2015 International Conference on Computational Science and Computational Intelligence

Software Architecture of a Mobile Robot

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Abstract--- **Software architecture is the bridge between business goal and software system. Choosing and designing an architecture that satisfies the functional as well as the quality attribute requirements (reliability, security and performance, etc.) is vital to the success of the system. This applies equally to any application domains of computer software e.g. Artificial Intelligence Application, Embedded Software, Engineering/ Scientific Software, System Software, Application Software and Web Applications. Among the above mentioned software application domains, mobile robotics is an emerging and young discipline with a lot of experimentation and learning in architecture, design and development lifecycle phases of mobile robots. For example there are as yet no widely accepted standards, guidelines, best practices and methodologies for architecture, design and operating systems of mobile robots.**

This article is written with the focus of designing the architecture of a mobile robot using Siemens 4 View architecture approach. The focus is mainly on applying the Siemens 4 View approach in it true sense to architect the software system of a mobile robot.

I. INTRODUCTION

The question of architecture is of paramount importance when one chooses to address higher level competencies of a mobile robot: how does a mobile robot navigate robustly from place to place, interpreting data, localizing and controlling its motion all the while? For this highest level of robot competence, which we term navigation competence, there are numerous mobile robots that showcase particular architectural strategies [3]. This paper is an attempt to architect architecture of a mobile robot's software system using one of the well-known software architecture design approach in the industry i.e. Siemens' 4 Views.

Mobile robots have a broad set of applications and markets. There is one fact that is true of virtually every successful mobile robot: its design involves the integration of many different bodies of knowledge. No mean feat, this makes mobile robotics as inter disciplinary a field as there can be. To solve locomotion problems, the mobile robotics must understand mechanism and kinematics; dynamics and control theory. To create robust perceptual system, the mobile robotics must leverage the fields of signal analysis and specialized bodies of knowledge such as computer vision to properly employ a multitude of sensor technologies. Localization and navigation demand knowledge of computer algorithms, information theory, artificial intelligence and probability theory [3].

On the other hand, in addition to the diversity of the bodies of knowledge involved into development of a mobile robot, coming up with the right architecture of a mobile is also of utmost importance. The chosen architectural designing approach is based on best architecture practices for industrial systems which separates different engineering concerns, thus reduces the complexity of the architecture design activities [4]. The four views of the said Siemens' 4 Views approach are:

- Conceptual View: In the conceptual view, the product's functionality is mapped to a set of decomposable, interconnected components and connectors. The functional requirements are central concern [4].
- Module View: In this view, modules are organized into two orthogonal structures: decomposition and layers [4].
- Execution Architecture View: It describes the system structure in terms of its runtime platform elements e.g. OS tasks, processes, threads.
- Code Architecture View: This view is concerned with the organization of the software artifacts [4]. This view is out of the scope for this paper.

There are many architectures proposed and practiced for mobile robots e.g. Control Loop Architecture, Layered Architecture, Implicit Invocation, Blackboard Architecture and other hybrid architectures [6]. Different approaches are followed in the above mentioned architectural designs. The Siemens 4 View architectural design approach is used in this paper.

Although the requirements gathering and analysis is not part of this paper however in order to come up with the software architecture for the mobile robot we need to define the scope of the mobile robot's software system which in turn will define boundaries the software system architecture of the mobile robot. In this attempt given below are the critical functional requirements, non-functional requirements and a high level list of use cases in an attempt to package the related requirements and start a transition form system requirements model to the design and architecture model. This exercise will help in defining the scope of the work, system boundaries and to provide the bases for design and architecture decisions for the problem in hand.

A. Functional Requirements

Table 1: Functional Requirements (FR)

Requirements	Type	Priority	Risks/Issues
The mobile robot must be able to move forward and backward	Motion Control	High	1. Encounter with obstacles and unknown objects. 2. Movement Speed and acceleration
The mobile robot must be able to turn left and right	Motion Control	High	1. Encounter with obstacles and unknown objects. 2. Turning speed and acceleration to avoid stumbling and unsteadiness
The mobile robot must be able to sense the wet floor	Percepti on	Medium	Sensing the wet floor without contact of the wheels to water/wet floor
The mobile robot must be able to sense/detect obstacles and objects in its path of motion	Percepti on	High	Unknown and unidentifiable obstacles or objects may be encountered
The mobile robot must be able to change its path on encounter with obstacles	Planning	High	
The mobile robot must be able to detect moving/transient objects or wet floor in its path of motion and plan appropriate	Percepti on, Planning	Low	Calculation of the relative speed and distance with the moving objects and avoid collections with the

978-1-4673-9795-7/15 $31.00 © 2015 IEEE
DOI 10.1109/CSCI.2015.185

Requirements	Type	Priority	Risks/Issues
action.			
In future there is a requirements to be able to intelligently consume power from alternative power sources e.g. Solar Power.	Planning	High	Behavior and response when neither primary nor alternative source of energy is not available may be unexpected
The mobile robot must be able to detect light, shadows and dark areas to choose the appropriate source of power and mode of operations according to the ability to detect and recognize objects and obstacles	Perception	Medium	Wrong information from the sensors may lead to unexpected actions
The mobile robot must be configurable for different floor plans	Localization	High	
The mobile robot must be able to remember the environment and its position for a specific floor plan	Localization	High	
Among detected objects the mobile robot must be able to recognize the target objects for collection/pickup	Localization	High	
The mobile robot must be able to determine the proper movement/action for target objects for collection or obstacles for avoidance in its path of motion.	Planning	High	There may be unlimited situations/views of an encountered object or obstacles and hence the robot may not be able to perform as expected under certain situations
The mobile robot must be able to pickup objects of the specified shape and color. Up to weight of 1 KG having a dimensions 2 cubic inch and put them at a specific place/location or vassal	Motion Control	High	
The mobile robot must be able to move at least with a speed of 5 meter per minute. In future the motion speed requirements may be more demanding	Motion Control	High	Smooth movement, acceleration deceleration is very critical for avoiding toggling and misbalance
The mobile robot must be able to move smoothly on hard and straight floor. In future there may be a requirement of working on the inclined floor with carpets on it	Motion Control	High	How to avoid the situation if floor is not smooth or broken at certain places
The mobile robot will keep the record of all of its activities, decisions, actions, data gathered from the sensors along with the status and response of its electrical, mechanical and electronic parts for performance reporting, analysis and maintenance	Others (Knowledge/Database)	High	

Legends - Type: Environment, Perception, Localization, Planning, Motion Control, Others
Priority: High, Medium, Low

B. Non Functional Requirements

Table 2: Non Functional Requirements (NFR)

Requirements	Type	Priority	Risks/Issues
The mobile robot must be able to use Solar Energy as its primary power source and chargeable battery as backup source of energy.	Adaptability	High	Availability of appropriate intensity of light is critical
In the presence of Solar Power Source the mobile robot must be able to not only consume power from solar energy but also be able to charge its batteries.	Adaptability	Medium	Availability of appropriate intensity of light is critical
The mobile robot must be configurable for different floor plans through Wireless/Bluetooth interface	Interfacing and Interoperability	Medium	The Wireless/Bluetooth technology needs to be tested
The mobile robot software system must be able to handle the unknown faults in the software and sometimes noisy/fuzzy information sent from the sensors	Reliability	High	
The mobile robot's software system must be upgradeable for future enhancements and bug fixing with minimum change and impact on hardware and other components	Maintainability, Changeability	High	
Overwrite/ reset interface must be available to ensure the safety in case the mobile robot malfunction	Safety	High	
The software system must be designed with different configurable components for specifying certain values and thresholds related to robot functionality and working	Usability	Medium	
The mobile robot must provide interface with the output device to configure the mobile robot software and hardware by setting/resetting the configuration information.			

Legends- Type: Quality Attributes (Usability, Reliability, Performance, Supportability) Other (Security, Safety, Maintainability, Changeability, Dependability, Interfacing and Interoperability, Effectiveness, Extensibility, Resilience, Adaptability)
Priority: High, Medium, Low

Exclusions:

Certain requirements may not be part of the scope of mobile robot and it is always a good idea to document the exclusions from the scope of work e.g. there are no overhanging obstacles.

Use Cases:

A brief list of high level use case is extracted from the requirements to initially visualize the major modules of the mobile robot's software system

Table 3: Use cases

Package	High Level Use Cases	Package	High Level Use Cases
Perception	SenseEnvironment	Motion	ExecuteControlInstruction
	InterpretSensorData	Supervisor	ConfigureSoftwareSystem
Localization	PredictPosition		UpgradeSoftwareSystem
	Observe		GetStatistics
	MeasurePrediction		AnalyzeStatistics
	MatchObservation	Communication	SendInformation
	EstimatePosition		ReceiveInformation
Planning	PlanPath		RequestInformation
	AoidObstacle	Knowledge Base	LogSensorData
	PickupObject		Log Electrical Data
	ControlLocalization		LogMechanicalData
Control	ExecutePath	EventManager	SubscribeEvent
	PowerOn		UnsubscribeEvent
	PowerOff	Scheduler	ScheduleEvent
	Reset		UnScheduleEvent
	Sleep		

The functional and non-functional requirements along with the use cases for the mobile robot lead to the following major components and considerations with two major areas i.e. Mobile Robot Infrastructure and the Environment in which it operates. The infrastructure can further be classified in to hardware and software. Moving forward the software system of a mobile robot must be able to perform the certain major functions for the mobile robot i.e. Perception, Localization, Planning and Motion Control. This will be discussed in greater detail in the Software Architecture in the subsequent section on this paper.

This paper work is organized into following sections. Section 1 gives introduction explaining the topic, significance of the topic, background information, different industry approaches, problem statement along with a broader solution to the problem. Section 2 gives Software Architecture for the Mobile Robot using Siemens 4 View approach. Section 3 conclusion of the paper, Section 4 future work and Section 5 specifies references.

II. Software Architecture for the Mobile Robot Using Siemens 4 View Approach

Siemens 4 View Architecture Design approach as specified earlier in the Section 1 employs Global analysis as backbone techniques for developing and refining the Siemens 4 Views Architecture and is a recurring activity which is performed with emphases on different areas while developing conceptual, module, execution and code views. For the sake of simplicity the common activities of the global analysis are given at a single place at the start of the Siemens 4 View Architecture.

A. Factor Table:

Table 4: Factor Table

No.	Organizational Factors	Flexibility and Changeability	Impact
O1: Delivery of Required Features			
O1.1	Requirements are prioritized with respect to importance	The priority of requirements is changeable as per feasibility for delivery	The impact is low

No.	Technological Factors	Flexibility and Changeability	Impact
T1: Hardware			
T1.1	Sensors and camera to capture the environment information	Improvements in sensors and onboard camera's capability are expected every year because of rapidly changing technology	The technology improvements have high impact on the mobile robots capabilities to process the input data and respond more accurately. This also impacts the factor T2.1
T1.2	Mechanical hardware	No major changes are expected	Low impact is expected on the software architecture
T1.3	Onboard computer hardware	Significant improvements are expected every year specially in the areas of processing power, memory and storage space	Low impact is expected on software architecture
T1.4	Power source	Improvements in the battery time are expected every year	No impact on the software architecture. However high impact on user satisfaction because of long functioning of the mobile robot
T1.5	Communication technology/devices	Signifying improvements are expected in the wireless hardware devices e.g. Bluetooth, Wi-Fi, etc	High impact of change on the software architecture. This also impacts the factor 2.4
T2: Software			
T2.1	Image and signal processing software	Significant improvements are expected in the image and signal processing technology	The technology improvements have high impact on the mobile robots capabilities to process the input data and respond more accurately. This is also impacted by the factor T1.1
T2.2	Software development technology/platform	Improvements in software technology are always expected	Low impact on the software architecture is evaluated
T2.3	Onboard computer operating system	Improvements in current onboard computer operating system are expected. Also new operating systems for mobile devices are expected to release with more capabilities for mission critical robots	Low impact on the software architecture with the currently defined scope of mobile robot
T2.4	Communication technology/protocol	Signifying improvements are expected in the wireless communication/protocol e.g. Bluetooth, Wi-Fi, etc	High impact of change on the software architecture. This also impacts the factor 1.5

No.	Product Factors	Flexibility and Changeability	Impact
P1: Perception			
P1.1	Distinguish and use multiple sensor's output intelligently	There may be changes in number, type and quality and of output sensors	The impact on the software architecture is high
P1.2	Sense, detect and recognize obstacles and objects in its path of motion	The future enhancements require the detection and reorganization of moving/transient objects in addition to the permanent objects which are feed in through the floor plan	High impact on the software architecture because of need for added sophisticated hardware sensor and new software modules/components.
P2: Localization			
P2.1	Floor plan extraction	The future requirements need ability to learn about the environment and be able to update the floor plan with the information about moving/transient objects for future use.	High impact on software architecture because of the need to intelligently update the floor plan
P2.2	Manipulate the position during movement with reference to the environment and fed in floor plan information using latest technology	Changeability: Within two years there will be requirements to calculate and manipulate the position of the remote using GPS.	High impact on software architecture because of incorporation of new technology
P3: Planning			
P3.1	To determine the appropriate movement/action plan for avoidance of obstacles in its path of motion	The future requirement for the mobile robot is to be able to detect moving/transient objects and plan appropriate action for collection avoidance	High impact on software architecture as advanced hardware and new software modules/components needs to be developed
P4: Motion Control			
P4.1	Movement speed	In future the motion speed requirements may be more demanding	High impact on the software architecture because of quick processing needs for interpretation, localization, planning, control and motion.
P4.2	Ability to move smoothly on different floor surfaces e.g. smooth, inclined, rough.	In future there may be a requirement of working on the inclined floor with carpets on it	The ability to detect the inclined and carpeted floor needs added sensors and software functionality and has high impact on the software architecture

B. Issue Cards

From the influencing factor as specified in the preceding section, issues are identified based on the following criteria:

- Issues arising from the set of factors that may be difficult to fulfill or because of conflicting factors.

- Issues arising from the constraints and limitations offered by the influencing factors
- Issues arising from the high degree of changeability requirements specified by the influencing factors
- Issues arising from the need of coming up with a common solution for global requirements or problem in the target system

The identified issues are addressed with solution and strategies as documented below

Table 5: Issue Cards

Issue: Sensor Aliasing
Description: How to distinguish multiple sensors' output?
Influencing Factors
P1.1: Distinguish and use multiple sensor's output intelligently
Solutions: Output of each sensor/input device must be uniquely identifiable
Description: The solution lies in the ability to uniquely identify the output of each sensor/input device along with the capability to process and interpret the information, for perception, consistently.
Strategies
1. The output of each sensor/input device must be uniquely identifiable 2. The components for sensing and interpretation must be configurable with the sensor/input device to uniquely identify each sensor/input device and associate the type and nature (e.g. periodic raw data, streams of information) of information expected from the each sensor/input device. 3. The components for sensing and interpretation must be configurable to associate the appropriate processing logic for the incoming data from each sensor/input device.
Related Strategies
NA
Issue: Differentiating/recognizing objects, obstacles, and floor
Description: How to distinguish the objects, obstacles and floor plan
Influencing Factors
P1.2: Sense, detect and recognize obstacles and objects in its path of motion P2.1: Floor plan extraction
Solutions: Objects coloring and pattern recognition
Description: Assign different color to objects, obstacles, floors and wall
Strategies
1. Assign colors to the objects (targets for pickup), obstacles (i.e. transient and permanent) e.g. obstacles are of red color, floor is of white color, objects are of blue color etc. 2. In addition to color coding, pattern recognition should be used to intelligently differentiate objects
Related Strategies
NA
Issue: Predict and estimate position during movement
Description: How to exactly estimate its current position in the environment. This issue can rise when mobile robot is slipped or displaced without adjusting its new location in the environment
Influencing Factors
P2.2: Manipulate the position during movement with reference to the environment and fed in floor plan information
Solutions: Use of positioning system
Description: Use of a reference based or coordinate based positioning technology to keep the robot updated about its position in the environment
Strategies
1. GPS technology should be used to keep the robot updated about its current location in the environment with reference to the floor plan
Related Strategies
NA
Issue: Recognize the environment during movement
Description: How to exactly recognize the environment specially provided with diverse obstacles and objects including the transient/moving.
Influencing Factors
P2.1: Floor plan extraction P3.1: To determine the appropriate movement/action plan for avoidance of obstacles in its path of motion P4.1: Movement speed
Solutions: Use of positioning system
Description: Use of a reference based or coordinate based positioning technology to keep the robot updated about its position in the environment
Strategies
1. The mobile robot will also update the floor plan if it finds changes in the fed in floor plan 2. The mobile robot will process the changes in the floor plan, transient /moving objects and obstacles with highest priority to plan the appropriate control and motion in the real time. For this mechanism to implement high priority events must clearly be defined in the software system for immediate processing and response.
Related Strategies
1. GPS technology should be used to keep the robot updated about its current location in the environment with reference to the floor plan 3. Assign colors to the objects (targets for pickup), obstacles (i.e. transient and permanent) e.g. obstacles are of red color, floor is of white color, objects are of blue color etc. 2. In addition to color coding, pattern recognition should be used to intelligently differentiate objects
Issue: Recognition of floor surface
Description: How to detect and react for different types of floor surfaces e.g. smooth, inclined, rough
Influencing Factors
P3.1: To determine the appropriate movement/action plan for avoidance of obstacles in its path of motion P4.2: Ability to move smoothly on hard and straight floor.
Solutions: Use of special sensors
Description: Use of special sensors that are able to detect the inclined and carpeted floors.
Strategies
1. Special Sensors should be used to detect different types and conditions of floor surfaces
Related Strategies
1. The mobile robot will also update the floor plan if it finds changes in the fed in floor plan 2. The mobile robot will process the changes in the floor plan, transient /moving objects and obstacles with highest priority to plan the appropriate control and motion in the real time. For this mechanism to implement high priority events must clearly be defined in the software system for immediate processing and response.

C. *Conceptual View*

As specified earlier in the section 1 the there are three (3) major areas of consideration while designing the architecture of a mobile robot: Infrastructure (software and hardware) and environment. A high level conceptualization of the mobile robot infrastructure system is given below in context of the environment.

TABLE 6: DESCRIPTION OF CONCEPTUAL VIEW

Software Infrastructure
Perception
The robot must interpret its sensors to extract meaningful data. The mobile robot's perception and awareness about the environment is generated in two distinct steps i.e. sensing: and interpretation. Sensing is about picking up information from the environment for generating perception of how the world is e.g. Visual, Tactile, Optical, Audio etc and information extraction and interpretation is to enable the mobile robot to determine its relationship to the environment by making measurements with its sensors and then using those measured signals for making Localization, planning and motion control. The sensing generates raw data and information extraction and interpretation process the data into meaningful information for further processing and decision making.
Localization
Localization enables the mobile robot for map building and localization through which the mobile robot determine its position in the environment.
Planning
The robot must decide how to act to achieve its goals. The mobile robot achieve this in the planning process that comprises on two distinct activities i.e. Cognition which generally represents the purposeful decision making and execution that a system utilizes to achieve its highest-order goal and Path Planning which, given a map and goal location, path planning involves identifying a trajectory that will cause the robot to reach the goal location when executed. Path planning is a strategic problem-solving competence, as the robot must decide what to do over the long term to achieve its goals. Planning process generate one or a sequence of actions or tasks to achieve the goal based on the perceived information of the real world e.g. path planning, multi-robot cooperation, standing in a queue, etc. In the current paper the scope is path planning.
Motion Control
The robot must modulate its motor outputs to achieve the desired path/trajectory which it achieves through Path Execution and Acting to move in or interact with the environment. This may result in the change of environment e.g. Communication, Displacement, Visual / Sound etc.
Hardware Infrastructure
Hardware infrastructure comprises of wheels, battery, arms, sensors, effectors, motors, camera, CPU, electronic circuits, memory, data storage space, speakers, lights, data exchange and interfacing devices (wireless, Bluetooth, USB), power cabling and data communication network/medium. The hardware infrastructure will be controlled and operated by the mobile robot software application. The details of hardware and its architecture are not part of this paper. However the hardware will be referred to in context of the software architecture discussion.
Environment
The real world in which the mobile robot works is its environment. It can be a supermarket, laboratory, room or even a remote planet, etc. Everything that is part of the real world e.g. people, objects, obstacles forms the environment for the mobile remote. A robot has to learn from the environment to decide its actions to be taken.

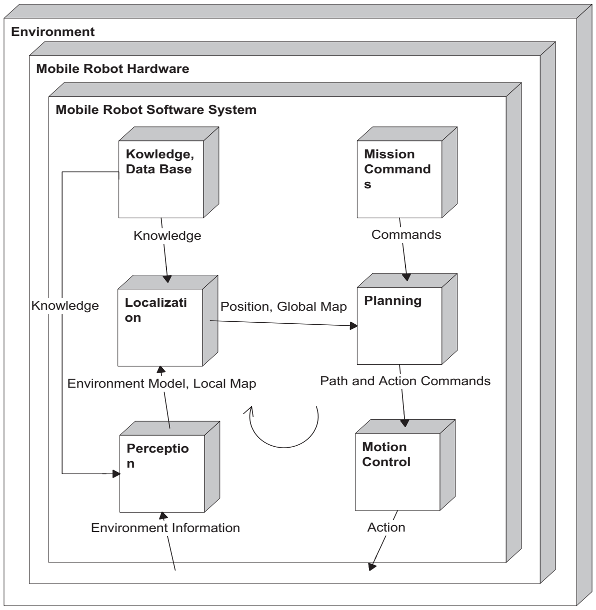

Figure 1: Conceptual View

D. *Module View*

The mobile robot's module view is given in Figure 2 in which system is viewed as collection of subsystems (olive green boxes) comprising of modules (light yellow boxes) performing specific functionality. In order to save space the layers of the software system are also identified (tea pink boxes) along with the dependencies and the communication links. Here the concept of Real-time Service Bus (RSB), like Enterprise Service Bus as a backbone of Service Oriented Architecture, which addresses the demanding and mission critical communication requirements of real-time and mission critical systems yet providing the means of communication on top of open standard protocols and allowing the components of the systems to be loosely coupled and highly cohesive. Also the concept of subscription based services required from other subsystems and modules is implemented. This architectural design decision is supported by incorporating the incorporation if Scheduler, Event Manager and Real Time Service Discovery and Subscription Manager Modules.

E. *Execution View*

The mobile robots execution view is given in the Figure 3 which specifies the software system structure in context of the runtime platform elements. The architectural design concepts introduced in the Module View are further visualized in the Execution View in context of the runtime environment.

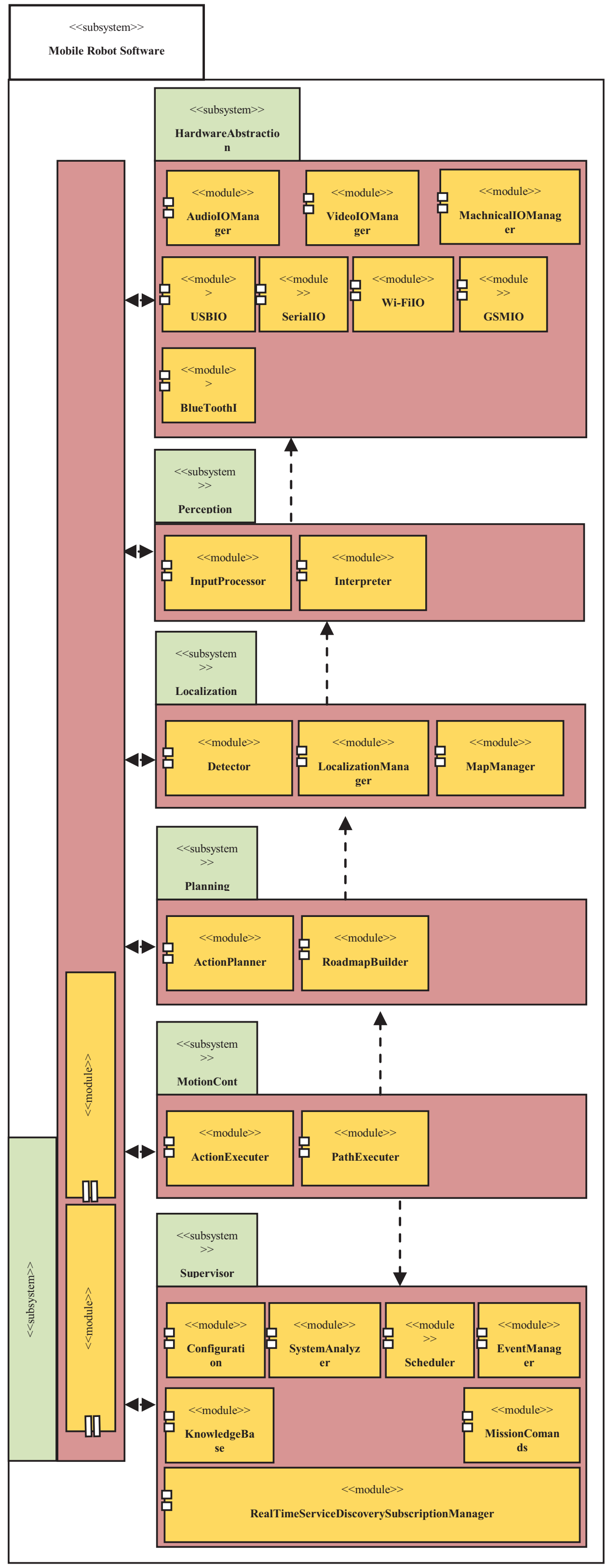

Figure 2: Module View

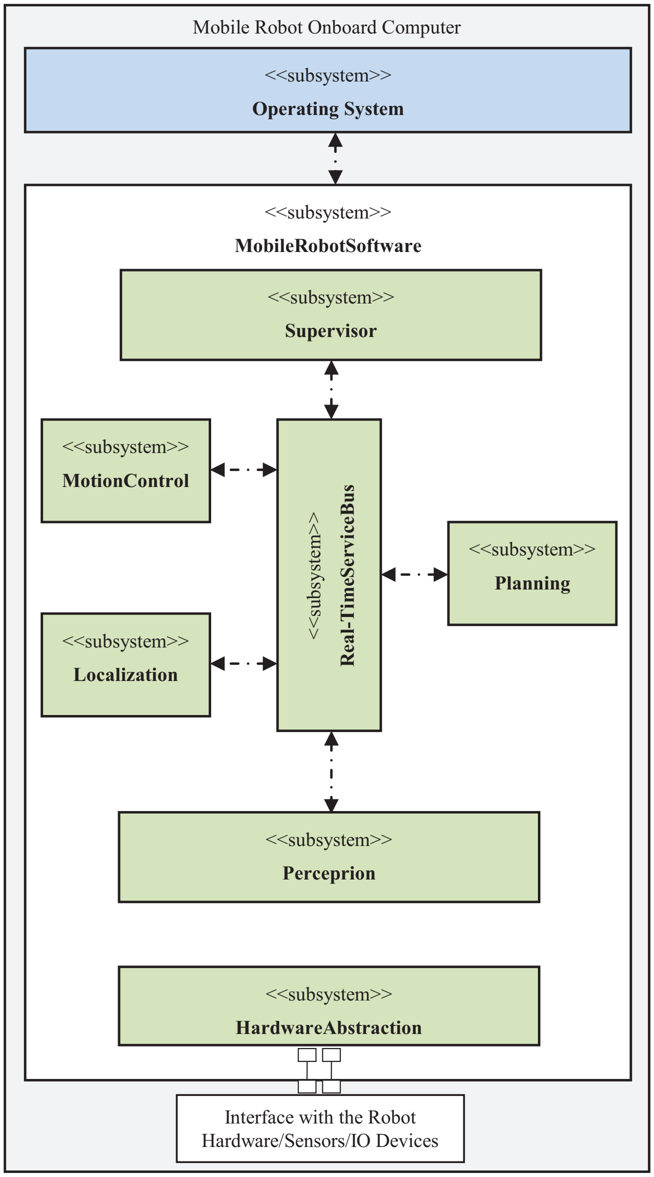

Figure 3: Execution View (Overall Architecture Overview)

III. CONCLUSION

This article is an attempt to architect the software system of a mobile robot with emphases on applying Siemens 4 View approach for Software System Architecture Design. The attempt to architect the real time software system makes the architecture and design exercise more challenging with a many considerations of environment, hardware, software and most importantly mission critical and real time nature of the target system. In this challenge Siemens 4 View proved to be very effective in bridging the gap in between the requirements and detailed design and eventually development of the software system by identifying the critical factors of the system and addressing the risks and issues. Siemens 4 View approach provides a proactive framework to learn and address the issues well before the time when they become problems and very costly to address.

IV. FUTURE WORK

While writing this article and practically being involved in the architecture design of a real time software system for mobile robot it is observed that The Siemens 4 View approach needs more integration with software development lifecycle phases and related articles e.g. There is no mechanism for traceability of requirements from Software Requirements Specifications and Use Case documents into the Siemens 4 View artifacts which makes the change management of the architecture a cumbersome task and may result in high risk and costly corrections in the later stages of the Software System development Lifecycle.

Moreover the terminology used in the Siemens 4 View Approach needs to be adapted to Unified Modeling Language for standardization and consistency e.g. instead of using the concept of Components the concepts of Modules is used that sometimes creates ambiguity.

Another critical area identified for future work may be research on the concept of implementation of Real-time Service Bus (RSB), like Enterprise Service Bus as a backbone of Service Oriented Architecture, which addresses the demanding and mission critical communication requirements of real-time and mission critical systems yet providing the means of communication on top of open standard protocols and allowing the components of the systems to be loosely coupled and highly cohesive.

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