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Abstract: This article aims at giving an overview of the current status and potential perspectives, including the open points, for space applications of the Integrated Modular Avionics (IMA) concept defined and developed by the aeronautic industry.

At first, a status will be made on the current of the on-board data-handling system for the space applications, in particular the way CNES pushed the concept of platform and the way it has been spread by industry for non-CNES programs (under ESA contract, commercial market, international cooperation): from SPOT earth observation to telecom satellites including scientific missions based on PROTEUS and MYRIADE platforms will be described.

Then it will be demonstrated to which extent the IMA concept is not yet directly applicable in the context of the space domain: technical (constraints/limitations on rad-hard processors, limited volume of embedded applications, mission-criticality of all on-board applications...), organisational constraints (ESA, national agencies and the various industry actors) and specific other space domain (market and associated investment budgets) will be detailed.

In the last part, it will be presented how and which of the concepts inherited from IMA are however considered relevant for space. In particular the various technical fields have been explored and will be presented in various area such as ARINC 653 standards (system partitioning and segregation), software standardisation of architectures and associated building blocks (isolation of applications and independent development and validation), engineering methods, associated tools. The organisational problems and associated business model will also be considered (need for architecture and design authority funding the investment, responsible for technical requirements and maintenance).

Preliminary studies and a roundtable have been held within the space domain and a work plan established in order to gain from the IMA experience and fill the technology gaps. However the lack of visibility on the real issues behind the IMA and still missing answers to some questions (lessons learnt from aeronautic world are partly hidden from the external) are dramatically decreasing the spin-in process efficiency....

Keywords: IMA, standardisation,

1. Introduction

The IMA concept has been created and deployed in the aeronautic domain in order to optimise the development and validation effort of the on-board functions by offering a common standard core (made of on-board computer hardware -CP-OM-, bus -AFDX- and on-board software middleware including ARINC 653 compliant operating system and standard APIs).

Space domain agencies and industry are facing the same constraints and needs as the aeronautic ones in particular in terms of:
- Cost and efficiency optimisation,
- Schedule reduction,
- Increasing on-board complexity and autonomy,
- Evolution and concentration of organisations,
- Reliability and criticality.

There is a need for changing the way (technical and organisational) to design and develop satellites and space systems: standardisation is a key issue already identified ten years ago.

2. Standardisation tentative

2.1 Concept of platform

In order to standardise or at least develop once common avionics for several missions, in the eighties, appeared the concept of satellite platforms: the idea consisted in physical and functional decoupling of the basic avionics and housekeeping functions (power, AOCS, thermal, TM/TC) constituting the platform from the mission functions (payload instruments). This concept enabled already mutualisation of engineering, design and validation effort between several mission of the same types:

- SPOT family of satellite, under ASTRIUM prime contract was based on an ASTRIUM/CNES MARKII platform concept declined into SPOT1, 2, 3, ERS 1, 2. MARKIII (MARKII follow-on) supported SPOT4, ENVISAT, SPOT5, METOP missions (and their military cousins HELIOS1 and 2).
• PROTEUS platform was designed and developed by CNES/TAS and supports various scientific missions such as JASON1, 2, CALIPSO, COROT.

• For the telecom satellites, both ASTRIUM (EUROSTAR 2000/3000) and TAS (AVIONICS 4000) invested on their own on full reusable platforms declined easily, faster and cheaper for the needs of the commercial telecom operators. A common initiative funded by ESA and CNES, ALPHABUS, currently under development has been invested on what will be the future telecom platforms for both prime contractors extending the concept of platform to some kind of common standard avionics building blocks.

• For cheap and less stringent missions, CNES has invested in the late nineties into a small micro-satellite platform, MYRIADE, and already various missions have been developed and launched (DEMETER, PARASOL,…), some are still under development (PICARD, TARANIS). The concept has been made available to the prime contractors for their own applications (e.g. ASTRIUM has based the ALSAT satellite on this platform for a commercial earth observation export program). This concept has been considered also very attractive for military cheap missions.

The lessons learnt from those platforms investments show a real and effective cost reduction. However, and except in the telecom world, the number of missions for each platform remains very low (up to 10-15 at most).

2.2 Satellite avionics architecture and platform concept limitations

Despite the real gains obtained thanks to platforms, a survey shows that 80% non-recurring costs of the satellites are mission dependent and not only on instruments/payloads. This means that for each mission the impact of the specific requirements on the platform are quite high, in particular in the software development and validation.

The reasons for such major impact of each mission on the platform design are partly hidden and industry confidential. This is due mainly to the competition between prime contractors, but also to the customer-supplier relationship between agencies and primes. It is therefore very difficult to access the real internal cost data. Out of the in-house CNES experience gained on MYRIADE, but also to the PROTEUS CNES funded platform, it was made possible to outline a first list of those reasons.

The platform was supposed to implement all and only generic and standard features. However :

• There is a strong coupling between the mission and the platform : the performance of the final system links the instrument capabilities with the platform ones (e.g in earth observation and most scientific mission satellite pointing is directly defining the mission performances),

• The interfaces (space to ground protocols, operations) are specific to the final customer (ESA, CNES, commercial export…),

• Some constraints are also coming from the launcher leading to satellite/platform design impacts,

• There is a strong dependency between hardware and software (processors, I/O management, on-board protocols). Obsolescence of components is very difficult to master from the software side (e.g. on MYRIADE platform migration from T805 processor to ERC32/LEON imply a major software redesign).

• The processor resources are very limited (European rad-hard product lines : ERC32 offers only up to 20 MIPS). This leads to software optimisation, degrading the reusability (modularity, parameterised functions,…).

• The reliability has to be kept very high and the projects prefer to run a complete software validation and qualification for their mission rather than relying on a generic validation performed once.

All those aspects lead for each mission to major consequences on the platform software, and very often a complete redesign and qualification are necessary.

2.3 Improvement needs

In order to reduce significantly the software cost, the following have to be explored :

• How to maximise generic features,

• How to increase decoupling between the various functions,

• How to improve reuse process and architecture, and provide the evidence of gains in terms of validation effort,

• How to decrease cost of specific functions ?

3. Expected benefits from the IMA concept

Given the limitations outlined §2.2 and the improvement needs on the platform concept §2.3, space agencies are looking to what has been invested in the others domains for the development of embedded real-time software in order solve the same kind of questions.
It is to be noted that this paper focuses on the IMA concept rather than other initiatives such as AUTOSAR in the automotive world, because:

- the constraints in terms of criticality aspects and associated rules have been seen very close from each other: DO178B software engineering and quality standard corresponds nearly one to one to space ECSS E40/Q80,
- the notion of avionics and some associated functions are similar between an aircraft and a spacecraft,
- the IMA concept has been seen as more mature because effectively implemented and flying today whereas AUTOSAR is still under development.

It is not the objective of this paper to describe in details the IMA concept. However, an analysis of the main IMA offered features conducts to isolate the fundamental following aspects:

- standard on-board computer resources including full CPU boards: processor, I/O, bus,…
- standard certified RTOS and common API for all software functions (ARINC 653),
- standard common software validation means.

Both standard hardware and software implement time and space partitioning capabilities in order to guarantee the independency of the functions running on the same computer.

The effectively observed benefits from this approach are:

- develop once the standard features,
- increase of reliability of the common complex generic software (and hardware) achieved throughout extensive testing,
- embed software functions on the same computer having different criticality levels without risk of error propagation between functions,
- embed software functions within the same computer without risk of error propagation between functions,
- develop and validate functions incrementally and independently from the others,
- optimise use of computer resources by late allocation of software functions to computers,

As a matter of fact, in terms of organisational aspects, IMA concentrates the various competences on appropriate suppliers leading to an increase of the efficiency of the corresponding teams:

- the function supplier can concentrate on the functional aspects without any particular knowledge of the hard-real time kernel, resource management, I/O, etc…
- a change of function supplier would not affect the system level,
- the IMA supplier can focus on the tricky real time concurrency problems (shared resources, tasking, scheduling) and develop those very critical software with dedicated process effort (including robustness).

4. Why not IMA for space?

Without having full access today to the data and the convergence process that took place years ago inside the aeronautic community, it is very difficult to assess the validity of the IMA concept for the space needs.

Nevertheless, the contacts initiated in the scope of preliminary studies and the help provided gently by the aeronautic people in order to explain the context and provide first answer to the raised questions, enabled to better characterise the differences between the two worlds and assess the validity of the approach step by step.

A workshop was held in ESA on the topic beg. October 2007. It provided additional inputs in order to assess the IMA approach in space context to the preliminary already conducted studies on the subject. It was the forum for open discussions within the space community together with invited aeronautic people.

The main differences between space and aeronautic have been isolated and classified into five categories:

- technique
- market
- organisation
- strategy
- culture

4.1 Technique

Obviously the technical needs are not completely shared by the two domains:

- time and space partitioning: it appears that aircrafts have to mix-up very critical functions (Cat A: flight control commands, braking, …) together with none critical ones (Cat E: flight entertainment). Satellites only on-board medium critical functions and almost of the same criticality level (Cat B-C). Another way saying all functions on-board the satellite are at-least mission-critical and therefore all developed
according the subsequent engineering and quality rules.

- **Standardisation**: it is a clear objective shared by the two communities but there is still need for specific aspects. IMA is today “standard” within the same aircraft family (space platforms ?), but not compatible from an IMA supplier to an other. This means that it is not obvious whether it is affordable to standardise the envelope of needs in order to share the same computer resources and associated basic software for all satellites types.

Moreover the consequences of such a concept would preclude the following:

- **Processors and computers**: due to environmental constraints for space applications, it is not possible to fully reuse the hardware boards and processors developed by the aeronautic people. Dedicated and still very limited series of rad-hard processors are needed.

- **CPU and memory resources**: today an ERC32 is providing only 20 MIPS associated with a few Mbytes of memory. As a consequence the tendency in terms of avionics is more to decentralise and spread the processing into dedicated computers rather than concentrating within single units. The IMA would imply to have powerful processors enabling to support the IMA features (memory footprint, CPU overhead) and concentrate software functions. This problem will progressively disappear with the new generations of powerful european rad-hard processors (LEON, GINA, …).

- **Computer and bus architecture**: the IMA concept has not only impact on software architectures. It relies also on a physical segregation of I/Os and memory not existing today in space avionics.

- **On-board software architecture**: implementation of full ARINC 653 operating system induce a major impact on the current existing on-board software architectures and off-the-shelf building blocks. Applying such a design would mean a complete redesign and validation of them.

- **On-board software reliability**: implementation of full ARINC 653 operating system induce a increased complexity: time and space partitioning features in the RTOS were difficult to develop, debug and maintain. Furthermore, the experience shows that validation of RTOS (ref. [3]) is very difficult, and today mainly rely on the validation achieved on the full software for the satellite software. This aspect has been properly tackled by the aeronautic people but remain a key issue where exchange of experience will be necessary.

Technically, both developed IMA off-the-shelf hardware and software can not be directly reused without complete re-assessment of needs (possibly less stringent) and redesign in order to suit to technical existing rad-hard processors, computers, …

4.2 Market – return on investment:

Given the technical implication on the spacecraft avionics, it appears that the cost of IMA for space in terms of level of investment would be very high. This point is not disputed today by the aeronautic people.

By lack of access to the confidential real figures, it is very difficult for the space community to estimate the cost of such an investment. Even if those figures were made available, transposition within the space context, 10 years later, would not be fully valid anyway.

Macroscopic evaluation of both markets is however providing the following information:

- Current aircrafts contain roughly one hundred computers and four hundred functions whereas satellites count at most twenty computers and a maximum of thirty functions.

- In terms of series, an aircraft is supposed to be designed for more than one hundred items, whereas satellite platform count at most 10.

In that context, it is not obvious that the gain on each computer development (hardware + software) would be sufficient except if maybe if the standardisation is achieved at the complete community level (between all agencies and all prime contractors). But as a matter of fact, is it technically realistic (and really desirable in particular in terms of risk) to achieve this harmonisation at the level of the space community, whereas the aeronautic people have one “IMA” per product line (which corresponds approximately to satellite platforms).

In any case, redevelopment from scratch of an IMA-like concept for space would not be affordable.

4.3 Organisation

In the aeronautic world, the IMA is supported by the aircraft manufacturer and contracted to one or several suppliers.

Given the market constraints outlined §3.2, it would not be profitable for the satellite prime contractors to do the same (and already looking at the current situation achieved at platform level). Therefore IMA for space would imply to create an IMA design authority, and select supplier(s) at a consortium level (including agencies + prime contractors) based on a common investment.

For the function supplier, the implication of IMA is also very important. The risk of such a rationalisation
at their level is to lose completely low level expertise on board computers and basic software.

Furthermore, each function supplier need then to acquire IMA architecture background in order to provide software functions fully meeting the IMA constraints and development rules.

The cost and impact in this area has to be properly mastered and challenged: the gain provided by IMA on the supplier has to be compared with the training effort and support from IMA supplier.

The function supplier is also no longer providing fully integrated and validated packaged solutions (hardware + software). In terms of responsibility, the concept creates strong interactions between IMA, function suppliers and the system level:

- In terms of schedule: IMA framework has to be made available to the function supplier,
- In terms technical responsibilities, when an anomaly occurs in a function, the question may arise of whom is responsible and supposed to investigate,
- Same question may appear at system integration level.

Out the visibility we have today, the IMA aeronautic experience does not reveal problems in this area. But it seems that the IMA was much anticipated, and the level of accompanying effort was very high in order to prevent any schedule conflict: the technical segregation concept was fully validated before having made available to the suppliers. This is one of the major lessons learnt from their experience: it can not be implemented incrementally on projects and should be mature enough before being applied.

4.4 Strategy

The space community in Europe is organised very differently than in the aeronautic domain. The customers are mainly institutional, national agencies (CNES, DLR, ASI, BNSC… ) and the ESA. All those actors have a strong interest in decreasing the cost of space missions, but without endangering their own national interests (which aim at maximising the implication of their industry on space programs).

An harmonisation process is in place in order to make technical consistent decisions. But this process is very long and heavy even at least to converge and fund technical studies. One could imagine how long it could take to converge on a such a major issue.

In the context of the aeronautic world, the IMA was pushed the airliners, which common interest was to decrease the cost of aircrafts. It was then declined by the aircraft manufacturers, and imposed to the suppliers. The decision making was somehow easier because it was a top-down process driven by economical interests regardless the implication on the suppliers (which market part remain quite comfortable at the end).

In the space domain, they are few actors and it would be very dangerous to decide such a change without any preceding assessment of impact on all of them: it would be very dangerous (and not at all desirable) to stress any of the fragile suppliers with their associated know-how…

3.5 Culture

With this very complex network of actors, and possible reluctance of some of them for short term economical interests, and technical risks, the space community has to face also its history and culture. Space has been during tenth of years one of the leading engine producing brilliant and competing solutions at the time only technical objectives were assigned to projects without stress on economical constraints.

Today, under more and more economical pressure, this community is reluctant to change things that have been investing stone after stone and which efficiency have been flight proven. It is clear also that again for economical short term constraints, both industry and agencies are not in favour of taking high risk and therefore do not push very hard for experiencing any major breakthrough.

Last, and not specific to the space domain, engineers prefers slight innovations on what they know and master, rather than reusing existing concepts they have not invented nor experienced themselves: this “not-invented-here” syndrome is really preventing a proper cross-domain fertilisation and rationalisation.

Was it easier in the aeronautic world to provoke such an earthquake? Probably not, but the reality of the market and the very hard competition between aircraft manufacturers was a matter of survival. Today in the space business, at least for what concerns the institutional market in Europe, deciding IMA for space is not -at short term at least- a matter of life or death.

5. IMA for space or something else ?

For all the reasons depicted §3, IMA as such will not be applied and reused in the space domain. However something looking like IMA should emerge based on similar concepts but on an adapted technical rationale associated with a dedicated organisation and funding.

In particular due to the culture and decision making process, a step by step approach will be preferred to any other violent breakthrough.

5.1 consolidation of needs
There is a need for future missions:

- to reuse software and invest on common core rather than developing several times the same pieces of software (IO, services, middleware…)
- to on-board autonomy functions, less critical, and very difficult to validate.
- within payload / instrument computers, the high critical FDIR shall coexist within the same computer with low critical data processing: the need is to develop the low critical functions with adapted engineering standards (and therefore accept less reliability). This approach is acceptable only if this does not endanger the high critical functions through segregation capabilities.
- for maintenance in flight, to ease reloading of functions without reloading (and stopping) the full software.
- for geo-return on European projects, it is needed to split the on-board software development on several function suppliers. The independence of the software development process between functions is necessary such a context.

This preliminary list of needs should be properly refined, and classified from top basic mandatory needs down to optional desirable ones: this would drive the roadmap for incremental step by step implementation and deployment of the concept.

5.2 challenge of technical solutions and impacts

- As a prerequisite focus first on standardisation of software engineering (E40, Q80) architectures and interfaces (SOIS, PUS).
- Impact on hardware side (including resources aspects) shall be assessed carefully because it seems that the expected benefits will be very limited if MMU as well I/O are not physically segregated. Cache/registers flushing at each partition switch will cost on the software performance. Injection of constraints in the hardware roadmap.
- Definition of the appropriate robustness level: select the capabilities to be implemented in the RTOS (dynamical checks, physical barriers), in the associated tools (static software checks at compilation step).
- Definition of the appropriate genericity level: It is to better to customise optimised solutions according to family of applications instead of fully generic inducing complexity in particular in the configuration process.
- Compare with other experienced approaches providing also segregation capabilities such as ASSERT, CORDET, DISCO, CNES TMSCM…

Many studies have been initiated already in order to consolidate the implications and prototype solutions to be experienced on the space use cases:

- Impact on RTEMS will be assessed (CNES + ESA studies), because RTEMS is spread on the space applications and per essence, the impact on the existing reused software would be minimised and possibly smoother than with other RTOS. Nevertheless the other RTOS will be evaluated in the scope of the CNES study.
- Real implementation is to be evaluated for SYMBOL-X payload function. CNES, in charge of this software will inject dedicated requirements in this area.

Those studies have to be structured and complemented by others in order to secure all the technical issues before any decisions. A dedicated roadmap has to be written in order to address all of them.

5.3 organisational

In parallel to the technical studies, some analysis shall be conducted in order to identify by whom and how IMA for space should be managed and decisions taken.

The business model has to be carefully assessed and defined by all the actors, in a wider context where an organisational model is already under discussion on the way to develop and share software building blocks.

- The agencies should clearly identify the targeted needs and found a funding scheme of all the preliminary assessment studies.
- The technical design authority board should be created in order to define and agree on targeted “reasonable” and “incremental” level of specifications (to be standardised within the appropriate ECSS place-holder).
- Both agencies, prime contractors and software suppliers should identify the investment they are ready to perform. This should be consolidated in order to show how the resulting project costs would decrease.

6. Key dates and short term roadmap

Trying to draw where IMA for space stands today, lead to the following key dates and events already held:

- 2006: preliminary tentative studies initiated by ESA (TRP + GSTP). Only technical activities started on ARINC 653 and on-board software impacts.
- June 2007: CNES presents the paper “IMA for space: status and perspectives” [1] in the scope of CISEC day on IMA. The status was difficult to
depict due to a very large number of questions and lack of knowledge on the concept and the way it was implemented.

- End September: IMA day in the scope of ADCSS workshop in ESTEC/ESA the Nederland where the results of preliminary studies were presented. After the roundtable, a preliminary roadmap was established and reflected here in this paper.

And at very short term:

- January 2008: key meeting to be held between ESA, CNES and prime contractors (TAS, ASTRIUM) in order to define the scope of a structuring study involving all the parties and covering all major issues.

- End 2008 (hopefully): the roadmap will be consolidated together will risk, cost and organisational analysis. Would the consortium be then in position to create the IMA for space project?

7. Conclusion

IMA concept will not be reused as such by the space community because it does suit to the needs, the constraints (technical, organisational, costs, risks…). Nevertheless most of the ideas behind the IMA concept are valid and the experience gained in the aeronautic field is very profitable in order to capitalise the lessons learnt and decline for space the key drivers of what would be or should be invested instead (and as a consequence save time and money).

Already preliminary activities have been conducted and will be structured efficiently with an associated roadmap in 2008.

A clear and unambiguous signal has still to be given by all the contributing actors of the space domain in order to confirm the future of IMA for space. Would OpenSpace project be launched in 2008?

8. Acknowledgement

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9. References


10. Glossary