Application of SysML to design of ATCA based LLRF Control System

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***Abstract*—The paper presents the methodology of design of ATCA based LLRF system for XFEL linear accelerators. The LLRF system is used to control RF field in superconducting accelerating cavities regulating amplitude up to 0.03% and phase up to 0.03 deg. It is complex mixed analogue-digital control with latency of order of few tens of nanoseconds. The ATCA architecture was chosen due to high availability and reliability. The system design process is based on systematic and formal approach using SysML language and tools. This modern methodology changes the way of system description from "document centric" to "model centric". It allows easy communication inside the designers team that is very important in wide international collaboration. In the design process the Use Case description of system functionality was applied. The hierarchical structure and requirements for subsystems was derived from the top level requirements and defined functionality of the system. The functions of various SysML diagrams are presented together with discussion which parts of the system are best described by which diagram type. Both structural and functional views of the system are presented. Since the discussed LLRF system will have distributed architecture the particular effort was put on interfaces description. The SysML tool used in the project was used not only to build SysML model but also allows to estimate project cost using Use Case Points method. This feature is very beneficial in preparation of the project budget.**

***Index Terms*—LLRF, Accelerator, SysML, ATCA.**

I. Introduction

THE XFEL (X-Ray Free Electron Laser) will be build in the next few years at DESY Hamburg [1]. The laser will be driven by electron linear accelerator controlled by the LLRF system. The control system must be designed in a robust fashion since the components placed in the tunnel are not accessible during accelerator operation. It must fulfill the requirements of various stakeholders: photon beam users, accelerator operators, RF experts, controls 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 components of the hardware platform should be available for 20 years of expected machine operation. Therefore the new hardware architecture was chosen based on ATCA telecommunication standard. It is a modern architecture and it is expected to exist for the long time in the market. It has built-in features supporting extremely high availability as well (up to 0.99999). The design process of the new LLRF system is being carried by wide international collaboration. Therefore the easy communication of designers and good documentation of the system is crucial. I has decided that a modern System Engineering design methodology will be used in the project. The project documentation must be prepared in a way assuring consistency with the system model. It must be easy readable, easy understandable, complete and up to date. It should also support the costing of design and production of the system.

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Manuscript received October 25, 2008; revised November 23, 2008.

II. System Engineering

The system engineering is an area of engineering science that helps to deal with complex and heterogeneous systems that cannot be designed efficiently with traditional design methodologies. The need for systems engineering arose with the increase in complexity of systems and projects. Systems engineering encourages the use of tools and methods to better comprehend and manage complexity in systems. It organize the design process starting from requirements analysis. Then alternative solutions of the design problem should be investigated and evaluated. For that purpose the models of the system must be developed and evaluated against the compliance with requirements taking into account the overall aspects: operation, time, test, production, cost and planning, training and support and disposal. System engineering requires special languages to communicate design ideas between the engineers from different disciplines in the project.

III. SysML language

SysML is defined as an extension of a subset of the Unified Modeling Language (UML) using UML's profile mechanism. SysML uses seven of UML 2.0's thirteen diagrams, and adds two diagrams (requirements and parametric diagrams) for a total of nine diagram types (Table I) [12], [13]. The hierarchy of the diagrams allows individual task managers to develop detailed subsystem descriptions in a consistent framework.

IV. LLRF system for XFEL

The main part of XFEL accelerator will be superconducting Linac consisting of 24 RF stations. The single RF station of XFEL will consist of 4 accelerating cryhomodules (each composed of 8 superconducting cavities) and a klystron supplying the RF power controlled by the LLRF system [1]. The RF system will have similar architecture as the one operated presently in FLASH (**F**ree-Electron **LAS**er in **H**amburg) [2],

TABLE I
DIAGRAM TYPES

SysML Diagram	Purpose
Activity	Show system behavior as control and data flows. Useful for functional analysis.
Requirement diagram	Show system requirements and their relationships with other elements. Useful for requirements engineering.
Block Definition diagram	Show system structure as components along with their properties, operations and relationships. Useful for system analysis and design.
Internal Block diagram	Show the internal structures of components, including their parts and connectors. Useful for system analysis and design.
Use case diagram	Show system functional requirements as transactions that are meaningful to system users. Useful for specifying functional requirements. (Note potential overlap with Requirement diagrams.)
Sequence diagram	Show system behavior as interactions between system components. Useful for system analysis and design.
Parametric diagram	Show parametric constraints between structural elements. Useful for performance and quantitative analysis.
State Machine diagram	Show system behavior as sequences of states that a component or interaction experience in response to events. Useful for system design and simulation/code generation.

[7]. The LLRF (Fig. 1) of the XFEL will be designed as a closed loop digital control (identical to the LLRF operated in FLASH).

The LLRF control system has to drive RF stations keeping stable amplitude and phase of RF field in cavities (with given accuracy) in spite of beam influence, noises and drifts in the system and other disturbances. It has to react properly on various events like cavity quench, excessive radiation level, beam loss and vacuum degradation. This exception handling is omitted in the Fig. 1 but it plays an important role in the designed system.

The state of RF electromagnetic field filling the accelerating cavities is measured by sensors determining electric field, forward power and reflected power signals (Vacc, Ainc, Aref - see Fig. 1). All of them are RF signals and their digital processing requires downconversion to intermediate frequency (IF) signals, preserving information about the amplitude and phase of RF field. The IF signals are sampled by ADCs (Analogue to Digital Converters) and the computation block has to calculate the I and Q (**I**n phase and **Q**uadrature) components [10]. Consequently the I and Q components of the original RF signal will be determined. The samples of accelerating voltages (Vacc - see Fig. 1) from all cavities driven by the same RF power station (klystron) are used to calculate the vector sum. The current value of vector sum is compared to the setpoint and the error signal is driving a regulator that can be a simple PI controller or much more complex filter [6], [8], [9]. Regulator outputs (I and Q) drive the vector modulator through DACs (Digital to Analogue Converter), providing the required input signal to the klystron which drives the cavities. The cavities should be tuned to resonance at RF frequency (1.3 GHz). One of the problem is to compensate the Lorenz force that for high field gradient detune the cavities from resonance due to their mechanical deformation (Lorenz Force Detuning - LFD). For that purpose the piezo tuners (PZT - see Fig. 1) excite the cavity mechanically in a way that compensates the deformation caused by electromagnetic field [6]. Signals from several other systems (e.g. vacuum, cryho, laser) are connected through the control system based on DOOCS (Distributed Object-Oriented Control System) [11].

The design of ATCA based new LLRF control system for XFEL is currently a work in progress and it is far from being completed. On the other hand even in this early stage the SysML model of the system is quite large. Therefore this paper presents only the part of the project. The authors focused on the top level view of the system and the piezo compensation system for Lorenz Force Detuning (Piezo Controller).

A. Requirements for LLRF system

The majority of requirements for LLRF system comes from the top level requirements for the machine [2], [3], [4], [5]. For example one of the main requirement concerning the performance of LLRF system is the regulation precision (i.e. 0.03% for amplitude and 0.03 deg. for phase) needed for stable beam. But there are many other requirements concerning reproducibility, reliability, operability and performance. The simplified requirements diagram for the LLRF system showing the main categories of requirements is presented in Fig. 2.

More detailed look into requirements diagram for Piezo Controller system is presented in Fig. 3. The main performance requirement for Piezo Controller (compensate LFD up to 500Hz) and the derived requirements for the piezo driver are placed in this diagram. It is indicated in the diagram that piezo driver satisfies the requirements on bandwidth and maximum output voltage and current. There are also another requirements concerning reliability and piezo life-time management. They are not satisfied at the current stage of the project.

The requirements diagram in SysML allows to propose and approve requirements and indicate which system elements satisfy the requirement. It is also possible to search the project for not yet satisfied requirements.

B. Context Diagram

After the requirements are collected the context diagram of the system should be prepared (Fig. 4). It presents the system under development as a blackbox with connections to all interfaced systems. The context diagram also shows actors - the direct interaction partners for which services and interfaces have to be developed. In the case of LLRF system the actors are machine operators. It should be noted that operators do not contact LLRF system directly but rather through the control system. The context diagram allows to determine the initial information flows between the LLRF system and the environment.

C. Structural description

The structure of the system is represented in SysML in the form of Block Definition Diagrams (BDD - see Fig. 7) and Internal Block Diagrams (IBD - see Fig. 8). The BDD defines the components (blocks) used to build the system and their relationships (like generalization, association, nesting and dependency). It does not show the connections between blocks! The internal structure of the system together with the interfaces to other parts is described in IBD. The piezo controller is interfaced to some part of LLRF system providing the data about detuning (Low Level Application that computes detuning on the base of RF signals) and on the other side it is connected to the piezo actuator driving it with the compensating pulse. The additional piezo sensor probes the mechanical vibrations of the cavity that is used to compensate microphonics.

D. Behavioral description

The behavioral description of the system is defined by the Use Case diagrams supported by Activity Diagrams and Sequence Diagrams, both related to the execution of particular use case. The set of use cases for the whole LLRF system is presented in Fig. 5. It consist of use cases covering normal operation of the machine (including startup), commissioning, maintenance and diagnostic. Much simpler set of use cases was identified for Piezo Controller (See Fig. 6). The use case is described by corresponding activity and sequence diagram. For the Use Case “Compensate LFD” the activity diagram is presented in Fig. 9. The execution path includes reception detuning data from previous pulse through the data link, computation of parameters of compensating pulse, upload the pulse waveform to the output generator and two activities executed in parallel: pulse generation and recording data from piezo sensor. The same execution path is presented in sequence diagram (Fig. 10) but from different perspective. This diagram presents the detailed signals and data flow between the system components. The sequence diagram also shows how activities are allocated to the system components.

V. Cost estimation

The project cost consist of two main components: hardware costs and sotware costs. The hardware costs can be estimated on the base of market prices for the system components but the software cost is much more difficult to estimate. The system engineering and the use case description of the system functionality offer the possibility to estimate software cost. The use cases related to system functionality can be evaluated in terms of effort needed to implement the software. There are numerical rules allowing assignment of the cost to the use case basing on the use case complexity (maesured in terms of transaction numbers etc.). The modern SysML tools already includes needed rules and equations but several scaling factors must be tuned to obtain results close to the reality. The Fig. 11 presents the estimation of the cost for the three use cases defined for Piezo Controller.

VI. Conclusion

Complex systems such as the LLRF control for the European XFEL require work-processes and tools to guarantee a successful outcome. The attempt to combine of modern system engineering methodologies with the modeling language SysML and the SysML Modeling tool Enterprise Architect (EA) has proven to be very promising in a large international collaboration between research labs, universities and industry.

Acknowledgment

The authors would like to thank Mr. Tim Weilkiens for his support and valuable discussions.

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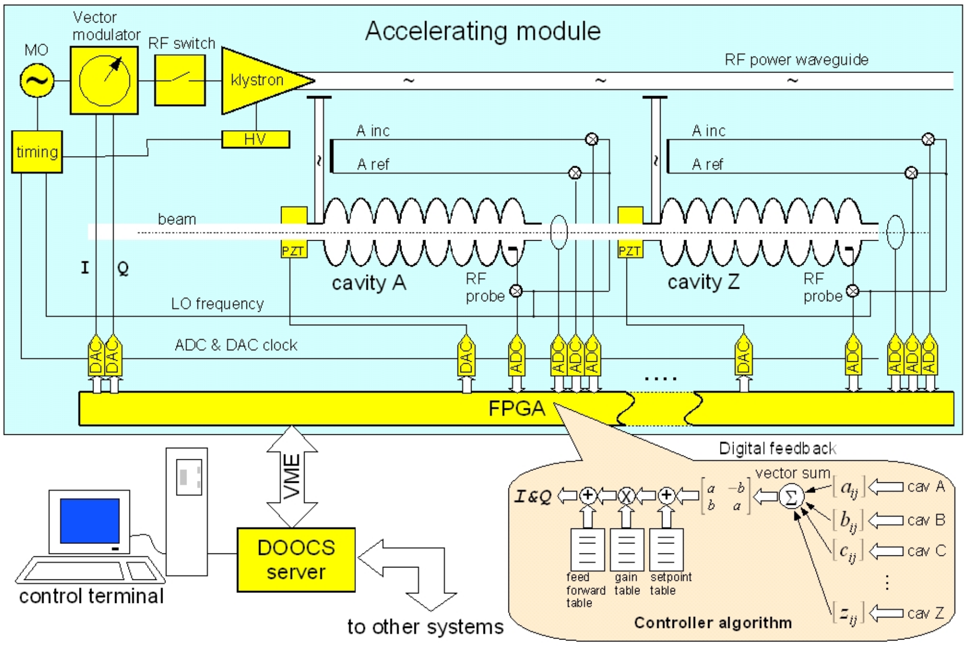

Fig. 1. LLRF system - simplified diagram

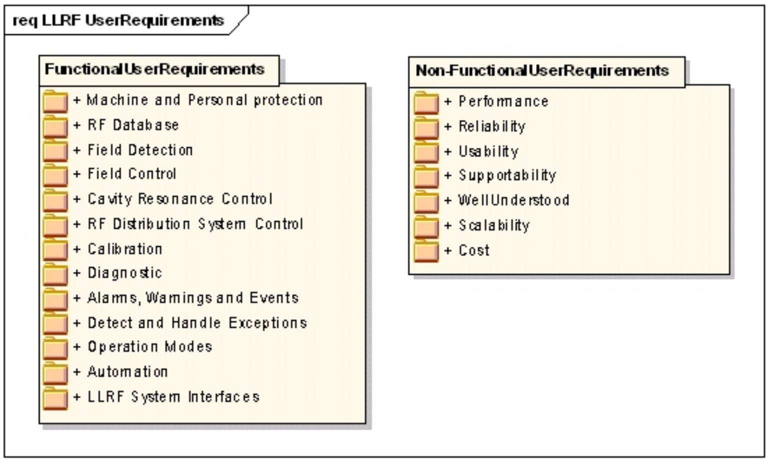

Fig. 2. Requirements categories for LLRF system

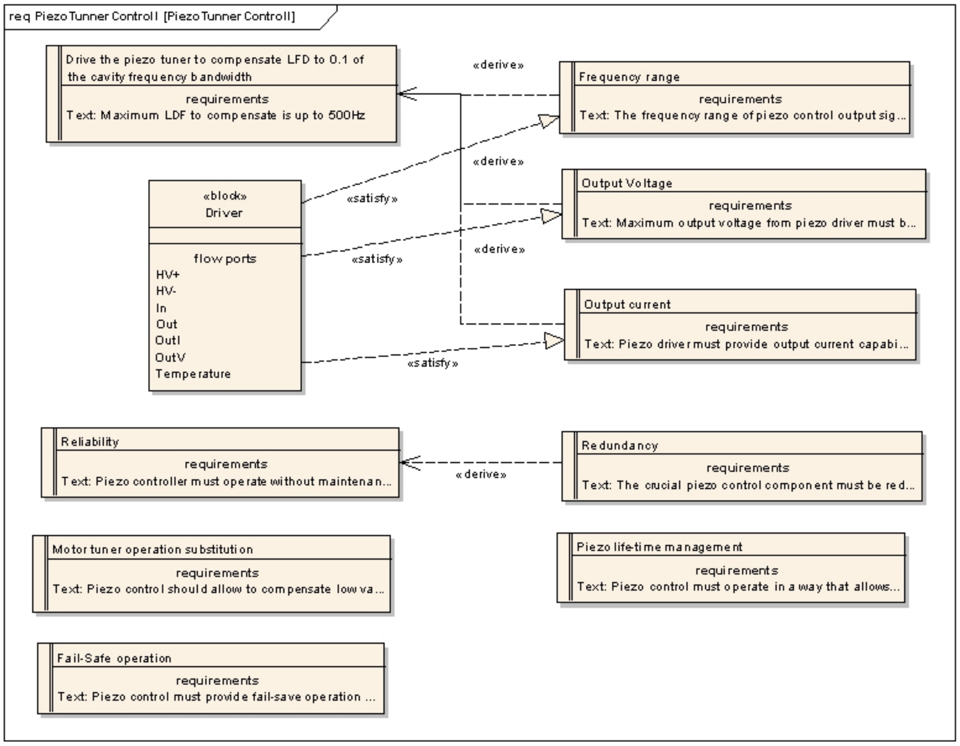

Fig. 3. Requirements diagram for Piezo Controller

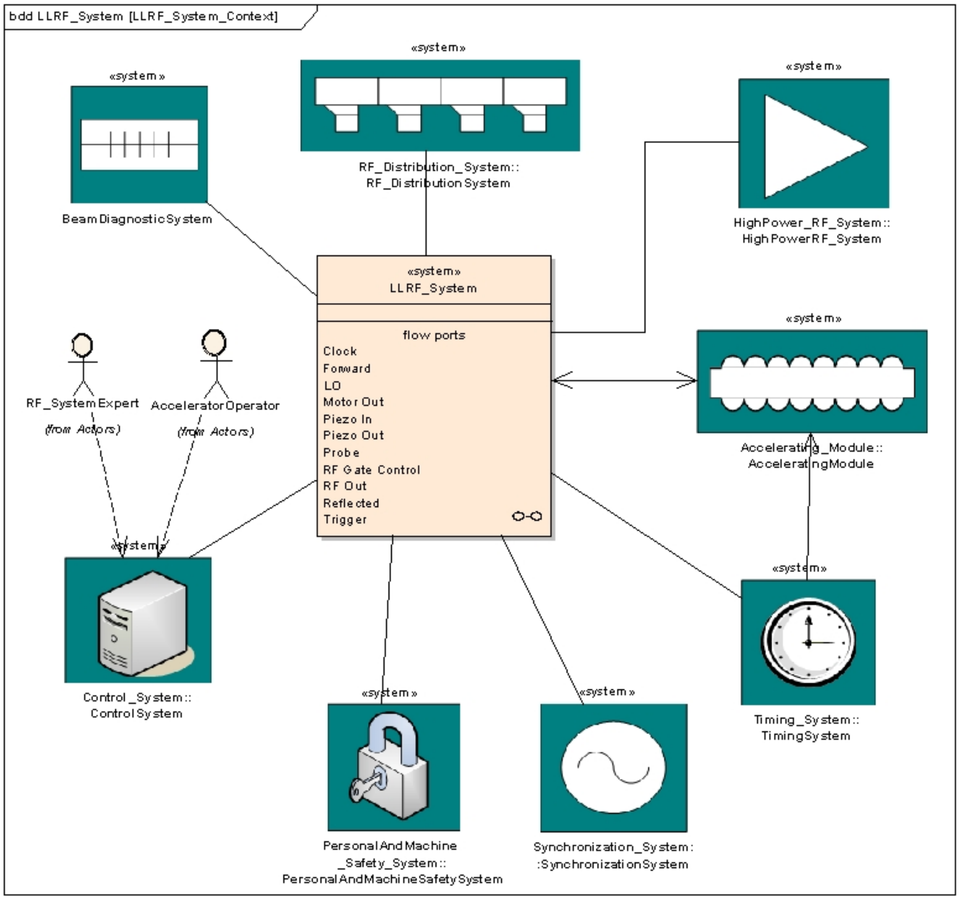

Fig. 4. Context diagram for LLRF system

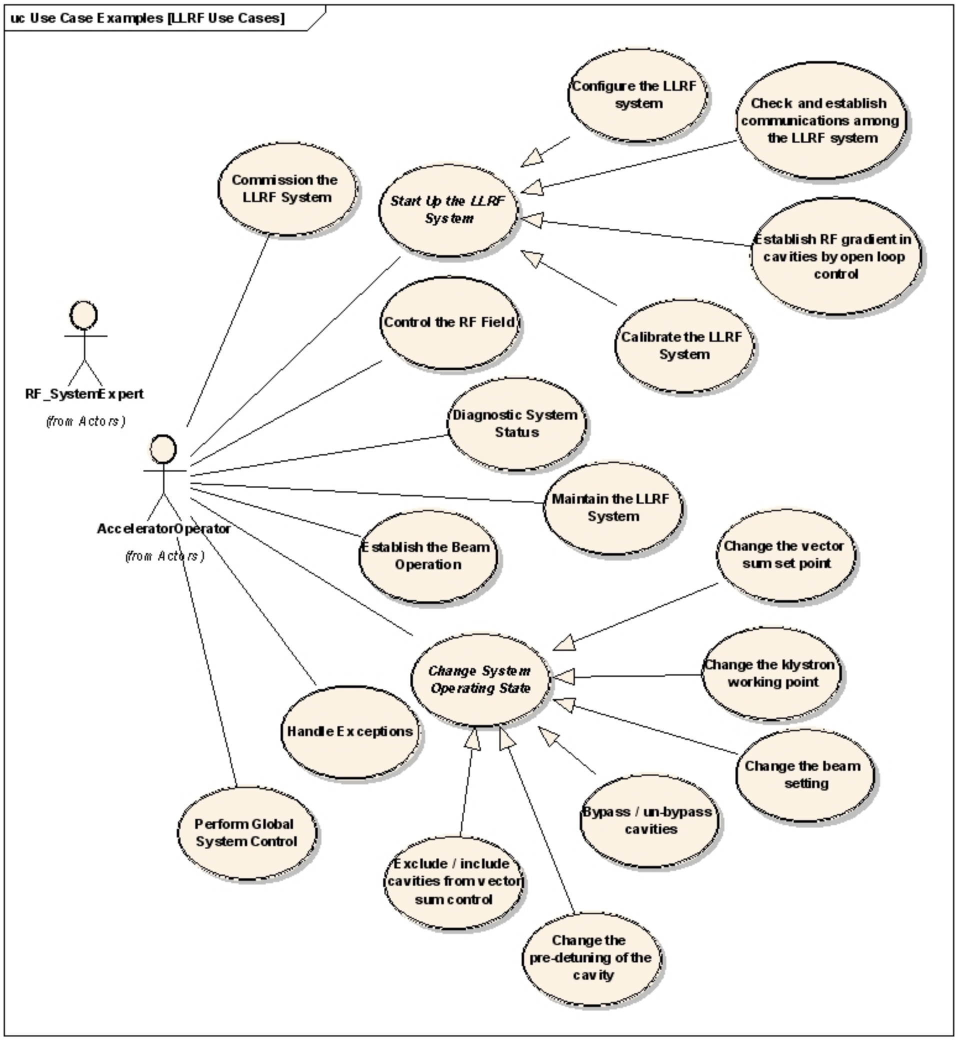

Fig. 5. Use Case diagram for LLRF system

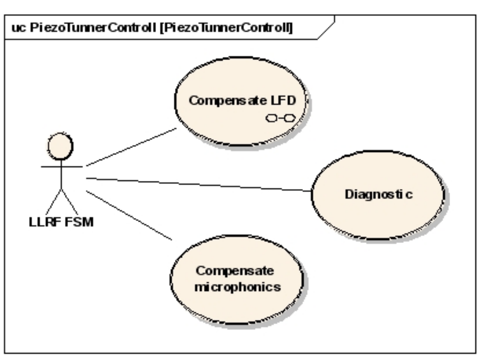

Fig. 6. Use Case diagram for piezo control system

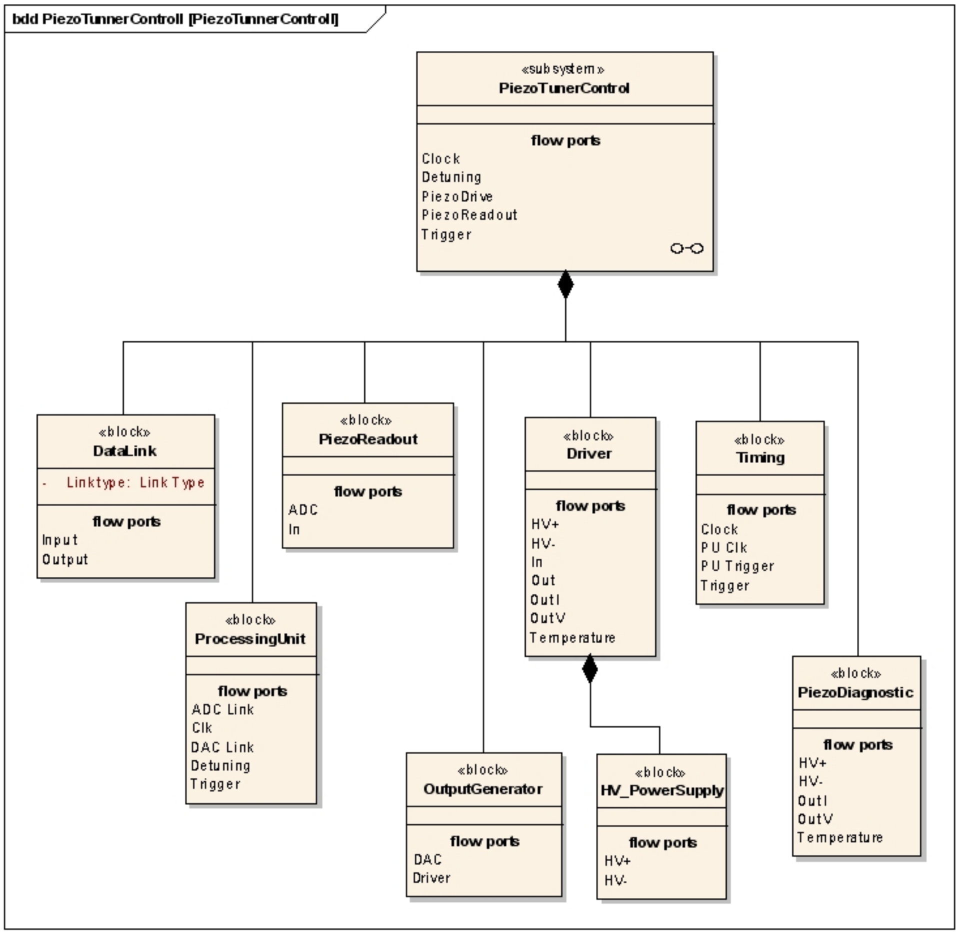

Fig. 7. Block definition diagram for piezo controller

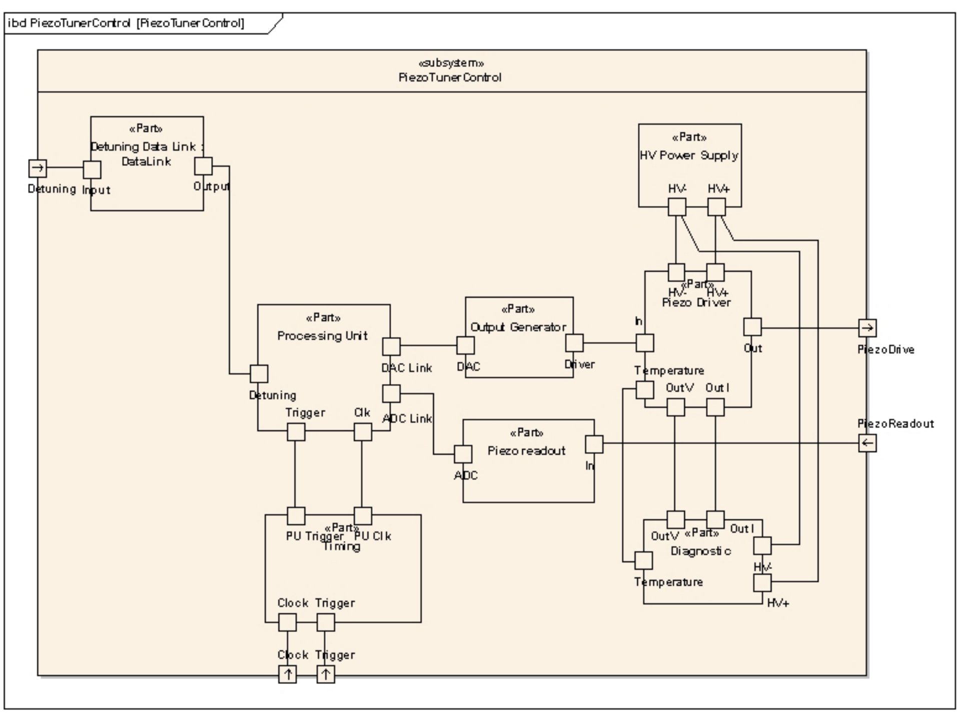

Fig. 8. Internal block diagram for piezo controller

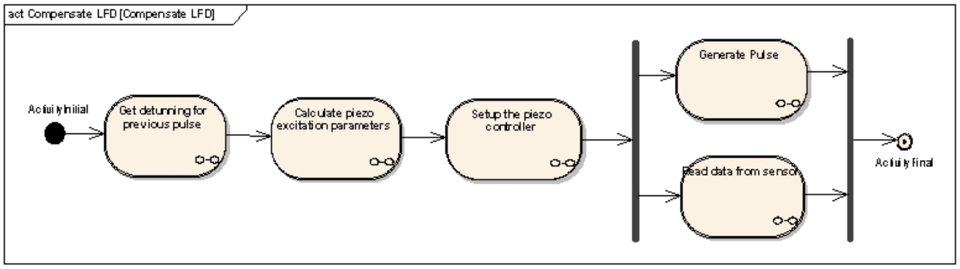

Fig. 9. Activity diagram for use case "Compensate LFD"

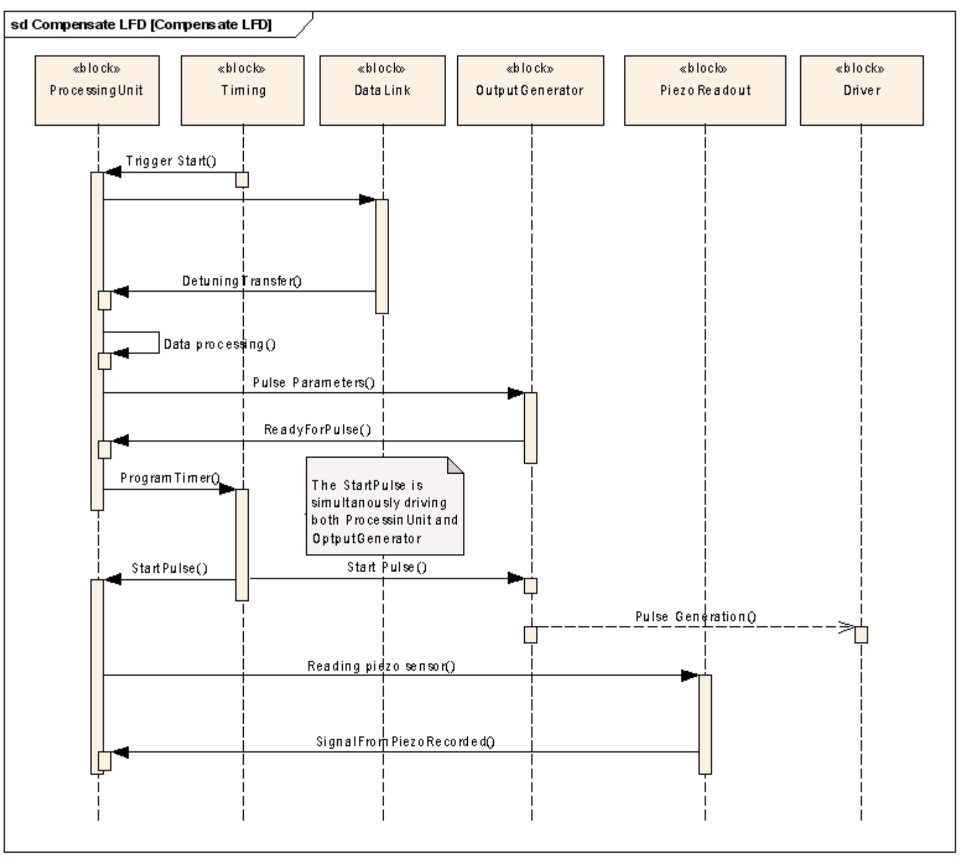

Fig. 10. Sequence diagram for use case "Compensate LFD"

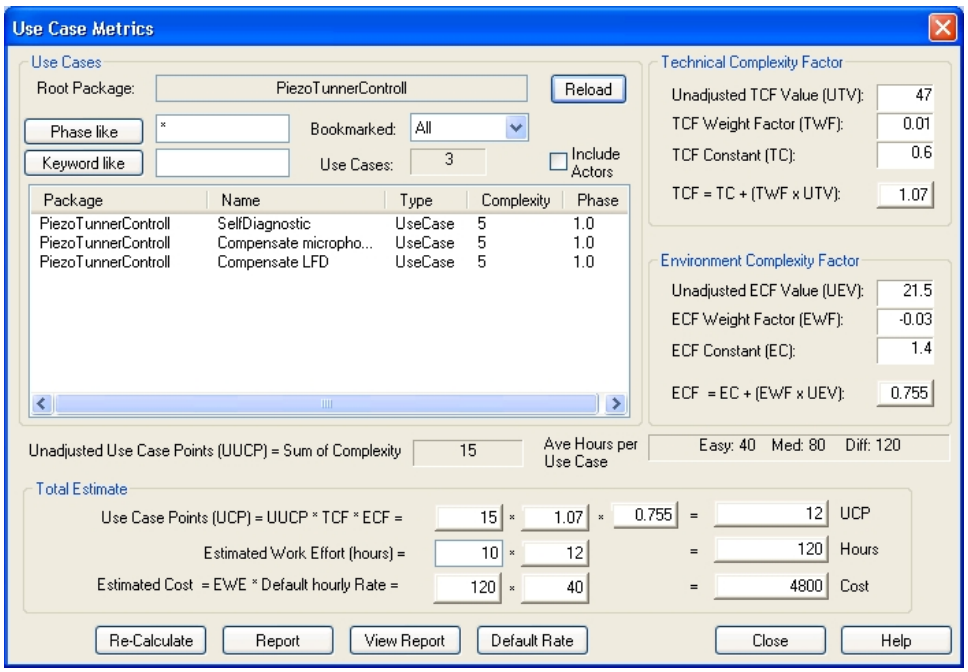

Fig. 11. Cost estimation for the Piezo Controller use cases with Enterprise Architect (SysML tool)