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Airborne Sensor Thermal Management Solution

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1. Executive summary

The customer wants to outfit aircraft (de Havilland Twin Otter) with optical sensors. In previous product generations the sensor line-of-sight direction was fixed – the sensor's direction relied on the orientation of the aircraft. The next generation sensor will be packaged in a rotatable turret so that the line-of-sight is reasonably independent of the aircraft's orientation. This turret will be mounted on a boom protruding from the side of the aircraft.

Figure 1. Concept image of Twin Otter with rotatable turret mounted on a boom.

A significant amount of heat is generated inside the turret (from motors, electronics, and a cryo-cooler). While the aircraft is on the ground, allowing the heat to remain in the turret would raise the temperature enough to negatively affect sensor operation. The problem is compounded when the turret is sitting in direct sunlight and in hot conditions. Therefore, a thermal management system is needed to keep the sensor within its operating temperatures – and this is the system that must be developed.

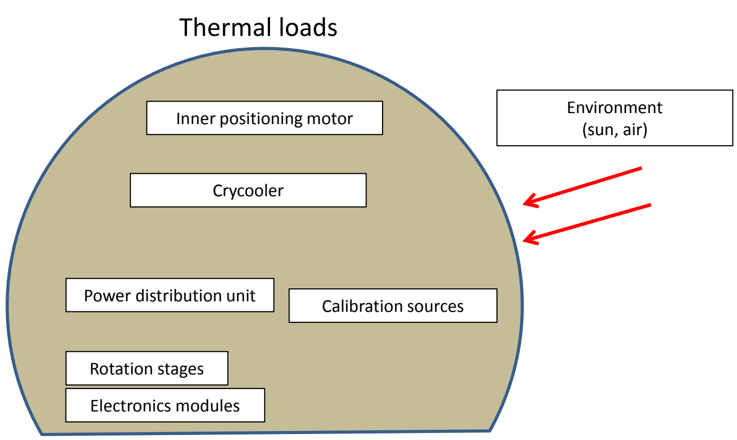

Figure 2. Thermal loads on turret.

2. Mission description

The customer is interested in imaging items of interest on the ground with an airborne sensor. The goal is to have the sensor ready for operation at any time while on the ground or in flight.

The customer has chosen to fully enclose the sensor using a commercially available turret that allows the sensor to rotate (as opposed to mounting it at a fixed angle or from the side of the aircraft). An operator inside the cabin operates the sensor through a graphical user interface on a computer. The customer intends to perform minimal maintenance on the system once it is placed into use.

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The sensor components are known to generate significant amounts of heat – in addition to the heat load caused by direct sunlight and/or hot weather. Unabated inside the turret, the resulting temperature rise would impact the sensor's function. This is a real concern when the unit is powered on to perform pre-flight checks; only at altitude can we assume that the ambient air will be cold enough to cool the volume. For most components heating is not expected to be needed at high altitudes because they have been operated successfully in similar systems in the past.

Therefore, a Payload Thermal Management system is needed to keep the sensor components inside the turret at their proper operating temperatures at all phases of its operation, and this is the system in question.

Mission

Develop a payload thermal management solution for the sensor components within the turret.

Goals

- Keep sensor components within operating temperatures.
- Preserve ability for the sensor to look to the side.
- Limit user-executed maintenance activities to interaction with the graphical user interface.

Objectives

- Maintain heat-mitigating capacity of 10% more than absolutely necessary.
- Maintain functionality of turret.
- Use commercially available parts where possible.

Business Rationale

- Mounting the sensor inside a turret gives the needed sensor pointing flexibility, but is inherently a challenge to keep the sensor at the desired operating temperatures when the aircraft is on the ground.
- A thermal management solution is needed to keep the sensor components at acceptable operating temperatures.

Stakeholders

The payload thermal management system is intended to fulfill a straightforward need for the overall sensor system. The active and passive stakeholders were identified after developing a concept of operations that was based upon interviews with the customer's liaison.

<u>Active Stakeholders</u>

The active stakeholders were identified as those that will have direct interaction with the system.

- *Operator*

  An operator inside the aircraft cabin will operate the sensor system (including the thermal management system) via a graphical user interface. The operator is expected to focus on the data that is being collected rather than actively managing the thermal loading on the turret.

- *Maintenance crew*

  The maintenance crew will perform any maintenance that cannot be performed via the graphical user interface. This group is expected to perform simple tasks that require little to no training.

- *Cryo-cooler, Power Distribution Unit, Calibration Sources, Telescope*
  The cryo-cooler and calibration sources are heat loads that need to be managed so that they stay within operating temperatures. The power distribution unit is a heat load that needs to be managed to mitigate its effects on the cryo-cooler and calibration sources. The telescope must be maintained at a certain temperature, but itself is not a heat load.

- *Electric Power System*
  All components of the sensor system (including the thermal management system) that require power will need to draw it from the aircraft's electric power system. This is composed of an Uninterruptable Power Supply (UPS), as well as the aircraft's own power once the engines are switched on.

  Note that this means that <u>from the perspective of the thermal management system, the electric power supplied by ground facilities is also included in this category</u> – the power extension cord would plug into the aircraft's power system, from which the thermal management system will draw power. However, we determine that the extension cord from ground facilities is a passive stakeholder because it does not interact directly with the system.

<u>Passive Stakeholders</u>

The passive stakeholders were identified as those that will influence the success of the system but do not directly interact with the system.

- *Pilot*
  Maneuvers made by the pilot will influence the thermal and mechanical loads the system will see. Beyond the addition of the sensor turret to his aircraft, he/she should not be otherwise affected by the sensor's thermal management system.

- *Ground facilities and utilities*
  Each airport has its own set (or lack of) ground facilities and utilities. Any utility or equipment not carried on-board the aircraft will need to be provided by the airport ground facilities.

- *Customer (sponsor)*
  The funds, tools, and staff that the customer provides will influence how the system will be treated and used.

- *Customer (data customer)*
  Feedback from the customer's analysts about the quality of the collected data will influence whether the system can be considered a success or not.

- *Software developers*
  The thermal management system will need to be controlled through software written by the developers.

- *Weather*
  The weather (due to geography, season, altitude, time of day) will influence the thermal loads that the system will see. Temperature, airspeed, and incident solar radiation are the primary considerations.

- *Neighboring turret/cabin systems*
  The structural, optical, and electronic systems also require space in the turret or aircraft cabin. These systems will likely compete for space and access with the thermal management system.

- *Top-level system integrator*
  The turret-mounted sensor system can be considered part of a larger system that includes the aircraft itself. This larger system is designed and controlled by a system integrator. Required interfaces (e.g., utilities, data transmission) will need to be agreed upon with the system integrator.

Stakeholder Sacred Expectations/Key Acceptance Criteria:

1. The thermal management system must support sensor functions:
   a. on the ground
   b. in the air.
2. The thermal management system must meet the physical constraints of the aircraft and turret. It must not inhibit the safe operation of both the aircraft and turret.
3. The thermal management solution must not require much maintenance nor training to maintain.
4. The thermal management system must support the following themes of operation:
   a. Anytime
   b. Anywhere
5. The thermal management system must be practical enough to be reproduced on a large scale.
6. The thermal management system must be delivered on-time to maintain schedule with the overall sensor system delivery (prototype).

3. System Operational Context and Reference Operational Architecture

A. The "As-is" contextual description

Currently, the sensor systems are packaged in an enclosed volume that is in turn mounted on the outside of the aircraft. The sensor components are cooled using heat exchangers. A 50/50 mix of ethylene-glycol and water is used as the heat transfer fluid that is cooled using a rack-mounted chiller. The chiller rejects heat to the cabin air.

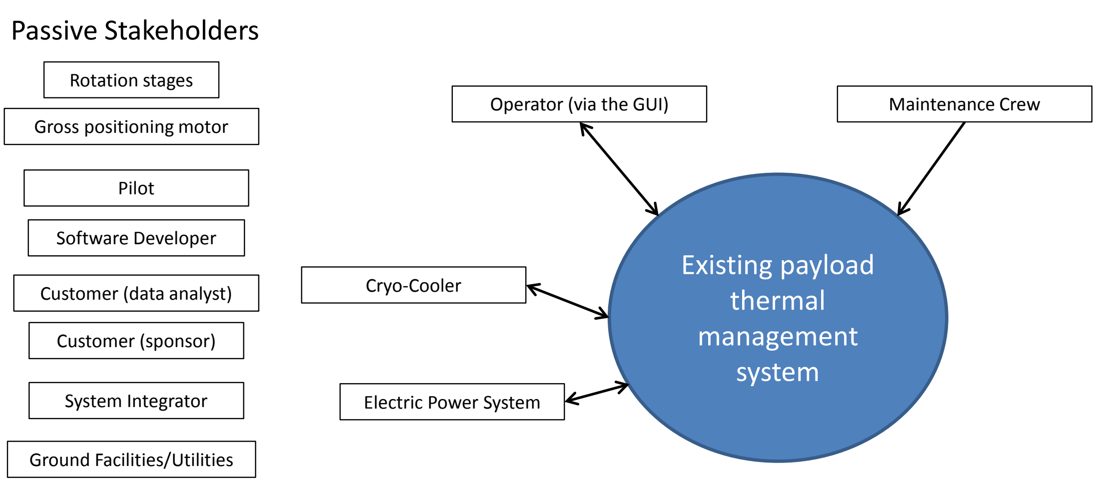

Figure 3. Context Diagram of the "As-Is" System.

We should note that in the existing system, the cryo-cooler is the only item that is directly cooled by the system. All other heat sources (other sensor components, weather) affect the system by passing on their heat loads to the cryo-cooler or the water lines that run through the volume. The cryo-cooler (shown below) is a commercial off-the-shelf component.

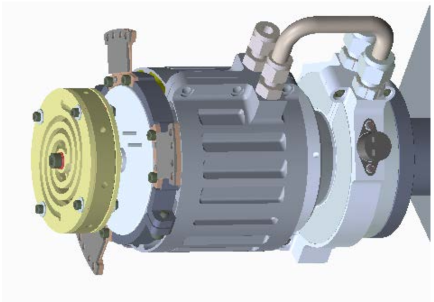

Figure 4. Cryo-cooler.

B. The "To-be" contextual description

The future concept is a sensor system that is mounted inside a rotatable turret (which itself is mounted on a boom cantilevered from the side). The future thermal management system will perform the same function as the "as-is" system, but with the constraint that it must support the functionality of the sensor inside a turret. In addition, two more components will require cooling (power distribution unit, calibration sources). We should also remember that we cannot ignore the heat load of direct sunlight; we cannot shade the turret.

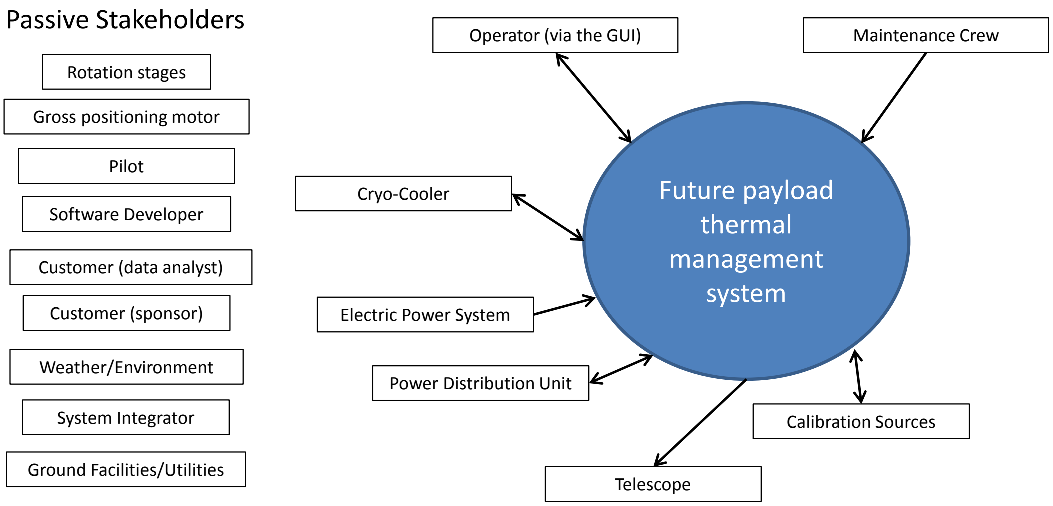

Figure 5. Context Diagram for "To-Be" System.

The rotation stages are used to manipulate mirrors to direct the sensor to look out the turret or at the calibration sources. The powered motors add a near-insignificant heat load because of the low duty-cycle.

The inner positioning motor is used to move the sensor within the turret. The heat load generated by it is not well understood, but is not expected to be significant because it is hardly used when the aircraft is on the ground. When it is used, the aircraft would be in flight and the rushing airstream is more than sufficient to cool it.

4. System Drivers and Constraints

The sensor thermal management system has no real purpose if it stands on its own. It is really better described as a subsystem of a larger system (the sensor package). So in the plainest terms, the goal of the thermal management system is to support the sensor system's mission: keep the sensor system within operating temperatures regardless of location and weather.

There are a few constraints on the system that must be considered:

The overall sensor system will need to be fully operational by October 2015, when it will be field-tested. Therefore, expediency will be a key driver.

Moreover, there are customer perceptions and desires that will influence the chosen thermal management solution. These constraints arise from experience with previous generation sensors.

The customer is resistant to the following:

- Using water lines in/out of the turret to cool the electronics. Concerns have been expressed about water leaks and the damage that can be done on the sensor.
- A thermal solution that cannot be contained entirely on the aircraft (e.g., a "cooling cart" that cools the turret while it is on the ground, but is carted away just before takeoff). The customer does not want to have to limit the aircraft to airfields outfitted with a cooling cart.
- A chiller (if used) other than one that is rack-mounted. For convenience of packaging, installation, and transport, the customer wants to keep all cabin-located sensor equipment (including the chiller) in electronics racks.

Moreover, the thermal management system must work in harmony with other parts of the sensor system (optics, electronics/data, power) – as determined by primarily the sensor system engineer (not the thermal management system engineer).

5. Operational Scenarios

The sensor system (and therefore thermal management system) has a well-defined single usecollect EO-IR data. This system is expected to operate both on the ground and in the air. When it is on the ground, we can expect that it would be used at any airport in the world during any season.

With regards to thermal management, we can envision two scenarios in plain terms: extreme hot and extreme cold. The order of operations remains the same for both cases, but the thermal management needs will be different. We assume here that the extreme hot environment will only happen when the sensor is idling/calibrating on the ground (i.e., a tarmac in the desert). We also assume that the extreme cold condition will be in-flight – those temperatures are much lower than ground temperatures.

"As-Is" Operational context of the system

To help understand how the thermal management system will interact with the upper-level systems, the basic steps in the operational scenario of the "as-is" sensor system are ordered below:

Table 1. "As-is" Contextual Description.

Step	Description	Duration (minutes)
1	Check vacuum pressure of the sensor.	1
2	Verify that the chiller is on and the pump is circulating water. (Turn it on if it is not).	1
3	Check cryo-cooler temperature. (Turn on cryo-cooler if it is not on).	1
4	Start computer/control software used to monitor focal plane assembly temperature and cryo-cooler power consumption.	10
5	Wait until focal plane achieves temperature (if it is not already).	60-90
6	Turn on calibration sources and readout electronics.	1
7	Wait for calibration sources to reach temperature.	5
8	Perform "deselect" operation on focal plane assembly and load the data into the assembly.	20
9	Turn off calibration source, mirror rotation stages (Power Distribution Unit and readout electronics are still on).	1
10	Unplug aircraft from extension cord (wall power), switch to Uninterrupted Power Supply (UPS) and wait for aircraft engine to power on.	10-30
11	Power on aircraft engines. Turn on remaining computer systems. Turn on calibration sources, mirror rotation stages, and context camera.	15
12	Taxi to runway.	5
13	Takeoff, ascent, and proceed to destination.	15-90
14	Collect data at destination.	360
15	Return home while saving processed data onto computers. Turn off computers when done. Descend and land.	15-90
16	Taxi to hangar and turn off engine. Switch to UPS power once engine is off.	5
17	Plug in extension cord into aircraft and cease using UPS power.	10-15
18	Maintain chiller and cryo-cooler on (sensor system standby until next mission).	0

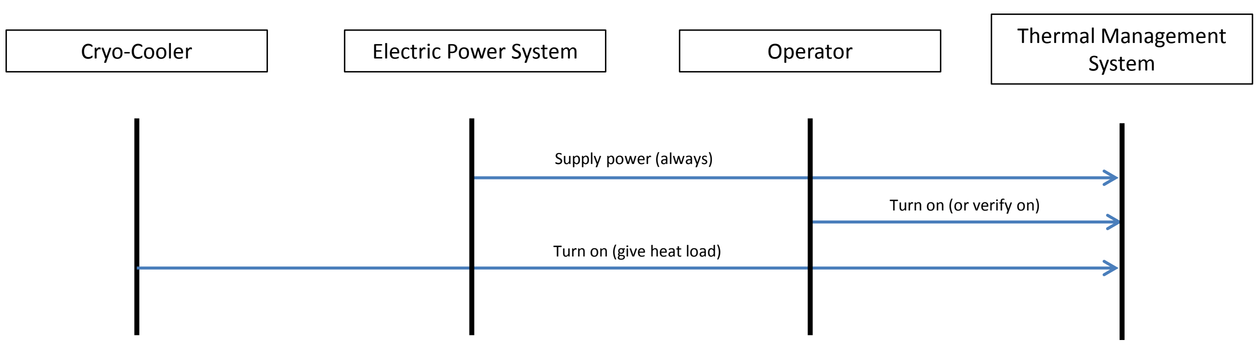

Figure 6. "As-Is" System Sequence Diagram.

"To-be" Operational context of the system

The "to-be" system will have additional heat loads because components that were previously located in the aircraft cabin are now located in the turret. The order of operations remains largely the same.

Table 2. "To-be" Contextual Description.

Step	Description	Duration (minutes)
1	Check vacuum pressure of the sensor.	1
2	Verify that the chiller is on and the pump is circulating water. (Turn it on if it is not).	1
3	Check cryo-cooler temperature. (Turn on cryo-cooler if it is not on).	1
4	Start computer/control software used to monitor focal plane assembly temperature and cryo-cooler power consumption.	10
5	Wait until focal plane achieves temperature (if it is not already).	60-90
6	Turn on calibration sources and readout electronics.	1
7	Wait for calibration sources to reach temperature.	5
8	Perform "deselect" operation on focal plane assembly and load the data into the assembly.	20
9	Turn off calibration source, mirror rotation stages (Power Distribution Unit and readout electronics are still on).	1
10	Unplug aircraft from extension cord (wall power), switch to Uninterrupted Power Supply (UPS) and wait for aircraft engine to power on.	10-30
11	Power on aircraft engines. Turn on remaining computer systems. Turn on calibration sources, mirror rotation stages, and context camera.	15
12	Taxi to runway.	5
13	Takeoff, ascent, and proceed to destination.	15-90
14	Collect data at destination.	360
15	Return home while saving processed data onto computers. Turn off computers when done. Descend and land.	15-90
16	Taxi to hangar and turn off engine. Switch to UPS power once engine is off.	5
17	Plug in extension cord into aircraft and cease using UPS power.	10-15
18	Maintain chiller and cryo-cooler on (sensor system standby until next mission).	0

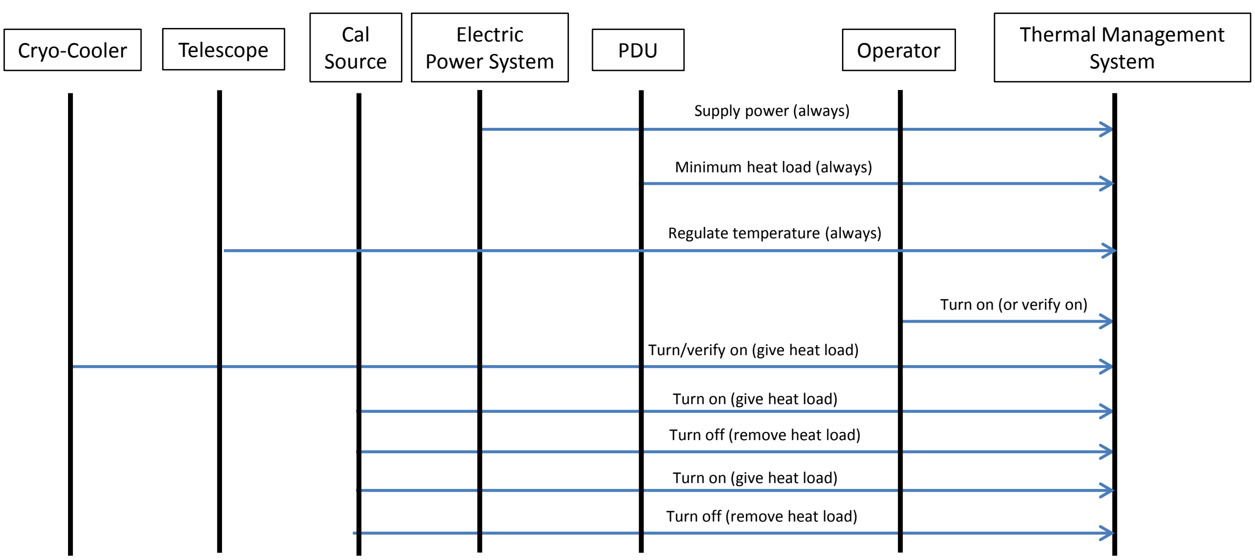

Figure 7. "To-be" System Sequence Diagram (Operations).

Note here that the temperature of the telescope is regulated by the thermal management system. Although the telescope does not generate heat itself, it can give the system a heat load based on the heat it absorbs from the ambient turret air.

We should note that a very important passive stakeholder (the ambient weather) does not interact directly with the system, but can certainly influence its performance. Because the weather does not interact directly with the system, it is not included in these sequence diagrams. (An argument could be made to include it as an active stakeholder, and if it were, then it would be shown to impose a positive heat load while the aircraft is on the ground, and then impose a negative heat load while the aircraft is at altitude).

We also envision maintenance-oriented and performance-oriented scenarios where the operator or maintenance technician must diagnose problems with the thermal management system.

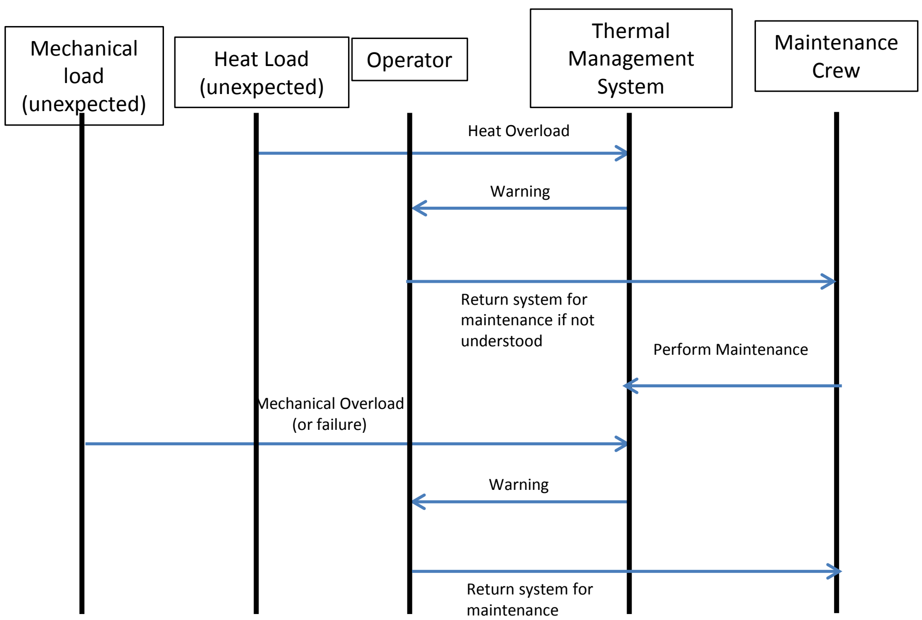

Figure 8. "To-Be" System Sequence Diagram (Maintenance).

Notice that we have included unexpected mechanical and heat loads in order to show their interaction with the system that would induce warnings and require returning the system for maintenance (since we cannot expect to have trained and experienced personnel available).

6. Implementation Concepts Selected and Rationale

Because the system is narrowly defined and its function relatively straightforward, we find it difficult to imagine a multitude of unique system solutions to the problem. However, we have imagined a few solutions that may differ from those existing or conventional.

Aircraft cabin chiller and ground-based cooling cart

An intuitive concept is to maintain the rack-mounted chiller in the aircraft cabin, and it would circulate the 50/50 water-glycol mix throughout the cooling lines that go into the turret. From experience, we know that rack-mount chillers have limited cooling capacity when the reject air temperature is hot (45C), and that the cabin can easily reach these temperatures when the aircraft is on the ground. Therefore, we envision a ground-based "cooling" cart that has sufficient capacity that can be carted and connected to the turret. The chiller would circulate cold water into the cooling lines through a feedthrough. When the aircraft is at altitude, the chiller is capable of drawing heat from the cabin and adding it to the water (like a heat pump) and ensure that the calibration sources do not get too cold (although the calibration sources have thermo-electric coolers that can be reversed and efficiently become heaters). Although an efficient solution that addresses the different environments, it limits deployment to airports with such a cart.

Aircraft cabin chiller and turret heat shield
Like the above, the aircraft has a chiller, but a simple tarp or reflective foil would be placed on the turret to shield it from incident sunlight. (The shield is not needed when it is at altitude, and so we do not see a reason to go through the trouble of modifying the turret to make the surface permanently reflective). Obviously, this reduces the heat load from the sun, but does not mitigate the hot air temperatures on the ground.

Compressed air
We note that if the air temperature of the turret were sufficiently low enough (20C), then it would not really need active cooling (the cryo-cooler can be cooled using natural convection over a finned heat sink, and has been demonstrated to do so). Therefore, we envision that we could roll up a compressed air cylinder to the turret, plug in a compressed air line into the turret, and then let the expanding air cool down the turret and displace the hot air. Once the aircraft is ready for take-off, the cylinder would be carted away and the high altitude temperatures would be sufficient to cool the turret. Once again, the thermo-electric coolers could be reversed to maintain the calibration source temperatures in case it got too cold. The main drawback is that this setup would require a constant supply of compressed air, in addition to turret modifications to accommodate the compressed air feedthroughs/vents.

Aircraft cabin chiller only
In this concept, we would only have a chiller in the aircraft cabin. This would be sized to keep up with the hot air temperatures on the ground. However, it would draw a significant amount of power, and it may not be easy to find one that is rack-mountable. Moreover, all chiller-based solutions are not preferred because of the perception that they lend themselves to springing leaks and damaging the sensor components.

Thermal storage
In another concept, we envision that the turret could be modified so that the shell would be well insulated from the outside (such as vacuum insulation) but also be lined with a thermal battery on the inside. The thermal battery could be “charged” with cold water via feedthroughs just after the turret is sealed. Regardless of whether the turret is on the ground or in the air, the thermal battery would maintain a reasonable operating temperature for the turret’s interior. This would require extensive modifications to the turret, making it a riskier operation.

Table 3. Pugh Matrix for System Selection. Underlined Items represent sacred requirements.

	Cabin chiller & Ground cooling cart	Cabin chiller & heat shield	Compressed air	Cabin Chiller only	Thermal Storage
Support ground and air operation	2	0	1	1	1
Maintain safe operation of aircraft and turret	2	2	2	2	1
Low maintenance	1	1	2	1	1
"Anytime, anywhere, in a moment's notice" operation	0	1	1	2	1
Large-scale reproduction	1	2	1	2	0
On-time delivery (prototype)	1	1	2	2	0
	7	7	9	10	4

From the Pugh matrix, we can conclude that pursuing a "cabin chiller only" system may prove to be the proper solution to the problem. This is not entirely surprising, as the other options would have limited deployment, schedule, or functionality. In addition, the main difference between the existing system and the proposed system is the addition of heat loads, although we did consider whether there might be better solutions than what is currently in use. Perhaps given the time and resources, the other solutions may have been worth pursuing.

7. Proposed System Operational Architecture

Based on the chosen system, the system operational architecture remains virtually the same. However, because we are interested in maintaining ground and flight operations, feedback from the system to the user is also needed so that problems that arise are addressed in a timely manner. We can envision different scenarios based on thermal inputs and maintenance-related problems through an operational architecture diagram, more detailed than the one given in Section 5 because we have now chosen the solution.

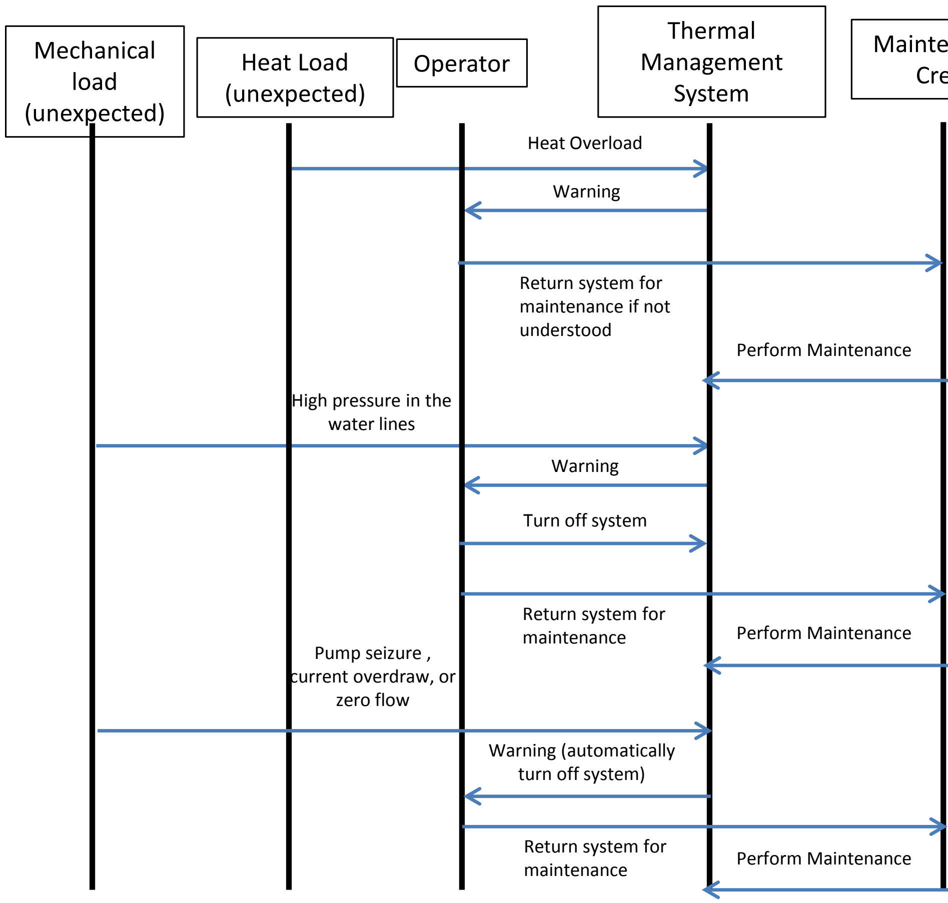

Figure 9. Proposed System Interaction Diagram.

We can also envision the system in terms of its physical components.

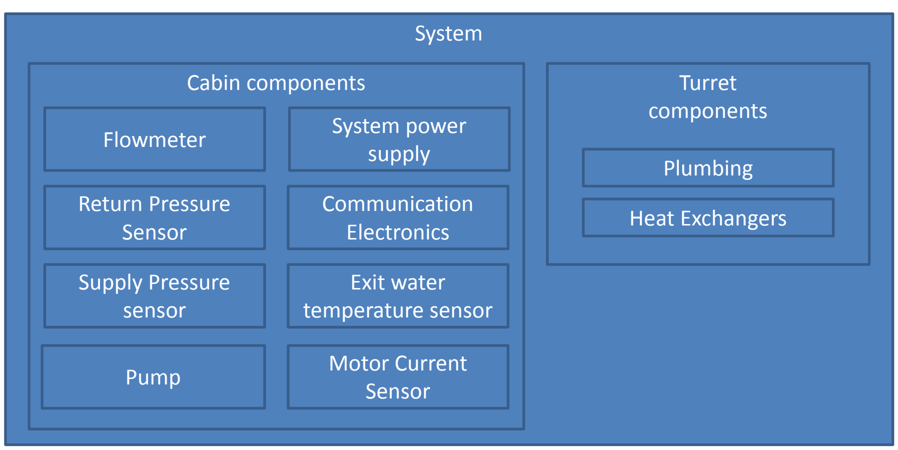

Figure 10. Proposed system physical block diagram.

8. System Requirements

Based on the customer expectations and the solution we have chosen, we have developed a set of functional and non-functional system requirements.

Table 4. System Requirements Matrix.

Requirement	Verification Method	Stakeholder Expectation	Functional?
Turret-located components must fit within the envelope	Inspection	2	N
Perform maintenance once a year or less.	Design	3	N
Do not require any utility beyond on-board power supply	Inspection	4	N
Can perform function in -10C to 45C temperatures.	Test	1	Y
Capable of 24/7 operation.	Design	4	Y
Use 80% commercially available parts.	Inspection	5, 6	N
Confine cabin-located equipment to electrical racks.	Inspection	2	N

9. Organizational and Business Impact

From the perspective of the customer and even the engineering team, there will be little organizational impact as a result of this new system. However, the business impact is immense: the customer is eager to receive prototype sensors, test them, and have them produced on a larger scale for global use. It is therefore critical to meet both schedule and reproducibility. Therefore, there is a large impetus to use tested solutions that are understood and can reduce time to the field.

However, if it becomes clearer that the proposed chiller system solution is insufficient, the customer would be willing to explore less conventional options in order to meet its expectations. But since this thermal management solution is supporting a larger function, it is less desirable to use unconventional systems. However, if thermal management was the customer's primary need, then it may be worth taking the risk to develop other options.

10. Risks and Technology Assessment

The path we have chosen poses a minimal risk compared to its counterparts. The technology is available from manufacturers, is well understood, and has been proven to work before. However, this solution is not entirely without risk – we may find it difficult to find a chiller that satisfies our requirements. In this case, we may need to explore other options or accept the limitations of a chiller that satisfies only the sacred requirements.