**Project Title:** Integrated Security of Wireless Sensor Networks

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**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.

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**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 vehicle's plate has been captured.

Actors: Vehicle, Human

Flow of Events:

- 1. Closest sensors are activated.
- 2. The sensors track the vehicle.
- 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 Case 3. 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.
Use Case 4. 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.
Use Case 5. 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

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Acoustic sensor</th>
<th>Control system(CS)</th>
<th>Camera</th>
<th>Acoustic sensor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>detects movement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>sends info to CS</td>
<td>process info</td>
<td>captures the plate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>activates camera</td>
<td>sends info to CS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>identifies nearest acoustic sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>activates acoustic sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>goes to idle state</td>
<td></td>
<td>starts tracking</td>
</tr>
</tbody>
</table>

- Vehicle arrives at parking exit
- Vehicle detects movement
- Vehicle sends info to Control system(CS)
- Control system(CS) process info
- Control system(CS) activates camera
- Camera captures the plate
- Camera sends info to Acoustic sensor 2
- Acoustic sensor 2 identifies nearest acoustic sensor
- Acoustic sensor 2 activates acoustic sensor
- Acoustic sensor 2 goes to idle state
- Acoustic sensor 2 starts tracking
Use Case 6. 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 Case 7. 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**
  - Transition to **On** on receiving signal for approaching vehicle.
  - Transition to **Off** on low battery.
  - Transition to wait for more vehicles on no vehicles.

**Camera sensor**

- **Idle**
  - Transition to **On** on receiving signal to take picture.
  - Transition to **Alert state** on finish operation.
  - Transition to **Idle** on battery low.

- **On**
  - Transition to **Idle** on battery low.

- **Off**
  - Transition to **Idle** on low battery.
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:
## Requirements Table

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Name</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Energy efficiency</td>
<td>The system should be energy efficient</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Number of sensors</td>
<td>The number of the sensors should be such in order to optimize energy efficiency with respect to cost and detection probability</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Sensor states</td>
<td>Sensors should have different states (off, idle, active)</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Accurate detection and communication</td>
<td>The system should be accurate in detection and communication</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Sensing range</td>
<td>The sensing range of the acoustic sensor should be limited to one lane of the road.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(use a reverse shotgun polar diagram for the acoustic sensor-width: 4m)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Time constraint in messages</td>
<td>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 takes to go the same distance d</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Detection probability</td>
<td>We need the sensor network to have a 95% probability of detection</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Antenna power</td>
<td>The power of the antenna should be enough to allow communication between the sensors</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>CCS response time</td>
<td>The response time of the Central Control System (CCS) to messages from the cameras should be less than the time the vehicle takes to go to the first acoustic sensor</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Multiple requests</td>
<td>The Central Control System (CCS) should be capable of responding on time to simultaneous requests</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>System operation</td>
<td>System should work even if one or more acoustic sensors stop operating</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Misoperating sensor</td>
<td>System should turn off a misoperating sensor</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Weather adaptability</td>
<td>System should adapt to weather changes</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Cost efficiency</td>
<td>The system should be cost efficient</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Security</td>
<td>The system should be secure</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Encryption</td>
<td>The messages should be encrypted</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>CCS security</td>
<td>The Central Control System (CCS) should have methods to identify intrusions and prevent attacks</td>
</tr>
</tbody>
</table>
## Derived Requirements

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

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

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

\[
\text{Energy Consumption} = \text{percentage}_1 \times \text{Rx} + \text{percentage}_2 \times \text{Tx} + \text{percentage}_3 \times \text{Pd},
\]

- 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 \(X\)
  
  \[X_i = 1 \text{ for only one value of } i = 1, 2, \text{ and } 3. \text{ Otherwise, } X_i = 0.\]

- Selection of the laser sensor is represented by variables \(Y\)
  
  \[Y_i = 1 \text{ for only one value of } i = 1, 2, \text{ and } 3. \text{ Otherwise, } Y_i = 0.\]

- Selection of the camera sensor is represented by variables \(Z\)
  
  \[Z_i = 1 \text{ for only one value of } i = 1, 2, \text{ and } 3. \text{ Otherwise, } Z_i = 0.\]

- Selection of the local control system is represented by variables \(L\)
  
  \[L_i = 1 \text{ for only one value of } i = 1, 2, \text{ and } 3. \text{ Otherwise, } L_i = 0.\]

- Selection of the central control system is represented by variables \(C\)
  
  \[C_i = 1 \text{ for only one value of } i = 1, 2, \text{ and } 3. \text{ Otherwise, } C_i = 0.\]
Formula for System Cost:

\[ \text{Cost } C = N_1 \cdot C_{AS1} \cdot X_1 + N_1 \cdot C_{AS2} \cdot X_2 + N_1 \cdot C_{AS3} \cdot X_3 + N_2 \cdot C_{LS1} \cdot Y_1 + N_2 \cdot C_{LS2} \cdot Y_2 + N_2 \cdot C_{LS3} \cdot Y_3 + N_3 \cdot C_{CS1} \cdot Z_1 + N_3 \cdot C_{CS2} \cdot Z_2 + N_3 \cdot C_{CS3} \cdot Z_3 + N_4 \cdot C_{LCS1} \cdot L_1 + N_4 \cdot C_{LCS2} \cdot L_2 + N_4 \cdot C_{LCS3} \cdot L_3 + C_{CCS1} \cdot C_1 + C_{CCS2} \cdot C_2 + C_{CCS3} \cdot C_3 \]

Formula for Performance:

\[ \text{Accuracy } R = N_1 \cdot R_{AS1} \cdot X_1 + N_1 \cdot R_{AS2} \cdot X_2 + N_1 \cdot R_{AS3} \cdot X_3 + N_2 \cdot R_{LS1} \cdot Y_1 + N_2 \cdot R_{LS2} \cdot Y_2 + N_2 \cdot R_{LS3} \cdot Y_3 + N_3 \cdot R_{CS1} \cdot Z_1 + N_3 \cdot R_{CS2} \cdot Z_2 + N_3 \cdot R_{CS3} \cdot Z_3 + N_4 \cdot R_{LCS1} \cdot L_1 + N_4 \cdot R_{LCS2} \cdot L_2 + N_4 \cdot R_{LCS3} \cdot L_3 + R_{CCS1} \cdot C_1 + R_{CCS2} \cdot C_2 + R_{CCS3} \cdot C_3 \]

Formula for Energy Consumption:

\[ \text{Energy } E = N_1 \cdot E_{AS1} \cdot X_1 + N_1 \cdot E_{AS2} \cdot X_2 + N_1 \cdot E_{AS3} \cdot X_3 + N_2 \cdot E_{LS1} \cdot Y_1 + N_2 \cdot E_{LS2} \cdot Y_2 + N_2 \cdot E_{LS3} \cdot Y_3 + N_3 \cdot E_{CS1} \cdot Z_1 + N_3 \cdot E_{CS2} \cdot Z_2 + N_3 \cdot E_{CS3} \cdot Z_3 + N_4 \cdot E_{LCS1} \cdot L_1 + N_4 \cdot E_{LCS2} \cdot L_2 + N_4 \cdot E_{LCS3} \cdot L_3 + E_{CCS1} \cdot C_1 + E_{CCS2} \cdot C_2 + E_{CCS3} \cdot C_3 \]

Design Objective

- Minimize cost and energy consumption and maximize accuracy

Minimize:

\[ \text{Energy } E = 50 \cdot 0.6481 \cdot X_1 + 50 \cdot 0.7628 \cdot X_2 + 50 \cdot 1 \cdot X_3 + 12 \cdot 0.6378 \cdot Y_1 + 12 \cdot 0.8586 \cdot Y_2 + 12 \cdot 1 \cdot Y_3 + 5 \cdot 0.6015 \cdot Z_1 + 5 \cdot 0.8333 \cdot Z_2 + 5 \cdot 1 \cdot Z_3 + 3 \cdot 0.7143 \cdot L_1 + 3 \cdot 0.8095 \cdot L_2 + 3 \cdot 1 \cdot L_3 + 0.6030 \cdot C_1 + 0.7528 \cdot C_2 + 1 \cdot C_3 \]
Subject to

• \( K \leq 50 \times 0.013333 \times X_1 + 50 \times 0.015833 \times X_2 + 50 \times 0.02 \times X_3 + 12 \times 0.011667 \times Y_1 + 12 \times 0.015 \times Y_2 + 12 \times 0.018333 \times Y_3 + 5 \times 0.015 \times Z_1 + 5 \times 0.018333 \times Z_2 + 5 \times 0.025 \times Z_3 + 3 \times 0.066667 \times L_1 + 3 \times 0.075 \times L_2 + 3 \times 0.083333 \times L_3 + 0.5 \times C_1 + 0.833333 \times C_2 + 1 \times C_3 \leq 2 \)

• \( L \leq 50 \times 0.9375 \times X_1 + 50 \times 0.958333 \times X_2 + 50 \times 1 \times X_3 + 12 \times 0.94949494 \times Y_1 + 12 \times 0.969697 \times Y_2 + 12 \times 1 \times Y_3 + 5 \times 0.92857 \times Z_1 + 5 \times 0.95918 \times Z_2 + 5 \times 1 \times Z_3 + 3 \times 0.6 \times L_1 + 3 \times 0.8 \times L_2 + 3 \times 1 \times L_3 + 0.666667 \times C_1 + 0.8 \times C_2 + 1 \times C_3 \leq 0 \)

• \( X_1 + X_2 + X_3 = 1 \)
• \( Y_1 + Y_2 + Y_3 = 1 \)
• \( Z_1 + Z_2 + Z_3 = 1 \)
• \( L_1 + L_2 + L_3 = 1 \)
• \( C_1 + C_2 + C_3 = 1 \)

Bounds

• \( 0 \leq X_1 \leq 1 \)
• \( 0 \leq X_2 \leq 1 \)
• \( 0 \leq X_3 \leq 1 \)
• \( 0 \leq Y_1 \leq 1 \)
• \( 0 \leq Y_2 \leq 1 \)
• \( 0 \leq Y_3 \leq 1 \)
• \( 0 \leq Z_1 \leq 1 \)
• \( 0 \leq Z_2 \leq 1 \)
• \( 0 \leq Z_3 \leq 1 \)
• \( 0 \leq L_1 \leq 1 \)
• \( 0 \leq L_2 \leq 1 \)
• \( 0 \leq L_3 \leq 1 \)
• \( 0 \leq C_1 \leq 1 \)
• \( 0 \leq C_2 \leq 1 \)
• \( 0 \leq C_3 \leq 1 \)

Value Constraints

• \( X_1, X_2, X_3, Y_1, Y_2, Y_3, Z_1, Z_2, Z_3, L_1, L_2, L_3, C_1, C_2, \) and \( C_3 \) 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

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Each combination of L and K corresponds to each set of solution variables.
The results from the optimization are presented on the table below:

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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

<table>
<thead>
<tr>
<th>Point #</th>
<th>cost</th>
<th>performance</th>
<th>energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.5816</td>
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<td>-23.6401</td>
<td>56.9003</td>
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</tbody>
</table>

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:

- Camera Sensor: Component CS1.
- Local Control System: Component LCS3.
- Central Control System: Component CCS2.

The system total cost is $13020.