ENGN2225 Systems Engineering Design

Portfolio: Leak Detection System for Parabolic Trough Solar Power Plant

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1. Introduction

Parabolic trough solar power plants generate electricity by converting the heat energy from the sun to a useful work. Sets of curved mirrors called parabolic trough concentrators focus the solar radiation on tubular receivers which are situated along the focal line of the parabola (Lovegrove and Stein, 2012). As the heat transfer fluid (HTF) such as thermal oil, water/steam or molten salt runs through the tubular receivers, it is typically heated to 400˚C (Hoffschmidt et al., 2012). The heated fluid can be directly used to run power cycles or this heat can be extracted and passed on to a separate fluid that is used only for the power cycle. To utilise the solar radiation as much as possible, the mirror-receiver assemblies track the movement of the sun throughout the day. Mirror-receiver assemblies in series are illustrated in figure 1.

Figure 1. Parabolic trough solar concentrators (SEIA, No date provided)

The tubular receivers used in parabolic trough solar power plants consist of two tubes, one inside the other. While the HTF only flows in the inner tube, the outer tube serves to reduce the convection heat loss by maintaining a vacuum around it. The outer tube also helps prevent oxidation of the hot inner tube surface (Price et al., 2002). This double tube design may seem disadvantageous in terms of absorbing the most amount of solar radiation but the use of anti-reflective glass tubes and the solar-selective absorber surface ensures that it still maintains high performance (Price et al., 2002). The problem with this design, however, is the high failure rate which is around 4 ~ 5% per annum (Price et al., 2002). It has been also observed that the leakage is frequent at the joints where the receiver tubes connect to the main pipe lines that link other infrastructure (Ibarguren et al., 2013). Consequently, HTF leakages are an important factor that must be considered in the power plant maintenance routine. HTF leakage presents safety issues as some HTFs are flammable (including the frequently used thermal oils), with a further problem of the toxicity of the HTF to the staff and the environment (especially molten salts HTF) (Price et al., 2002). On top of that, leakage is an unnecessary loss of resource and reduces the overall efficiency of the power plant and thus directly impacts on the profit of the plant. Consequently, the detection of leakage is vital to the safe and effective operation of parabolic trough solar power plants.

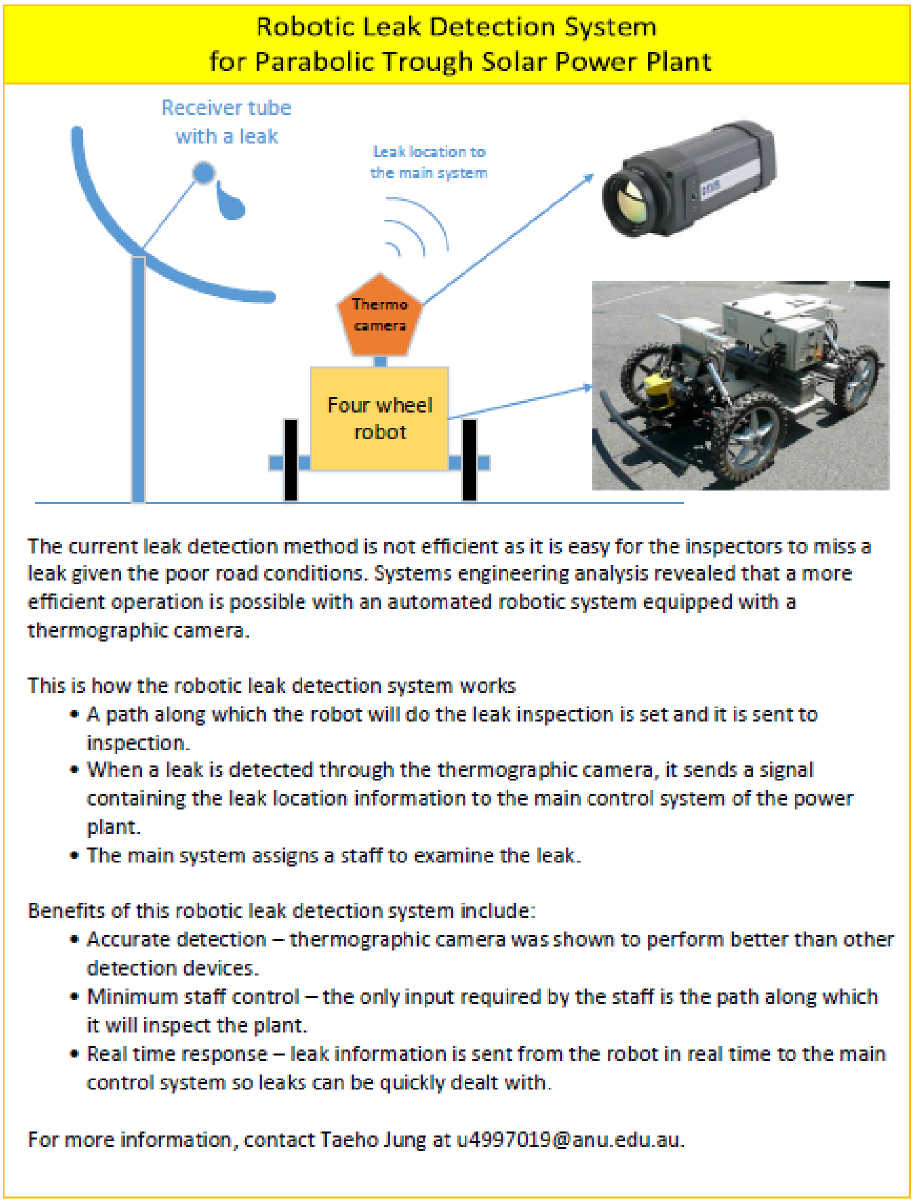
Ibarguren et al. (2013) reported that an inefficient leakage detection method has been embraced in Valle 1 and 2 parabolic trough solar power plants in Spain, owned by Terresol Energy Investments, S.A.. Currently, the leak detection is performed by human inspectors on a moving car using a thermographic camera. The road condition is not ideal (dirt roads with some poorly asphalted roads), and the vast size of the solar field makes the inspection even more difficult. Total area of Valle 1 and 2 is $2.30\times10^6 m^2$ (NREL, 2012) and it takes approximately two hours to complete the inspection by the current method (Ibarguren et al., 2013). Keeping the camera in field of view on a bumpy car while analysing the data on the camera for two hours would not be an easy task and it is expected to be prone to missing a leak. This paper investigates three leak detection systems for Valle 1 and 2 parabolic trough solar power plants through systems engineering approach.

2. Summary of systems engineering analysis and design communication

The following systems engineering approach was employed in this paper.

1. Requirements engineering: Requirements were identified and prioritised. The most important requirements were that the solution must be able to detect and locate leaks. Trade-offs were identified through the House of Quality (HoQ).
2. System function definition: Three solutions were proposed: a robotic system with a thermographic camera, a robotic system with an acoustic detection device, a non-robotic pressure measurement system. Functional flow block diagrams (FFBDs) illustrated that non-robotic system provided a simpler solution. Despite this, this option was eliminated as it did not meet two of the design requirements.
3. Subsystem integration: Subsystems of the robotic system were identified and graphically represented on a functional block diagram (FBD). FBD helped keep the system as modular as possible.
4. System attributes: Attributes of the robotic system were identified and the ‘sensor’ subsystem was found to be the most important subsystem.
5. Verification: Test procedures were created in order to test ‘robustness’ and ‘throughput’.
6. Evaluation: Evaluation matrix was used to quantitatively rank the three proposed solutions. It ranked the robotic system with a thermographic camera the highest.

From the above six analysis stages, the robotic system with a thermographic camera was chosen as the most appropriate solution for the Valle 1 and 2 parabolic trough solar power plants. In order to effectively communicate this result with the company, a brochure was chosen as a means to provide the basic information about the solution. (figure 2). A large portion of the brochure was devoted to a diagram illustrating the concept and also engineering specific terms were avoided so that people without engineering background can easily understand. If the company is interested in implementing the solution, a meeting with the company representatives and engineers would be required. There, a more detailed illustration of the concept will be presented. It would be good if the presentation involves a real prototype or at least a computer simulation of how the system will work. Choosing both the brochure and the presentation with visual aids will help the clients fully grasp the ideas presented to them. This is backed up by Henderson (1991) and Ganah et al. (2000) who asserted the importance of visual aids in communication especially when various parties are involved in engineering projects.



Robotic Leak Detection System
for Parabolic Trough Solar Power Plant

The current leak detection method is not efficient as it is easy for the inspectors to miss a leak given the poor road conditions. Systems engineering analysis revealed that a more efficient operation is possible with an automated robotic system equipped with a thermographic camera.

This is how the robotic leak detection system works

- A path along which the robot will do the leak inspection is set and it is sent to inspection.
- When a leak is detected through the thermographic camera, it sends a signal containing the leak location information to the main control system of the power plant.
- The main system assigns a staff to examine the leak.

Benefits of this robotic leak detection system include:

- Accurate detection – thermographic camera was shown to perform better than other detection devices.
- Minimum staff control – the only input required by the staff is the path along which it will inspect the plant.
- Real time response – leak information is sent from the robot in real time to the main control system so leaks can be quickly dealt with.

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Figure 2. Brochure as a means of communication.

3. Application of theory

This section provides details of how systems engineering analysis theory and tools were used to arrive at the final recommended solution.

3.1. Requirements engineering

Identifying requirements of a solution is an important concept in systems engineering. This process directs the project in a way to reflect the customer's needs and thus increases the customer satisfaction. Customer requirements are usually obtained from a client meeting but it was not possible to conduct a meeting with the power plant for this portfolio. Instead, customer requirements were created by asking 'what are the ideal properties or characteristics that the leak detection system should have?' from the perspective of the power plant owner. The following eight requirements were created.

1. Cheap
2. Detects leaks
3. Locates leaks
4. Reliable
5. Durable
6. Efficient
7. Autonomous
8. Compatible: Compatible means that the inspection system can operate without any alteration to the current hardware and software systems of the power plant.

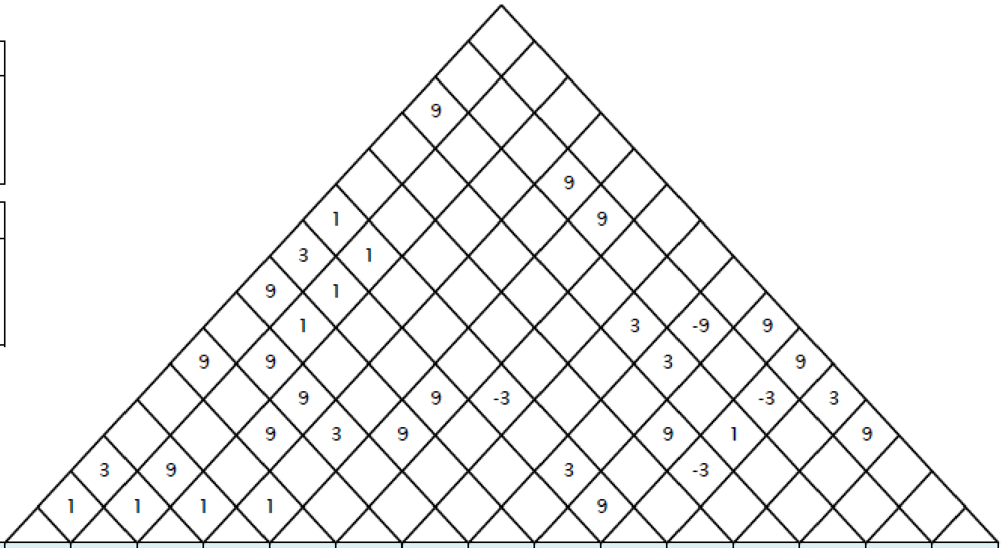
These were then compared by the pairwise analysis (table 1). The analysis results revealed that 'detects leaks' is the most important requirement and 'cheap' is the least important.

Table 1. Pairwise analysis

	Cheap	Detects leaks	Locates leaks	Reliable	Robust/Durable	Efficient	Autonomous	Compatible	Score	Rank
Cheap		0	0	0	0	0	0	0	0	8
Detects leaks	1		1	1	1	1	1	1	7	1
Locates leaks	1	0		1	1	1	1	1	6	2
Reliable	1	0	0		1	1	1	0	4	4
Durable	1	0	0	0		1	0	0	2	6
Efficient	1	0	0	0	0		0	0	1	7
Autonomous	1	0	0	0	1	1		0	3	5
Compatible	1	0	0	1	1	1	1		5	3

Correlations	
Positive	+
Negative	-
No Correlation	

Relationships	
Strong	9
Moderate	3
Weak	1



	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Relative Importance	Functional Requirements / Customer Requirements (Explicit and Implicit)	Keeps pipe within operating range of sensor	Communicates with main system	Stores information	Readily integrable to software system	Readily integrable to hardware system	Process info from sensor correctly	Gives location information	Operable in poor road condition	Operable in hazardous environment	Doesn't disintegrate easily	Light weight	Parts easily replaceable	High efficiency	Min investment cost	Min maintenance cost
1	Effective leak detection mechanism	9	9	1			9							3		
2	Effective mechanism to locate leak	9	9	1			9	9	1							
3	Compatible		3	1	9	9		3	9	9					9	3
4	Low failure rate	9	9				9	9			9			3		3
5	Automous	3	9		9	9		9	9	3					3	3
6	Durable								9	9	9	3	9		3	9
7	Minimum inspection time								9	3	3	9		9	3	9
8	Minimum cost				9	9			3	3	3	3	9	3	9	9
	Measurement metric	° (degrees)	bits/s	bits	number of new software	m^3	bits	bits	° (slope), m (elevation)	°C, rate of reaction	N (force), number of parts	kg	number of parts	time, failure rate	$	$/year

Figure 3. House of Quality

From the customer requirements, more specific design requirements and their engineering characteristics were developed. Eight design requirements are listed below.

1. Effective leak detection mechanism
2. Effective mechanism to locate leak
3. Compatible
4. Low failure rate
5. Autonomous
6. Durable
7. Minimum inspection time
8. Minimum cost

Relationships between these design requirements and the engineering characteristics were analysed on the house of quality (HoQ) in figure 3. HoQ revealed that many of the design requirements and the engineering characteristics that were thought independent of each other have dependencies in fact. Note there are trade-offs between ‘doesn’t disintegrate easily’ and ‘parts easily replaceable’, ‘minimum investment cost’ and ‘process info from sensor correctly’. To make a system non-disintegrable, it would be better to have all the components built in some sort of a protective container to minimise the exposure to the environment, including the sensor. However, this may seriously downgrade the effectiveness of the sensor by impeding the signal strength. Also, this may make replacing parts more difficult especially if the components are sealed off completely in the container. Therefore, developing a system that is durable and highly sensitive can be a challenge and the investment cost associated with it may be high. Also, as the road condition is rough, it may require advanced features to stably operate if a solution is to involve an automobile, indicating another trade-off between the cost and the performance. The major insight obtained from this section is that there are trade-offs to keep in mind throughout the project and the final solution must be well balanced between these competing requirements.

3.2. System function definition

Functions are discrete actions that need to be taken to achieve the goal of the system (Department of Defence (USA), 2001). Functional analysis brings together the requirements identified in the previous section into a coherent functional description of the system (Department of Defence (USA), 2001). A functional flow block diagram (FFBD) will be used to perform the functional analysis in this paper. Based on the design requirements, three possible detection system have been selected as the candidates for solution.

Solution 1: Ibarguren et al. (2013) suggested an autonomous robotic system for the leakage detection. The system comprises a four-wheel robot with a thermographic camera mounted on top. GPS is used to guide the robot along the predetermined route and a robotic arm is designated to keep the pipe lines in field of view of the camera if deviation occurs. Figure 4 shows the robot (developed by Robosoft) and thermographic camera used by Ibarguren et al. (2013) in their study.

Solution 2: Instead of the thermographic camera, an acoustic detection system can be mounted on the same four-wheel robot system considered by Ibarguren et al. (2013). The acoustic detectors detect leaks by picking up the sound wave generated by the fluid escaping the pipeline (Zhang, 1997).

Solution 3: The consequence of any leakage is a pressure drop across the pipeline and thus this can be used to detect the leakage (Zhang, 1997). This method would not need autonomous robots as detectors can be placed along the pipeline.

Figure 4. a) Four wheel robot; b) and c) thermographic camera
(image from Ibarguren et al. (2013))

Figure 5 shows the FFBD for the robotic system. Both electric and hydrocarbon fuel based robots were considered as the operating specifics is not known. For the non-robotic system in figure 6, it was assumed that pressure measurement devices were attached along the pipeline at regular intervals. No separate preparing stages would be required for the non-robotic system as the controlling software would be incorporated in the power plant’s main system. That is, starting and shutting down of the non-robotic system would be done automatically at the start and the end of the plant operation.

The major advantage of the non-robotic system is that it can continuously inspect the plant and an immediate leak detection is possible. Not only that, issues with the road condition and sensor controlling to maintain reasonable signal strength are all together eliminated, making the system simpler, as evident in the FFBDs. Nevertheless, the drawback of the non-robotic system is that a new receiver model is required to enable the pressure measurement which leads to an increased investment and R&D cost. Even if such model exists, transmitting the acquired information back to the main control centre is still problematic as the transmission system needs to be able to survive the concentrated solar heat possibly exceeding 400˚C. Again, either developing a heat resistant signal system or purchasing such existing system, both options will be expensive. Although the FFBD showed that the non-robotic system was an attractive solution due to its simple operation, there are issues with the cost and compatibility. Therefore, it is concluded that the non-robotic system is not a feasible solution and the analysis from now on will be focused on the robotic system only.

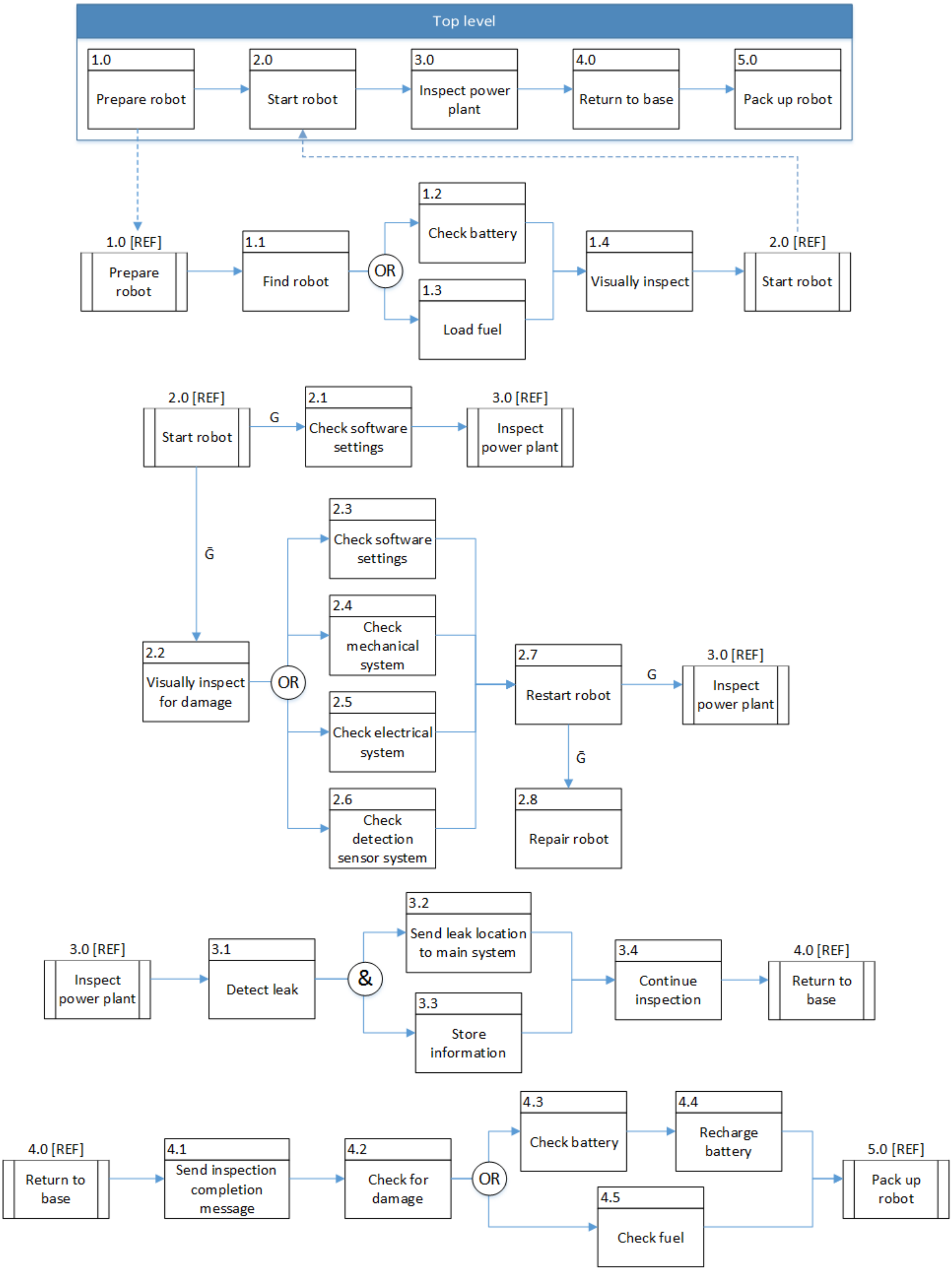


Figure 5. FFBD for robotic system

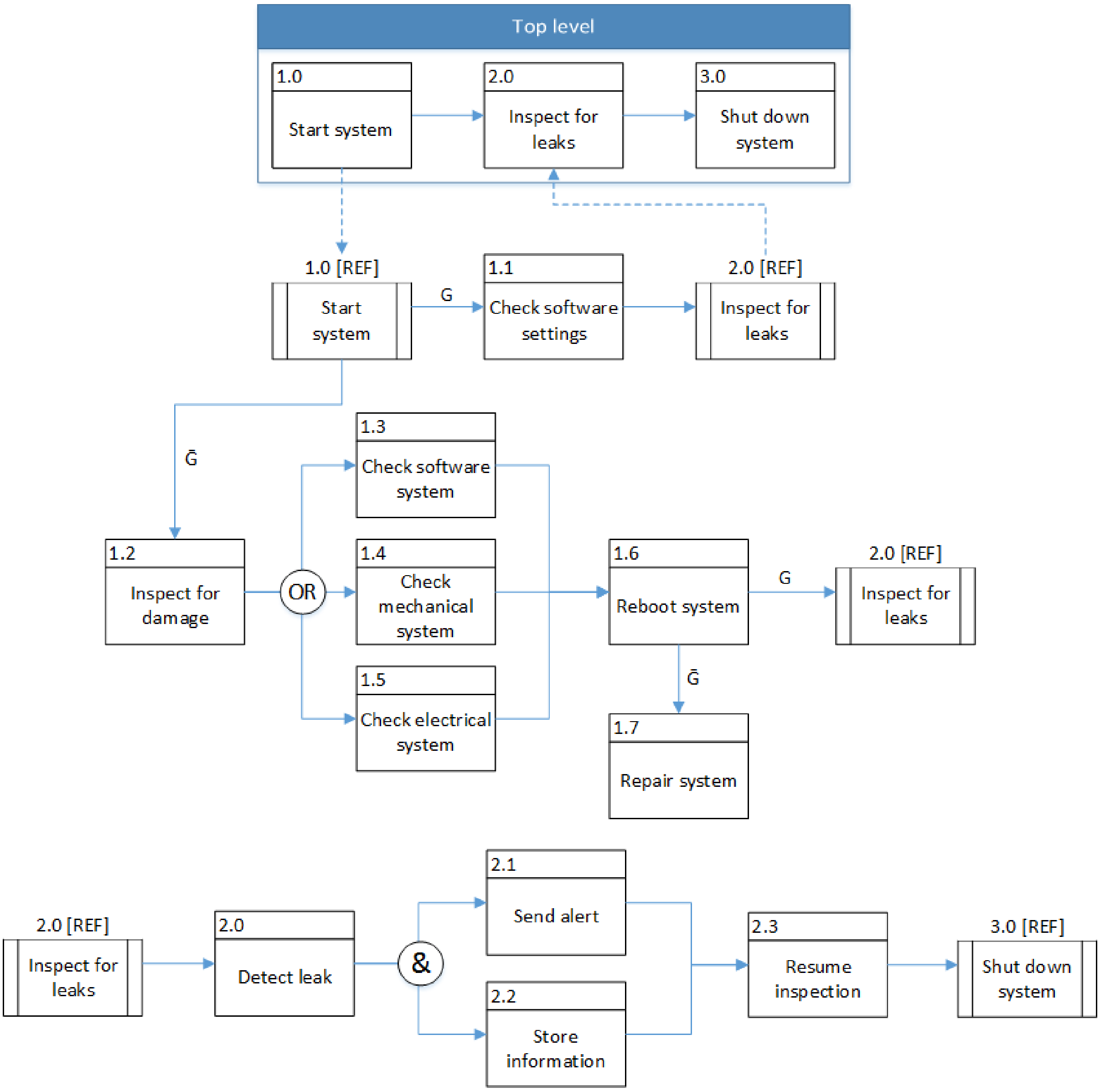


Figure 6. FFBD for non-robotic system

3.3. Subsystem integration

In this section, closely related functions that were found in figure 5 will be grouped together and interactions between the groups will be identified. This is called functional allocation and is designed to break down the system into smaller elements to achieve a system that is as modular as possible (Blanchard and Fabrycky, 2011). In this paper, this will be done using the functional block diagram (FBD). A system boundary chart was firstly constructed to find elements that will be present in the FBD. Table 2 presents system boundary chart for the robotic system. According to this, an FBD was constructed, as provided in figure 7.

Through the FBD, the system was able to be organised in a concise manner. Note that the 'power' subsystem is listed separately in the 'internal' column of the system boundary chart but it is split into three sub-elements under the 'transportation', 'sensor' and 'communication' subsystems in the FBD. This was done to ensure the modularity of the system. If 'power' were a separate subsystem then removal of or change in this subsystem would not have been easy without having a great impact on the rest of the system. Also, ‘memory’ subsystem was included under the ‘sensor’ subsystem as it did not have any interactions with subsystems other than ‘sensors’. FBD was an effective tool that allowed to spot the parts that interfered with the modularity of sub-systems. These improvements would not have been possible if only the system boundary chart was used.

Table 2. System boundary chart for robotic system

Internal	External	Outside
Transportation	Terrain condition	Price of fuel
Sensor	Location of robot	Battery capacity
Communication	Sign of leak	Weather
Memory	Path for robot to travel on	
Power	Proximity of pipe from sensor	
	Leak information	

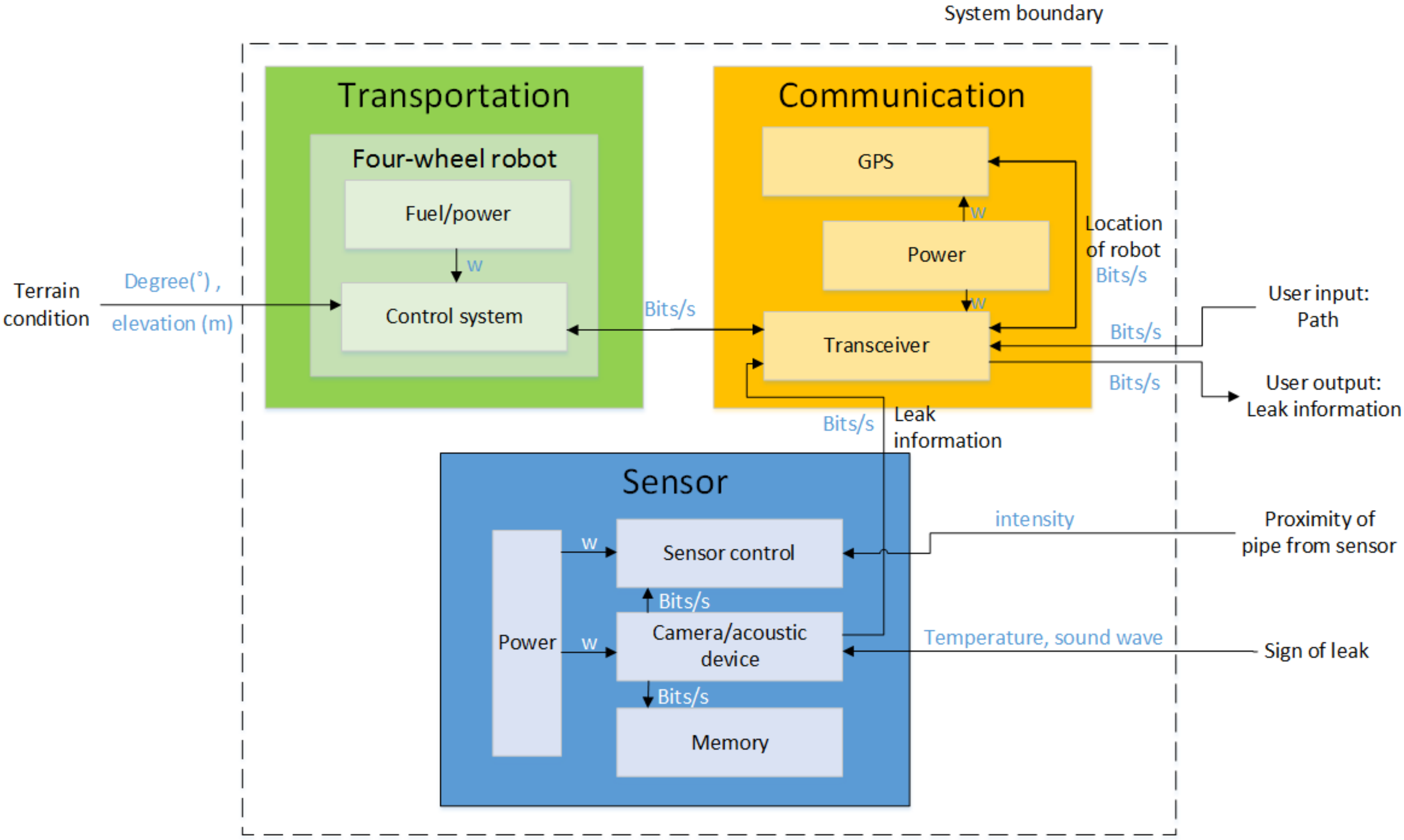


Figure 7. FBD for robotic system

3.4. System attributes

System attributes are non-functional qualities that the final product should have. Attributes can be organised in a systematic way in an attributes cascade. Table 3 shows the attributes cascade for the robotic system. ‘Effective leak detection mechanism’, ‘Effective mechanism to locate leak’ and ‘low failure rate’ design requirements were combined to a single attribute ‘A 1.0

Performance’ and ‘Compatible’ was relocated to a sub-attribute of the ‘A 5.0 Minimum cost’ primary attribute.

Table 3. Attributes cascades for robotic system

Primary attributes	Secondary attributes	Tertiary attributes	Related subsystem
A 1.0 Performance	A 1.1 Accuracy	A 1.1.1 Proximity	Sensor
	A 1.2 Efficiency	A 1.2.1 Autonomous	Transportation
		A 1.2.2 Responsiveness	Communication, Sensor
A 2.0 Reliable	A 2.1 Continuity	A 2.1.1 Throughput	Sensor, Communication
		A 2.1.2 Stability	Sensor, Communication
	A 2.2 Monitorability	A 2.2.1 Archivability	Sensor
		A 2.2.2 Instrumentability	Sensor, Communication
A 4.0 Durable	A 4.1 Robustness	A 4.1.1 Replaceability	Sensor, Transportation
		A 4.1.2 Maintainability	Sensor, Transportation
	A 4.3 Adaptable	A 4.3.1 Extensibility	Transportation, Sensor, Communication
A 5.0 Minimum cost	A 5.1 Minimum investment cost	A 5.1.1 Compatibility	Transportation, Sensor Communication
	A 5.2 Minimum maintenance cost	A 5.2.1 Robustness	Transportation, Sensor, Communication

Definitions of some unclear terms used in the attributes cascade are explained below. They were taken from Masood (2013) except ‘proximity’ which was defined by the author.

- Proximity: the system remains close enough to the pipe to receive good signal.
- Responsiveness: the system responds to interactions with minimal delay.
- Throughput: the system can handle a specified number of interactions within a specified duration without degradation in terms of other qualities.
- Monitorability: ability for operators to easily see how the system is operating.
- Archivability: older data can be relocated to separate data storages.
- Instrumentability: the system is capable of recording various operational metrics that can be analysed and reported on.
- Stability: the system exhibits infrequent failures.
- Adaptability: ability to change system components.
- Extensibility: ability to easily add new features.
- Replaceability: ability to replace system in future.

- Compatibility: the system is compatible to the existing software and hardware systems.

‘Sensor’ subsystem occurred most frequently in the cascades and this shows how important this subsystem is. This does not downgrade the importance of the other two subsystems though, as many primary attributes can only be achieved when all three subsystems work collaboratively with each other. This also means that a small change in a part of the system can have knock-on effects on the rest of the system.

3.5. Verification

Solutions must be verified to confirm they meet the set requirements. Testing is an effective way of achieving this. Two attributes will be tested in this section: robustness and throughput. The outlined test procedures are indicative only and more rigorous testings must be adopted during the development of an actual system to ensure safety and quality of the system.

Robustness attribute will be verified using the proof of concept. Robustness is important as it is directly related to the length of the product life cycle and thus the cost. During the leak detection, the system may come in contact with the HTF or the heat storage material. In such situations, it needs to remain chemically inert and withstand the heat. The following test ensures that the cover material is highly resistant to the deformation (corresponding to high modulus of elasticity) and does not turn brittle after exposure to the hot chemicals (high ductility means it does not shatter).

Attribute: A 5.2.1 Robustness
Test person: Technician
Test procedure

1. Prepare a bath of HTF at 400˚C.
2. Submerge the test segment of the cover material in the bath and leave it for 30 minutes.
3. Remove from the bath.
4. Measure the stiffness of the material (measure the modulus of elasticity).
5. Cool it to ambient temperature.
6. Test ductility of the material.

Pass/fail criteria: Pass if the decrease in modulus of elasticity and ductility are less than 10% of the values before the test.

Throughput was chosen for testing as the system must be able to handle many different information smoothly to operate efficiently, comprising as one of critical customer requirements. This attribute can only be tested once a prototype is built as the attribute is satisfied when multiple interactions are processed smoothly without degradation in any of the system performance. In this testing, ten leaks positioned along a straight pipeline will be used. Further testing with more complex conditions is recommended after the system passes this test. Passing this test will ensure that the system can handle multiple leaks and follow the predetermined path at the same time.

Attribute: A 2.1.1 Throughput
Test person: Technician
Test procedure

1. Build a test environment: it should have ten leaks along a straight pipeline.
2. Input the path.
3. Send the prototype system for inspection.
4. After the inspection, check the leak information sent to the remote receiving system.
5. Check the actual path taken.

Pass/fail criteria: Pass if all ten leak information is correctly registered on the main system and the actual path taken deviates less than 1m from the set path.

3.6. Evaluation

After verifying that the solution meets attributes and requirements comes the evaluation stage where the solution is compared to other competing solutions. The evaluation matrix is a tool that can evaluate the performance of each solution quantitatively.

Scale 5 = Exceeds compliance 3 = Full compliance 1 = Partial compliance 0 = Non-compliance	**Weighting**		**Robotic, thermo camera**		**Robotic, acoustic detection**		**Non-robotic, pressure drop**	
	Rank	Weighting	Relative compliance	Weighted value	Relative compliance	Weighted value	Relative compliance	Weighted value
Detects leaks	1	8	5	40	5	40	1	8
Locates leaks	2	7	3	21	3	21	3	21
Compatible	3	6	5	30	5	30	0	0
Reliable	4	5	3	15	1	5	1	5
Autonomous	5	4	3	12	3	12	5	20
Durable	6	3	3	9	3	9	3	9
Efficient	7	2	3	6	3	6	5	10
Cheap	8	1	3	3	5	5	1	1
	Totals			136		128		74

Figure 8. Evaluation matrix

Figure 8 shows the evaluation matrix for the three leak detection systems. Compliance ratings were given based on the report by Zhang (1997). It shows that the total for the non-robotic system is significantly lower than those for the robotic systems. This validates the elimination of this as a possible solution at the early stage. The robotic system with a thermographic camera scored the highest although the system with an acoustic detection device was not far away. The most significant deciding factor between the two was the 'reliable' requirement. Although the camera is a bit more expensive, it produces lower false alarms than the acoustic device. Since the cost was the least important requirement, the more reliable thermographic camera was a better solution. This was effectively reflected on the final scores as well. As a result, the robotic system with a thermographic camera is recommended as the most suitable solution for detecting leakages in Valle 1 and 2 parabolic trough solar power plants.

4. Conclusions

A systems engineering approach has been applied to investigate and evaluate three leak detection systems for Valle 1 and 2 parabolic trough solar power plants. The robotic system with a thermographic camera was determined to be the most suitable leak detection system. In order for this result to be effectively conveyed to the power plant representatives and the staff, communication methods emphasising visual representations were selected. From this portfolio project, the author learnt the value of systems engineering approach in solving engineering problems. Considering the system as a whole, a more thought-through and well-polished end result was produced which could not have been achieved if the problem was approached in the conventional way.

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