LLRF SYSTEM REQUIREMENTS ENGINEERING FOR THE EUROPEAN XFEL

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Abstract

The LLRF system of the European XFEL must fulfil the requirements of various stakeholders: Photon beam users, accelerator operators, RF experts, control system, beam diagnostics and many others. Besides stabilizing the accelerating fields the system must be easy to operate, to maintain, and to upgrade. Furthermore it must guarantee high availability and it must be well understood. The development, construction, commissioning and operation with an international team require excellent documentation of the requirements, designs and acceptance test. For the RF control system of the XFEL the new system modelling language SysML [1] has been chosen to facilitate the systems engineering and to document the system. SysML uses 9 diagram types to describe the structure and behaviour of the system. The hierarchy of the diagrams allows individual task managers to develop detailed subsystem descriptions in a consistent framework. We present the description of functional and non-functional requirements, the system design and the traceability between requirements and system design.

INTRODUCTION

The LLRF system of the European XFEL is complex due to the large system scale and the need for automation including exception detection and handling. The requirements from all the stakeholders should be collected and considered for system design.

Requirements engineering provides formal methodologies for requirements collection and analysis, the typical processes include [2]

- Stakeholder analysis: identify the persons and external systems that will involve the LLRF system design and will be potential to raise requirements.
- Requirements elicitation: capture requirements from the information provided by the stakeholders.
- Requirements modelling: express the requirements in structured way, model the system interfaces, data/signal types and interactions.
- Requirements analysis: completeness checking, consistency checking and traceability analysis, and so on.
- Requirements verification: review and verify the requirements by the stakeholders.

LLRF SYSTEM FOR EUROPEAN XFEL

The architecture of the RF system for the European XFEL is shown in Figure 1. A power amplifier provides the RF power necessary for establishing the accelerating fields in the cavities. The cavity field is measured and then compared to a set-point. The resulting error signal is amplified and filtered and drives a controller for the incident wave to the cavity. A frequency and phase reference system provides the necessary RF signals. Frequency tuner (motor and piezo) are used for slow and fast resonance control. The timing system provides triggers for pulsed operation and clocks for data acquisition.

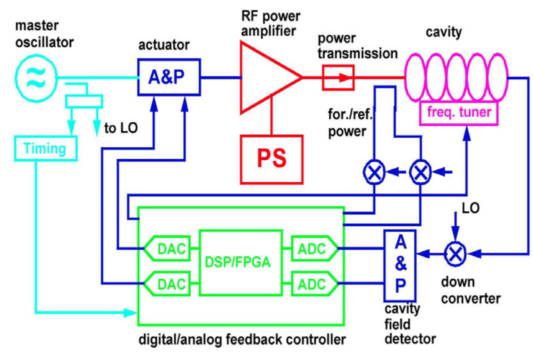

Figure 1: LLRF system architecture.

The LLRF system for the European XFEL has the features listed below

- High field stability requirements: up to 0.003% for amplitude and 0.005 deg. for phase.
- Large scale: it has more than 30 RF stations and for each RF station, there are up to 32 cavities to be controlled, and there are around 300 analog signals and 3000 digital signals to be processed.
- The development is carried out by international teams.
- The system utilizes many different technologies which belong to different domains, such as RF signal processing, digital and analog hardware, digital signal processing, cavity theory, and so on.

In order to handle the complexity of the system, the formal systems and requirements engineering methods will be used for system design and the Systems Modelling Language (SysML) will be used for system description.

SYSML LANGUAGE

SysML is a Domain-Specific Modelling language for systems engineering. It supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems. SysML was originally developed by an open source specification project, and includes an open source license for distribution and use. SysML is defined as an extension of a subset of the Unified Modelling Language (UML) using UML's profile mechanism. SysML uses seven of UML 2.0's thirteen diagrams, and adds two diagrams

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(requirements and parametric diagrams) for a total of nine diagram types. SysML also supports allocation tables, a tabular format that can be dynamically derived from SysML allocation relationships.

The SysML diagrams are shown in Figure 2.

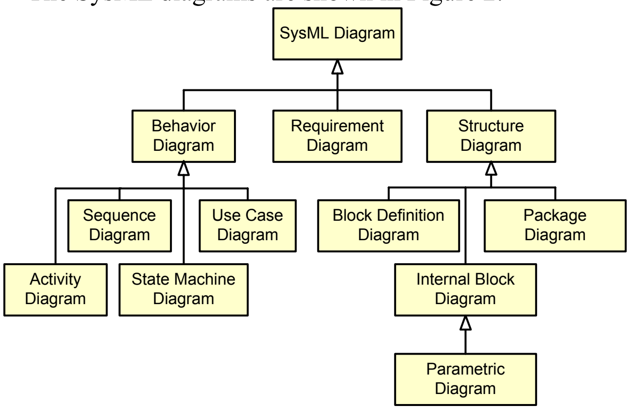

Figure 2: SysML diagrams.

REQUIREMENTS ENGINEERING FOR LLRF SYSTEM

The requirements engineering processes are applied to the LLRF system for the European XFEL. The top to down approach is used, which analyze the system requirements and interfaces in a staged and recursive way (Figure 3). Firstly, the LLRF system is viewed as a black box, the user requirements from the stakeholders to the LLRF system will be collected and analyzed, the external visible interfaces will be defined, the data/signal types through the interfaces will be modelled, and the interaction between the LLRF system and the stakeholders via the interfaces will be specified. And then, the LLRF system will be break down to subsystems (gray box), the same activities such as requirements specification, interface definition and data/signal types modelling will be carried out on each subsystem. Similarly, the system will be break down further and same analysis will be carried out until to the components level (white box) which is ready for hardware and software design.

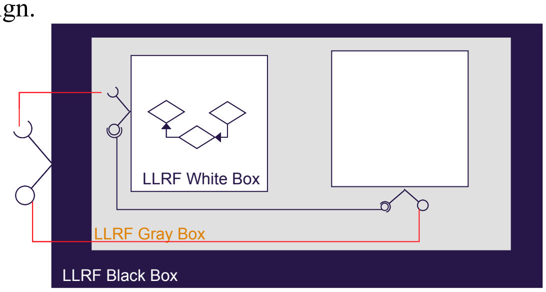

Figure 3: Staged and recursive strategy for requirements engineering development (the nested interfaces from black box to gray box are shown).

The results of requirements engineering are promising for specifying the LLRF system. Here shows the results and progresses for the LLRF requirements engineering at black box stage.

Stakeholder Analysis

The stakeholders of the LLRF system include all the persons and external systems which will influence or interact with the LLRF system. For stakeholder analysis, the questions below should be answered

- Which persons are involved in the project?
- Which roles can be differentiated?
- Which are the most important stakeholders (priorization)?
- How can external stakeholder be involved?
- What is their capability level regarding systems engineering and SysML?

Based on the stakeholder analysis, the LLRF system context can be identified, which is shown in Figure 4.

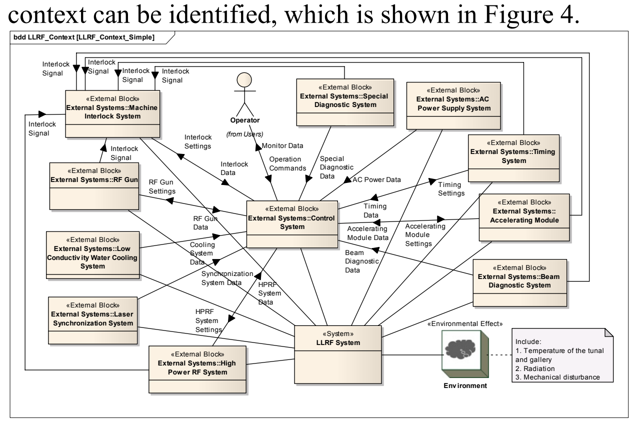

Figure 4: Context diagram of the LLRF system for the European XFEL.

Requirements Elicitation

The requirements are collected from the stakeholders and then analyzed; the requirements structure and traceability are shown in Figure 5. And Figure 6 shows some examples of the user requirements.

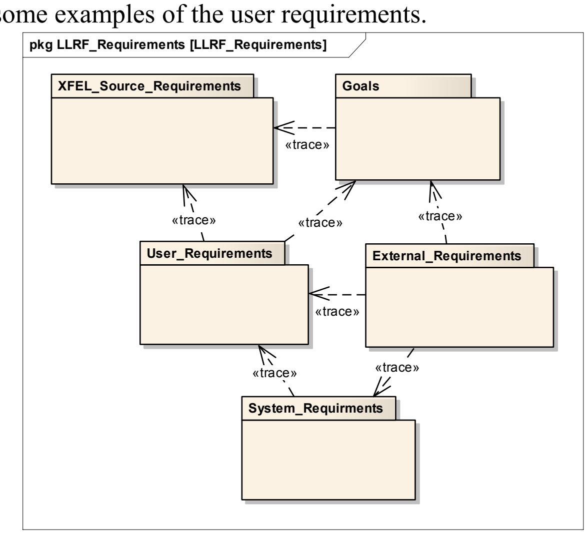

Figure 5: The structure and traceability of the LLRF requirements.

[USER REQUIREMENTS]

ID	Name	Text
UR1	Set RF field voltage and phase for each RF station	The user should be able to set the RF field voltage and phase to defined working point for each RF station with the LLRF system
UR1.1	Change rate of the RF field voltage and phase	The change rate of the RF field voltage and phase in different linac sections are: * Gun, L0: Once per day * L1, L2: Once per shift * L3: Frequently, +/- 1.5% within pulse train, larger voltage and phase change may happens within 1 minute
UR1.2	RF field voltage setting range	The required range for RF field voltage settings of an RF station is: * 0 * V_min to V_max The V_max is defined by the cavity limits and klystron power limits experimentally
UR1.3	Time available for RF field voltage change	Changing the RF field voltage for beam energy adjustment in the main linac should take less than 1 minute
UR2	Maintain RF field stability	Maintain stability of voltage and phase of the RF field of individual RF stations within given tolerances for the range of useable operating parameters
UR2.1	Phase and amplitude stability definition	The stability of the RF field is defined by the amplitude and phase error referred to the set point (may be time varying)
UR3	Provide RF reference signals	Provide highly stable RF references at specified frequencies at selected locations,

Figure 6: Examples of the LLRF user requirements.

Interfaces and Interactions

The interfaces between the LLRF system and the external systems shown in the context diagram are modelled with SysML. As an example, the interfaces between LLRF system and Accelerator Module are shown in Figure 7. The interactions between LLRF system and the external systems via the interfaces are modelled with use case and sequence diagrams, which are shown in Figure 8 as an example.

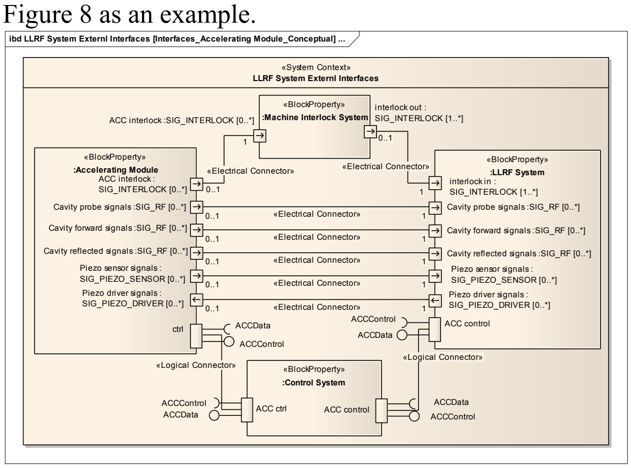

Figure 7: Example – LLRF external interface with accelerator module.

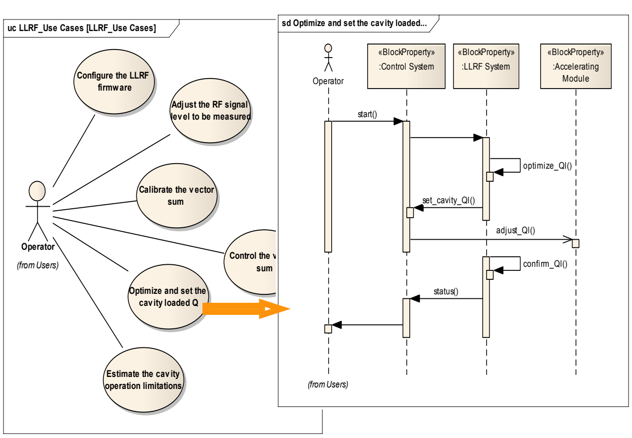

Figure 8: Example – Use case diagram and sequence diagram for interaction modelling.

Functional Breakdown Structure

Based on the system requirements, the LLRF functional breakdown structure can be defined which shows the system structure in the viewpoint of functions.

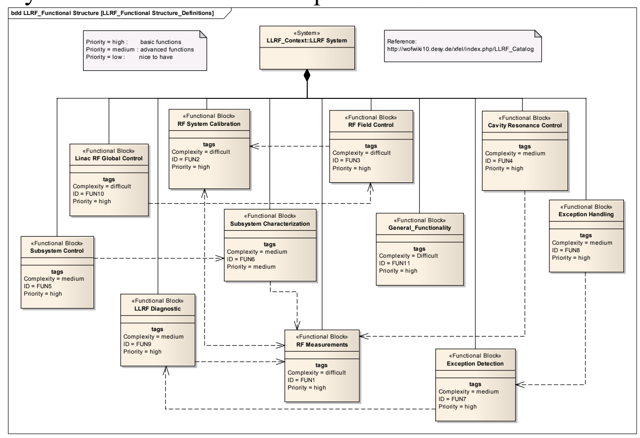

Figure 9: LLRF functional break down structure.

Requirements Verification

The system requirements should be verified by checking if it can be fulfilled by the system design like the functional structure. In the system design stage, the requirement verification must be done from time to time. Figure 10 shows an example of the requirement verification with SysML.

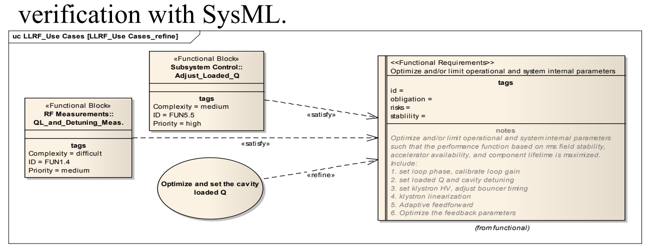

Figure 10: Requirements verification.

CONCLUSION AND OUTLOOK

Requirements engineering approach works well for LLRF requirements capture and analysis. The LLRF black box analysis is ready for the Conceptual Design Review (CDR). The future plan is to perform the gray box (subsystem level) analysis, including trace subsystem requirements to high level system requirements, subsystem interface definition and interaction modeling, system architecture design (partitioning the functional structure to hardware/software structures) and system internal behavior modeling. And the final goal is to finish the full requirements specification for the LLRF system.

REFERENCES

[1] Weilkiens, T., “Systems Engineering with SysML / UML”, 1st edition, 2008, Morgan Kaufmann Publishers Inc., ISBN 0123742749.

[2] Goguen, J. & Jirotka, M. (Ed.). (1994). Requirements Engineering: Social and Technical Issues. London: Academic Press.