analogue converters, communication interfaces and other peripherals. The chosen DSC variant occupies an SMD 100-pin LQFP package with dimensions of 14×14 mm (see Fig. 3). Device supply voltage range is from 1.71 to 3.6 V and its temperature range (ambient) is from –40 to +105 °C.

Fig. 3. NXP Digital Signal Controller implemented as the main IC in Z-Pilot Nano. The used variant is installed into an SMD LQFP 100-pin package with dimensions 14×14 mm.

The digital signal controller is communicating over I^{2}C interface with a number of devices on the PCB of the autopilot as denoted on Fig. 2 with two-way arrows. Further, the DSC is managing four motor controllers through one-way signals.

The inertial and altimeter sensors of the autopilot are of the MEMS type (microelectromechanical systems). The utilization of MEMS sensors into UAV autopilots has peaked lately [6–8].

Altimeter measurements are performed by means of a digital barometer IC – MPL3115A2 (Fig. 4 – left). This device employs a MEMS pressure sensor with range of 20 to 110 kPa. The pressure range translates to altitude range from –500 m to +12000 m from sea level. As already stated, the digital communication interface is I^2C. This device also implements an accurate thermometer. The sensor output accuracy is 20-bit for pressure/altimeter information and 12-bit for temperature data. The altimeter accuracy guarantees maximum altitude resolutions of 10 cm. Analogue signals are internally digitized by means of 24-bit high-resolution ADCs. There is an on-chip processing of the acquired data, which eliminates the need for compensation calculations from the DSC (host controller). MPL3115A2 offers a variety of operating modes that include engaging an interrupt signal, setting up a polling only mode, autonomous data acquisition, etc. The device is extremely low-powered and consumes only 40 μA per measurement per second. Supply voltage range is from 1.95 to 3.6 V. The package is SMD LGA type and has dimensions of 5.0×3.0×1.1 mm. Temperature range of operation is from –40 to +85 °C.

Fig. 4. ICs engaged in Z-Pilot Nano as sensors. From left to right: Digital barometer MPL3115A2; Digital IMU – LSM9DS1 top view; LSM9DS1 bottom view.

The other three sensor devices are packaged in one IC – LSM9DS1. This integrated circuit hosts a digital 3-axis gyroscope, a digital 3-axis accelerometer, a digital 3-axis magnetometer (digital compass), and a digital thermometer. All four devices communicate with the DSC through I^2C interface. The chip is powered by 1.9 to 3.6 V supply voltage and consumes not more than 4.6 mA of current. Operating temperature range is from –40 to +85 °C.

The gyroscope has angular rate range of ±245/±500/±2000 degrees per second. Its maximum output data rate (ODR) is 952 Hz and its accuracy is 16 bits.

The digital accelerometer acceleration range is ±2/±4/±8/±16 g and its maximum output data rate (ODR) is 952 Hz, again at 16-bit accuracy. The digital compass's range is ±4/±8/±12/±16 gauss, which equals ±0.4/±0.8/±1.2/±1.6 mT. Maximum magnetometer ODR is 80 Hz and data accuracy is 16 bits. The digital thermometer inside the LSM9DS1 device has temperature range from –40 to +85 °C and accuracy of 12 bits. The temperature sensor ODR is 59.5 Hz.

There are four motor controllers on board of the Z-Pilot Nano autopilot. Each motor controller is capable of delivering 3 A output current and thus manage 4 micro-motors of the 7×20 mm type or 3 micro-motors of the 8.5×20 mm type. A dual MOSFET transistor IC has been employed in the motor controllers – the si4564dy from Vishay, see Fig. 5. The IC contains one N-channel and one P-channel MOSFET transistor with on-state resistance of not more than 20 mΩ. Total switching capacitance of one motor controller's MOSFET ICs is 3215 pF. The energy loss for one switch on/switch off cycle is hence:

(1) $$E = \frac{C \times V^2}{2} \times 2 = 3215 \times 10^{-12} \times 3.3^2 = 35 \times 10^{-9}\ \mathrm{J}$$

Where the voltage transition was calculated at the regulated 3.3 V voltage supply of the controlling DSC chip.

Fig. 5. Dual MOSFET transistor IC si4564dy manufactured by Vishay, employed in motor controllers. Contains two MOSFETs – one N-channel and one P-channel transistor.

The switching frequency is 60 kHz. It follows that the switching power loss is:

(2) $$P = E \times 60000 = 2.1\ \mathrm{mW}$$

For all four motor controllers the switching power loss is equal to 8.4 mW. At 3.3 V supply voltage this power consumption translates to 2.5 mA current draw for all four motor controllers.

Table 1 summarizes all devices installed in the autopilot with their supply voltage range, current consumption, and operating temperature range.

There are still more devices of minor significance in the autopilot, such as voltage regulator, current sense circuit, filtering capacitors, etc. The latter are not elaborated on in this article for their implementation being trivial.

Table 1. Major parameters of the devices employed in Z-Pilot Nano

Device	Supply voltage range	Typical current consumption	Operating temperature range
Digital signal controller	1.71 ÷ 3.60 V	50.10 mA	-40 ÷ +105 °C
Barometric sensor	1.95 ÷ 3.60 V	0.04 mA	-40 ÷ +85 °C
Gyroscope	1.90 ÷ 3.60 V	4.00 mA	-40 ÷ +85 °C
Accelerometer and digital compass	1.90 ÷ 3.60 V	0.60 mA	-40 ÷ +85 °C
Motor controllers (four units)	2.60 ÷ 16.00 V	2.50 mA	-40 ÷ +85 °C
Overall voltage range:	2.60 ÷ 3.60 V		
Total typical current drain:		57.24 mA	
Overall temperature range:			-40 ÷ +85 °C

The autopilot is powered by a single cell Li-Ion battery and thus all voltage requirements in Table 1 are fulfilled.

Printed circuit board

The construction of Z-Pilot Nano has been establish around a printed circuit board with dimensions of 50×25 mm. The board offers general purpose input/output connections, as well as, general purpose analogue inputs. There is a connection for external I^2C devices; connections for motor wiring and a 6-pin socket for programming the digital signal controller (see Fig. 6).

All elements are surface mount. Some devices have leadless packages. Hence, the soldering process of the prototype requires special laboratory equipment for precise device positioning and heating.

The first prototype of the autopilot has been built on 1 mm thick printed circuit board. This thickness proved to be overdone and resulted in 5 g overall autopilot weight. Another prototype is under construction using 0.4 mm thick FR-4 board. The calculations show that the new prototype will weigh around 3 g. The autopilot, as mentioned earlier, is capable of driving 16 micro-motors of the

7×20 mm type. Managing a 16-rotor aircraft, the autopilot will have a negligible weight share of the aircraft weight. When the new prototype is installed in the Bulgarian Knight micro-drone it will occupy only 2.5 % of the total aircraft weight – the current prototype takes up the inacceptable 4.1 % of the total drone weight.

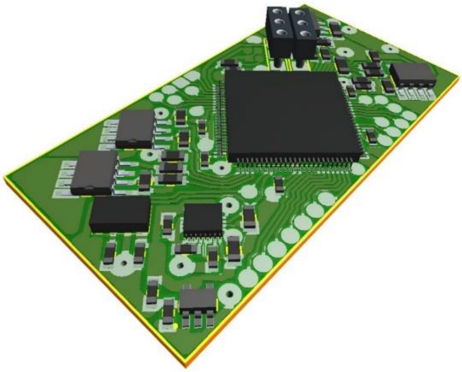

Fig. 6. The Z-Pilot Nano printed circuit board. The board dimensions are 50×25 mm, weight: 3-5 g (see text).

Conclusions

The author is constantly developing the Z-Pilot Nano and enhancing its characteristics. The roadmap is leading to the installation of the device into micro-drones of various types [9], most of which are multirotor drones with the number of rotors greater than or equal to 12. Further, Z-Pilot Nano is envisioned as the major controlling circuit of land and sea unmanned vehicles and robots, as well as different standalone devices implemented in measuring diverse parameters of the environment.

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АВТОПИЛОТ ЗА ДВАНАДЕСЕТОКОПТЕРИ, БАЗИРАН ВЪРХУ КВАТЕРНИОНИ – ЧАСТ II

С. Забунов

Резюме

Статията “Автопилот за дванадесетокоптери, базиран върху кватер-нииони – част I” беше публикувана в списанието *Aerospace Research in Bulgaria*, книжка 28, година 2016. Теоретичният модел, създаден тогава, се разви и достигна прототипна фаза. Този малък според своите размери, но голям в зависимост от своите възможности, автопилот сега е представен в настоящата статия.

Автопилотът получи номенклатурна идентификация “Z-Pilot Nano” и текущата версия на разработката е 1.0. Устройството е подробно описано от гледна точка на своята основна платформа на приложение – микро-дроновете, тежащи не повече от 250 g. Z-Pilot Nano е инсталиран на микро-хеликоптера „Български рицар“, като цялата машина има тегло 121 g.

Платката на автопилота е подходяща както за различни видове без-пилотни летателни апарати, така и за безпилотни наземни или водни машини, поради своята гъвкавост и висока производителност.