LIGHT FTI SYSTEM – THE FIRST TRULY LIGHT WIRELESS SYSTEM FOR FLIGHT TEST INSTRUMENTATION

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ABSTRACT

Although wireless instrumentation systems are available for rotating applications, they do not satisfy the real cost, weight and cycles requirements of Flight Test organizations. On the other hand, low weight and low intrusiveness instrumentation equipment are available for industrial measurement e.g. in the frame of Industry 4.0, but those do not cover the measurement requirement for FTI applications, like bandwidth.

The Light FTI System is a common development of the Airbus Group. It is a highly innovative MEMS sensor network system based on BLE / UWB wireless technology, which is the first to tick all the boxes of the requirements of FT organizations regarding low weight, low cycle installation, low intrusiveness, high operational autonomy, high operational wireless range, and high bandwidth measurement. Its development has been led in a cooperative manner between the business units of the Airbus Group over several continents. This paper will present the technical challenges of the system as well as the organizational challenges of the development. It will describe the outstanding technical results of the first truly light FTI system, which the FTI community has always been dreaming of.

Keywords: FTI, wireless, MEMS, UWB, BLE, I3C, PTP

REQUIREMENTS FOR LIGHT FTI

Flight Test Instrumentation systems are used on all aerospace platforms during development and certification testing. Size and weight of the system depend on external criteria as e.g. the number of analogue parameters or the specificity of the measurement like on rotating parts. The sensing technologies and the measurement electronics used nowadays have undergone some evolutions during the last decades, enabling the higher integration of electronics as well as the distribution of Ethernet based acquisition, reducing consequently the weight of the FTI systems. Nevertheless, these evolutions have recently reached a stabilization.

The requirements for the Light FTI system were put together by the different FTI groups of the Airbus Group business units. They shall set a new goal in weight as well as in cost and cycles. Reducing weight is one of the main contributors for limiting the intrusiveness of the FTI in the tested platforms. Weight shall be cut down in focusing on sensing and acquisition equipment hardware as well as on wireless connection technology. Furthermore, a price reduction shall be reached in selecting measurement electronics of high figure markets, keeping standard and high accuracy requirements. Costs shall also be slowed down in making the installation of the system quicker and easier, which eventually results in cycle reduction.

Consequently, the usability of a light FTI will be increased in building a natural bridge to specific applications.

Low cost and high accuracy sensing elements will be connected to avionic-compatible buses and shall offer flexible pre-processing needed on HUMS systems.

The flexibility offered by reduced weight and intrusiveness as well as easy to install FTI system makes it ideal for troubleshooting applications on customer aircraft.

Drastic weight reduction shall also extend the usability of the FTI system to much enhanced measurement capabilities like on rotating parts, e.g. on helicopter main and tail rotors, as well as on propellers assemblies.

The autonomy of the Light FTI system shall support usual testing operations without limitation. The system shall be able to rely on traditional power supply but also on battery, solar or energy harvesting solutions.

The architecture of the Light FTI system shall be based on nodes: each acquisition node shall support 32+ sensors and transmit its measurement data over wireless to a receiving node. Time synchronization shall be possible over the PTP V2 protocol [4]. The acquisition characteristics shall support synchronous sampling in the 1-5 kHz range.

The wireless range shall cover distances between acquisition and receiving nodes between 1 and 80 m line of sight, in order to satisfy installation requirements of all Airbus Group platforms, from helicopters to airliners. It shall be compliant with EMI/EMC constraints and international regulations.

Real-time streaming shall be possible on the interface Ethernet of the system, which shall be also able to record internally.

DEVELOPMENT STRATEGY

The project has been set as cooperation between the Airbus Group business units. The development partner is the Airbus China Innovation Centre ACIC. ACIC works to explore, identify and accelerate delivery of innovation projects for Airbus and its customers, leveraging the local innovation ecosystem in China including talents, partners and resources. Airbus' expertise in flight test instrumentation shall be combined in the requirement, development and validation phases of the project.

The goal of the cooperation is to focus on China's advanced connectivity and sensing technologies in developing partnerships with local partners, as many electronics international giant companies have entities in Shenzhen. Intellectual property shall remain in the Airbus Group and Export Control regulations shall be respected.

The development is led by ACIC, on behalf of a cooperative project organization in Europe. Iterative development steps have delivered prototypes to be validated by the FTI groups of the Airbus entities Operations, Helicopters and Defence and Space.

SURVEY ON EXISTING TECHNOLOGIES

The original architecture of the Light FTI project consists of multiple MEMS sensors (2 to 8 on one TX), one TX (transmitter board) and one RX (receiver board).

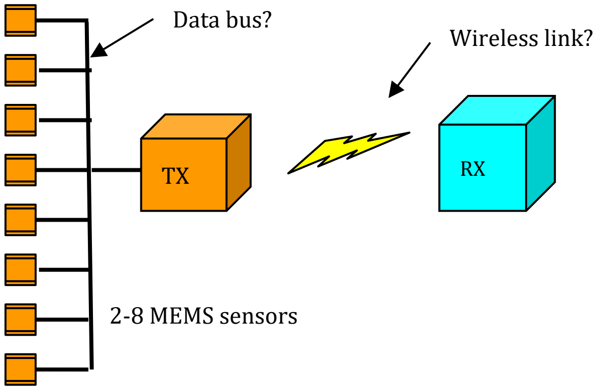


Figure 1: Technology selection for Light FTI

The major questions fall on the selection of the bus between TX and MEMS sensor, and the wireless link between TX and RX.

Data bus selection

We compare three mainstream buses, I2C, SPI, and the I3C bus newly launched by MIPI [1] [2], and we think I3C bus is the most suitable one because of:

- The simplicity of wire connection for multiple slave connections
- Satisfying data rate
- Support synchronous mode

See Table 1 below.

Wireless link selection

We compare three wireless links, Wi-Fi, UWB [3] and BLE5 [5], and consider all factors, and finally we choose UWB and BLE for high and low speed data transmission.
See Table 2 below.

MEMS sensor selection

In the market, there are three mainstream companies (ST Micro, TDK and BOSCH) providing MEMS sensors supporting the I3C interface. We started the project by using LSM6DSOX and LPS22HH, which are motion sensors and pressure sensors. We also did research in the market and identified ICM-45686 and ILP22QS as good candidates for the next iterations.
See Table 3 below.

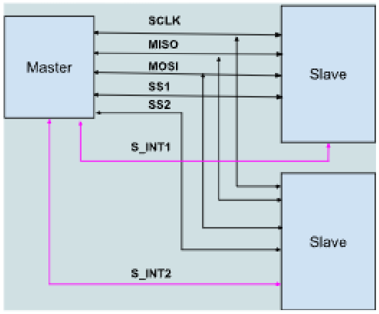
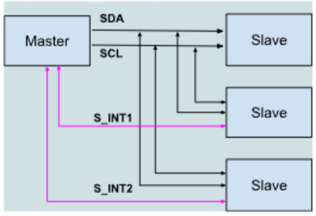
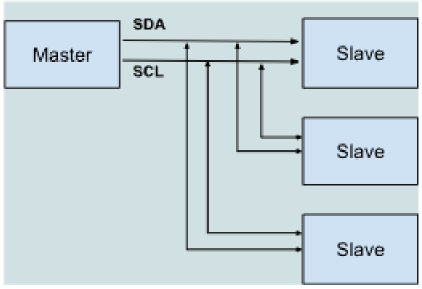
	SPI	**I2C**	**MIPI I3C**
			
Designed	1979	1982	2016
Number of wires	4 wires (plus separate wires for each required interrupt signal)	2 wires (plus separate wires for each required interrupt signal)	2 wires (support in-band interrupt, no need for separate wire)
Effective Data Bitrate	Approx. 60 Mbps max at 60 MHz for conventional implementations (Typically: 10 Mbps at 10 MHz	3 Mbps max at 3.4 MHz (Hs) 0.8 Mbps max at 1 MHz (Fm+) 0.35 Mbps max at 400 KHz (Fm)	Up to 100Mbps max at 12.5 MHz (Typ.:10.6 Mbps at 12 MHz SDR)
Slave address	No need, use SS (slave select) pin	Static	Dynamically assigned during initialization. Slaves may have static address at start

Table 1: Data bus selection

	Wi-Fi	**UWB**	**BLE 5**
IEEE spec	802.11 a/b/g	802.15.4	802.15.1
Frequency band	2.4 GHz / 5 GHz	3.1 - 10.6 GHz	2.4 GHz
Number of RF channels	14 (in 2.4 GHz band), 24 (802.11n) to 27 (802.11a) (in 5 GHz band), 26 (in 4.9 GHz band)	15	79
Range	<150m	<100m	<75m
Max signal rate	54Mbps	27Mbps	2Mbps
Channel bandwidth	Up to 40 MHz at 2.4 GHz, Up to 160 MHz at 5 GHz	>500MHz	1MHz
Power consumption	Medium	Low to medium	Low

Table 2: Wireless link selection

	LSM6DSOX	LPS22HH	ASM330LHHX	ILPS22QS	ICM-42688	ICM-45686	BMI323
Brand	ST Micro	ST Micro	ST Micro	ST Micro	TDK	TDK	BOSCH
Launched	2019	2019	2022	2021	2020	2023	2022
Type	Motion	Pressure, temperature	Motion	Pressure, temperature	Motion	Motion	Motion
I3C bus compatibility	Yes (SDR)	Yes (SDR)	Yes (SDR)	Yes (SDR)	Yes (SDR and DDR)	Yes (SDR and DDR)	Yes (SDR)
External clock in	No	No	No	No	No	Yes	No
Grade	Consumer	Consumer	Auto	Industrial	Consumer	Consumer	Consumer

Table 3: MEMS sensor selection

DEVELOPMENT STEPS

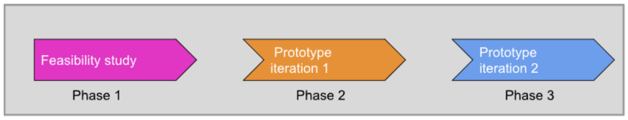


Figure 2: Development steps

Feasibility study

Wireless test

Purpose: The aim of wireless test to find out the boundary of range vs packet loss, and the behavior of both wireless links in rotating mode.

Test strategy: we use the off-the-shelf BLE and UWB modules, configure them in different transmission powers, using the original antenna and high gain antenna for comparison. The tests were done in different ranges (5, 25, 50, 75 and 100m)

Conclusion: devices with BLE and UWB and in fixed mode are able to achieve stable data transmission without packet loss at 50m (with UWB the range could be up to 100m). However, in rotating mode, we see both in BLE and UWB mode, the max range is only at 5m.

See Table 4 below.

I3C Bus test

Purpose: The aim of I3C bus test is to validate the functionality of I3C bus and find out the max acceptable clock frequency in different lengths and in different numbers of slaves.

Test strategy: we use the NXP/RT600 EVK as master, and tested in two configurations of MEMS sensor:

- MEMS module with twisted cable; Table 5 below
- MEMS chips mounted on Flex PCB. Table 6 below

	Packet loss (ppm)	Distance (m)	TX power (dBm)	Speed Mode	Antenna	Status
BLE	0	25	7	LE 2M	Original PCB antenna	Fixed
	0	50	6	LE 2M	High gain antenna	Fixed
	0	5	8	LE 1M	Original PCB antenna	Rotating(5Hz)
	0	5	2	LE 1M	High gain antenna	Rotating (60Hz)
UWB	0	100	30	6.8Mbps	Original antenna	Fixed
	0	5	6	6.8Mbps	Original antenna	Rotating (5Hz)

Table 4: Wireless tests

Max acceptable clock frequency in different lengths	Distance (cm)	Clock frequency (MHz)
MEMS module and cable	30	12.5
	120	10
	130	8
	180	6
	280	4
MEMS chip and FPCB	190	10
	300	7
	400	5
	500	4

Table 5: MEMS tests

Max acceptable clock frequency in different number of slaves	Number of slaves	Clock frequency (MHz)
MEMS module and cable LSM6DSOX @ 104Hz LPS22HH @ 50Hz	1 (1x LSM)	12.5
	4 (4x LSM)	10
	5 (5x LSM)	8
	9 (5x LSM + 4x LPS)	5
	10 (6x LSM + 4x LPS)	4

Table 6: MEMS tests

Conclusion: when I3C clock frequency increases (data speed increases as well), the range for data transmission will decrease, and the data transmission on Flex PCB is much better than cable connection. When I3C clock frequency increases, the quantity of slaves will reduce accordingly.

Prototype iterations

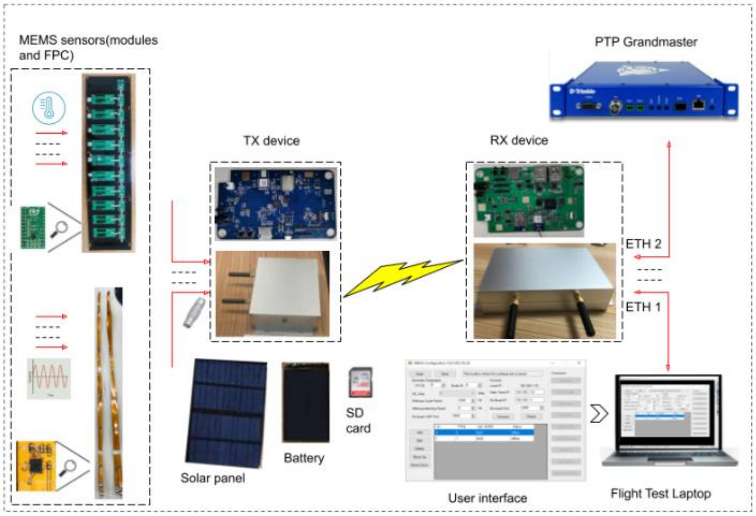


Figure 3: System architecture of iteration 1

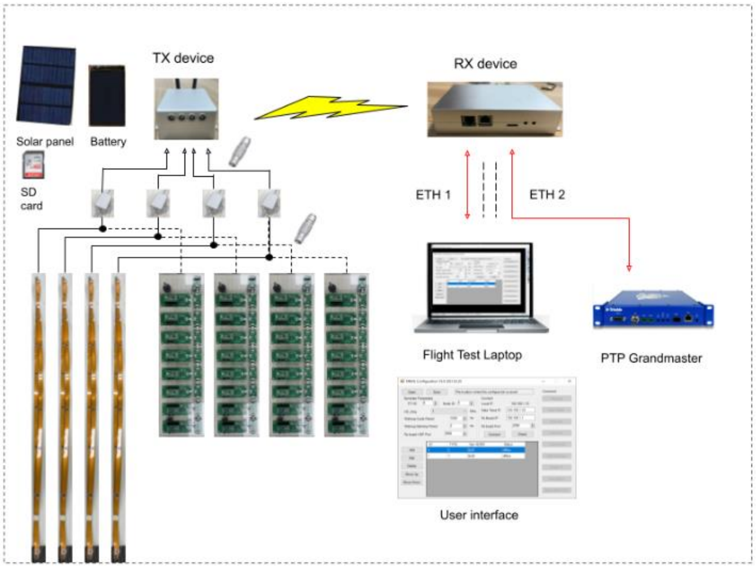


Figure 4: System architecture of iteration 2

Technical targets of iteration 1 and 2

Hardware: Both TX and bridges are based on i.MX.RT600 MCU from NXP. For the bridge, one side is connected with two types of MEMS sensors (LSM6DSOX and LPS22HH) from ST Micro, the other side is connected with TX through SPI data bus. RX is based on i.MX.RT1170 MCU from NXP. Both TX and RX are integrated with UWB and BLE, where realized by Decawave DW3000 chip and Nordic nRF52840 chip.

Data transmission: End user clicks the start acquisition button on the PC tool, and then the command will be transferred from RX to TX, then to the bridge. The bridge will relay to the MEMS sensors through the I3C bus and activate the synchronous mode simultaneously by sending CCC commands in broadcast mode. When the MEMS sensors are acquiring data, the data and its timestamp will be stored in FIFO. The bridge will read the data stored in the FIFO regularly (interval depends on wireless link, 20ms on UWB and 50ms on BLE mode) and send them to the TX. The TX will send the data to RX wirelessly over UWB or BLE mode regularly (20ms in UWB mode and 50ms in BLE mode). All the data will be packed in ED247 format in the bridge before sending to TX. When RX receives data from TX, the data will be directly transparently transmitted to Ethernet port and sent in UDP format.

Synchronization:

- PTP synchronization: when RX is connected to the PTP master, it can receive the PTP-v2 messages in two-step mode and the clock of RX will be synchronized (the target accuracy is 1µs).
- Wireless synchronization: when communication between TX and RX is established, they will communicate regularly (20ms in UWB mode and 50ms in BLE mode). When RX receives the data from TX, it will return an ACK (acknowledge) packet to TX and record the current time as T1 and send it back to TX through the ACK packet. T2 receives the ACK packet and records the current time T2 and gets the time of T1. T2 - T1 = Delay + Offset. Delay can be smoothed by algorithms. The offset can be calculated to revise the clock of TX.
- MEMS synchronization: the clock of the bridge will synchronize with TX through the SPI bus. The bridge sends CCC commands to MEMS periodically for the sampling synchronization. The bridge will get the data and its timestamp from the MEMS FIFO. As the timestamp is a counter instead of a clock value, the timestamp will be converted to a clock value with reference to the clock of the bridge, and packed with the data.

TECHNOLOGICAL CHALLENGES

Data Integrity

Guaranteeing the reliable transfer of sensor data is always a significant challenge.

The first challenge is coming from the data transmission over I3C bus. Most people think the I3C bus is just for the board level, but we questioned it and did quite many experiments. Finally, we got positive results, which show that the I3C bus can also work with cable connection. As we know from our feasibility study, the factor of clock frequency, distance and the number of slaves in the bus will determine the data integrity. For example, when we set the clock frequency as 12.5MHz, once the distance of communication is over 30cm, we see the packet loss will occur. Therefore, we must find the limitation of the distance and the number of slaves corresponding to different I3C clock frequencies we can set, to avoid the packet loss issue.

The second challenge is coming from the wireless link. Due to the nature of wireless networks, to achieve ultra-low packet loss is very difficult, also when we are choosing the UWB and BLE 5 as wireless links. Both wireless links allow packet loss up to 1%; however, the target of the project is to achieve 1-ppm packet loss. Therefore, the resend mechanism for both wireless links is necessary to mitigate the packet loss in the wireless data transmission.

Time synchronization

As explained above, there are three synchronization mechanisms applied in the prototype. It is relatively easy to realize the PTP synchronization with desirable accuracy. However, the challenges on the MEMS synchronization and wireless synchronization are significant. When dealing with MEMS synchronization, firstly we realized that each MEMS sensor has its own clock, the sampling rate is not constant neither within (i.e. in time) nor between the MEMS sensor. Even though we synchronize the MEMS clock with the bridge clock and activate the synchronous mode of the I3C bus, which forces all the MEMS sensors in the same bus to have the same sampling rate, the difference of the clock of each MEMS will eventually result in undesirable spikes periodically. Moreover, the low resolution of MEMS timestamp also leads to undesirable distribution of the sampling period. As for the wireless synchronization, the difficulty is on the algorithm to calculate the delay between TX and RX to achieve the required accuracy.

ORGANIZATIONAL CHALLENGES

The setup of the project featured some organizational challenges, mostly “by design”.

The different time zones between the working groups on different continents could have been perceived as a difficulty. Design in China, the test, bug discovering and reporting on several Airbus sites in Europe, troubleshooting and bug correction in China were made sequentially and iteratively. Thanks to the efficient usage of collaborative tools and to the high flexibility of the project team, the development did not suffer time zone related delays.

FT instrumentation requirements are very specific; FTI is indeed a niche in the global instrumentation market. Synchronization and sampling, data formats, operation constraints are obvious aspects for experienced FTI engineers, but need to be translated accordingly into relevant requirements for even high tech developers of the commercial electronics industry.

Very specific test and validation tools had to be deployed by the different actors of the project. The innovative technologies implemented in Light FTI e.g. I^{3}C, UWB as well as format e.g. ED247 had to be validated by both the developers and the testers, notwithstanding the more standard bricks like Ethernet and PTP synchronization. The data analysis software SANDRA, developed in-house at Airbus Helicopters, played a high supportive role in the trans-labs validation of the prototypes.

A more trivial but not neglectable challenge during the project was the synchronization of the test plan and resources within the different entities. The different phases of the project delivered several prototypes; the planning of the tests was distributed between the available resources on the different sites, according to the operational requirements or restrictions of local projects

RESULTS AND LIMITATIONS

Requirements	Target of Iteration 1	Target of Iteration 2	Completion
MEMS	Gyroscope, acceleration, temperature and pressure MEMS sensors. Full function of I3C bus, e.g., dynamic addressing, synchronous mode. 1xTX supports up to 8x sensors. 2x form factors (MEMS modules and Flex PCB) of sensors for testing.	1xTX connects with 4x bridges through SPI data bus and each bridge connects with up to 8x sensors. 1xTX supports acquisition of up to 32x sensors.	OK
Wireless	Data transmission on UWB (DW1000) and BLE (nRF52840). Wireless synchronization on both wireless links (requirement>UWB: 5us, BLE: 3ms). Wireless wakeup realization on both wireless links.	Upgrade the UWB chip from DW1000 to DW3000. Payload speed of UWB and BLE shall be more than 2.5Mbps and 300Kbps. Low power RTC on RX.	UWB: 47us BLE:8ms Both results are still under improvement.
Data	Data formatting ED247. Packet loss measurement on UWB and BLE (target: 1ppm). Record duration above 1 hour		Packet loss: UWB :15 ppm(distance of 15m) BLE> under improvement.
PTP	Support PTP v2 PTP synchronization, requirement:10us		OK. PTP synchronization: less than 5us
Power	TX is powered by a battery and supports the power supply of the solar panel.	In operational mode, the autonomy shall be more than 30h (UWB) and 55H(BLE). In sleep mode, the autonomy shall be more than 200h (UWB) and 150H(BLE).	The power consumption in operational mode can meet the target, the result in sleep mode still under improvement.
PC software	MEMS configuration. Start/stop acquisition	Status of connection indication	OK
Product size		Size reduction on TX	TX:110*79*30mm;PCB size:80x70mm

Table 7: project results

FUTURE STEPS

Although there are many imperfections with the current prototype, we still plan and define the targets for the next iterations, the major targets for future steps are:

Power:

- Battery type: TX shall use Ni-MH battery.
- Battery life duration and removability.

Synchronization:

- System synchronization accuracy: TX shall be able to stay synchronized with the PTP master at: ±100µs accuracy for BLE/ ±1µs accuracy for UWB.

- Sensor synchronization: The maximum delay between the acquisitions of two sensors set at the same sampling frequency shall be less than 0.3% of the set sampling period.

Ethernet communication:

- Topology: It shall be possible to chain different Rx modules. (Daisy chain function).
- Payload speed: Min payload speed: BLE: 1Mbps; UWB: 6Mbps.
- ICMP/ARP service: The Rx shall provide all needed services to reply to ICMP requests/ARP requests.

System characteristics:

- Topology: Rx shall be able to acquire data from multiple TX.
- Wireless capability: The system shall be able to wirelessly operate with a minimum of 25m between modules in an aircraft environment.
- Wireless transmission packet loss: Packet loss from wireless transmission shall be less than 1ppm.
- Autonomy: The TX shall be able to operate for 55h on battery at maximum workload and 500h in sleep mode.

Furthermore, an industrialization of the development will be planned in a next project step, in order to reach an operative robustness of the product in terms of mechanical integration (housing incl. mounting) and electrical integration (e.g. with adapted EMI protective electronics around the implemented chips).

GLOSSARY

ACIC:	Airbus China Innovation Centre
BLE:	Bluetooth Low Energy
ED247:	Technical Specification for Virtual Interoperable Simulation for Tests of Avionics Systems in Virtual or Hybrid Bench
FTI:	Flight Test Instrumentation
HUMS:	Health and Usage Monitoring System
I2C:	Inter-Integrated Circuit V2
I3C:	Inter-Integrated Circuit V3
MEMS:	Micro-electromechanical systems
MIPI:	Mobile Industry Processor Interface
PTP:	Precise Time Protocol
PCB:	Printed circuit board
RX:	Receiver
SPI:	Serial Peripheral Interface
TX:	Transmitter
UWB:	Ultra-Wide Band
Wi-Fi:	Wireless Fidelity

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