Lisa-S 2.8g autopilot for GPS-based flight of MAVs

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ABSTRACT

Recent advances in sensor miniaturization have enabled the development of a miniaturized fully functional autopilot. In this article, the open hardware and open software Paparazzi-UAV **L**isa-**S** micro autopilot is presented, weighing only 2.8 grams and measuring 2 by 2 centimeters. It incorporates 2-way telemetry with a ground station, a Spektrum DMS2/DSMX remote control, an IMU (Inertial Measurement Unit), a Magnetometer, a GPS module and a 32-bit 72 MHz processor for stabilization and navigation. As an illustration, the **L**isa-**S** has been mounted on various miniature multi-rotors. Mounting it on a Ladybird quadrotor leads to a 8.5 by 8.5 cm system weighing 27 grams (excluding battery). Flight results are shown of the Ladybird performing autonomous GPS-based navigation missions outdoors.

1 INTRODUCTION

Micro Air Vehicles (MAVs) can serve a wide range of different missions, requiring a certain level of autonomous flight. The core element making this possible is the *autopilot*, which controls the vehicle on the basis of incoming (sensory) information. A crucial capability for many current practical applications, such as land survey or exploration of outdoor environments, is GPS-based flight [1, 2].

While most of the current applications and research involve MAVs of a mass ranging from 500 grams to 1 kg (cf. [3]), there is an increasing focus on much smaller MAVs in the order of tens of grams [4, 5, 6, 7]. While such MAVs have a high potential to be widely used thanks to their small mass and size, they typically lack a functional miniature autopilot with onboard autonomous GPS navigation. An example of a 16 gram MAV that does have this capability is the 'Black Hornet' [8]. This (expensive) MAV is made for military use, and is equipped with a fully integrated closed hardware and closed source autopilot. In order to make significant progress both in science and for civil applications, it is highly desirable to have a low-cost, powerful, and generic miniature autopilot that allows modifications to both hardware and software.

In this technical paper, we present the (currently) smallest open source and open hardware autopilot in the world, which can be used on very small and light-weight MAVs. The autopilot design is based on the open source Paparazzi-UAV [9, 10, 11, 12, 13] autopilot framework.

Paparazzi-UAV has officially supported at least 13 different autopilot hardware designs over the past 10 years. When integrating these autopilot boards as well as other open-source autopilot designs [13, 14] into a UAV, the realization was made that a significant amount of the weight, size and complexity came from the need to attach additional sensors, data links, GPS receivers, remote control links and motor controllers to the main autopilot board. The total system hereby very often became much larger than the autopilot board itself.

With the design and production of the miniature autopilot **L**isa-**S** all those issues were addressed. This fully functional autopilot weighs only 2.8 grams and measures $2 \times 2 \times 0.5$ cm. The design of the **L**isa-**S** autopilot was done in close cooperation between the MAVlab[1] of the TUDelft and 1 Bit Squared[2], commissioned by the MAVlab.

In the remainder of this article, we first describe the **L**isa-**S** main board and its development (Section 2). Subsequently, we delve further into the communication module, the SuperbitRF (Section 3). The use of the **L**isa-**S** is illustrated by means of installing it on nano quad rotors, of which flight test results are shown (Section 4). Finally, we conclude in Section 5.

2 LISA-S

2.1 Hardware description

The **L**isa-**S** autopilot incorporates all sensors and computer power to fly an unstable platform like a multirotor, autonomously towards defined GPS coordinates. Everthing is integrated in a 20 by 20 by 5 millimiter package with a weight of only 2.8 grams. The computation power comes from a 72MHz 32bit ARM Cortex-M3 MCU with 64KB RAM and 512KB Flash. The Inertial Measurement Unit (IMU) sensors consist of an integrated 3-axis Gyroscope and 3-axis Accelerometer sensor from Invensense MPU-6000, the 3-axis magnetometer is the Honeywell HMC5883L and the barometer (altimeter) is the Measurement Specialities MS5611.

For GPS waypoint navigation a U-Blox Max-7Q module is integrated in the design. As a backup power source for the GPS a 0.011 Farad PAS3225P3R3113[3] supercapacitor is used. When swapping the battery of your MAV this capacitor

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[1] http://www.mavlab.lr.tudelft.nl/
[2] http://1bitsquared.com/
[3] Digikey 587-3260-6-ND

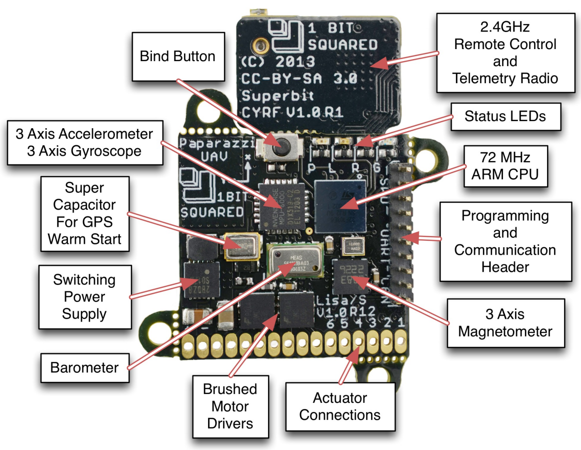

Figure 1: **Lisa-S** V1.0 R12 top: showing processor, IMU sensors, switching voltage regulator, GPS backup power super capacitor and dual MOSFET brushed motor drivers

keeps the U-Blox in backup battery mode for ∼20 minutes and a cold start is avoided when swapping batteries.

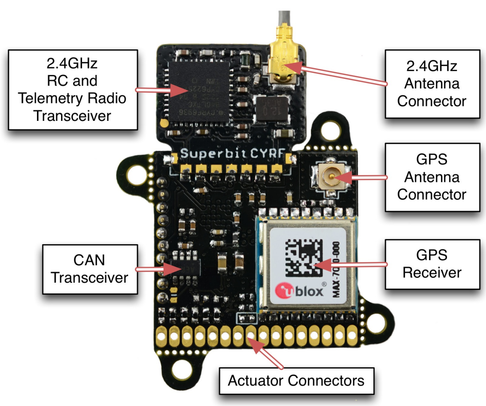

Figure 2: **Lisa-S** V1.0 R12 bottom: showing Ublox GPS module, CAN (Control Area Network) transceiver and Superbit CYRF radio module

To make the **Lisa-S** autopilot versatile and usable on a variety of platforms as for example: multicopters, fixed wing airplanes, helicopters or transitioning VTOL systems as well as ornithopters, great care has been given to the functions of the autopilot hardware. The **Lisa-S** has 6 PWM (servo) outputs. As an extra feature 4 of these can be used to directly drive DC motors thanks to Fairchild Semiconductor FDMC8030 MOSFET switches which are connected to 4 of the 6 PWM output channels. A Superbit CYRF RC and telemetry module can be added by simply soldering it to the respective pads on the autopilot. The autopilot is equipped with a Texas Instruments LM3668SD-3034 switching buck/boost converter, allowing a wide range of input voltages, making it perfect for operation from a 1S LiPO battery. To make the **Lisa-S** a powerful developers and researcher's tool, a UART port, a Maxim MAX3051EKA CAN interface and SWD programming/debugging interface are provided. Finally, the **Lisa-S** has a Bind/Boot tactile switch on the top side of the board. Hardware developments on the **Lisa-S** can be found on the Paparazzi-UAV **Lisa-S** wiki page[4]

2.2 Previous version

The initial design of the **Lisa-S** autopilot was initiated by the MAVlab of the TUDelft to make the Walkera Genius CP V2[5] nano helicopter fly autonomous. This led to the 20 by 20 millimeter size restriction and constrained weight limit. Most of the design is similar to the final version, but there are some differences.

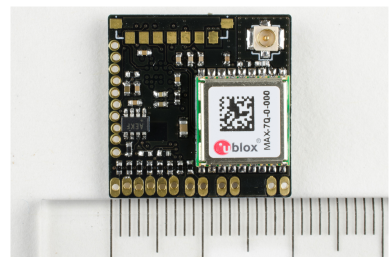

Figure 3: LISA/S V0.1 bottom: showing Ublox GPS module

Because a helicopter has 2 motors, only 2 (instead of 4) of the 6 PWM outputs were equipped with MOSFET DC motor drivers. In the first design, the GPS had no supercapacitor that is now serving as a backup power source while the main battery is being replaced. Every time the **Lisa-S** was powered up the U-Blox GPS module had to reacquire all the satellite information from scratch, resulting in a very lengthy reboot cycle, known as a cold start. The addition of the supercapacitor allows the GPS to reuse information acquired previously to shorten the time significantly from several minutes to seconds.

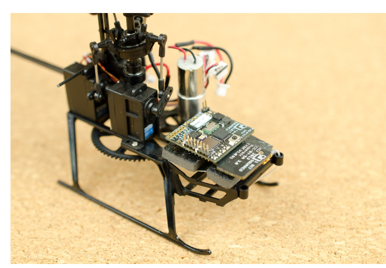

Figure 4: LISA/S V0.1 top mounted on a Walkera Genius CP V2 nano helicopter

No mounting holes were included in the initial design so

[4] http://wiki.paparazziuav.org/wiki/Lisa/S
[5] http://www.walkera.com/en/showgoods.php?id=492

mounting was done with a piece of double sided sticky foam tape. This had the disadvantage that a calibration step was needed before every flight.

3 SUPERBITRF

3.1 Hardware description

The SuperbitRF hardware is comprised of three main parts. The first part is the Superbit CYRF module, mounted on both the autopilot and the USBRF dongle. It is a miniature carrier board of 0.6 grams for the Cypress Semiconductor CYRF6936 2.4GHz radio transceiver chip[6]. To save weight it has no dedicated MCU, but instead it uses the 72MHz 32bit ARM Cortex-M3 MCU of the autopilot to implement the SuperbitRF protocol. During the design process the SuperbitRF module was designed as a separate part, with the intention of extending the capabilities of the communication module in the future. Eg.: adding an amplifier for extended range or changing the transceiver of a higher throughput radio transceiver supporting an integrated video stream.

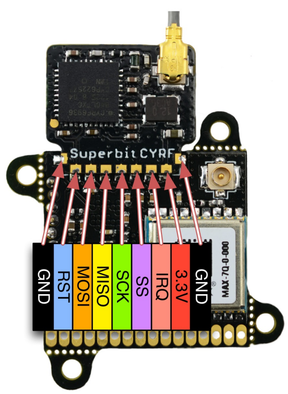

Figure 5: **L**isa-**S** with Superbit CYRF module

The second part is the SuperbitRF USBRF dongle, designed for the ground control station computer. It consists of a USB enabled 72MHz 32bit ARM Cortex-M3 MCU connected to the previously described SuperbitRF module. The SuperbitRF protocol and USB stacks are implemented on the ARM microcontroller, and it even supports other protocols.

The third part is a standard off-the-shelf Spektrum handheld RC transmitter, transmitting DSM2 or DSMX protocols. This transmitter is used for flying the MAV manually and to take over control if required for safety.

3.2 Protocol

The main focus of the SuperbitRF is maintaining a stable RC connection with an original Spektrum[7] transmitter, while adding the support of a datalink connection with the USBRF

[6] http://www.cypress.com/?docID=48819
[7] http://www.spektrumrc.com/

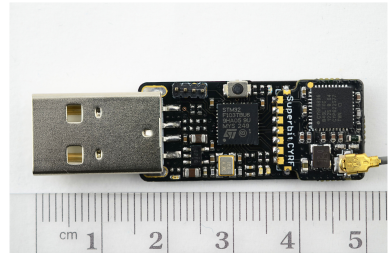

Figure 6: Superbit USBRF dongle

dongle. This is done by extending the Spektrum DSM2 and DSMX protocols[15] and thereby creating the new SuperbitRF protocol.

Reverse engineering and the work of Deviation[8] enabled a full understanding of the DSM2 and DSMX protocols. The original Spektrum RC protocol works by transmitting a maximum of 7 RC channels every 22 or 11 milliseconds on a certain RF channel in the 2.4GHz frequency band. After transmitting on this first RF channel it transmits the same 7 RC channels for redundancy on another RF channel, called frequency hopping. As a way of dealing with the interference of other Spektrum transmitters, the original protocol uses several tricks, one of which is sending two bytes of the transmitter identifier in every RC packet.

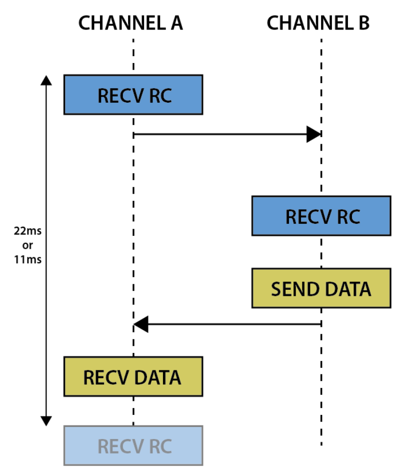

Figure 7: SuperbitRF protocol

After analysing the original Spektrum protocol a possibility was found to extend it with a datalink connection. Various ways of extending the protocol were considered and focused mainly on the 22ms DSM2 transmitters. By focussing mainly on the 22ms DSM2 transmitters the original RF redundancy packet was kept and the datalink was implemented without timing issues. The implementation of the SuperbitRF datalink is done by sending telemetry to the USBRF dongle on the redundancy channel right after the RC packet is re-

[8] http://www.deviationtx.com/

ceived. It then switches to the first channel to receive an uplink packet and another RC packet on the first channel.

By implementing the SuperbitRF extensions protocol as described, a safe RC connection was maintained even without the USBRF dongle for the datalink connection. To prevent the SuperbitRF datalink from interfering with the original RC connection, a different transmitter identifier was used while sending the telemetry and uplink packets.

4 Nano Quads

4.1 Hardware description

To test the performance of the **Lisa-S** autopilot, it is used as a stabilization and navigation computer for unstable MAVs: namely micro quadrotors. The first quadrotor built with the **Lisa-S** V0.1 was the 'Chouchou', which is an 5.7 by 5.7 cm, 26.5 gram (including 260mAh battery) brushless quadrotor. Micro SiLabs MCU based Supermicro 3.5A ESCs are connected to 4 **Lisa-S** PWM outputs. The ESCs are flashed with the open source BLHeli firmware [9] for better performance and the AP01 Micro Brushless 1100KV motors are used to drive the propellers from the Silverlit X-Twin R/C Bi-Wing airplane[10].

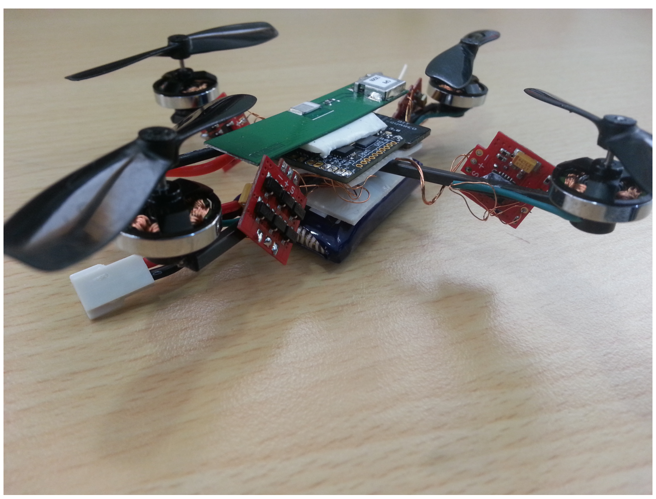

Figure 8: ChouChou 5.7x5.7cm brushless quad with **Lisa-S** and Taoglas PCB GPS antenna

The mounting holes of the **Lisa-S** V1.0 R12 are designed to fit on the 8.5 by 8.5 cm Walkera Ladybird quadrotor[11]. To achieve this, the mounting holes are placed on the side of the **Lisa-S** resulting in a 13 degree rotational offset around the yaw axis. This can be easily adjusted in the Paparazzi-UAV software, by adding a "body to IMU" parameter. The mounting holes are made optional by the addition of "mouse bite" breakoff points, making the tabs containing the mounting holes removable. If necessary the size of the main board can be reduced to the original dimensions of the **Lisa-S** V0.1 board design. To facilitate the conversion of the Ladybird to an autonomous system, an additional PCB (Printed Circuit Board) adapter is designed to fit the original Ladybird motor connectors. The converted RTF autonomous Walkera ladybird weighs 27g without battery. As an example, one can add a 350mAh battery weighing 8 grams, resulting in a weight of 35 grams.

Figure 9: Ladybird 8.5 by 8.5 cm with **Lisa-S** and the Taoglas Ceramic GPS antenna

To achieve good autonomous flight performance a high sensitivity GPS antenna is required. With weight and size limitations in mind, only two candidates were found suitable. The Taoglas 1575 MHz PCB Active Loop Module ALA.01.07.0095A[12] of 1.3 grams and measuring $45 \times 10 \times 2.3$ millimeters. And the Taoglass AP.10F.07.0039B 1575.42MHZ Ceramic Active LNA circuitry[13] of 3 grams and measuring $10 \times 10 \times 5.7$ milimeters.

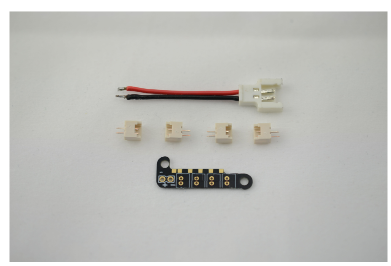

Figure 10: Ladybird conector PCB for **Lisa-S**

4.2 Flight test

Flight testing was performed with the Chouchou and the Ladybird quadrotors. The Chouchou quadrotor was first

[9] http://www.rcgroups.com/forums/showpost.php?p=25972443&postcount=3
[10] http://http://www.silverlit-flyingclub.com/xtwin_classic.htm
[11] http://www.walkera.com/en/showgoods.php?id=467
[12] http://www.taoglas.com/images/product_images/original_images/ALA.01.07.0095A.pdf
[13] http://http://www.taoglas.com/images/product_images/original_images/AP.10E.07.0039B.pdf

tested indoors and flown manually in stabilization mode. Resulting in a stable indoor flight, which proves the Paparazzi-UAV software was running fast enough to stabilize the unstable platform. Despite several outdoor flight attempts with the Chouchou, no successful autonomous GPS supported navigation flights were performed. The source of the issue can be found in the lack of an interference free spot for the Taoglas PCB GPS antenna to be placed on the tiny Chouchou airframe. Future attempts will be made with the Taoglas ceramic GPS antenna.

The Ladybird quadrotor was first flown successfully indoors manually in stabilization mode. Several autonomous GPS supported navigation flights were performed which included takeoff, waypoint flying and landing (figure11). The MAXTENA MIA GPS antenna was fitted on top of the MCU. This location is the spot with the least interference for the GPS, resulting in a position accuracy of less than 3 meters. Figure 11 shows the trajectory of the Ladybird during one of the flights.

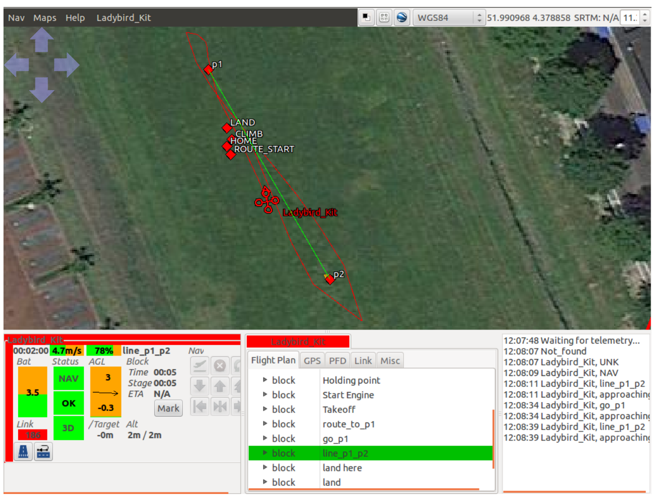

Figure 11: Paparazzi-UAV ground station during an autonomous flight of a **L**isa-**S** equipped Ladybird

4.3 *Lisa-S Technical Specifications*

For full Paparazzi-UAV **L**isa-**S** sytem specifications please refer to Table 1.

5 Conclusion

When it comes to autopilot size, one should not consider just the central processing board but the entire system. A miniature 2 by 2 centimeter autopilot board was developed called **L**isa-**S** which includes all the required components for both manual remotely controlled as well as fully autonomous GPS navigated flight of even unstable vehicles. Datalinks to a ground station, a GPS, remote control and even (brushed) motor controllers are all included in the board which means only 4 motors, a GPS antenna and a frame need to be added to create a nano GPS guided multicopter. Successful GPS navigated flights were performed using the Walkera Ladybird nano quadrotor frame and replacing its electronics with the **L**isa-**S**.

	Specification
Width	20.0 mm
Height	20.0 mm
Weight	2.8 grams
MCU	72MHz 32bit ARM Cortex-M3
RAM	64KB
Flash	512KB
Gyroscope	3 Axis
Accelerometer	3 Axis
Magnetometer	3 Axis
Altimeter	Barometer
GPS	52 channel U-Blox Max-7Q
GPS power Backup	11mF supercapacitor
Power	1S LiPO cell (2.5V-5.5V)
DC motors	4 MOSFET switches
PWM	6 RC servo outputs
UART	1 port
CAN	1 interface
prog./debugging	**S**erial **W**ire **D**ebug interface
LED	4 status LED indicators

Table 1: **L**isa-**S** Specifications.

The open hardware and open software **L**isa-**S** autopilot is hoped to advance the research and development of very lightweight, autonomous MAVs.

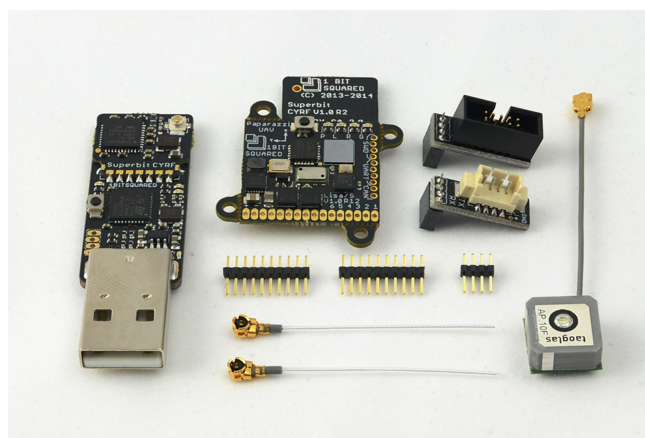

Figure 12: Ladybird starter kit **L**isa-**S**

Acknowledgements

We would like to thank all developers of the open source Paparazzi-UAV project[14] for their support making this a very powerful project.

[14] http://www.paparazziuav.org/

Photos in Figures 1-6, 9, 10 and 12 are credit to 1 Bit Squared[15].

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