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Academic experiences with an 802.15.4 based telemetry system for UAV applications

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Abstract

The Department of Aerospace Sciences and Technologies of Politecnico di Milano has recently launched the Chippy program, aimed to obtain a very low cost unmanned air vehicle platform capable of being used in support of didactic activity in support of the M. Sc. “Flight Testing” course, with the additional capability to serve as an affordable and dependable platform for research activities. Starting from the unique requirements in terms of weight, power consumption and cost originated by the particular characteristics of a 650g maximum takeoff mass, battery-operated, academy supported unmanned air vehicle, Chippy's telemetry system has been designed and implemented using IEEE 802.15.4 wireless protocol, which has shown to be capable to fulfil pretty well most of the requirements and constraints. Details are given on the integration of the system with the air platform, as well as on the concurrent development of the complementary ground station. Finally, results of the on-field testing and evaluation campaign are presented and commented.

Key words: TELEMETRY, UAV, IEEE 802.15.4, ZIGBEE, FLIGHT TEST

Background

Flight testing has had a key role in aeronautics from its very origin, but, in spite of its importance, “flight testing” as an engineering discipline is rarely considered as “the” subject of a dedicated graduate course, whereas normally flight testing theory is split among several of the more classical academic courses such as flight mechanics, flight dynamics and control, experimental techniques for aerospace, and similar. However, a comprehensive, one-stop shop course aimed to expose a graduate student in aeronautical engineering to the different facets of flight testing discipline would be extremely fruitful from a didactic point of view, to check the students understanding of the aircraft as a complex machine system of systems, let them integrate, synthesize and verify a vast multidisciplinary knowledge base acquired along their undergraduate and postgraduate curricula and let them learn how to operate in compliance with applicable regulations and procedures in a typical aeronautical working environment The above considerations were the main motivation for the Department of Aerospace Science and Technology (DAST) of the Politecnico di Milano to offer its students enrolled in the Master degree in aeronautical engineering a unique, dedicated “Flight Testing” course, conceived from the very beginning to addressing this discipline as closely as possible as it is currently implemented and operated in the aeronautical industry by means of a tight collaboration with renowned experts.

Given the concurrent availability of a department owned and operated Ultra Light Machine (ULM) aircraft, a Tecnam P 92 acquired in 1998 mainly for permitting aerospace engineering students to enjoy familiarization to flight missions, and of an in-house designed and developed ULM-dedicated Flight Test Instrumentation (FTI) system [1], it became natural to offer “Flight Testing” students an extremely valuable and unique opportunity. As part of their practical assignment for the exam, in fact, students attending the course are assigned the planning, briefing, actual in-flight execution, de-briefing and data processing of a real flight test mission, acting as the responsible Flight Test Engineer (FTE) on board under all respects. The flight test report that they eventually produce serves as the starting point for the final oral examination [2]. Up to the present time approximately one hundred “Flight Testing” students has lived, and enjoyed, their FTE experience in the annually organized student flight test campaign.

In order to better prepare students for their flown FTE mission, which constitutes the core of their practical part of the course, it has been considered that a preliminary, introductory hands-on flight test experience with an Unmanned Air Vehicle (UAV) could turn out to be very beneficial, provided it could be realised within the modest budget available. It has therefore been started the Chippy program, aimed to design and realize a very low cost UAV system properly equipped for performing basic flight test missions and acquire (sending it to a companion Ground Station in real time) the appropriate set of parameters to be used in support of the didactic activity within the "Flight Testing" course.

Chippy

Chippy has been greatly influenced by its academic origin, particularly in terms of low cost and ease of use. Entirely designed with open source tools (AVL [3] release 3.31 and XFOIL [4] release 6.97, both by Mark Drela), it is a 1200mm wide flying wing tailless aircraft with two control surfaces spanning the entire aperture of the trailing edges, entirely cut out from polyurethane foam reinforced with a balsa wood central spar and a balsa wood leading edge. Disposable solid polyurethane foam winglets are attached at wingtips by double-sided tape. A central rectangular bay reinforced with balsa wood accommodates avionics and a 2 cell Lithium-ion Polymer 7.4V, 1600 mAh rechargeable battery. A Lipotech 250W in-runner brushless DC motor driving a Graupner 4.7 x 4.7 pusher propeller is installed in the aft part of such bay, mounted on a plywood frame. Figure 1 shows the resulting AVL aerodynamic mesh.

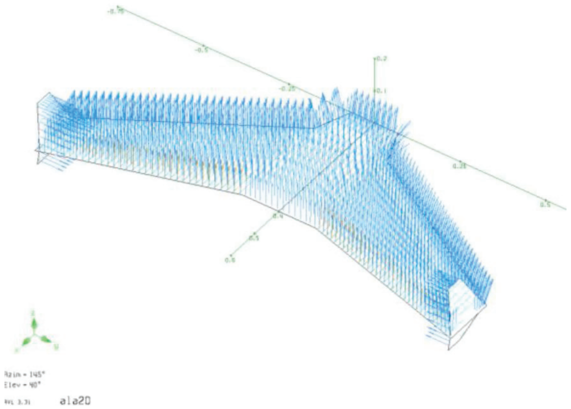


Fig. 1. Chippy AVL aerodynamic mesh.

The tremendous recent advance in the semiconductor industry, and particularly the capability of producing high-performance Micro Electro Mechanical System (MEMS) devices, has enabled Chippy to embark a wide variety of sensor with a very modest penalty in terms of volume and mass. The Global Positioning System (GPS) receiver is a uBlox NEO 6M based board coupled to an active patch antenna, providing a 4 Hz solution rate. Body-axis acceleration components and angular rates are acquired by InvenSense MPU6050, a device that combines a 3-axis gyroscope and a 3-axis accelerometer on the same silicon die together with an on-board digital motion processor providing measures at 50 Hz. A Honeywell HMC5883L, anisotropic magneto-resistive 3-axis digital compass is cast inside Chippy's left wing, where earth magnetic field is barely perturbed by the on-board magnetic masses and fields, and sampled at a rate of 50 Hz. Engine case temperature is measured with Texas Instrument LMT90 self-calibrated precision temperature sensor, and acquired at 10 Hz by the internal analog to digital converter of the Main Processing Unit (MPU), as is the motor current, sensed by Allegro Microsystems ACS712, Hall effect-based linear current sensor integrated circuit. Bosch BMP085 piezo-resistive absolute pressure sensor and SensorTecnics HCLA 0050 miniature amplified low differential pressure sensor, coupled to a thin Pitot tube, deliver 20 Hz air data measurements. Finally, Angle of Attack (AOA) is sensed with a vane and measured every 100 ms by a magnetic contactless rotary encoder, Austria Micro Systems AS5048B.

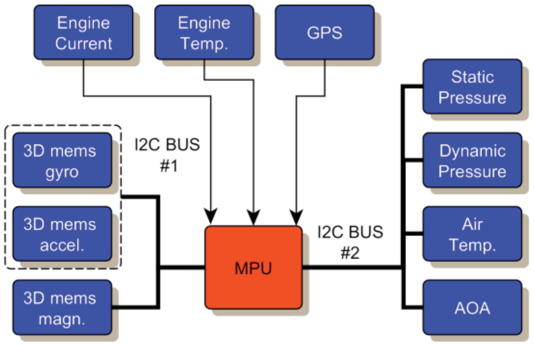


Fig. 2. Chippy sensor and avionic diagram.

The on board MPU is based on a 32 bit Cortex M4 core STM32F407 microcontroller by ST microelectronics running at 168 Mhz. It is worth to be noted that it incorporates a single precision hardware floating point unit, a particularly important feature, since it permits the fast and precise execution of the math-intensive algorithms implemented in Chippy's firmware. Data is logged onto a Secure Digital flash memory card directly managed form the MPU. Figure 2 illustrates Chippy's sensors and avionic block diagram, while Table 1 lists all acquired parameters with their sampling rate.

Tab. 1: Acquired parameters

Parameter	Rate (Hz)
GPS position	4
GPS velocity	4
GPS Time reference	4
Body-axis acceleration	50
Body-axis angular rate	50
Body-axis magnetic field	50
Static Pressure	20
Dynamic Pressure	20
Angle Of Attack	10
Outside Air Temperature	10
Pilot controls position	10
Servo actuators position	10
Engine current	10
Engine case temperature	10
Battery voltage	10
Override Switch	10
Test Point ID	10
Test Point control Switch	10

MPU firmware has been entirely developed using an open source tool-chain: Eclipse integrated development environment [5], ChibiOS/RT Real Time Operating System (RTOS) by Giovanni di Sirio [6], gcc compiler for ARM, as featured in YAGARTO Tools [7], and gdb in combination with OpenOCD providing debugging capabilities [8].

The main functions performed by the MPU are:

- Acquisition of parameters from the various sensors
- Real time computation of the different derived parameters needed for the mission
- Interfacing with flight controls
- Automatic Flight Control System (AFCS)
- Telemetry management
- Data logging
- Electronic Flight Test System (EFTS) management

The latter is quite an innovative capability, since it enables students to plan a mission, generate the relevant electronic flight card file and load it on the on board secure digital memory, have Chippy fly the mission following its progress in real time on the GS and finally process acquired data and produce a report, all with the negligible risks and the very moderate resources required to fly a 650g Maximum Take Off Mass (MTOM) machine [9] .It is worth to be empathised that, for safety reasons, Chippy is constantly controlled by a Pilot On Ground (POG), via a dedicated “traditional” Radio Control (RC) model transmitter and receiver pair.

Telemetry requirements

Chippy operating requirements asked for a telemetry link with the GS in order to:

- download acquired parameters in real time in order to permit the students to follow the progress of the test mission
- interact with the on-board systems

Additionally, a number of requirements and constraints came from the particular operating environment, namely:

- Line-of-sight operation, since regulations on UAV dictate that the POG should always have eye contact with the air vehicle
- Practical range below 1 km
- Low mass, small size, low power consumption

Finally, for a different UAV program being started at DAST aimed to realise a fleet of UAV and experiment fully autonomous formation flight, the capability to start experimenting an efficient point-to-multipoint link was considered desirable. Needless to say, the budget available telemetry system was very modest.

At the end of a survey on the commercial solutions available on the market only IEEE 802.11.x and IEEE 802.15.4 were judged as a viable solution-because of a previous unsatisfactory experience with a point-to-multipoint network. Bluetooth was not considered. The two candidate solutions were then compared on a number of performance indicators, as shown in Table 2. Eventually the decision was taken in favor of IEEE 802.15.4, mainly for the additional advantages in terms of weight deriving from a simpler integration with the rest of the on board systems.

Tab. 2: IEEE 802.11.x vs IEEE 802.15.4

	IEEE 802.11.x	IEEE 802.15.4
Mass	Low	Very low
Power consumption	Low	Very low
Interface	Ethernet	Serial
Integration effort	Medium	Very low
Bandwidth	Very high	Medium
Network size	Medium	Big
Risk of interference	High	Low

IEEE 802.15.4

The IEEE 802.15.4 standard provides the specifications of the Physical layer (PHY) and Media Access Control sub-layer (MAC) for a Low-Rate Wireless Personal Area Network (LR-WPAN). The PHY is responsible for managing the interface to the physical transmission medium (radio in our case), exchanging data bits with this medium, as well as exchanging data bits with the layer above (the MAC sub-layer). This one provides addressing and channel access control mechanisms. The MAC sub-layer together with the higher Logical Link Control (LLC) sub-layer are collectively referred to as the Data Link layer. The LLC is common to all IEEE 802 standards but can be ignored when dealing with IEEE 802.15.4 based applications.

The IEEE 802.15.4 standard was developed to meet the following requirements [10]:

- very low network complexity;
- ultra low power consumption;
- low data rate;
- use of unlicensed radio bands;
- low cost and easy installation.

Thus a LR-WPAN in IEEE 802.15.4 standard can be used for low-rate, low-power and low-cost applications: ambient and habitat monitoring, industrial control and monitoring, home automation, location aware services (for example assets/vehicles tracking), healthcare applications, toys and games.

Three possible unlicensed frequency bands are defined: 868 MHz band, 915 MHz band and 2.4 GHz band. The first band is used in Europe, allowing just one communication channel (868.0-868.6 MHz). The second band is used in North America, allowing up to ten channels (902-928 MHz). The 2.4 GHz band is used worldwide, providing 16 radio channels for unlicensed operations. The 868 and 915 MHz frequency bands offer certain advantages such as fewer users, less interference, and less absorption and reflection, but the 2.4 GHz band is more widely adopted for a number of reasons:

- worldwide availability for unlicensed use; 2.4 GHz band is also more commonly understood and accepted by the marketplace (also used by Bluetooth and the IEEE 802.11 standard);
- higher data rate (250 kbits/s) and more channels;
- lower power consumption (transmitter is on for a shorter time due to higher data rate).

In the standard two types of network nodes are defined: Full-Function Device (FFD) and Reduced-Function Device (RFD). A FFD can either act as a coordinator or as a normal device. There can be different Local Coordinators but only one FFD node can act as the network controller, known as the PAN Coordinator. Whereas, the RFDs cannot act as coordinators and they can only be connected to one FFD at a time. RFDs are merely used for very simple applications that require minimum capabilities. The LR-WPAN nodes can be arranged into 3 network topologies: Star (every node can communicate only with the PAN Coordinator), Cluster-tree (each node, except the PAN Coordinator, has a parent, may also have one or more children and can only communicate only with its parent and its children-if any), and Mesh (all devices are identical (except the PAN Coordinator) and can communicate directly with another node inside the network). For all the cited topologies if distance is greater than the radio range, a message can be passed from one node to another until it reaches its final destination (multi-hop communication). Among the various power management strategies adopted, modulation schemes (BPSK for 868/915 MHz, O-QPSK for 2.4 GHz) deliver minimized power consumption.

Chippy’s telemetry subsystem

Telemetry hardware, both on board and on the ground, is built around Texas Instruments cc2530 [11], a very integrated system-on-chip solution for IEEE 802.15.4 applications. The silicon device includes an RF transceiver and a microcontroller. The former operates in the 2.4 GHz band, with programmable output power up to 4.5 dBm and an excellent receiver sensitivity of -97 dBm. The latter is an industry-standard enhanced 8051, with of 256 KB of flash and 8-KB RAM, and for the present application runs the standard version of the Zigbee stack. The total mass of each node is limited to less than 10 g. Chippy's telemetry subsystem provides communication with the rest of the systems via a serial line, and for that purpose the particular settings of the Zigbee stack guarantee that user payloads of data up to 32 bytes long are transported into a single packet and delivered at the other node atomically.

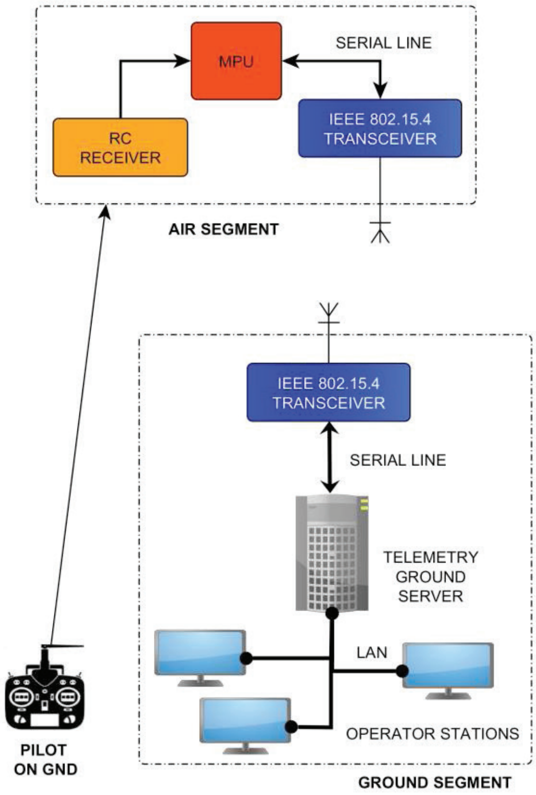


Fig. 3. Telemetry system architecture.

Figure 3 illustrates Chippy's telemetry system architecture. Data acquired on board is pre-formatted by the on-board MPU in 32 byte long telegrams, before being transferred to the telemetry subsystem via one of the Universal Asynchronous Receiver Transmitter (UART) available to be sent over the RF link at 250 kbit/s. With the present mix of parameters a total of 28 telegrams are sent over the telemetry link every second. Once it arrives to the ground telemetry data is managed by a Ground Station (GS) server process that applies a high level integrity and consistency check, saves all incoming data and formats it into a stream of User Datagram Protocol (UDP) packets that are immediately broadcast on a dedicated local area network. One or multiple ground operator stations can retrieve the particular data they need from such network and show it to the operator. A fully featured graphical ground station monitoring software has been developed using the Qt framework, as it can be seen in Figure 4.

Test Campaign

Started in September 2013, Chippy reached its initial operational capability in March 2014, when development was frozen and a thorough validation flights campaign was planned and executed. From early April through the first week of May 2014 a total of 24 flights were flown in 15 operation days. The experimental test range was an open air 100 m x 100 m field. Maximum speed reached was 35 m/s, with frequent high g (> 3) manoeuvers. The highest elevation from ground was in the order of 100 m above ground level. The GS antenna used was a 0 dB gain omni-directional rubber duck. Since the Zigbee chip used didn't give any run-time access to the link related parameters (i.e. received signal strength indication, statistics on retransmitted packets, etc.) in order to evaluate the quality and availability of the link it has been decided to include in every packet sent from the air platform to the ground a counter (i.e. packet sequence number) incremented at every transmission, and to check the logged received data for possible gaps in the sequence.

The results have been very satisfying: for the whole validation flights campaign the average packet loss rate has been below 0.5%. A detailed analysis on the outages revealed that in most of the cases the probable cause was somehow related to propagation issues, mainly due to the temporary unusual attitude of the air vehicle combined with poor geometry (air vehicle flying directly over the GS antenna).

Conclusions and future developments

The IEEE 802.15.4 based telemetry subsystem implemented on the Department UAV has demonstrated to fulfil the original requirements. Throughout the validation flights packet loss rate was limited to acceptable figures. Even the ground operator subjective perception looking at the telemetry screen gives a pleasant sensation of smoothness.

Future developments will start concentrating on fine tuning the many adjustable parameters of the Zigbee stack in order to further improve performance, both in terms of net available bandwidth and in terms of low latency, maybe following suggestions deriving from [12] [13]. In addition, provisions to monitor in real time intensity and quality of the link will be added.

In parallel it will be started the assessment of the performance of an extended point-to-multipoint link, with one GS and two air vehicles, in order to evaluate any degradation in terms of latency and net throughput.

Given the satisfactory performance in terms of link availability, one ambitious future development would be to remove the RC command chain and convey pilot on ground commands through the upstream telemetry link. This would provide important savings in the 800 € estimated whole system cost (the RC taking roughly half of it) and in the on-board weight, but needs trustworthy maximum latency bound in order to be efficiently implemented.

References

[1] A. Rolando, “Development of an integrated flight test instrumentation system for ultra light machines”, PhD dissertation, Department of Aerospace Engineering, Politecnico di Milano, Milano, 2008

[2] L.Trainelli, A. Rolando, G. Bonaita, P. Chimetto “Experiences in Academic Flight Testing Education”, Aircraft Engineering and Aerospace Technology, Vol. 86, N. 1, 2014, pp 56-66

[3] http://web.mit.edu/drela/Public/web/avl, date of visit May 6th 2014

[4] http://web.mit.edu/drela/Public/web/xfoil, date of visit May 6th 2014

[5] http://www.eclipse.org, date of visit: May 13th 2014

[6] http://www.chibios.org/dokuwiki/doku.php, date of visit: May 13th 2014

[7] http://www.yagarto.org, date of visit: May 13th 2014

[8] http://openocd.sourceforge.net, date of visit: May 13th 2014

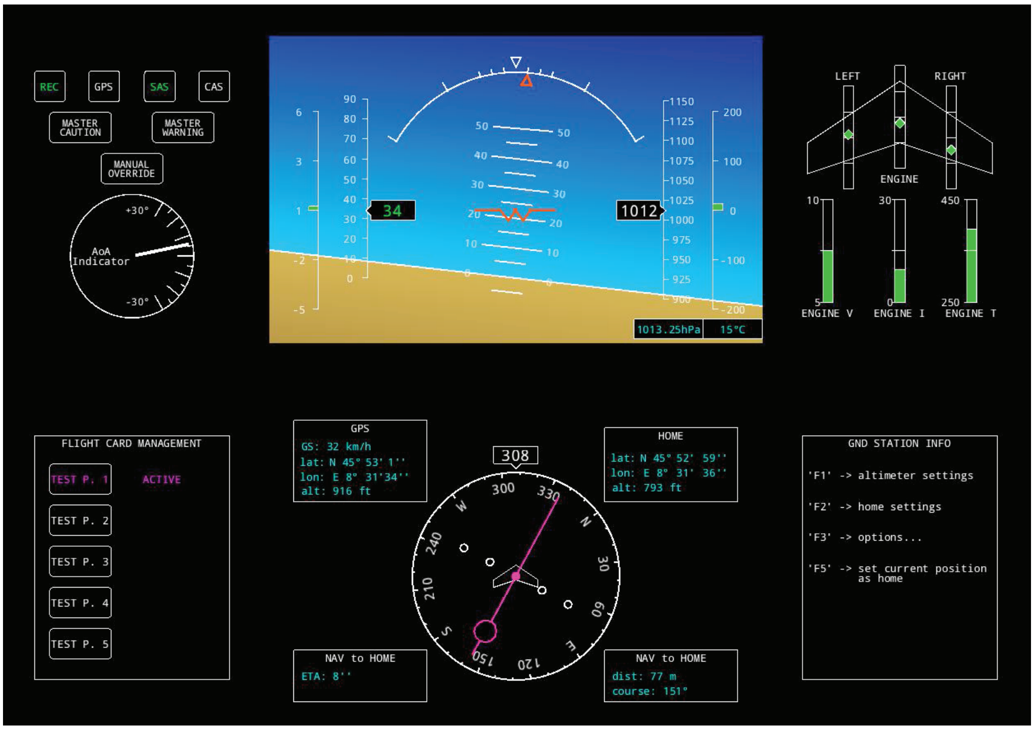
[9] A. Rolando, C. Cardani and F. Rossi, “A very low cost UAV platform for education in flight testing”, to be presented at the European 46th SETP and 25th SFTE Symposium, 15-18 June 2014, Luleå, Sweden

[10] 802.15.4-2011 - IEEE Standard for Local and metropolitan area networks - Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs), (Revision of IEEE Std 802.15.4-2006), 5 September 20

[11] http://www.ti.com/product/cc2530, date of visit May 26th 2014

[12] B. Latré, P. De Mil, I. Moerman, N. Van Dierdonck, B. Dhoedt and P. Demeester, “Maximum Throughput and Minimum Delay in IEEE 802.15.4”, Proceedings of the International Conference on Mobile Ad-hoc and Sensor Network (MSN’05), LNCS 3794, Wuhan, China, December, 2005, pp. 866-876

[13] B. Latré, P. De Mil, I. Moerman, B. Dhoedt, P. Demeester and N. Van Dierdonck. "Throughput and Delay Analysis of Unslotted IEEE 802.15.4.", Journal of Networks [Online], 1.1 (2006) 20-28, date of visit May 29th 20



1013.25hPa 15°C

GPS
GS: 32 km/h
lat: N 45° 53' 1''
lon: E 8° 31'34''
alt: 916 ft

HOME
lat: N 45° 52' 59''
lon: E 8° 31' 36''
alt: 793 ft

NAV to HOME
ETA: 8''

NAV to HOME
dist: 77 m
course: 151°

GND STATION INFO
'F1' -> altimeter settings
'F2' -> home settings
'F3' -> options...
'F5' -> set current position as home

Fig. 4. Ground Station screen capture.