SYSTEMS CONCURRENT ENGINEERING OF SPACE PAYLOAD AQUARIUS INSTRUMENT

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***Abstract**: This paper presents a System Concurrent Engineering approach applied to the development of the space payload Aquarius instrument with upfront life cycle process considerations. This approach anticipates the life cycle process issues, identifying and solving problems in advance. The approach was developed by Prof. Geilson Loureiro and has been used, since 1999, in more than 200 academic and industrial examples. The paper starts by presenting the approach, the Aquarius instrument overview as part of the Argentine SAC-D satellite and the application of the approach to this space payload example.*

***Keywords**: system concurrent engineering, aquarius instrument, SAC-D, satellite.*

1 Introduction

Satellite payloads are complex systems that have the function of fulfilling the space mission core purpose. It is composed of instrument and/or equipment depending on the objectives. They are considered multidisciplinary products. They must cope with extreme environmental conditions over their life cycle. They must undergo very strict assembly, integration and testing (AIT) procedures. There are many opportunities to improve productivity over satellite payload life cycle if a concurrent engineering approach takes place from the beginning of the satellite architecting stage. Traditional systems engineering approaches do not provide an overall view of the system during its various life cycle processes. They focus on an operational product development starting from product concept of operations. They also focus on the development organization that must be put in place in order to assure that the product meets its operational requirements. A product has life cycle processes other than operations and it must be recognized from the outset in order to promote gains in productivity in the product development organization, by the avoidance of late changes, and in other product life cycle process organizations, as the product will be developed taking into consideration their requirements. Life cycle process organizations themselves can be developed simultaneously to product development, when they are part of the scope of the whole system development effort (Loureiro, 2010).

This paper aims to present a system concurrent engineering approach applied to the development of a satellite payload. The approach is different from traditional systems engineering approach because it anticipates to the early stages of system architecting the product life cycle process requirements. It proposes to simultaneously develop, from the outset, the product and its life cycle processes performing organizations. Aquarius instrument of SAC-D satellite was chosen as an example of application. It was already at the stage D (Production /Qualification and Testing) of its life cycle at the time of the preparation of this paper. The main purpose is to present the System Concurrent Engineering approach along with the life cycle process of the Aquarius instrument showing the main concepts of the approach.

The paper is organized as following: Section 2 presents the Aquarius/SAC-D and a brief introduction about Aquarius instrument. Section 3 presents the system concurrent engineering approach. Section 4 discusses the advantages and opportunities for improving the proposed approach. Section 5 concludes this paper.

2 Aquarius/SAC-D

Aquarius/SAC-D mission is a partnership between the USA space agency (NASA) and Argentine space agency (CONAE) with launch scheduled for early 2011. CONAE is providing the service platform, SAC-D, the fourth spacecraft in the Scientific Application Satellite (SAC) program, and a complement of instruments. In addition to Aquarius, NASA will provide the launch, from NASA's Western Test Range at Vandenberg AFB, and the launch vehicle, Delta-II. Aquarius data will be sent from the MOC (Mission Operation Center) to the Goddard Space Flight Center for processing salinity related information. The salinity maps will be distributed to the public and eventually archived at the Physical Oceanography DAAC at the Jet Propulsion Laboratory (Le Vine, 2006).

2.1 Aquarius

Aquarius is a combination radiometer developed by NASA's Goddard Space Flight Center, consists of three highly sensitive, temperature-stable radiometer receivers and is the primary instrument for measuring the microwave emissivity of the ocean surface and scatterometer (radar) developed by the Jet Propulsion Laboratory (JPL), will make co-aligned, polarimetric radar backscatter measurements of the ~100-150 km sea surface footprint to correct for the effects of surface roughness in the radiometer's brightness measurement, operating at L-band (1.413 GHz for the radiometer and 1.26 GHz for the scatterometer). The prominent feature of this instrument is the antenna, a 2.5-m offset parabolic reflector with three feed horns. Under NASA's Earth System Science Pathfinder (ESSP) program, the Aquarius instrument designed to map the surface salinity field of the oceans from space, together with the SAC-D bus and several instruments provided by CONAE and its partners (Le Vine, 2006, Le Vine 2008 e M. Fischman 2009).

The principal objective of the Aquarius instrument is to provide monthly measurements of Sea Surface Salinity (SSS), providing the research community data to better understanding of interaction between ocean circulation and the global water cycle. The knowledge in the salinity field is important wherefore with the changes and variations in SSS (Sea Surface Salinity) may have an impact on climate. The main data-related goals of Aquarius are to provide the first global observations of SSS, covering surface of Earth once every 7 days and delivering monthly 150-kilometer resolution SSS maps over a 3-year mission lifetime (Aquarius Mission Overview).

3 Step by step of development

The systems concurrent engineering approach has the following steps:

a) Model the system life cycle, using for example behaviour and activity diagrams (IDEF0);
b) Identify stakeholders and their interest in each life cycle process scenario identified;
c) Capture and engineer stakeholder and system requirements;
d) Identify and analyze of system functional and architecture context at every life cycle process scenario;
e) Deploy down functionally and physically the functional and architecture contexts identified composing the system architecture.

The approach starts by stating the mission or main purpose of the system together with the model of its life cycle processes. The purpose in defining the system life cycle is to establish a framework for meeting the stakeholders' needs in an orderly and efficient manner, along the life cycle. This is usually done by defining life cycle stages, and using decision gates to determine readiness to move from one stage to the next. Skipping phases and eliminating "time consuming" decision gates can greatly increase the risks (cost and schedule), and may adversely affect the technical development as well by reducing the level of systems engineering effort (Haskins, 2010).

3.1 Behaviour diagram

The Behavior Diagram is a graphical representation with control sequencing from top to bottom. While it is not shown on the graphical construct, the Behavior Diagram model allows data inputs to a function to be characterized as either triggering (a control capability) or data update (not a control implementation). The Behavior Diagram specification of a system is sufficient to form an executable model allowing dynamic validation via discrete event simulation methods (Long, 2002).

A behavior diagram was prepared to demonstrate the main steps of the life cycle of the Aquarius instruments as shown in Figure 1, from initial development to disposal of the product and then down to a second level of detailing.

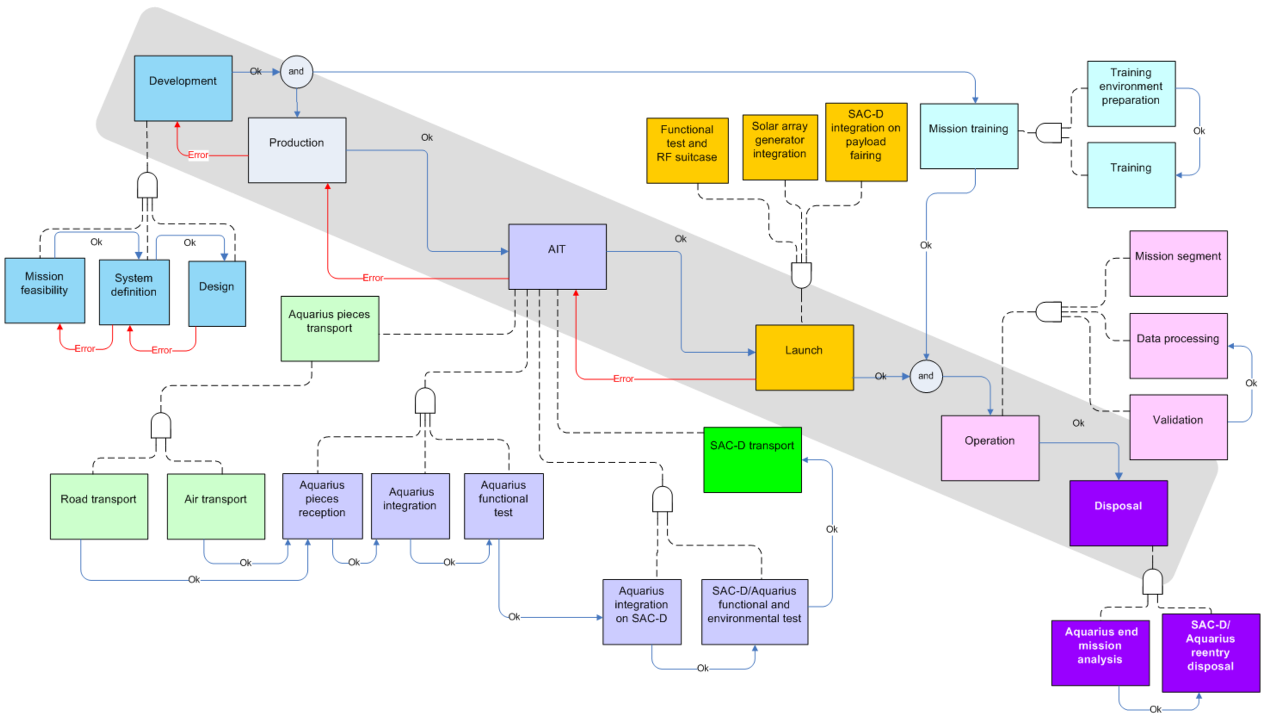


Figure 1. Behaviour Diagram.

3.2 IDFE0 diagram

For each stage of the life cycle of the product developed the IDEF 0 diagram with the inputs, outputs, controls and mechanisms, shows the key features and information exchange between the phases of the life cycle. The Figure 2 shows an IDEF 0 diagram into a higher level.

The primary content of the IDEF0 Diagram is the specification of data flow between system functions, allow the specification of control as an input to a function but does not have the capability to characterize that control in terms of constructs, as the Behavior Diagrams do. The specification of control with the IDEF0 notation is incomplete and, therefore, not executable. The IDEF0 Diagram also represents the mechanism (usually the component to which the function is allocated) which performs the function (Long, 2002).

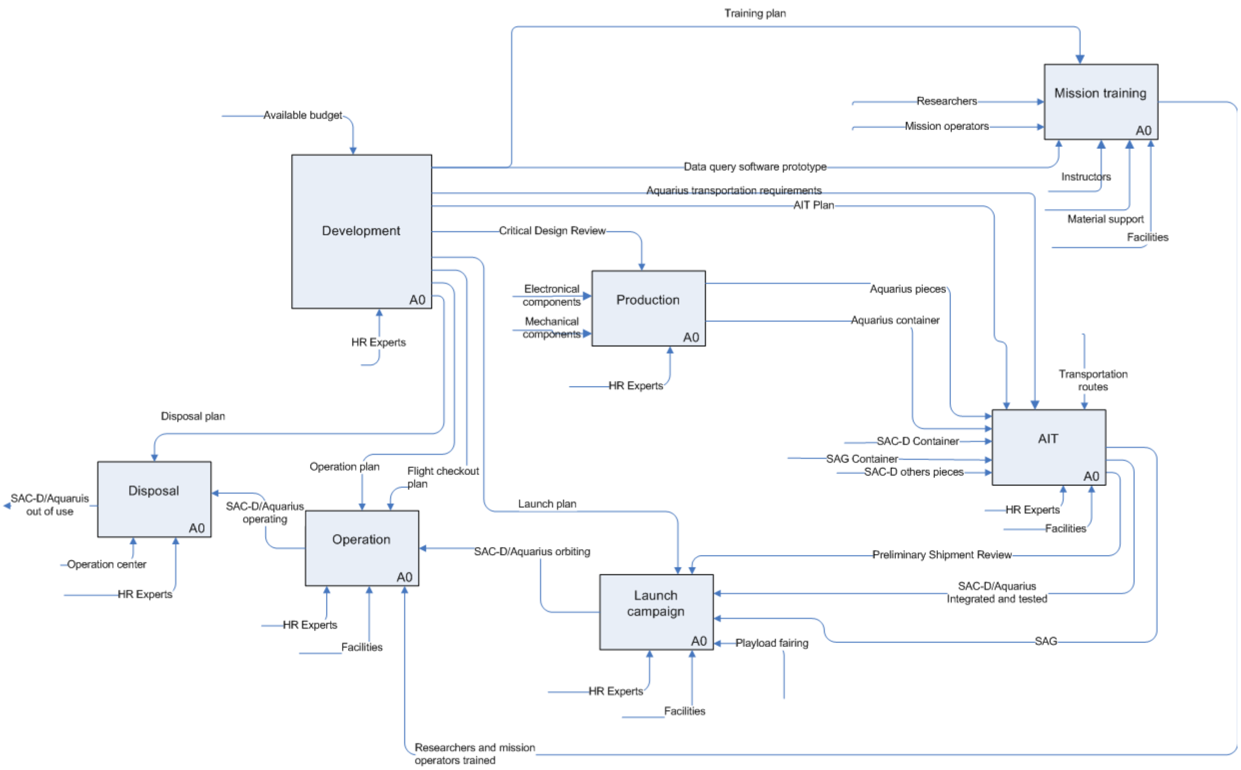


Figure 2. IDEF Behaviour Diagram.

3.3 Life cycle process identification

Diagrams presented in Figure 1 and 2 define the structure and behaviour of life cycle processes. These diagrams decompose the whole life cycle process into life cycle processes scenarios (composition or alternative scenarios). Stakeholders, functional context and architecture context will be identified at each life cycle process scenario.

For approach demonstration purposes, only four life cycle processes will be considered throughout this work. They are:

a) Integration and Data Processing processes for deriving product stakeholders, functional context and architecture context;
b) Functional testing and design processes for deriving organization stakeholders, functional context and architecture context.

3.4 Stakeholders identification

The identification of stakeholders is performed by identifying the people or organizations who are affected by the attributes of the end product, its life cycle processes and their performing organizations within the scope of the development effort. A way of identifying the stakeholders is to separate the system into product and organization elements and investigate who are the people or organizations directly interacting with each of them.
For product, a question that can be made, in order to identify stakeholders, is: ‘who are the people who directly interact with the product during its potential life cycle scenarios?’ Observe that the question covers the entire life cycle and not only the end-product use.

For organization, i.e., each life cycle process performing organization within the scope of the development effort, stakeholders are the people outside that organization who can play a role in relation to the business using the IDEF0 notation in Figure 2, stakeholders can be obtained by answering the questions 'who are the sources of inputs', 'who are the mechanisms or sources of mechanisms', 'who are the controls or sources of control', 'who are the destination of outputs'.

Product and organizations may have stakeholders in common. The aim, at this stage, is to obtain a list of system stakeholders as complete as possible no matter how each stakeholder interacts with the system. (Loureiro, 1999)

Figures 3 and 4 present the stakeholders identified for the chosen processes.

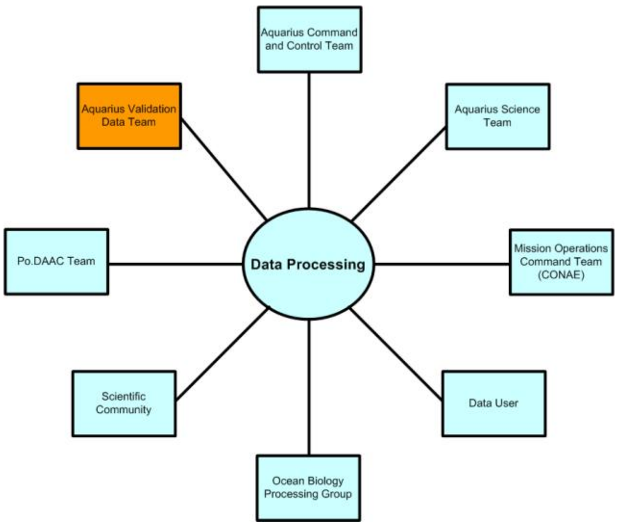


Figure 2 - Stakeholders of the product during the data processing process

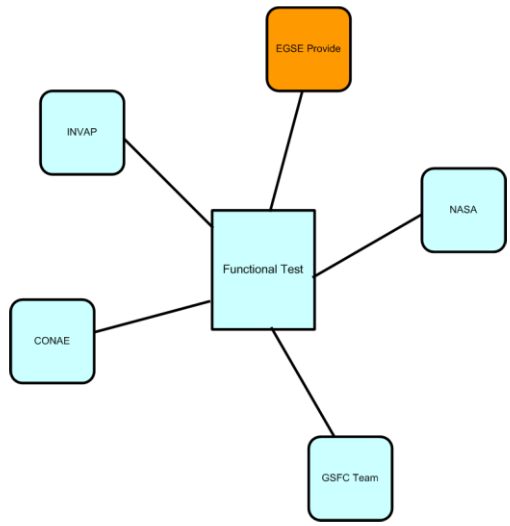


Figure 1 - Stakeholders of the functional testing organization

3.5 Interests, metric and measures of effectiveness (MOE)

For each stakeholder identified, requirements are captured and this can be made of many ways. For example, adapting the Yourdon's approach, cited by Loureiro (1999), it can be derived a systematic way of capturing stakeholder requirements. It uses the concept of 'events'. 'Events' can describe how stakeholders interact with the product, process and organization elements of the system. 'Events' have: 'stimulus' and 'response'. 'Stimulus' will derive the 'condition' information related to a requirement. 'Response' will derive the 'function' information of the requirement. The term 'metrics' is defined as: 'A measure of the extent or degree to which a product possesses and exhibits a quality, a property or an attribute' (Sprole, 1998).

These metrics are used to assess the stakeholders' needs satisfaction in order to assist in defining system requirements. Cited by Loureiro (1999), the IEEE-1220 standard defines measures of effectiveness as the metrics by which the customer will measure satisfaction with products produced by the technical effort. Measures of effectiveness reflect overall customer expectations and satisfaction. Key measures of effectiveness may include performance, safety, operability, reliability, and maintainability, or other factors.

A way of identifying measures of effectiveness is to identify the stakeholder concerns towards product, processes and organization. Concerns may also be used as a criteria for grouping requirements. The table 1 show interests, metrics and measures of effectiveness identified from stakeholder needs

Table 1. Interest of GSFS team.

Goal	Metrics	MOE
Visibility at NASA	1. Project delivered on schedule 2. Project delivered within cost 3. Projeto delivered in compliance with all requirements	1. Ready before the activities manufacturing 2. Cost exceeded from budget 3. Number of waves
Get the requirements of radiometer	1. Maximum Weight 2. Working range Radar 3. Lifetime	1. kg value 2. GHz value 3. years amount

3.6 Stakeholders and system requirements

The stakeholder requirements govern the system's development; and they are an essential factor in further defining or clarifying the scope of the development project. If an enterprise is acquiring the system, this process provides the basis for the technical description of the deliverables in an agreement – typically in the form of a system level specification and defined interfaces at the system boundaries (Haskins, 2006).

Table 2 shows the requirements that stakeholders must be able to perform and what the system must respond. Stakeholder and system requirements are captured with the life cycle perspective as mentioned earlier in this paper.

Table 2. Stakeholders and system requirements.

Number	Stk should be able to	The System should	Concern	Type	Compliance	Satus	PPO	Constraint	Verifiability	
									T/I/D	Procedure
R003	Define the number of screws for system integration in the SAC-D	Have no more than 40 screws to be integrated into the SAC-D	Integration	C	M	OK	Prod		I	xx.3
R004	Measure the total time of mechanical integration to SAC-D	Promote the integration of mechanical agility to SAC-D in a time not exceeding 48 hours	Integration	F/D	M	OK	Prod		T	xx.4

For each life cycle process, a context diagram is derived. The context diagram shows the system during a given life cycle process scenario in the central bubble, the elements in the environment outside the system and the flows of material, energy and information between system and environment. Figure 5 presents an example of such context diagram adding states of the elements of the environment that can drive modes of performing the process related to the central bubble.

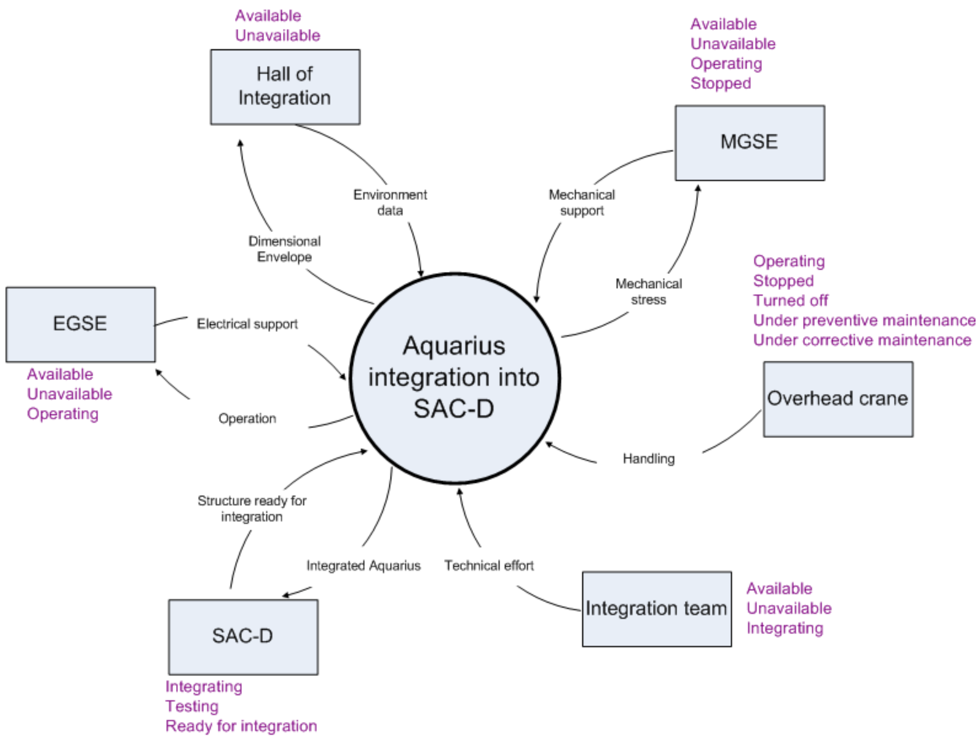


Figure 5. System context diagram.

Table 3 relates the states of the elements in the environment with modes of integrating the Aquarius payload into the SAC-D platform.

Table 3. Modes of 'Aquarius Instrument Integration on SAC-D'

The environment is ready to perform the integration activity of the SAC-D Aquarius	
Normal mode	
Environment	Status
MGSE	Operating
Overhead crane	Operating
Integration team	Available
SAC-D	Ready for integration
EGSE	Operation
Integration hall	Available

The environment is being prepared for integration activity	
Setup mode	
Environment	Status
MGSE	Stopped
Overhead crane	Under preventive maintenance
Integration team	Unavailable
SAC-D	Ready for integration
EGSE	Unavailable
Integration hall	Unavailable

The functional context diagram is the starting point for identifying the functions that the system must perform within each mode of performing a given life cycle process. From Figure 5 and Chart 3, functional and performance requirements can be derived for the product so that it can cope with the needs of the integration organization represented by the elements in the environment outside the system and interacting with it.

3.7 Architecture context diagram

The architecture context diagram depicts the system during a given life cycle process scenario, the elements in the environment outside the system interacting with it and the physical connections between the system and the environment. Instead of the flows in the context diagram (see Figure 5), the architecture context diagram depicts the physical interconnections that will support those flows. The architecture context diagram allows that physical external interfaces to be identified early in the development process and with a life cycle perspective. Figure 6 shows an example of such an architecture context diagram for the Aquarius instrument during its integration process.

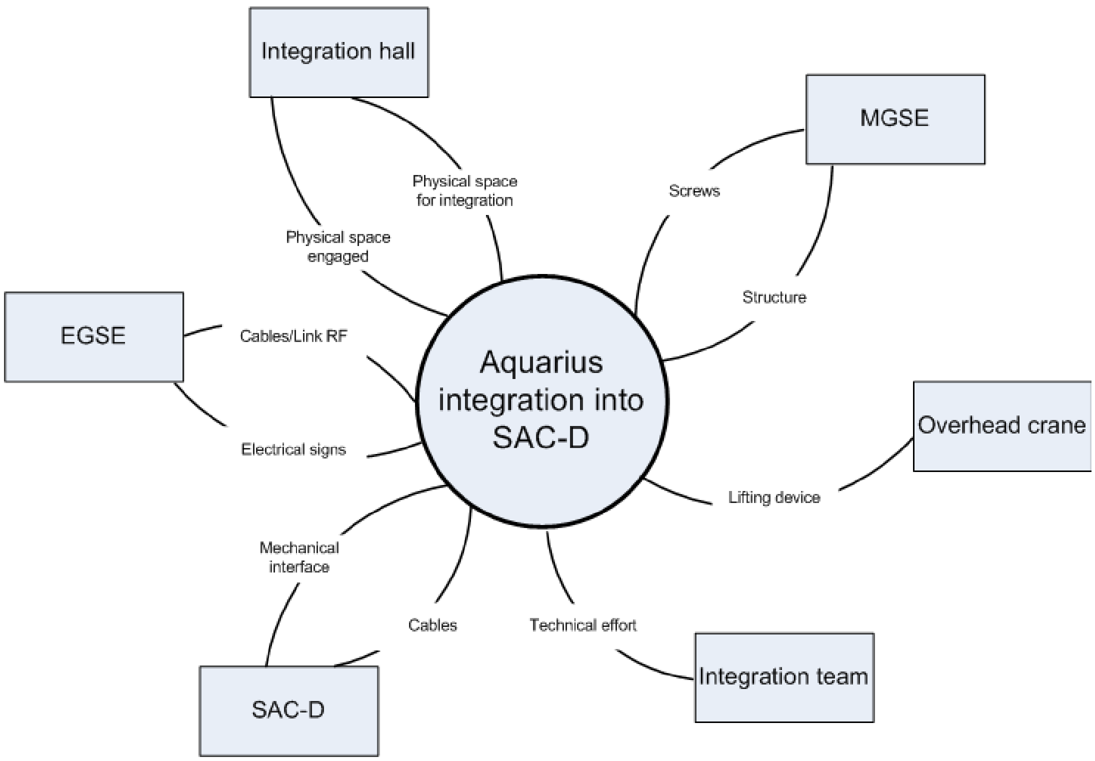


Figure 6. Architecture context diagram

3.8 Hierarchical decomposition of the context diagram

High level system requirements are progressively decomposed into subsystem and component requirements. This is done in any systems engineering exercise. However, using the systems concurrent engineering approach, as the context diagrams were produced for every system scenario, requirements on the system will be systematically captured for every life cycle process. System functional and physical architectures must represent the structure and behaviour of the system.

Figures 7 and 8 represent the functional structure and behaviour of the system during its integration. Figure 9 represent the physical structure of the system during integration.

Of course there are elements in the approach, that is also part of the traditional systems engineering approach, that were not shown in this paper. For example, hazard and risk analysis are also performed from each context at every scenario. Table 4 show an allocation matrix that is also an element of the traditional systems engineering

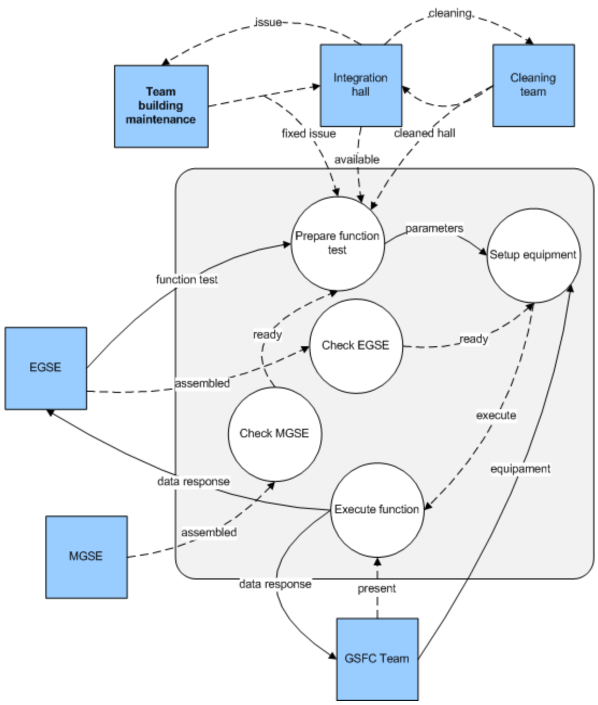


Figure 7 – Functional structure of the Aquarius during integration

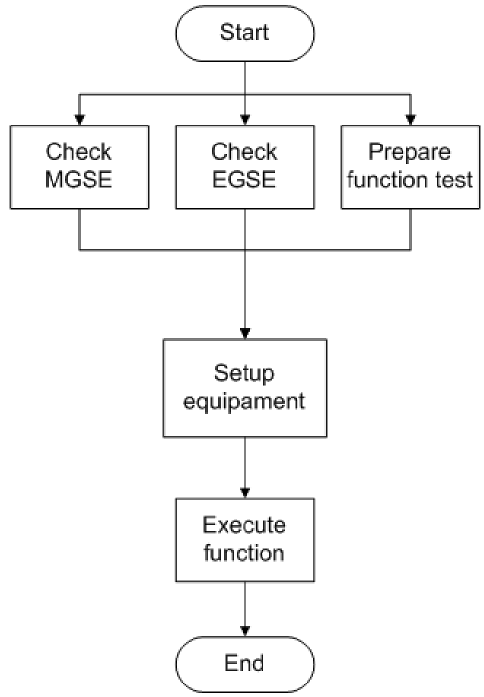


Figure 8 - Functional behaviour of the Aquarius during integration

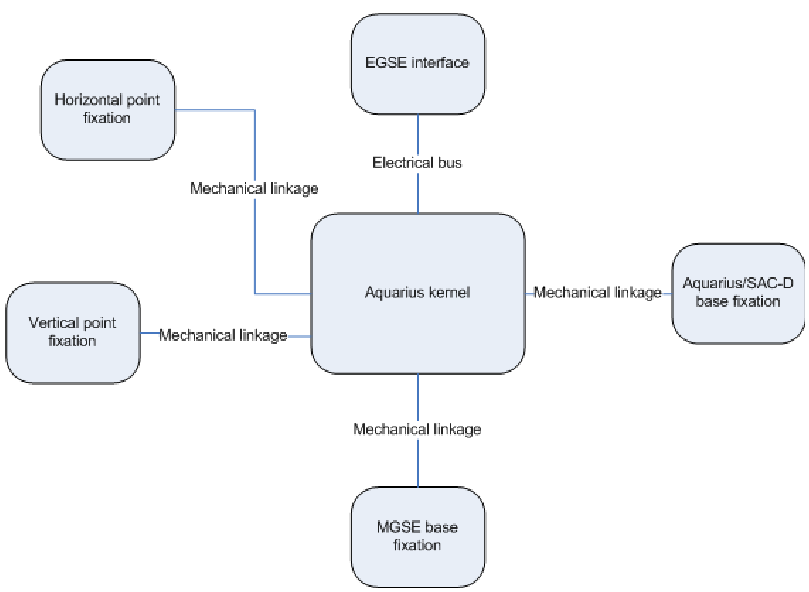
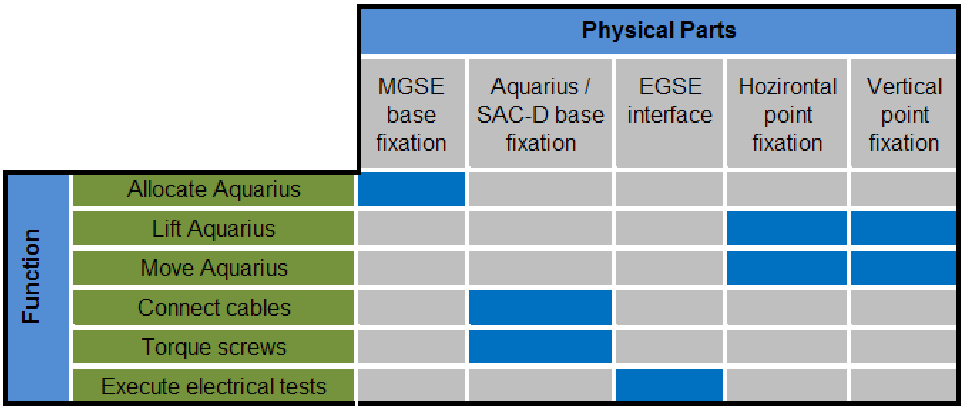


Figure 9. Physical structure of the Aquarius during integration

Table 4. Allocation Chart (As an example the physical part "horizontal clamp point implements the functions of Hoisting Aquarius and Moving Aquarius" as show below.)



4 Discussion

In this section we discuss the difference between traditional and system concurrent engineering approach for a better understanding. We should not consider only customer and user as stakeholder of interest as in the traditional approach, but stakeholders related to all process of product life cycle must be taken into consideration.

In the traditional systems engineering approach the functional context analysis are performed only for operational scenarios of the product and for product development organization processes. However a system solution is composed by product and organization elements and any other elements that must be considered for the mission success.

In the systems concurrent engineering approach requirements of entire product life cycle can be anticipated to the initial phase of system architecting process, where the stakeholder and system requirements are captured for all product life cycle process scenarios. The anticipation of those requirements will allow for less changes during product development and life, reduced time to delivery and, therefore, reduced cost. The more complex the system, the greater the potential for productivity gains by using the systems concurrent engineering approach.

5 Conclusion

This paper presented a system concurrent engineering approach for a satellite payload. The proposed approach presented how life cycle process requirements can be anticipated to the early stages of the development of a system. Concurrent engineering has been traditionally successful for the development of parts and this approach shows a way of using it also for the development of complex systems. The paper focused on the product elements of the Aquarius payload but the same approach is also used to develop the organization elements of the system. Details on how to develop simultaneously the product and organization elements can be found in the paper "Lessons learned in 12 years of space systems concurrent engineering" (Loureiro, 2010).

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