A Survey on Open-Source Flight Control Platforms of Unmanned Aerial Vehicle

Emad Samuel Malki Ebeid
University of Southern Denmark

Martin Skriver
University of Southern Denmark

A Survey on Open-Source Flight Control Platforms of Unmanned Aerial Vehicle

Emad Ebeid
The Mærsk Mc-Kinney Møller Institute
University of Southern Denmark,
Denmark
esme@mmmi.sdu.dk

Martin Skriver
The Mærsk Mc-Kinney Møller Institute
University of Southern Denmark,
Denmark
maskr@mmmi.sdu.dk

Jie Jin
School of Electronic Engineering
Dublin City University,
Ireland
jie.jin4@mail.dcu.ie

***Abstract*—Recently, Unmanned Aerial Vehicles (UAVs), so-called drones, have gotten a lot of attention in academic research and commercial applications due to their simple structure, ease of operations and low-cost hardware components. Flight controller, embedded electronic component, represents the core part of the drone. It aims at performing the main operations of the drone (e.g., autonomous control and navigation). There are various types of flight controllers and each of them has its own characteristics and features.**

This paper presents an extensive survey on the publicly available open-source flight controllers that can be used for academic research. The paper introduces the basics of UAV system with its components. The survey fully covers both hardware and software open-source flight controller platforms and compares their main features.

***Index Terms*—Unmanned Aerial Vehicle (UAV), Drones, Flight Controllers, Open Platforms, Survey.**

I. Introduction

By 2022, drone market for commercial application expects to reach as much as 22.15 billion $, growing at a Compound Annual Growth Rate (CAGR) of 20.7% from 2015 to 2022 [1]. The usage of the drones is expected to continue to grow for public safety use along with military applications [2]. In that regard, several drone platforms have been developed by industries and academia to enable its engagement in different life aspects (e.g., agriculture, transport, energy, security, etc.). In the past few years, several open-source UAV platforms (Hardware, Software, or both) have been developed by communities and research projects to test and implement various UAV applications [3]. In contrast, there are very few research papers that cover a small and old part of such platforms.

In 2010, the authors in [4] have presented a survey of the autopilot systems for small or micro UAVs systems. Their objective is to provide a summary of the available commercial, open-source and research autopilot systems in the market at that moment for potential small UAV users. In 2011, the authors in [5] have made a survey on open-source hardware and software fixed-wing UAV platforms. They have shown a design of a small fixed-wing UAV based on one of the presented systems with its first field test. In 2012, the authors in [6] presented the publicly available open-source projects on quadrotor UAV system. In total, the paper has presented eight quadrotors with descriptions of their avionics, sensor composition, analysis of attitude estimation and control algorithms, and comparison of their additional features. In 2016, the authors in [7] have presented a general view of the implementation of open-source quadcopter platform to develop a quadcopter research testbed. The research aims at making the proposed platform expendable to be used in any application areas. In addition, the work very briefly mentioned a couple of open-source flight controller platforms that one of them has been used in their work.

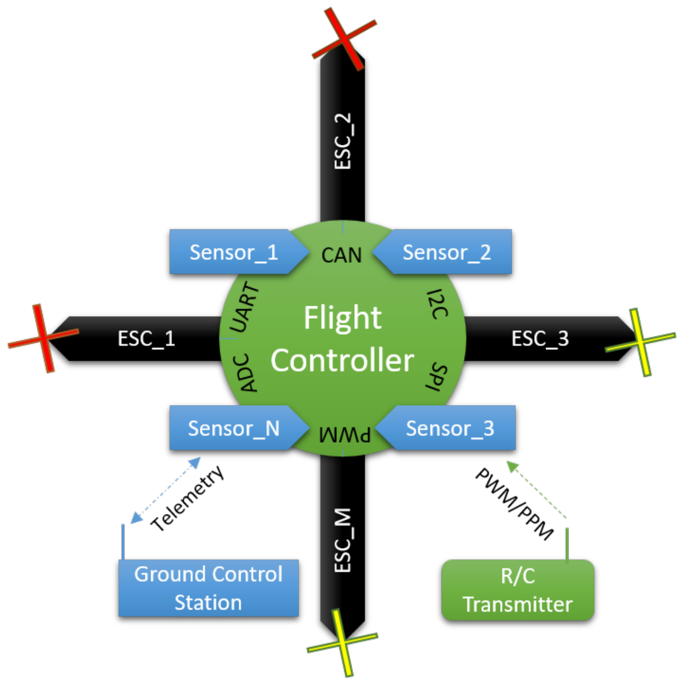


Fig. 1. UAV flight control (autopilot) system

In this work, we present the basics of the UAV system (Fig. 1 shows its components and will be explained in Section II) that is followed by a deep survey on Open-Source Hardware (OSH) and Open-Source Software (OSS) UAV flight control platforms that can be used in academic research. The survey explores 15+ open-source UAV platforms that are publicly available on the Internet. Moreover, the survey compares the features and specifications of each platform. Finally, this work highlights the stopped open-source UAV platforms. The readers should note that the information described in this paper is as of May 2017 and the photos are taken from the developer's websites.

This paper is structured as follows. Section II explains the main components of UAV system. Section III explores open-source hardware platforms. Section IV explores open-source software platforms. Section V draws the conclusion of this work.

II. UAV Basics

This section explains the main components of an autopilot system [8], a system that contains hardware and software components that are capable of completely or partially replacing human to guide drones in the fly [9].

A. Flight Controller

It is the main hardware board for processing and operations of the UAV system [7]. It controls the motors, interfaces with internal or external sensors, implements attitude estimation and the control law (e.g., Kalman filter), and navigation and communicates with ground control or neighbor UAVs. Its performance strongly depends on the embedded unit that is used. ARM, Atmel, Arduino, etc. units are used to build the flight controller. Most flight controllers use 32-bit processor and few use 8-bit ones. The open-source units will be explored in the following section. Fig. 1 shows the structure of UAV system, so-called autopilot system. The flight controller is in its middle and interacts with the other units via standard communication interfaces (e.g., Controller Area Network (CAN), Pulse Width Modulation (PWM), Universal Asynchronous Receiver/Transmitter (UART), etc.).

B. Propulsion System

For multi-rotor UAVs, it is often Brushless DC motor (BLDC)s controlled by an Electronic Speed Controller (ESC) that are used to drive the propellers but in some cases typical for drones below 250 g, brushed motors are used to spare the cost of ESCs. Fixed-wing UAV does also often use a BLDC for the propeller and servo motors for the flaps [10]. Another popular variation of fixed wing drones are using propeller like a multi rotor drone for Vertical Takeoff and Landing (VTOL) and fly like a fixed wing drone once its in the air. The drone flies like a fixed-wing but for positioning critical flights, takeoff and landing it uses the propellers like a multi-rotor.

A newer UAV type is the bio-inspired concept that uses flapping wings driven by servo motors as a propulsion system [11, 12].

C. Sensors

UAVs use sensors to detect changes in the surroundings that allow them to collect critical data about the object they are inspecting and maneuver better. Various types of sensors are used in a UAV to record changes and collect a variety of information. The common sensors are:

1) Inertial Measurement Unit (IMU): It is the main component of inertial navigation systems and maneuver in UAV system. It uses a combination of accelerometers and gyroscopes for accurately estimate UAVs' attitude including roll and pitch. In addition, it uses magnetometers, a supplement of accelerometer and gyroscope, to measure the heading (i.e., yaw) and to measure and report a drone's specific force, angular rate, and the magnetic field surrounding the drone.

2) Barometer: It is used to measure atmospheric pressure and calculates the drone's altitude. It can detect if the drones move few centimeters.

3) GNSS: Global Navigation Satellite System (GNSS) [13] measures the drone location by calculating how far it is from predefined satellites such as Global Positioning System (GPS), GLONASS, Galileo, and BeiDuo. The accuracy of the GNSS receiver depends on the number of satellites fix and Dilution of Precision (DOP). Typically, a low-cost GNSS module, using L1 bandwidth, has a precision $\approx$ 5 meters. Therefore, other sensors such as IMUs and barometers are combined with the GNSS to improve the drone's accuracy. Worth noting that the GNSS system is slower than the local sensors but it gives an absolute position rather than relative one.

D. Communication Systems

Two different types of communications are used to interact with the drones. They are as follows.

1) Ground Control Station (GCS): It is a software application that runs on the computational unit (PC, tablet, etc.) [14]. It is used to communicate wirelessly with the drone to monitor where it is flying, set waypoints, or execute new commands. QGroundControl, Mission Planner, APM Planner are some examples of GCS applications. In order to send and receive such data, a telemetry hardware radio unit is needed to be attached to the computational unit to perform such operation. It implements MAVlink protocol serial connection [15].

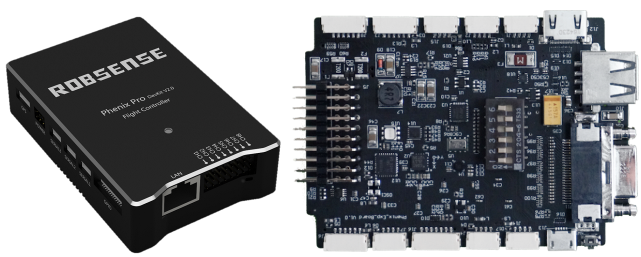
2) Radio Control (R/C) transmitter: It is used to minimally control the drone's movement (throttle) and orientation (pitch, roll, and yaw). The control commands are mapped into PWM (multi-channel) or Pulse Position Modulation (PPM) (single channel) signals and transmitted to the flight controller. Afterwards, the controller used them to control the drone's motors.

III. Open-Source Hardware Platforms

This section explores different OSH platforms and summarizes their features in Table I. OSH platform means that the hardware design (i.e. mechanical drawings, schematics, bills of material, Printed Circuit Board (PCB) layout data, Hardware Description Language (HDL) source code and integrated circuit layout data), and the software that drives the hardware, are all released under free/libre terms [16].

A. FPGA based platforms

1) Phenix Pro: It is built on reconfigurable System on a Chip (SoC) designed and developed by RobSense Tech, founded in 2015 and located in Hangzhou China. The flight controller is equipped with the real-time operating system and Linux-based Robot Operating System (ROS). The flight platform supports 20+ interfaces including on-board sensors, mmWave radar, Lidar, thermal camera, ultra-vision HD video transceiver via software defined radio, etc. In addition, its hardware (FPGA) acceleration enables computer vision and Deep Neural Network algorithms applications. It runs FreeRTOS based UAV real-time operating system (PhenOS) that contains a built in multi-task scheduling, and ROS for intelligent algorithms and hardware resources management. Fig. 2-a shows Phenix Pro flight controller and Fig. 2-b shows its circuit board. The schematic of this platform is closed-source, however, the project's software is open under The GNU General Public License (GPL)v3 license.

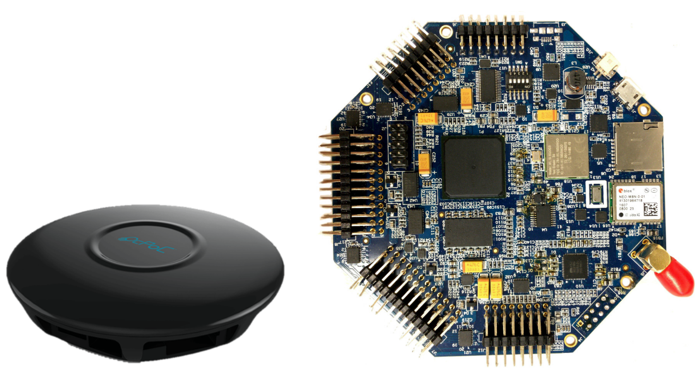


(a) (b)

Fig. 2. Phenix Pro flight controller. (a) Enclosure, (b) Circuit board

2) OcPoC: Octagonal Pilot on Chip (OcPoC) is developed by Aerotenna Company, founded in 2015 and located in Bioscience and Technology Business Center, University of Kansas, USA. OcPoC expands its input and output capabilities to include fully programmable PWM, PPM, and GPIO pins to integrate with a vast number of different sensor additions. It also includes many other standardized connectors for peripherals such as GPS, CSI camera link, and SD card. It runs *ArduPilot* software platform (see Section IV-A) and implements real-time processing of sensor data simultaneously.

Fig. 3-a shows OcPoC flight controller and Fig. 3-b shows its circuit board. The schematic of this platform is closed-source.



(a) (b)

Fig. 3. OcPoC flight controller. (a) Enclosure, (b) Circuit board

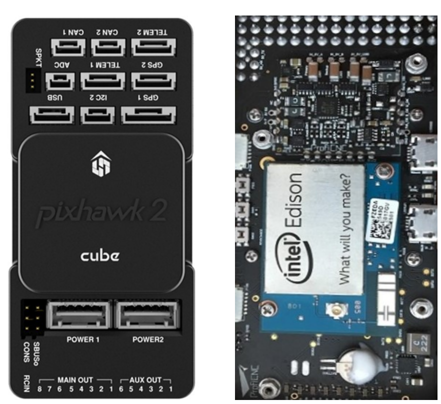
B. ARM-based platforms

1) PIXHAWK/PX4: It is a computer vision research based flight control designed by Computer Vision and Geometry Lab of ETH Zurich and Autonomous Systems Lab [17]. It is an evolution of the PX4 flight controller system (i.e., enclosure and perhaps modified connections). It consists of a PX4-Flight Management Unit (FMU) controller and a PX4-IO integrated on a single board with additional IO, Memory and other features. In addition, it works closely with the Linux Foundation DroneCode project (see Section IV-E). Fig. 4-a shows PIXHAWK flight controller and Fig. 4-b shows its main circuit board; PX4. The project is available under the Berkeley Software Distribution (BSD) license.

(a) (b)

Fig. 4. PIXHAWK/PX4 flight controller: (a) Enclosure (b) Circuit board.

2) PIXHAWK 2: It grows from the Pixhawk Hardware Project and done as a group effort by the PX4 and Ardupilot teams. It is a small cube, has triple redundant IMU's, and up to 3 GPS modules. All connection (I/Os) to the cube is in one single DF17 connector. Its carrier board has an interface to Intel® Edison (works as a companion computer). Fig. 5-a shows PIXHAWK 2 enclosure and Fig. 5-b shows its circuit board. The Pixhawk 2 schematics are open under the CC-BY-SA-3.0 license.



(a) (b)

Fig. 5. PIXHAWK 2 flight controller: (a) Enclosure (b) Circuit board.

3) Paparazzi: It is the first and the oldest open-source drone hardware and software project. It is developed in Ecole Nationale de l'Aviation Civil (ENAC) UAV Lab since 2003 [18]. It encompasses autopilot systems and ground station software for multi-copters/multi-rotors, fixed-wing, helicopters and hybrid aircraft [19]. In March 2017, ENAC Lab released a new autopilot named *Chimera* that is based on the latest STM32F7 Microcontroller Unit (MCU). Fig. 6 shows Paparazzi Chimera circuit board. The hardware and software of the project are available under the GPL license.

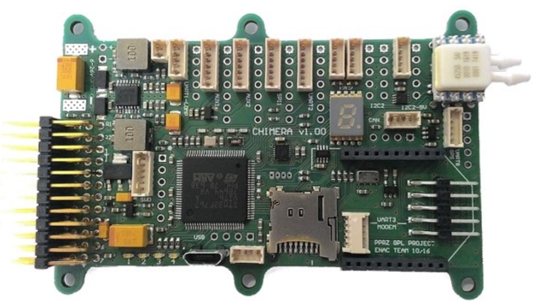
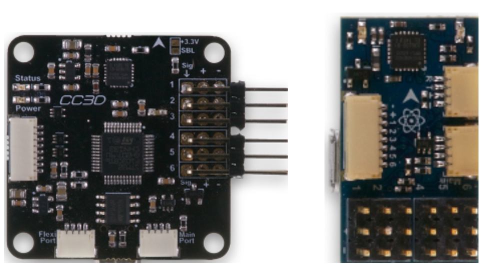


Fig. 6. STM-based flight controllers: Paparazzi Chimera

4) CC3D & Atom: They are two flight controllers have the same functionalities but different in size. They are developed by OpenPilot which became LibraPilot recently. The CC3D and Atom flight controllers have all types of stabilization hardware which run the OpenPilot/LibraPilot firmware (see Section IV-D). They can be configured to fly any airframe from fixed-wing to an octocopter using the OpenPilot/LibraPilot. The hardware and the software of the project are available under the GPLv3 license. Fig. 7-a and b show CC3D and Atom circuit boards, respectively.

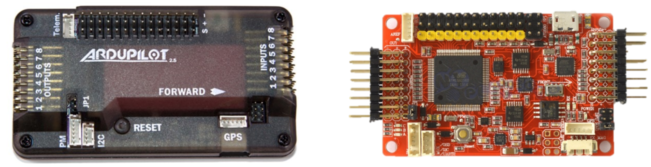


(a) (b)

Fig. 7. Flight controller board: (a) CC3D (b) Atom.

C. Atmel-based platforms

1) ArduPilot Mega (APM): It is an Arduino Mega-based autopilot system developed by DIY Drones community as an upgrade of *ArduPilot* flight control. It is able to control autonomous multi-copters, fixed-wing aircraft, traditional helicopters, ground rovers and antenna trackers. Fig. 8-a shows ArduPilot Mega (APM) v2.8 unit and Fig. 8-b shows its circuit board. The project is open under GPLv3 license.



(a) (b)

Fig. 8. ArduPilot Mega (APM) autopilot: (a) APM 2.8 unit (b) APM 2.8 circuit board.

2) FlyMaple: It is a Quadcopter controller board, based on the Maple Project. The design of FlyMaple is based on the maple, which is an Arduino style ARM processor. FlyMaple is aimed to run on the balancing robots, mobile platform, helicopters and quad-copters which require IMUs and high-performance real-time controllers. Fig. 9 shows Flymaple flight controller board. The project is under GPLv3 license.

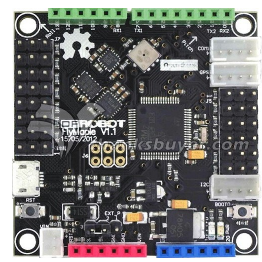


Fig. 9. FlyMaple flight controller board

D. Raspberry Pi based platforms

1) Erle-Brain 3: It is Linux based open pilot for drones developed by Erle Robotics, Spain. It combines an embedded Linux computer (Raspberry Pi) and a daughter board (PXFmini) containing several sensors, IO and power electronics. The PXFmini is an open hardware autopilot shield for making robots and drones meant for the Raspberry Pi family. It is built on top of the Dronecode Foundation technologies (see Section IV-E). Fig. 10-a shows Erle-Brain 3 autopilot and Fig. 10-b shows its parts (PXFmini + Raspberry Pi). The PXFmini schematics are open under the Creative Commons Attribution-NonCommercial-ShareAlike (CC BY-NC-SA) license.

(a) (b)

Fig. 10. Erle-Brain 3 autopilot: (a) Erle-Brain 3 (b) PXFmini + Raspberry Pi.

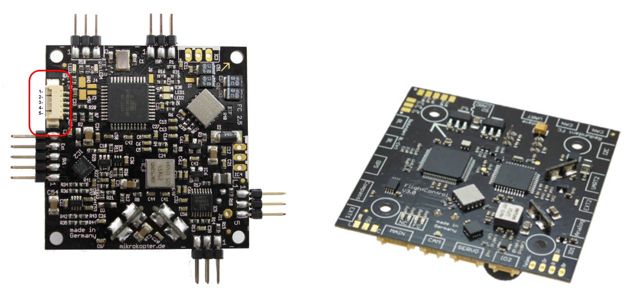
E. No longer active OSH projects

This section shows the stopped open-source hardware projects that one can avoid to search for.

1) AeroQuad: It was Arduino-based platform developed for quadrotor autopilot. The project has stopped in 2015 however, its software is online available [20]. Fig. 11 shows its flight controller.

Fig. 11. AeroQuad flight controller circuit board

2) Mikrokopter: The Mikrokopter v2.5 was the latest open-source flight controller that was based on an ATMEGA1284P-AU MCU. Its electronic schematics are available to download in [21]. For the newer v3.0, its main focus is on the redundant systems, however, its electronic schematics are not open-source until the writing of this article. The Mikrokopter flight controllers v2.5 and v3.0 are shown in figure 12.



(a) (b)

Fig. 12. Mikrokopeter flight controllers: (a) v2.5 (b) v3.0

3) MatrixPilot: It was for a fixed-wing UAV controlled by the UAV Development Board v3 from Sparkfun that has the 16-Bit Digital Signal Controller dsPIC30F4011 from Microchip (see Fig. 13). The board is retired, but the schematics are available under the Creative Commons Attribution Share-Alike 3.0 (CC BY-SA 3.0) license. The software is available in [22].

IV. Open-Source Software Platforms

This section explores different OSS platforms and summarizes their features in Table II. OSS platform means that the source code of computer applications is made available with a license. The license gives the copyright holder the rights to study, change, and distribute the software to anyone and for any purpose [23].

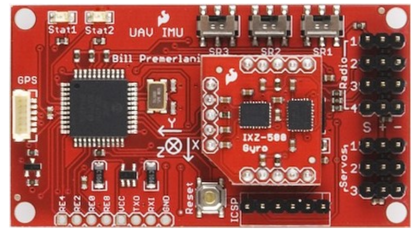


Fig. 13. UAV Development board v3 from Sparkfun used by the MatrixPilot.

A. ArduPilot

It is widely used, full-featured and reliable autopilot software. It is capable of controlling any vehicle system imaginable, from conventional airplanes, multirotors, and helicopters, to boats and even submarines [24]. The software was originally developed for 8-bit ARM-based MCUs to run on its own board *ArduPilot* that was replaced by ArduPilot Mega (APM) (see Section III-C1) and has evolved to be optimized for use with 32-bit ARM-based MCUs. However, it can run under Linux, opening up whole new classes of electronics like Single Board Computers, all the way up to a full PC system. The software of the project is available under the GPLv3 license.

B. Multiwii

It is a flight control software developed for Arduino platforms and based on sensors from Nintendo Wii, but it can be ported to other sensors and platforms [25][26]. It supports from two to eight propellers (e.g., a Tricopter, a Quadcopter or a Hexacopter). The source code is released under the GPLv3 license.

C. AutoQuad

AutoQuad is a project developing ESC based on open-source hardware and flight controllers based on open-source software [20]. The flight controller has been developed through product generations for more than 6 years[27]. The firmware is written for the STM32F4 series MCU with a CORTEX M4 processor and Floating Point Unit (FPU). It supports up to 14 BLDCs and is compatible with QGroundControl. The source code is released under the GPLv3 license.

D. LibrePilot

It starts in July 2015 and focuses on research and development of software and hardware to be used in a variety of applications including vehicle control and stabilization, unmanned autonomous vehicles and robotics [28]. The project was built on the top of OpenPilot project (see Section IV-F2). It runs on various ARM-based closed-source flight controller boards.

The software of the project is available under the GPLv3 license.

E. Dronecode Community

It is a none profit organization governed by The Linux Foundation where the goal is to develop cheaper, reliable and better software [29]. A lot of partners are involved and

TABLE I
COMPARISON BETWEEN OPEN-SOURCE FLIGHT CONTROLLER HARDWARE PLATFORMS.

Platform	Processor	Sensors	Interfaces	Power Consumption (watt)	Dimensions (mm)	Weight (g)	URL
Phenix	Xilinx Zynq SoC (ARM Cortex-A9)	HUB, IMU, GPS, LED	CAN, HDMI, Camera Link, LVDS, BT1120-PL	2.6	73.8 * 55.8 * 18	64	www.robsense.com
OcPoC	"Cyclone V" / "Xilinx Zynq" FPGA SoC (ARM Cortex-A9)	IMU, Barometer, GPS, Bluetooth, WiFi	PWM, I2C, CAN, Ethernet, SPI, JTAG, UART, OTG	4	42(D) * 20(T)	70	www.raerotenna.com
PIXHAWK/ PX4	ARM Cortex-M4F	IMU, Barometer, LED	PWM, UART, SPI, I2C, CAN, ADC	$\approx$ 1.6	81.5 * 50 * 15.5	38	www.pixhawk.org
PIXHWEK2	STM32F427	IMU, Barometer, LED	PWM, UART, SPI, I2C, CAN, ADC	-	Cube: 35*35	-	www.proficnc.com
Paparazzi (Chimera)	STM32F767	IMU, Barometer	XBEE, PWM, UART, SPI, I2C, CAN, AUX	-	89 * 60 * -	-	www.paparazziuav.org
CC3D	STM32F	gyro, accelerometer	SBus, I2C, Serial	-	36 * 36 * -	8	http://opwiki.readthedocs.io/en/latest/user_manual/cc3d/
Atom	STM32F	gyro, accelerometer	SBus, I2C, Serial	-	15 * 7 * -	4	http://opwiki.readthedocs.io/en/latest/user_manual/cc3d/
APM 2.8	ATMEGA2560	IMU, Barometer, LED	UART, I2C, ADC	-	70.5*45*13.5	31	www.ardupilot.co.uk
FlyMaple	STM32	IMU, Barometer	PWM, UART, I2C	-	50x50x12	15	www.emlid.com
Erle-Brain: PXFmini	Raspberry Pi shield	IMU, Barometer	PWM, UART, I2C, ADC	-	31*73	15	www.erlerobotics.com

D: Diameter, T: Thickness.

TABLE II
COMPARISON BETWEEN OSS FLIGHT CONTROLLER PLATFORMS.

Platform	Running Processor	Programming language	Website	Source Code Link
ArduPilot	32-bit ARM	C++	www.ardupilot.org	www.github.com/ArduPilot
MultiWii	8-bit ATmega328	C	www.multiwii.org	https://code.google.com/p/multiwii/
AutoQuad	32-bit ARM	C	www.autoquad.org	www.github.com/mpaperno/aq_flight_control
LibraPilot	32-bit ARM	C++	www.librepilot.org	www.bitbucket.org/librepilot & www.github.com/librepilot

the open-source code base includes communication, hardware, software, and simulation. More than 1200 developers are working on code for this project and it has already been applied in many commercial and open-source products. The community provides software for OSH PIXHAEK, FlyMaple, Erle Brain 2, etc. (for more details, see Section III). The software is available in [29].

F. No longer active OSS projects

This section shows the stopped open-source software projects that one can avoid searching for.

1) JAviator: It was a research project of the Computational Systems Group at the Department of Computer Sciences of the University of Salzburg, Austria [30]. The project was running from 2006 to 2013. The goal of the project was to develop high-level real-time and concurrent programming abstractions and test them on UAV. The project delivered three layers of software; JAviator Plant (JAP), Flight Control System (FCS), and Ground Control System (GCS). The FCS software is written in C, runs on Robostix-Gumstix stack that contains ATmega128 processor, and implements the flight control algorithms. The source code is available in [31].

2) OpenPilot: It was an open-software UAV project for model aircraft aimed at supporting both multi-rotor and fixed-wing aircrafts. It stopped in 2015 and reshaped again as the roots of LibrePilot (see section IV-D).

V. CONCLUSIONS

This paper has presented UAV basics and reviewed more than 15 different open-source hardware and software flight control platforms that can be used for academic research. The paper has explored the processing capabilities, sensor composition, interfaces, and compares the different features of the open-source UAV platforms. In addition, the paper has highlighted the stopped open-source UAV platforms.

Acknowledgment

The research leading to these results has received funding from *Free the Drone (FreeD)* project (www.sdu.dk/freed) that is funded by Innovationsfonden Denmark (https://innovationsfonden.dk).

References

[1] Statistics MRC., "UAV Drones - Global Market Outlook (2016-2022) ," 2016.

[2] PwC, "Clarity from above: PwC global report on the commercial applications of drone technology." [Online]. Available: http://preview.thenewsmarket.com/Previews/PWC/DocumentAssets/433056.pdf

[3] C. Nam and S. Danielson, "Development of a Small UAV with real-time video surveillance," in *American Society for Engineering Education*. American Society for Engineering Education, 2011.

[4] H. Chao, Y. Cao, and Y. Chen, "Autopilots for small unmanned aerial vehicles: A survey," *International Journal of Control, Automation and Systems*, vol. 8, no. 1, pp. 36–44, 2010. [Online]. Available: http://dx.doi.org/10.1007/s12555-010-0105-z

[5] J. Mészarós, "Aerial surveying UAV based on open-source hardware and software," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 37, p. 1, 2011.

[6] H. Lim, J. Park, D. Lee, and H. J. Kim, "Build your own quadrotor: Open-source projects on unmanned aerial vehicles," *IEEE Robotics & Automation Magazine*, vol. 19, no. 3, pp. 33–45, 2012.

[7] S. Sabikan and S. W. Nawawi, "Akademia Baru Open-Source Project (OSPs) Platform for Outdoor Quadcopter ," *Akademia Baru*, vol. 24, no. 1, pp. 13–27, 2016.

[8] X. Chengqi, Q. Cen, and Z. Yan, "Design and research of human-computer interaction interface in autopilot system of aircrafts," in *2009 IEEE 10th International Conference on Computer-Aided Industrial Design Conceptual Design*, Nov 2009, pp. 1498–1501.

[9] Z. Yang, F. Lin, and B. M. Chen, "Survey of autopilot for multi-rotor unmanned aerial vehicles," in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Oct 2016, pp. 6122–6127.

[10] D. L. Gabriel, J. Meyer, and F. du Plessis, "Brushless DC motor characterisation and selection for a fixed wing UAV," in *AFRICON, 2011*, Sept 2011, pp. 1–6.

[11] Festo, "SmartBird." [Online]. Available: https://www.festo.com/smartbird_en

[12] Clear Flight Solutions, "Robirds." [Online]. Available: https://clearflightsolutions.com/methods/robirds

[13] P. D. Groves, *Principles of GNSS, inertial, and multisensor integrated navigation systems*. Artech house, 2013.

[14] D. Perez, I. Maza, F. Caballero, D. Scarlatti, E. Casado, and A. Ollero, "A Ground Control Station for a Multi-UAV Surveillance System," *Journal of Intelligent & Robotic Systems*, vol. 69, no. 1, pp. 119–130, 2013. [Online]. Available: http://dx.doi.org/10.1007/s10846-012-9759-5

[15] L. Meier, P. Tanskanen, F. Fraundorfer, and M. Pollefeys, "Pixhawk: A system for autonomous flight using onboard computer vision," in *Robotics and automation (ICRA), 2011 IEEE international conference on*. IEEE, 2011, pp. 2992–2997.

[16] Free Software Foundation, "GNU Operating System," https://gnu.org/philosophy/free-hardware-designs.en.html.

[17] L. Meier, P. Tanskanen, L. Heng, G. H. Lee, F. Fraundorfer, and M. Pollefeys, "PIXHAWK: A micro aerial vehicle design for autonomous flight using onboard computer vision," *Autonomous Robots*, vol. 33, no. 1, pp. 21–39, 2012.

[18] P. Brisset, A. Drouin, M. Gorraz, P.-S. Huard, and J. Tyler, "The paparazzi solution," in *MAV 2006, 2nd US-European Competition and Workshop on Micro Air Vehicles*, 2006.

[19] E. Baskaya, G. Manfredi, M. Bronz, and D. Delahaye, "Flexible open architecture for UASs integration into the airspace: Paparazzi autopilot system," in *2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*, Sept 2016, pp. 1–7.

[20] AutoQuad, "AutoQuad code base." [Online]. Available: https://github.com/mpaperno/aq_flight_control

[21] HiSystems GmbH , "MikroKopter." [Online]. Available: http://wiki.mikrokopter.de/en/FlightCtrl

[22] MatrixPilot , "MatrixPilot: An OpenSource Autopilot ." [Online]. Available: www.github.com/MatrixPilot

[23] A. M. S. Laurent, *Understanding Open Source and Free Software Licensing*. O'Reilly Media, Inc., 2004.

[24] ArduPilot Dev Team, "ArduPilot," http://ardupilot.org/about/.

[25] MultiWii, "MultiWii flight controller source code." [Online]. Available: https://code.google.com/archive/p/multiwii/

[26] ——, "MultiWii web page." [Online]. Available: http://www.multiwii.com/

[27] AutoQuad, "AutoQuad homepage." [Online]. Available: http://autoquad.org/

[28] LibrePilot Team, "LibrePilot Project," http://librepilot.org/.

[29] Dronecode, "Dronecode project." [Online]. Available: https://www.dronecode.org/

[30] S. Craciunas, C. Kirsch, H. Röck, and R. Trummer, "The JAviator: A high-payload quadrotor UAV with high-level programming capabilities," in *Proc. of the AIAA Guidance, Navigation, and Control Conference (GNC)*, Honolulu, HI, USA, August 2008.

[31] University of Salzburg, "JAviator Project." [Online]. Available: https://github.com/cksystemsgroup/JAviator/