Project Title: Integrated Security of Wireless Sensor Networks

Team members: Mohammad Al Yaman, Omar Sabir, Malak Alyousef, Dimitrios Spyropoulos

Abstract: The goal of this project is to enhance security in a military base. This will be done by designing a system that tracks vehicles inside the base and identifies any unauthorized actions of vehicles. The system will help us know the position of a vehicle any time and when it access specific areas within a military base.

Any vehicle should be first authorized in order to enter the base camp. Then, it is tracked by the acoustic sensors until it stops. Cameras are placed on the main gate and at parking lots to capture the plate of the vehicle and monitor a parking lot in an emergency situation. If during his route the vehicle enters or stops in an unauthorized area an alarm is activated and cameras start monitoring the place of interest.


Part 1: Problem Statement

Security of base camps is a major issue. Especially in crowded base camps, if an intruder succeeds to enter the base then it is easier for him to act without anyone noticing. However, it is probable that, if the intruder uses a vehicle, he will not follow a specified route. Therefore, by keeping track and controlling the movements of vehicles we deal with this part of the problem. The other, and more difficult, part is keeping track of irregular human movement. Moreover, the project should be studied carefully, because if not it might be expensive and hard to implement. Our mission is to provide a secure, efficient and cost effective sensor network for the tracking of vehicles.

Part 2: Use case development

Actors are vehicles which include cars, tanks and trucks and humans. A vehicle is the primary actor whether a human only interferes with the system. An actor diagram is presented below:
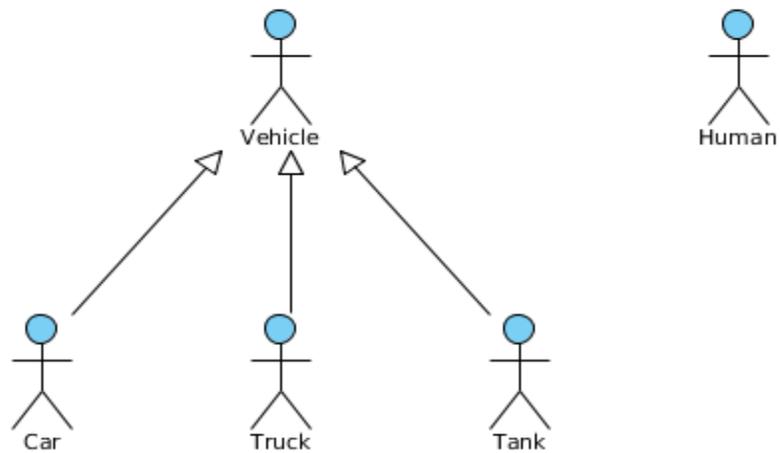
Use Case 1. Main gate access

Pre-conditions: The system is operational and no cars are moving in the base.
Actors: Vehicle.
Flow of Events:

- 1. The vehicle arrives at the entry gate.
- 2. A camera captures the license plate and sends it to the control system.
- 3. The control system authorizes access to specific parking lot(s).
- 4. The control system opens the gate.
- 5. The central control system activates the nearest acoustic sensor.
- 6. The gate closes

Alternative Flow of Events:

- 1. The vehicle arrives at the entry gate.
- 2. A camera captures the license plate and sends it to the control system.
- 3. The control system denies access to the base.
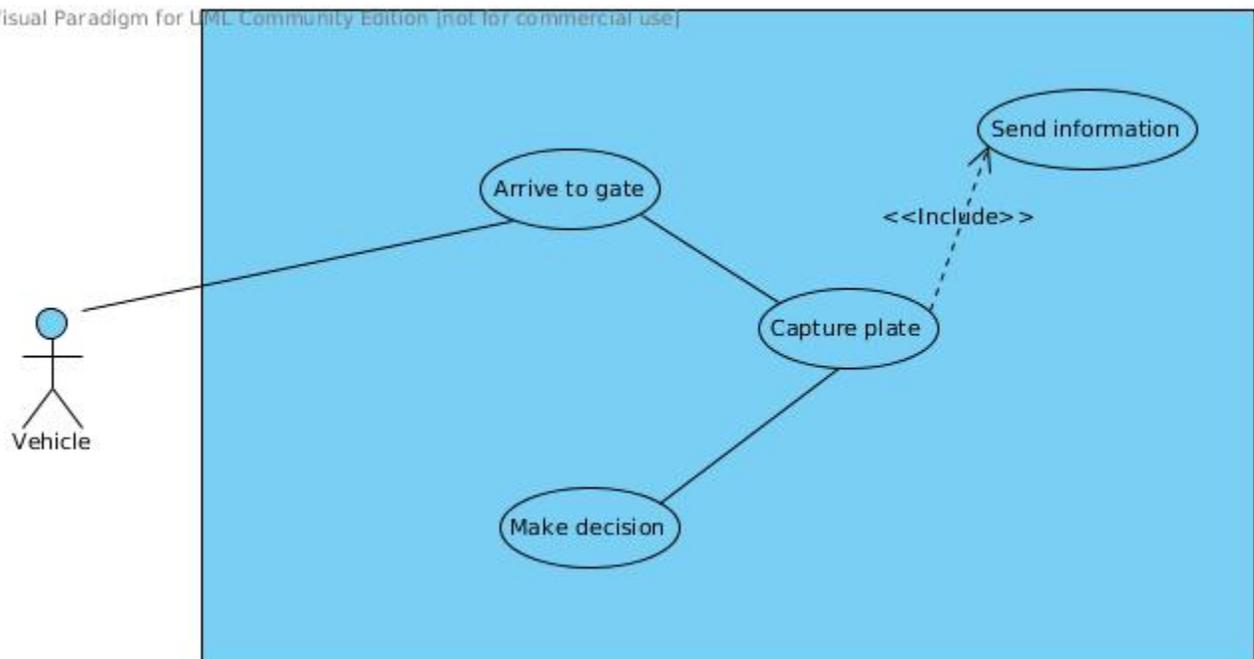
Post-conditions:
  Basic Flow: The vehicle is inside the base.
  Alternative Flow: The vehicle remains outside.

Related parts of structure: a node that has a camera, the central control system, a node that has an acoustic sensor.

Use Case 2. Single Vehicle Tracking
Pre-conditions: Vehicle starts moving out from a parking lot or enters through the main gate.
The vehicles plate has been captured.
Actors: Vehicle, Human
Flow of Events:

- 1. Closest sensors are activated.
- 2. The sensors track the vehicle.
- 3. Vehicle stops moving.
- 4. The control system checks if the vehicle is parked at an authorized place.
- 5. The system decides whether to raise an alarm or not.
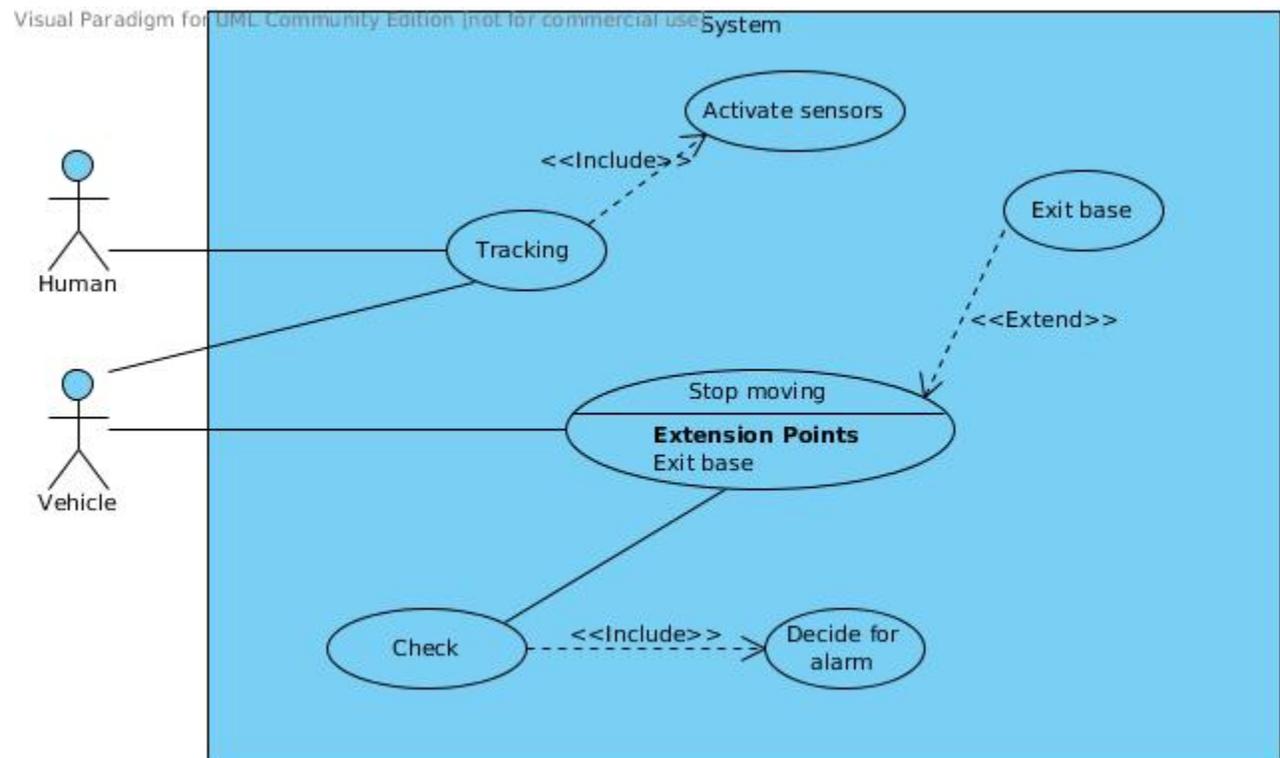
Alternative Flow of Events:

- 1. Closest intersections' sensors are activated.
- 2. The sensors track the vehicle.
- 3. Vehicle leaves the base.

Post-conditions:
  Basic Flow: State of the alarm.
  Alternative Flow: Vehicle outside the base.

Related parts of structure: the central control system, a node that has an acoustic sensor.

Use Case3. Intersection
Pre-conditions:.Vehicle(s) moves and arrives at an intersection.
Actors: Vehicle, Human
Flow of Events:

1. Vehicle approaches an intersection.
2. Last acoustic sensor on the straight road segment identifies vehicle and activates laser sensor.
3. Laser sensor informs local control system.
4. The control system activates sensors at the three possible directions.
5 .Vehicle crosses laser sensor.
6. Laser sensor identifies movement and sends message to the local control system.
7. Acoustic sensor identifies the direction of vehicle.
8. Control system turns off sensors that did not detect movement.
9. Tracking continues in a straight segment.

Post-conditions:
 Basic Flow: Moving direction.

Related parts of structure: a node that has a laser sensor, the local central control system, a node   that has an acoustic sensor.

Activity diagram

Vehicle	Laser sensor	Local control system	Acoustic sensor 1	Acoustic sensor 2	Acoustic sensor 3

moving towards an intersection

Gets information from previous sensor

Informs control system

Processes Information

Activates sensors

Start detecting

Start detecting

Start detecting

Crosses laser sensor

Identifies movement

Informs control system

Detects movement

Continue moving

Turn off unused sensors

Hand-off to next sensor

Turn off

Turn off

Continue moving

Continue moving

Sequence diagram

Vehicle	Acoustic sensor	Laser sensor	Local control system	Acoustic sensor 1	Acoustic sensor 2	Acoustic sensor 3

1: trigger

1.1: activate

1.1.1: inform

1.1.1.1: activate

1.1.1.2: ack

1.2: update state

1.1.1.3: activate

1.1.1.4: ack

1.1.1.5: activate

1.1.1.6: ack

2: trigger

3: trigger

3.1: informs

3.2: hand-off

3.1.1: turn off

3.1.1.1: ack

3.1.2: turn off

3.1.3: ack

Use Case4. Straight line-Acoustic sensors communication
Pre-conditions: Vehicle(s) starts moving along a straight road. First acoustic sensor is activated.
Actors: Vehicle
      Flow of Events:
      1. Activated sensor identifies the vehicle.
      2. Sensor activates its neighbor and sends information which vehicle to expect
      3. Sensor sends message to control system in order to update vehicle position.
      4. Sensor removes plate of vehicle from its stack.
      5. If stack empty sensor goes to idle state, else waits the other vehicle(s).
Post-conditions:
  Basic Flow: Vehicle arrives at an intersection or a parking lot or exit.

Related parts of structure: the central control system, a node that has an acoustic sensor.

Activity diagram

Vehicle	Acoustic sensor 1	Central Control System	Acoustic sensor 2

Moving

Identify vehicle

Send message

Start detecting

Send information

Update vehicle position

Remove vehicle plate from stack

stack empty   stack not empty

Goes to idle state

Wait for vehicle

Sequence diagram

Vehicle	Sensor 1	Central control system	Sensor 2

1: trigger

1.1: inform

1.2: update_position

1.3: remove_vehicle

1.4: update_state
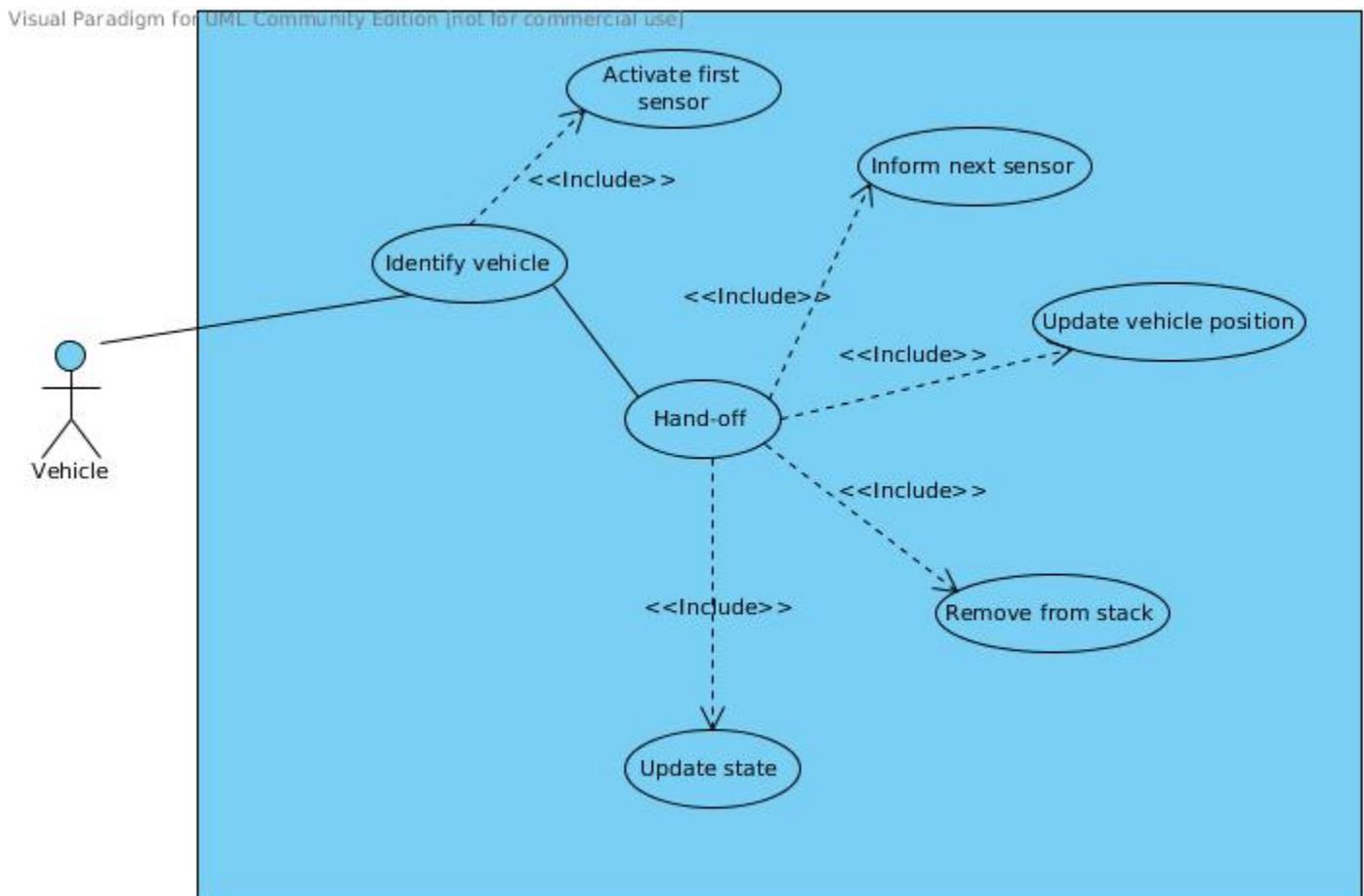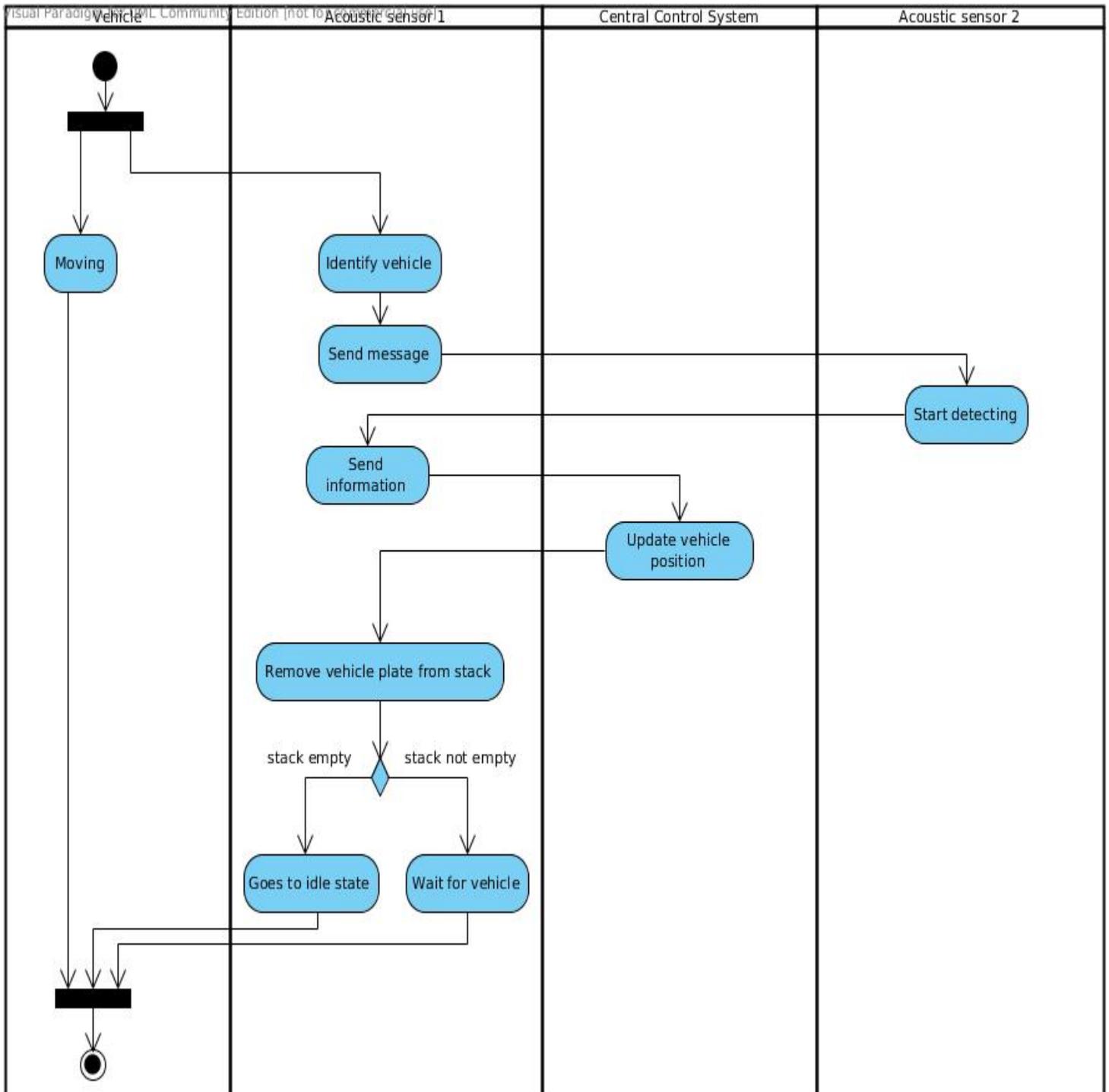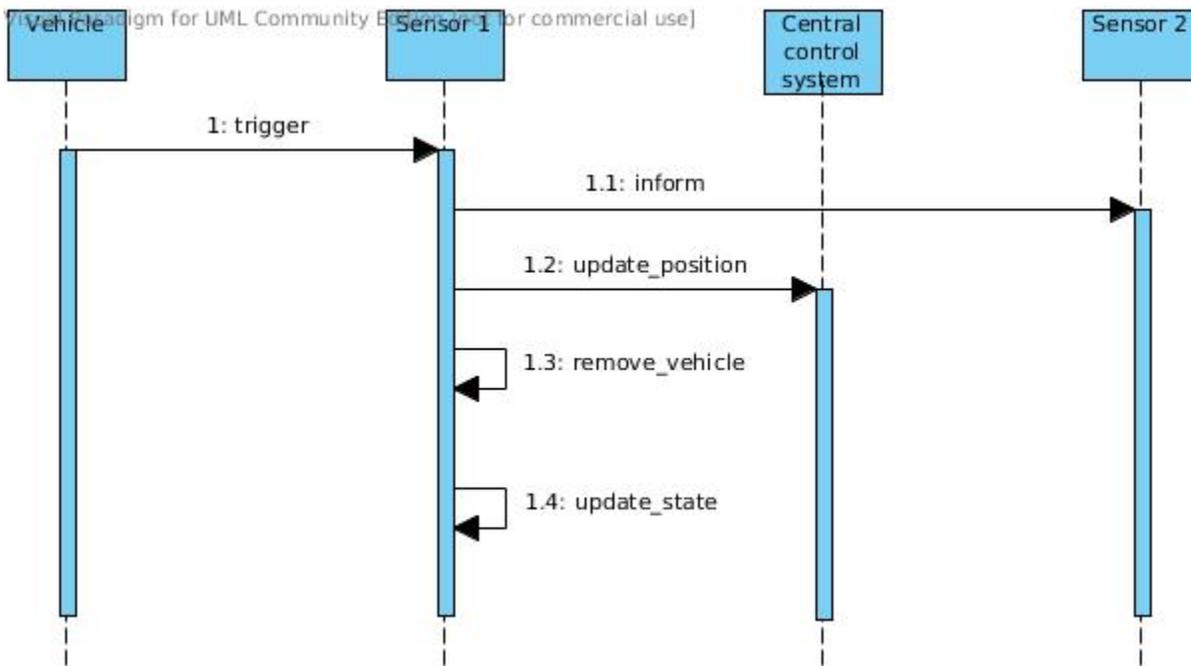
Use Case5. Exit from a parking lot-camera acoustic sensor communication
Pre-conditions: Vehicle(s) moves out of a parking lot.
Actors: Vehicle, Human
Flow of Events:
      1. Vehicle arrives at the parking exit.
      2. Movement detected by acoustic sensor.
      3. Acoustic sensor sends information to control system.
      4. Control system activates the camera.
     5. Camera captures the plate.
      6. Camera sends information to central control system (plate and position).
      7. Central control identifies nearest acoustic sensor.
      8. Central control system activates acoustic sensor.
      9. Camera goes to idle state.
      10. Tracking of the vehicle starts.
Post-conditions:
  Basic Flow: Vehicle is moving and tracked within the base.

Related parts of structure: a node that has a camera, the central control system, a node that has an acoustic sensor.

Activity diagram

Vehicle	Acoustic sensor	Control system(CS)	Camera	Acoustic sensor 2

arrives at parking exit

detects movement

sends info to CS

process info

activates camera

captures the plate

sends info to CS

identifies nearest acoustic sensor

activates acoustic sensor

goes to idle state

starts tracking

Sequence diagram

Vehicle	Acoustic Sensor	Control System	Camera	Acoustic Sensor 2

1: triggers

1.1: informs

1.1.1: process

1.1.2: activates

1.1.2.1: take picture

1.1.2.2: inform

1.1.2.2.1: updates state

1.1.2.2.2: activates
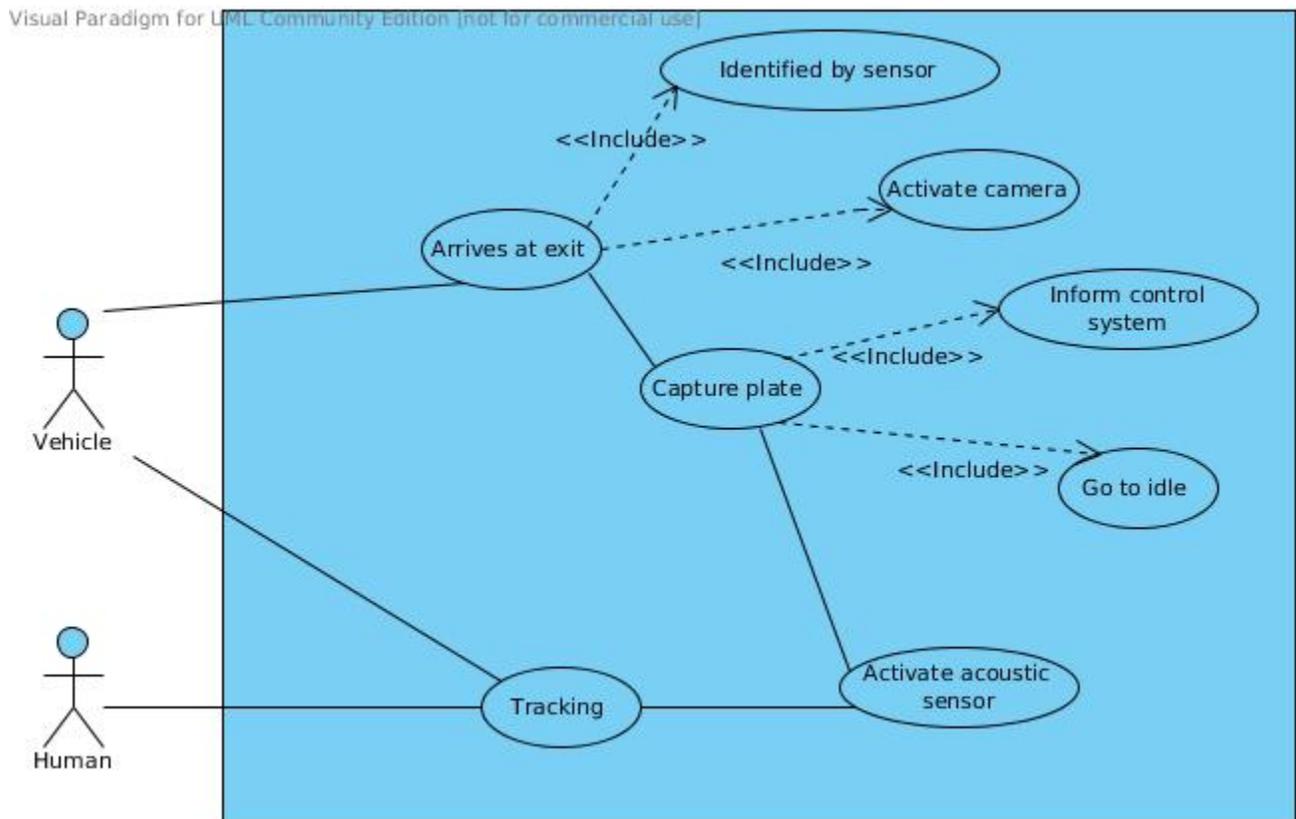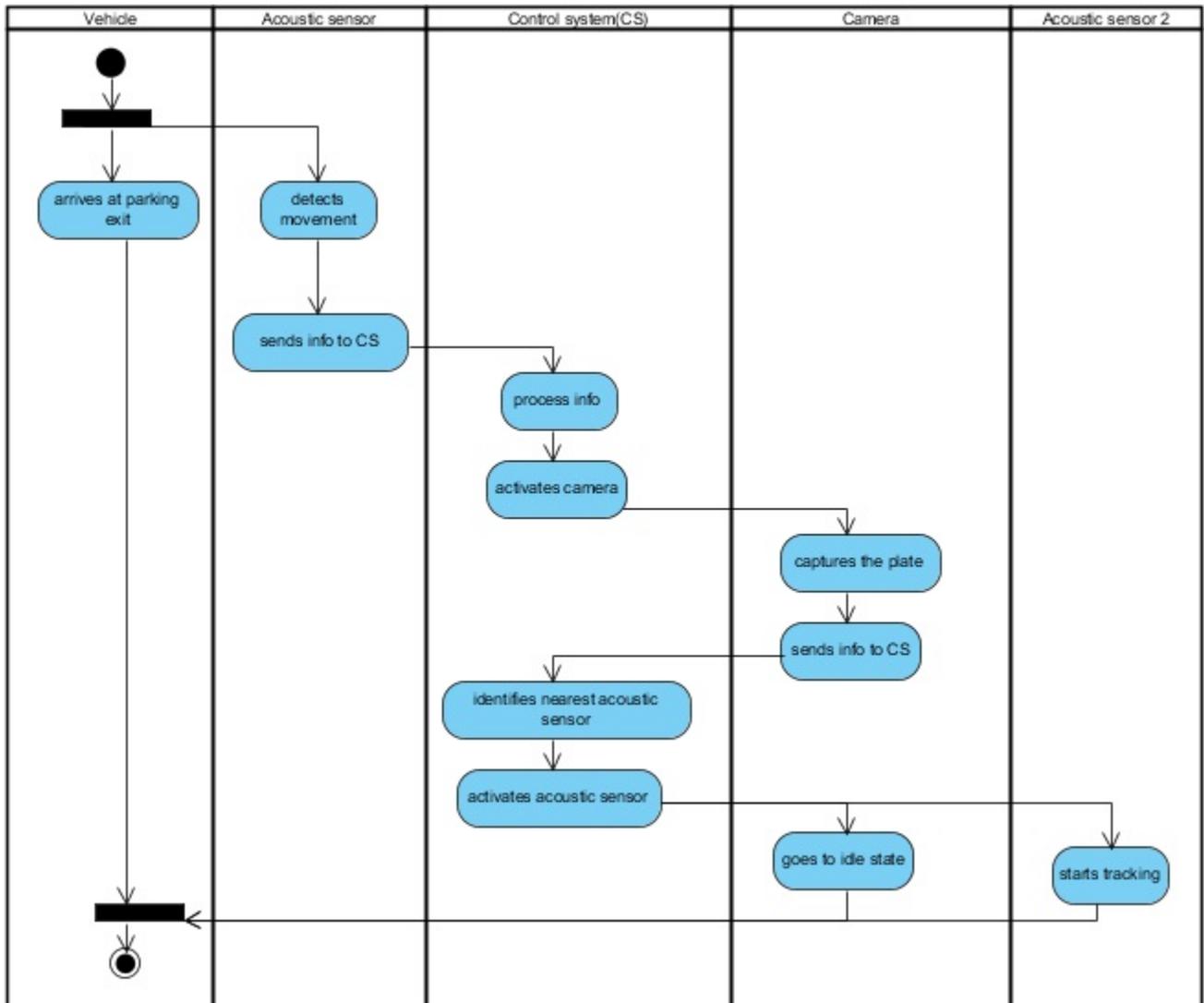
Use Case6. Entry in a parking lot.

Pre-conditions: Vehicle arrives at a parking lot.
Actors: Vehicle
Flow of Events:
      1. Acoustic sensor at the entry of the parking lot identifies vehicle.
      2. Acoustic sensor sends plate and position information to the central control system.
      3. Central control system checks if vehicle is authorized to enter the parking.
Post-conditions:
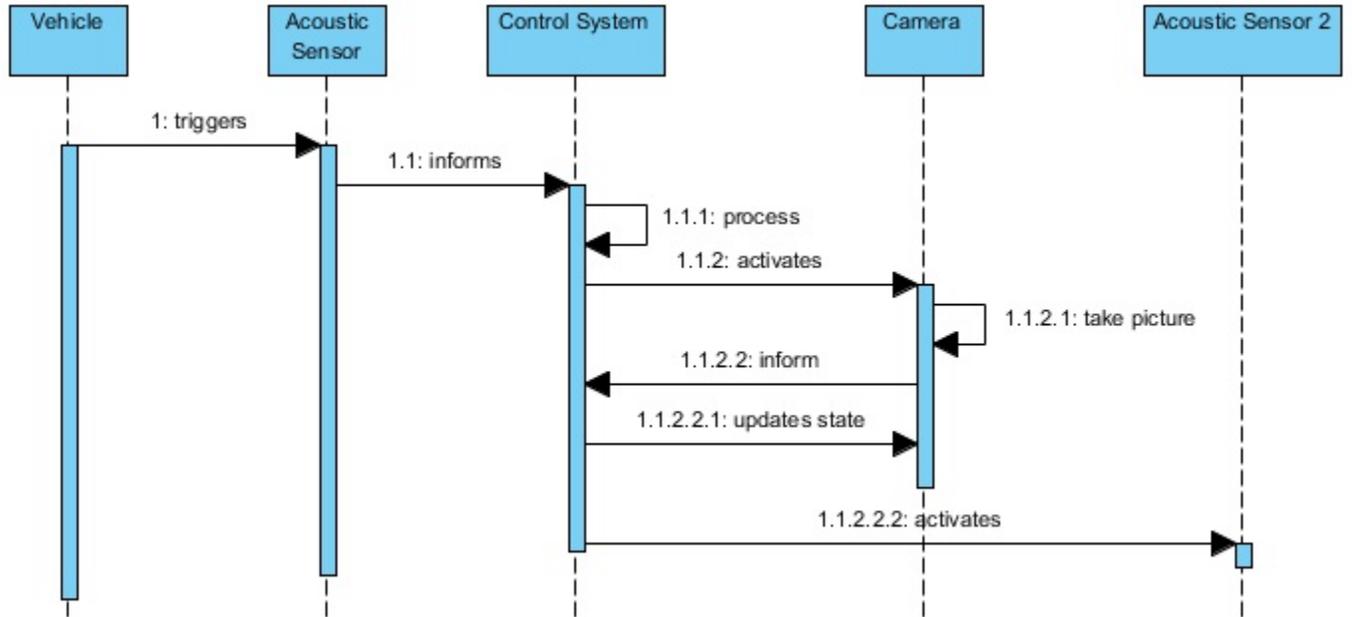 **Basic Flow:** Vehicle inside the parking lot. State of the alarm (on/off).

Related parts of structure: a node that has a camera, the central control system, a node that has an acoustic sensor.

Activity diagram

Vehicle	Acoustic sensor	Control system (CS)

- arrives at parking lot entry
- identifies the vehicle
- sends plate & position information to CS
- checks if the vehicle is authorized to enter parking lot

Sequence diagram

Vehicle	Acoustic Sensor	Control System

1: triggers

1.1: informs

1.1.1: process
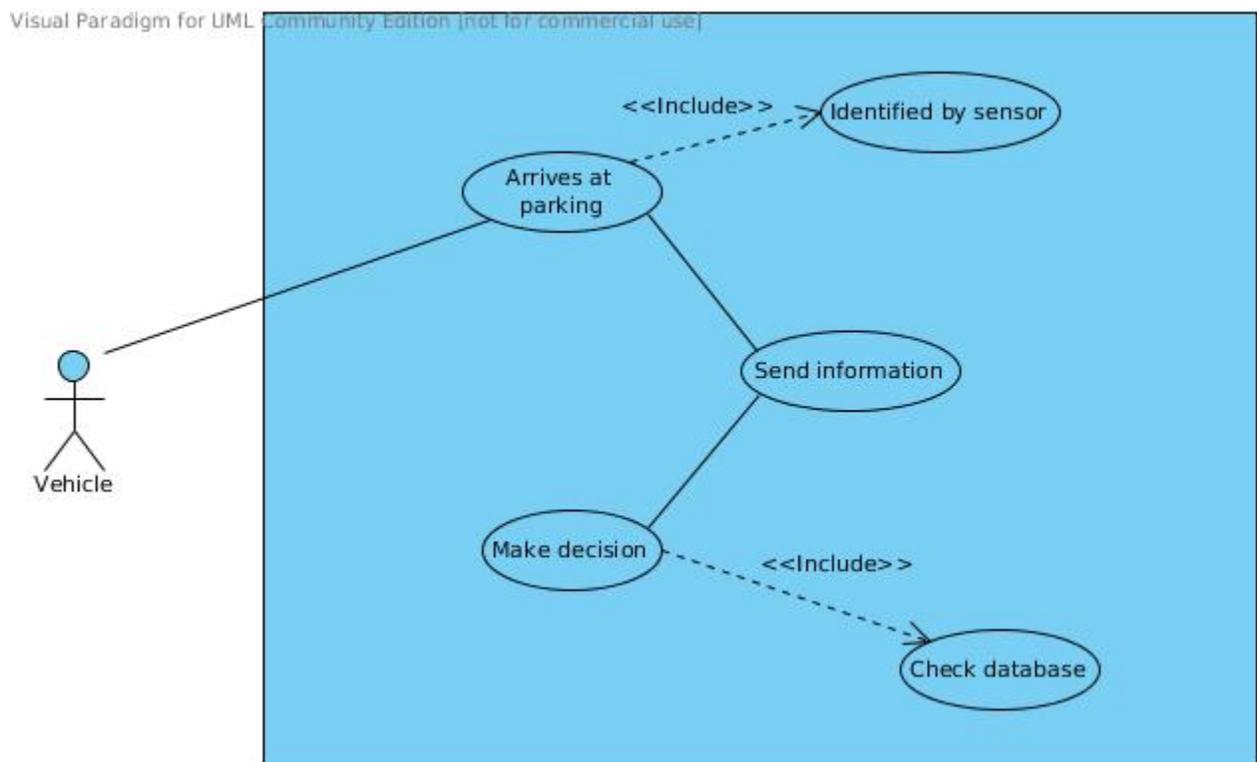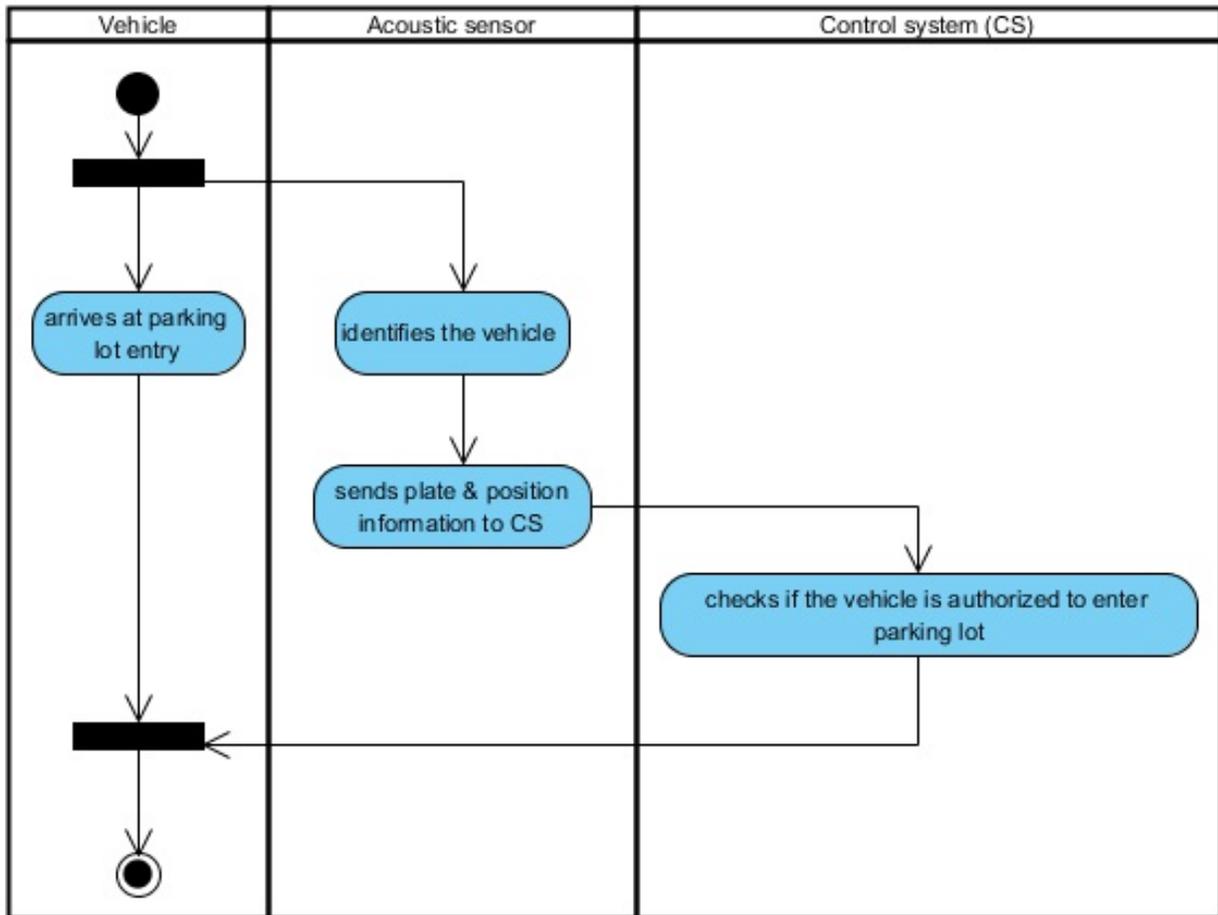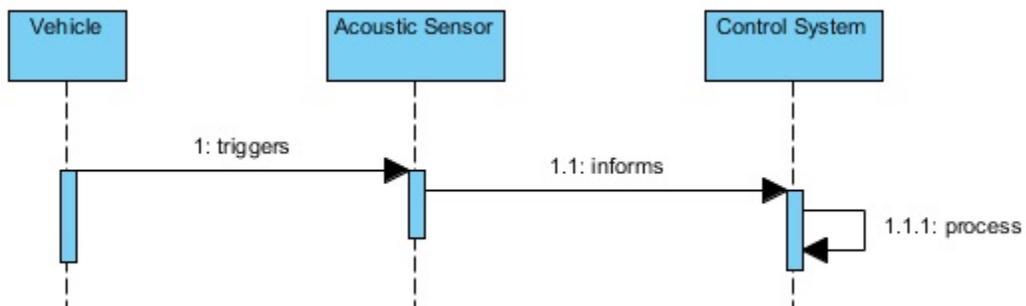
Use Case7. Acoustic sensor battery low
Pre-conditions: Acoustic sensor is operating.
Actors:
Flow of Events:
      1. Sensor detects battery level is low.
      2. Sensor informs central control system.
      3. Sensor is turned off.
      4. Central control system sends information to previous sensor to update
        neighbor information.
        (previous acoustic sensor makes the next working sensor its neighbor)
Post-conditions:
  Basic Flow: System operates. Acoustic node needs maintenance.

Related parts of structure: the central control system, a node that has an acoustic sensor.
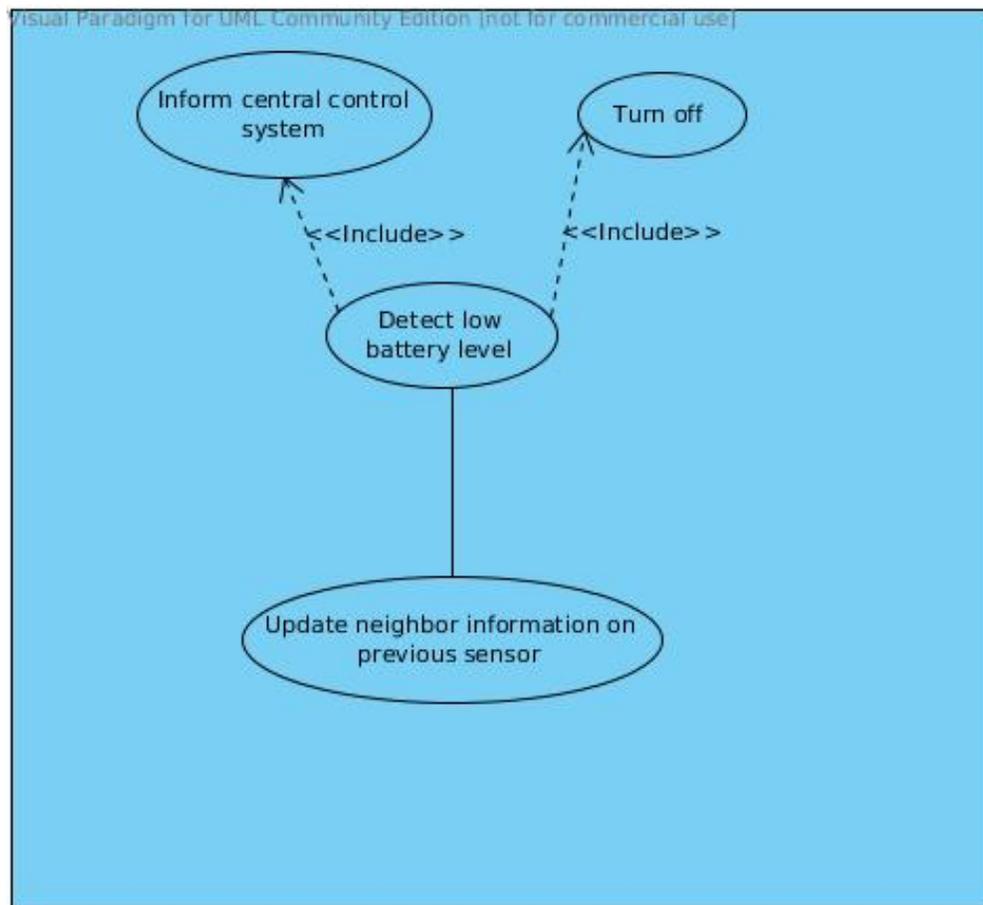
State machine diagrams

Acoustic sensor

Idle

low battery

Off

receive signal for
approaching vehicle

no vehicles

On

low battery

wait for more vehicles

Camera sensor

Idle

battery low

Alert state

receive signal
to take picture

finish operation

On

battery low
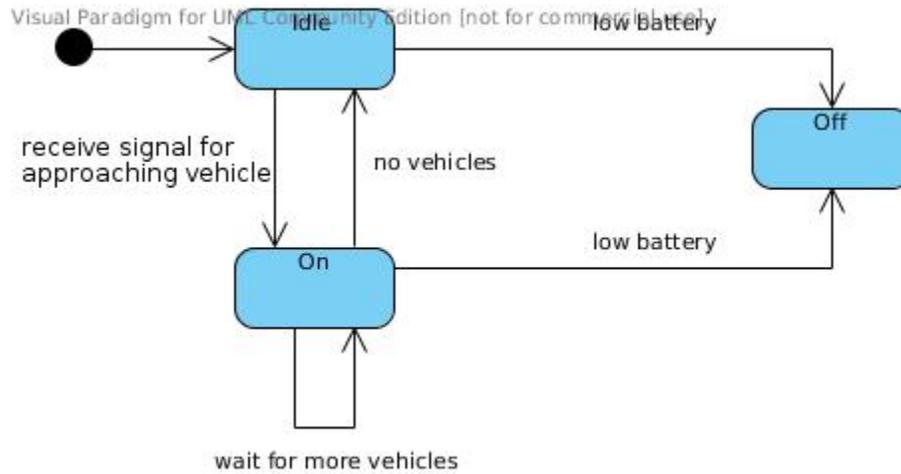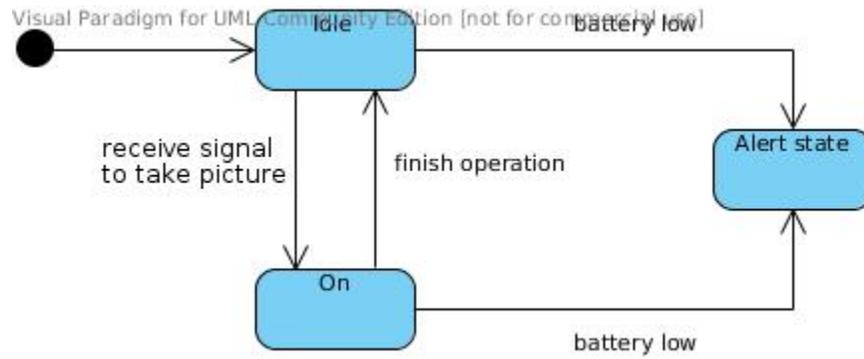
Part 3: Requirements

1. The system should be Energy efficient

   -The number of the sensors should be such in order to optimize energy efficiency, cost and detection probability.

   -Sensors should have different states.(off, idle, on)

2. The system should be accurate in detection and communication

   - The sensing range of the acoustic sensor should be limited to one lane of the road. (use a reverse shotgun polar diagram for the acoustic sensor- width: 4m).

   - Assuming 40 miles per hour maximum vehicle velocity and distance between acoustic sensors is d. The message from one sensor to the other should be transmitted in less than $t < d/50$ (there is also a margin of safety).

   - We need the sensor network to have a 95% probability of detection.

   - The power of the antenna should be enough to allow communication between two sensors.

   - The time response of the Central Control System to messages from the camera should be less than $t < d / 20$ (d distance between the camera and the acoustic sensor).

   - The CCS should be capable of responding on time to simultaneous requests
   .
   - System should work even if one or more acoustic sensors stops operating.

   - System could turn off a misoperating sensor.

   - System should adapt to weather changes.

3. The system should be cost efficient

   - The number of sensors used in the system should be optimized with respect also to energy efficiency

4. Security

   - The messages should be encrypted.
   - The CCS should have methods to identify intrusions and prevent attacks.

The hierarchy of requirements and how they are verified through the elements of the structure are presented below:

req [Package] Sensor Network [sensor_net_requirements]

«requirement»
Number of sensors
Id = "1.1"
Text = "The number of the sensors should be such in order to optimize energy efficiency with respect to cost and detection probability"

Minimization of the following function:

$F(x)=k1*F\_1(x)+k2*F\_2(x)+k3*F\_3(x)$

$F\_1(x)$: function representing the energy consumption (power of the antenna)

$F\_2(x)$: function representing the cost and depends on the number of sensors

$F\_3(x)$: function representing the detection probability

$k1, k2, k3$ maximum values of F_1, F_2, F_3 respectively to assume same order of magnitude

«requirement»
Energy efficiency
Id = "1"
Text = "The system should be energy efficient"

«requirement»
Node states
Id = "1.2"
Text = "Sensors should have different states (off,idle,on)"

«block»
Node
parts
: S_CPU
: Sensor
: Antenna
values
height : Real
neighbor_X : Real
neighbor_Y : Real
position_X : Real
position_Y : Real
state : String = "off"
Report_Status()

«verify»

«requirement»
Cost efficiency
Id = "3"
Text = "The system should be cost efficient "

«constraint»
Check cost
constraints
{Cost < 400000}
parameters
Cost : Real

«verify»

«block»
Local Control System
parts
: LCS_Antenna
values
CPU : Real
RAM : Integer
Turn_on()
Turn_off()
Send_message()
Process_message()
Encrypt()
Decrypt()

«verify»

«block»
S_CPU
values
cpu : Real
ram : Integer
Encrypt()
Decrypt()
Process_message()
Send_message()
Turn_on()
Turn_off()

«requirement»
Encryption
Id = "4.1"
Text = "The messages should be encrypted "

«verify»

«requirement»
Security
Id = "4"
Text = "The system should be secure "

«verify»

«block»
Central Control System
constraints
Response Time : Sensor Network::CCS response time
parts
: CCS_Antenna
: CCS_Antenna
: CCS_Antenna
: CCS_Antenna
CCS : Central Control System
Channel : Channel
values
CPU : Real
RAM : Integer
Response_time
Check_Status()
Turn_on()
Turn_off()
Encrypt()
Decrypt()
Operate_honeypots()
Send_message()
Process_message()

«requirement»
CCS security
Id = "4.2"
Text = "The Central Control System (CCS) should have methods to identify intrusions and prevent attacks "

«verify»

«requirement»
Sensing range

Id = "2.1"
Text = " The sensing range
of the acoustic sensor
should be limited to one
lane of the road.
"

Use a reverse
shotgun polar
diagram for the
acoustic sensor-
width: 4m

«requirement»
**Time constraint in
messages**

Id = "2.2"
Text = "Assuming 40 miles
per hour maximum vehicle
velocity and distance
between acoustic sensors
is d, the message from one
sensor to the other should
be transmitted faster than
the time the vehicle does for
the same distance d"

«verify»

«constraint»
Message traveling time
constraints
{time < distance/50}

parameters
time : Real
distance : Real

«requirement»
**Detection and tracking
probability**

Id = "2.3"
Text = "We need the sensor
network to have a 90%
probability of detection. "

«verify»

«constraint»
BER check
constraints
{1/2*erfc(sqrt(E_b/N_o)) < 0.01 }

parameters
modulation : Integer
N_o : Real
E_b : Real

«requirement»
Antenna power

Id = "2.4"
Text = "The power of the
antenna should be enough
to allow communication
between the sensors. "

«verify»

«constraint»
Propagation constraint
constraints
{P_trans= P_recv*((2*pi*freq*distance)/3*10^8)^2}

parameters

P_trans : Real
P_recv : Real
freq : Real
distance : Real

«requirement»
**Accurate detection and
communication**

Id = "2"
Text = " The system should
be accurate in detection
and communication"

«requirement»
CCS response time

Id = "2.5"
Text = "The response time
of the Central Control
System (CCS) to
messages from the camera
should be less than the
time the vehicle does to go
to the first acoustic sensor."

«verify»

«constraint»
CCS response time
constraints
{time < distance/20}

parameters
time : Real
distance : Real

«requirement»
System operation

Id = "2.7"
Text = "System should work
even if one or more
acoustic sensors stops
operating "

«verify»

«block»
Node
parts
: S_CPU
: Sensor
: Antenna

values
height : Real
neighbor_X : Real
neighbor_Y : Real
position_X : Real
position_Y : Real
state : String = "off"

Report_Status()

«requirement»
Multiple requests

Id = "2.6"
Text = "The Central Control
System (CCS) should be
capable of responding on
time to simultaneous
requests. "

«verify»

«block»
Central Control System
constraints
Response Time : Sensor Network::CCS response time

parts
: CCS_Antenna
: CCS_Antenna
: CCS_Antenna
: CCS_Antenna
CCS : Central Control System
Channel : Channel

values
CPU : Real
RAM : Integer
Response_time

Check_Status()
Turn_on()
Turn_off()
Encrypt()
Decrypt()
Operate_honeypots()
Send_message()
Process_message()

«requirement»
Misoperating sensor

Id = "2.8"
Text = "System should turn
off a misoperating sensor "

«verify»

«requirement»
Weather adaptability

Id = "2.9"
Text = "System should
adapt to weather changes "

«verify»

«constraint»
weather constraint
constraints
{modulation = weather}

parameters
modulation
weather

Requirements Table

#	ID	Name	Text
1	1	Energy efficiency	The system should be energy efficient
2	1.1	Number of sensors	The number of the sensors should be such in order to optimize energy efficiency with respect to cost and detection probability
3	1.2	Sensor states	Sensors should have different states (off,idle,on)
4	2	Accurate detection and communication	The system should be accurate in detection and communication
5	2.1	Sensing range	The sensing range of the acoustic sensor should be limited to one lane of the road. (use a reverse shotgun polar diagram for the acoustic sensor- width: 4m)
6	2.2	Time constraint in messages	Assuming 40 miles per hour maximum vehicle velocity and distance between acoustic sensors is d, the message from one sensor to the other should be transmitted faster than the time the vehicle does for the same distance d
7	2.3	Detection probability	We need the sensor network to have a 95% probability of detection.
8	2.4	Antenna power	The power of the antenna should be enough to allow communication between the sensors.
9	2.5	CCS response time	The response time of the Central Control System (CCS) to messages from the camera should be less than the time the vehicle does to go to the first acoustic sensor.
10	2.6	Multiple requests	The Central Control System (CCS) should be capable of responding on time to simultaneous requests.
11	2.7	System operation	System should work even if one or more acoustic sensors stops operating
12	2.8	Misoperating sensor	System should turn off a misoperating sensor
13	2.9	Weather adaptability	System should adapt to weather changes
14	3	Cost efficiency	The system should be cost efficient
15	4	Security	The system should be secure
16	4.1	Encryption	The messages should be encrypted
17	4.2	CCS security	The Central Control System (CCS) should have methods to identify intrusions and prevent attacks

Derived Requirements

Requirement	Behavior	Structure
1.Energy efficiency		
1.1 Number of sensors		X
1.2 Node states	X	
2. Accurate detection and communication		
2.1 Sensing range		X
2.2 Time constraint in messages	X	
2.3 Detection and tracking probability	X	
2.4 Antenna power	X	X
2.5 CCS response time	X	
2.6 Multiple requests	X	
2.7 System operation	X	
2.8 Misoperating sensor	X	
2.9 Weather adaptability	X	
3. Cost efficiency		
4. Security		
4.1 Encryption	X	
4.2 CCS security	X	X

Energy efficiency, Cost efficiency, Security, Accurate detection and Communication are the system level Requirements.

Traceability Matrix

Requirement	System Components		
	Object	Attribute	Function
1.Energy efficiency	Sensor Network		
1.1 Number of sensors	Sensor Network		
1.2 Node states	S_CPU : Node, CCS	state : Node	Turn_on(), Turn_off () : CCS Turn_on(), Turn_off () : S_CPU
2. Accurate detection and communication	Sensor Network		
2.1 Sensing range	Antenna: Node	gain, directivity, position_X, position_Y : Antenna	
2.2 Time constraint in messages	Channel	Length, Message_time: Channel	Transmit_message(): Channel
2.3 Detection and tracking probability	Sensor : Node	Accuracy: Sensor	
2.4 Antenna power	Antenna: Node CCS_Antenna: CSS LCS_Antenna: LCS Channel	Receiving Power: Antenna, CCS_Antenna, LCS_Antenna Transmitting_Power: Antenna, CCS_Antenna, LCS_Antenna frequency: Antenna, CCS_Antenna, LCS_Antenna length: Channel	Transmit(): Antenna, CCS_Antenna, LCS_Antenna Receive(): Antenna, CCS_Antenna, LCS_Antenna Modulate(): Antenna, CCS_Antenna, LCS_Antenna
2.5 CCS response time	CCS, Channel	Response_time: CCS length: Channel	Process_message(), Send_message() : CCS
2.6 Multiple requests	CCS	CPU, RAM: CCS	
2.7 System operation	Node		Report_status() : Node
2.8 Misoperating sensor	CCS		Check_status: CCS
2.9 Weather adaptability	Antenna: Node CCS_Antenna: CSS LCS_Antenna: LCS Channel	modulation: Antenna, CCS_Antenna, LCS_Antenna weather: Channel	
3. Cost efficiency	Sensor Network	Cost: Sensor Network	
4. Security	Sensor Network		
4.1 Encryption	S_CPU(Node), CCS, LCS		Encrypt(), Decrypt() : S_CPU, CCS, LCS
4.2 CCS security	CCS		Operate_Honeypots(): CCS

Explanation: S_CPU : Node, CCS -→ means that the object S_CPU of the Node block and the CCS is connected with the requirement

Abbreviations' index:

CCS: Central Control System

LCS: Local Control System

Part 4: Structure

Block Definition Diagram

«block»
Sensor network

constraints
Cost_check : Check cost
Propagation Constraint : Sensor Network::Propagation constraint

values
Cost : Real

Node25Node26Node5Node7Node3Node10Node11Node8Node16Node15Node6Node14Node17Node1Node4Node12Node19Node9Node2Node27Node28

CCS

Channel23Channel24Channel5Channel9Channel11Channel13Channel15Channel17Channel19Channel20

«block»
Node

values
height : Real
neighbor_X : Real
neighbor_Y : Real
position_X : Real
position_Y : Real
state : String = "off"

Report_Status()

«block»
Central Control System

constraints
Response Time : Sensor Network::CCS response time

parts
CCS : Central Control System
Channel : Channel

values
CPU : Real
RAM : Integer
Response_time

Check_Status()
Turn_on()
Turn_off()
Encrypt()
Decrypt()
Operate_honeypots()
Send_message()
Process_message()

«block»
Local Control System

values
CPU : Real
RAM : Integer

Turn_on()
Turn_off()
Send_message()
Process_message()
Encrypt()
Decrypt()

«block»
Channel

values
BER : Real
capacity : Real
length : Real
message_time : Real
noise : Real
obstacle : Boolean
weather : Integer

Transmit_message()

«block»
S_CPU

values
cpu : Real
ram : Integer

Encrypt()
Decrypt()
Process_message()
Send_message()
Turn_on()
Turn_off()

«block»
Sensor

values
accuracy : Real

Sensing()

«block»
Antenna

values
Directivity : Real
frequency : Real
gain : Real
modulation : Integer
position_X : Real
position_Y : Real
Reiceiving_Power : Real
Transmitting Power : Real
type : Integer

Transmit()
Receive()
Modulate()
Demodulate()

«block»
CCS_Antenna

values
frequency : Real
gain : Real
modulation : Integer
Receiving_Power
Transmitting_Power : Real
type : Integer

Transmit()
Receive()
Modulate()
Demodulate()

«block»
LCS_Antenna

values
frequency : Real
gain : Real
modulation : Integer
Receiving_Power : Real
Trasmitting_Power : Real
type : Integer

Transmit()
Receive()
Modulate()
Demodulate()

«block»
Obstacle

values
distance : Real
height : Real

«block»
Camera

values
range

Take_pictures()

«block»
Acoustic

«block»
Laser

«constraint»
BER check

constraints
{1/2*erfc(sqrt(E_b/N_o)) < 0.01}

parameters
modulation : Integer
N_o : Real
E_b : Real

«constraint»
CCS response time

constraints
{time < distance/20}

parameters
time : Real
distance : Real

«constraint»
Message traveling time

constraints
{time < distance/50}

parameters
time : Real
distance : Real

«constraint»
Check cost

constraints
{Cost < 400000}

parameters
Cost : Real

«constraint»
Propagation constraint

constraints
{P_trans= P_recv*((2*pi*freq*distance)/3*10^8)^2}

parameters
P_trans : Real
P_recv : Real
freq : Real
distance : Real

«constraint»
weather constraint

constraints
{modulation = weather}

parameters
modulation
weather

Parametric Diagrams

Part 5: Trade-Off Analysis:

System Performance Metrics:

-Accuracy

-Cost

-Energy Consumption

Decision Variables:

- Acoustic

-Laser Sensor

- Camera Sensor

- Central Control System

- Local Control System

Problem formulation:

For all functions that follow:

N1: The number of acoustic sensors.

N2: The number of laser sensors.

N3: The number of camera sensors.

N4: The number of local control systems.

-Cost = N1*C_X + N2*C_Y + N3*C_Z + N4*C_L+ C_C

C_X: The cost of one acoustic sensor.

C_Y: The cost of one laser sensor.

C_Z: The cost of one camera sensor.

C_L: The cost of one local control system.

C_C: The cost of the central control system.

-Accuracy: Because the malfunction of one sensor will affect the accuracy of the whole system, the following function can be used to measure the accuracy of the system.

Accuracy = R_X^N1 * R_Y^N2 * R_Z^N3 * R_L^N4 *R_C

R_X: The accuracy of one acoustic sensor.

R_Y: The accuracy of one laser sensor.

R_Z: The accuracy of one camera sensor.

R_L: The accuracy of one local control system.

R_C: The accuracy of the central control system.

To make the function, that is going to be used in CPLEX, linear, we take the log of the function, so our function will be:

-Accuracy = N1*log(R_X) + N2*log(R_Y) + N3*log(R_Z) + N4*log(R_L) + log(R_C)

-Energy Consumption = N1*P_X + N2*P_Y + N3*P_Z + N4*P_L + P_C

P_X: The power consumption of one acoustic sensor.

P_Y: The power consumption of one laser sensor.

P_Z: The power consumption of one camera sensor.

P_L: The power consumption of one local control system.

P_C: The power consumption of the central control system.

The power consumption of each sensor depends mainly on the power that the antenna needs for the transmission and receiving processes. Therefore, the following formula will be used to determine the energy consumption in each sensor node:

Energy Consumption = percentage_1*Rx + percentage_2*Tx + percentage_3*Pd,

Rx: The current consumption for transmission mode

Tx: The current consumption for reception mode

Pd: The consumption when sensor is powered down

percentage_1: The percentage of time the sensor is on Rx mode

percentage_2: The percentage of time the sensor is on Tx mode

percentage_3: The percentage of time the sensor is on Pd mode

(Data are going to be acquired from datasheets and reviews on the internet)

Integer Programming Formulation:

For the trade off analysis three alternatives will be used for each of the decision variables.

• Selection of the acoustic sensors is represented by variables X

$X_i = 1$ for only one value of $i = 1$, 2, and 3. Otherwise, $X_i = 0$.

• Selection of the laser sensor is represented by variables Y

$Y_i = 1$ for only one value of $i = 1$, 2, and 3. Otherwise, $Y_i = 0$.

• Selection of the camera sensor is represented by variables Z

$Z_i = 1$ for only one value of $i = 1$, 2, and 3. Otherwise, $Z_i = 0$.

• Selection of the local control system is represented by variables L

$L_i = 1$ for only one value of $i = 1$, 2, and 3. Otherwise, $L_i = 0$.

• Selection of the central control system is represented by variables C

$C_i = 1$ for only one value of $i = 1$, 2, and 3. Otherwise, $C_i = 0$.

Formula for <u>System Cost</u>:

$$
\begin{aligned}
\text{Cost } C = \; & N1*C\_AS1*X1 + N1*C\_AS2*X2 + N1*C\_AS3*X3 + N2*C\_LS1*Y1 + \\
& N2*C\_LS2*Y2 + N2*C\_LS3*Y3 + N3*C\_CS1*Z1 + N3*C\_CS2*Z2 + \\
& N3*C\_CS3*Z3 + N4*C\_LCS1*L1 + N4*C\_LCS2*L2 + N4*C\_LCS3*L3 + \\
& C\_CCS1*C1 + C\_CCS2*C2 + C\_CCS3*C3
\end{aligned}
$$

Formula for <u>Performance</u>:

$$
\begin{aligned}
\text{Accuracy } R = \; & N1*R\_AS1*X1 + N1*R\_AS2*X2 + N1*R\_AS3*X3 + N2*R\_LS1*Y1 + \\
& N2*R\_LS2*Y2 + N2*R\_LS3*Y3 + N3*R\_CS1*Z1 + N3*R\_CS2*Z2 + \\
& N3*R\_CS3*Z3 + N4*R\_LCS1*L1 + N4*R\_LCS2*L2 + N4*R\_LCS3*L3 + \\
& R\_CCS1*C1 + R\_CCS2*C2 + R\_CCS3*C3
\end{aligned}
$$

Formula for <u>Energy Consumption</u>:

$$
\begin{aligned}
\text{Energy } E = \; & N1*E\_AS1*X1 + N1*E\_AS2*X2 + N1*E\_AS3*X3 + N2*E\_LS1*Y1 + \\
& N2*E\_LS2*Y2 + N2*E\_LS3*Y3 + N3*E\_CS1*Z1 + N3*E\_CS2*Z2 + \\
& N3*E\_CS3*Z3 + N4*E\_LCS1*L1 + N4*E\_LCS2*L2 + N4*E\_LCS3*L3 + \\
& E\_CCS1*C1 + E\_CCS2*C2 + E\_CCS3*C3
\end{aligned}
$$

Design Objective

- Minimize cost and energy consumption and maximize accuracy

Minimize:

$$
\begin{aligned}
\text{Energy } E = \; & 50*0.6481*X1 + 50*0.7628*X2 + 50*1*X3 + 12*0.6378*Y1 + 12*0.8586*Y2 + \\
& 12*1*Y3 + 5*0.6015*Z1 + 5*0.8333*Z2 + 5*1*Z3 + 3*0.7143*L1 + \\
& 3*0.8095*L2 + 3*1*L3 + 0.6030*C1 + 0.7528*C2 + 1*C3
\end{aligned}
$$

Subject to

- K<= 50*0.013333*X1 + 50*0.015833*X2 + 50*0.02*X3 + 12*0.011667*Y1 + 12*0.015*Y2+ 12*0.018333*Y3 + 5*0.015*Z1 + 5*0.018333*Z2 + 5*0.025*Z3 + 3*0.066667*L1 + 3*0.075*L2 + 3*0.083333*L3 + 0.5*C1 + 0.833333*C2 + 1*C3 <= 2

- L<= 50*0.9375*X1 + 50*0.9583333*X2 + 50*1*X3 + 12*0.94949494 *Y1 + 12*0.969697 *Y2 + 12*1*Y3 + 5*0.92857*Z1 + 5*0.95918*Z2 + 5*1*Z3 + 3*0.6*L1 + 3*0.8*L2 + 3*1*L3 + 0.666667*C1 + 0.8*C2 + 1*C3 <= 0

-     $X_1 + X_2 + X_3 = 1$
-     $Y_1 + Y_2 + Y_3 = 1$
-     $Z_1 + Z_2 + Z_3 = 1$
-     $L_1 + L_2 + L_3 = 1$
-     $C_1 + C_2 + C_3 = 1$

Bounds

- $0 <= X_1 <= 1$,
  $0 <= X_2 <= 1$,
  $0 <= X_3 <= 1$,
  $0 <= Y_1 <= 1$,
  $0 <= Y_2 <= 1$,
  $0 <= Y_3 <= 1$,
  $0 <= Z_1 <= 1$,
  $0 <= Z_2 <= 1$,
  $0 <= Z_3 <= 1$,
  $0 <= L_1 <= 1$,
  $0 <= L_2 <= 1$,
  $0 <= L_3 <= 1$,
  $0 <= C_1 <= 1$,
  $0 <= C_2 <= 1$,
  $0 <= C_3 <= 1$,

Value Constraints

- X1, X2, X3, Y1, Y2, Y3, Z1, Z2, Z3, L1, L2, L3, C1, C2, and C3 are integers.

We change the values of K and L to get the different points with various cost, reliability and performance.

The following table is the different combination of K and L

| Point #	L	K
1	-54	1.6
2	-53.5	1.6
3	-45	1.7
4	-40	1.7
5	-39	1.8
6	-38	1.8
7	-35	1.9
8	-33	1.9
9	-31	2
10	-30	2
11	-29	2.1
12	-27	2.1
13	-25	2.2
14	-23	2.3
15	-20	2.3
16	-15	2.4
17	-10	2.4
18	-5	2.5
19	-1	2.6

Each combination of L and K corresponds to each set of solution variables.

The results from the optimization are presented on the table below:

Point #	X1	X2	X3	Y1	Y2	Y3	Z1	Z2	Z3	L1	L2	L3	C1	C2	C3	cost	performance	energy
1	1			1			1			1			1			1.5816	-53.483	45.812
2	1			1			1			1			1			1.5816	-53.483	45.812
3	1			1			1					1	1			1.6316	-40.1721	46.6691
4	1			1				1				1	1			1.6483	-38.7632	47.8281
5	1			1				1				1	1			1.6483	-38.7632	47.8281
6	1			1					1			1	1			1.6816	-36.9536	48.6616
7	1					1	1					1	1			1.7116	-34.7703	51.0155
8		1		1			1					1	1			1.7566	-30.6256	52.4041
9		1		1			1					1	1			1.7566	-30.6256	52.4041
10		1		1				1				1	1			1.7733	-29.2169	53.5631
11		1		1					1			1	1			1.8066	-27.4071	54.3966
12		1			1		1					1	1			1.8366	-25.2238	56.7505
13		1			1		1					1		1		2.1699	-23.6401	56.9003
14		1			1			1				1		1		2.1866	-22.2315	58.0593
15			1	1			1				1		1			1.94	-17.9567	63.6926
16			1	1			1					1	1			1.965	-12.1421	64.2641
17			1	1				1				1		1		2.315	-9.1498	65.573
18			1		1			1				1		1		2.395	-3.748	69.9193
19			1		1				1			1			1	2.595	0	71

Trade off Scenarios:

The distribution of the points in terms of "cost vs energy", "cost vs performance", and "performance vs energy" are shown in the following charts, some of the points overlap because some different combinations of K_1 and K_2 produced the same variable values.
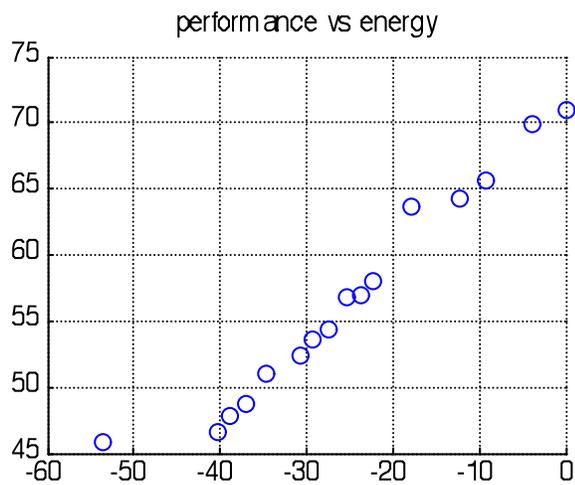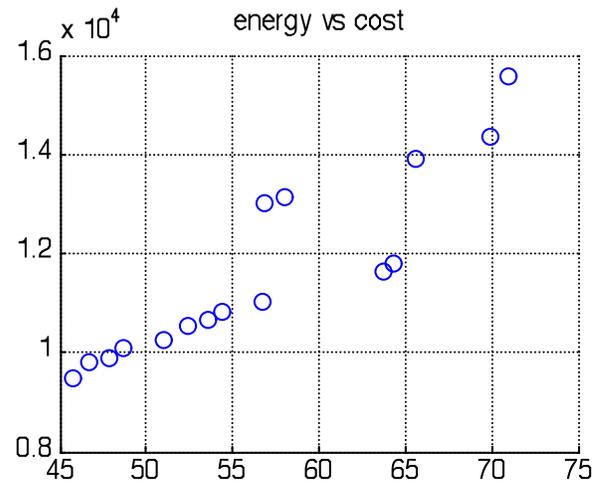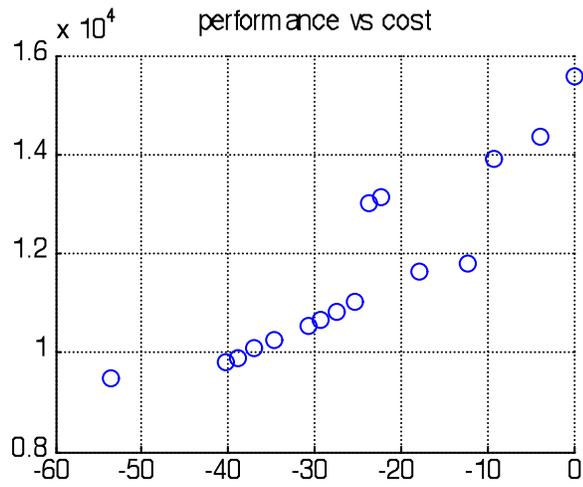
Points of Interest:

Points of interest are adjacent designs where an incremental increase in one desirable variable creates a much larger increase in another desirable variable. The later represents a point that will be studied later on, to determine optimality

Results:

Points of interest that are common to all three graphs are: 2, 6, and 13

Point #	cost	performance	energy
2	1.5816	-53.483	45.812
6	1.6816	-36.9536	48.6616
13	2.1699	-23.6401	56.9003

Comparison between point 2 & point 6:

We prefer point 6 because a 6% increase in cost and energy gives us a 30% increase in performance.

Comparison between point 6 & point 13:

We prefer point 13. Although it costs a 29% increase in cost and a 17% increase. We get a 36% increase in performance, which is highly desirable especially in a secured military base.

FINAL RESULT

According to the analysis, the final choice is "point 13" which has best results for the given constraints.

- **Attributes of Point 13**
  Cost = 2.1699, Energy = 56.9003, Performance = -23.6401

The de-normalized results of the analysis conclusion are as follows:

- Acoustic Sensor: Component AS_2.
- Laser Sensor: Component LS_3.
- Camera Sensor: Component CS_1.
- Local Control System: Component LCS_3.
- Central Control System: Component CCS_2.

  The system total cost is $13020.