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Architectural Analysis of a LLNL LWIR Sensor System

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Executive Summary

The architecture of an LLNL airborne imaging and detection system is considered in this report. The purpose of the system is to find the location of substances of interest by detecting their chemical signatures using a long-wave infrared (LWIR) imager with geo-registration capability. The detection system consists of an LWIR imaging spectrometer as well as a network of computer hardware and analysis software for analyzing the images for the features of interest. The system has been in the operations phase now for well over a year, and as such, there is enough use data and feedback from the primary beneficiary to assess the current successes and shortcomings of the LWIR system architecture. LWIR system has been successful in providing reliable data collection and the delivery of a report with results. The weakness of the architecture has been identified in two areas: with the network of computer hardware and software and with the feedback of the state of the system health. Regarding the former, the system computers and software that carry out the data acquisition are too complicated for routine operations and maintenance. With respect to the latter, the primary beneficiary of the instrument's data does not have enough metrics to use to filter the large quantity of data to determine its utility. In addition to the needs in these two areas, a latent need of one of the stakeholders is identified. This report documents the strengths and weaknesses, as well as proposes a solution for enhancing the architecture that simultaneously addresses the two areas of weakness and leverages them to meet the newly identified latent need.

Background

Lawrence Livermore National Laboratory's Global Security directorate has R&D programs that develop remote detection technologies. A long-wave infrared (LWIR) imaging spectrometer was one product of these programs. This spectrometer was integrated into a system designed for airborne data collection, and its detection capabilities were successfully demonstrated for a Department of Energy sponsor. News of the success prompted another government customer to request copies of the sensor system for its own aerial survey application of locating substances of interest. Schedule and aircraft constraints resulted in slight modifications to the LWIR spectrometer systems compared to the original, but the systems have been integrated and operated for a period of time allowing for good use data to be acquired. An analysis of the architecture of the modified LWIR systems is the subject of this report.

LLNL was contracted to build four LWIR systems in all. The customer also procured two other sensor systems to complement each LWIR system. The three sensor systems, designated 1, 2, and 3, were integrated on an aircraft by a pair of companies; we refer to these as companies 4 and 5. Company 4 is responsible for procuring the aircraft and modifying it to support the sensors, while Company 5 (a.k.a – the System Integrator) has been responsible for installing the sensors and providing the supporting systems and personnel to operate and maintain them. **Table 1** summarizes the stakeholders and their contributions to the customer's airborne sensor platform.

The LLNL sensor systems include a set of computers and software to acquire, calibrate, and exploit spectrometer data. The calibration and exploitation processes work on the acquired raw spectrometer data to detect and identify the spectral signatures of substances of interest. The customer preferred to not take make use of an end-to-end LLNL data processing flow and requested that another system developed by an alternative organization (designated DPP here) perform the calibration and exploitation steps of the data processing. This request prompted DPP to install their software system on the aircraft and for LLNL to modify their sensor system software to pass the sensor data to the DPP system for processing. The original LLNL calibration exploitation system has been retained and operated in parallel for diagnostic purposes. The DPP calibration-exploitation system would deliver the detection and identification results to the customer's data analysts.

Stakeholder	Whole Product Contribution
LLNL	Sensor 2 System – LWIR Imager
DPP	Sensor 2 data exploitation
Company 1	Sensor 1 System
Company 3	Sensor 3 System
Company 4	Aircraft operation
Company 5	System integration, sensor operation and maintenance, data delivery
Customer data analyst	User of the sensor products

Table 1 - Stakeholders and their contributions

Architecture Framework

The analysis of the architecture begins at a very high level by considering the architecture framework across four different spaces, that is, viewing the architecture through four different colored lenses. Table 2 shows the general framework across the columns. These upstream and downstream considerations follow the methodology presented in the MIT Systems Architecture course. Each row of the table is a different space over which to consider the architecture, and the four considered here follow that presented by Mr. Vick Tang, the person responsible for managing IT for IBM at the 1998 Winter Olympics. He recommended that the business, system, technology, and expression spaces be examined.

	Upstream		Downstream			
Space	**Why**	**What**	**How**	**Where**	**Who**	**When**
Business	Technology Transfer	Contracts, Agreements	Sensor community word-of-mouth	Conferences, meetings	Govt contractors	Sensor community events
System	Needs, requirements, "ilities"	LWIR sensor, supporting hw, computers, software,	LWIR data acquisition and processing	Aircraft, analyst's office	Operator, service personnel, analysts	During and after data collect
Technology	Remote Sensing	LWIR sensor system	Fly sensor	Aircraft	Operator, data analysts	In flight
Expression	Contracts, reputation	Science in the national interest	Images, reports	Field sites	Satisfaction, solid work relationship	Post data collect

Table 2: Architecture Framework for the LWIR System

It can be seen from the table that upstream, the LWIR system (like many systems at LLNL) is regarded as a technology that will eventually be transferred to another company that specializes in the production of systems in mass. The success of the LWIR system will contribute to increasing the reputation of LLNL in the eyes of the government sponsors in addition to meeting a national need. The downstream section of the table highlights that operators, data analysts, and service personnel will be directly impacted by the LWIR system. The system is fielded with regularity to collect data for processing, and therefore reliability and usability are two of the "ilities" that are a must with the system. There must also be a solid working relationship between LLNL and the support personnel, and this connection has been strong to date. In fact, our evaluation of the architecture of the LWIR system is made in light of lessons learned from the use of the sensor, observations from the support personnel of the System Integrator, and customer data analysts' feedback. The analysis of the architecture continues by describing the Level 1 architecture concept, needs, and goals.

Level 1 Concept, Needs, and Goals

The analysis of the LWIR architecture fundamentally involves analyzing the architecture concept and structure and assessing value delivery to all stakeholders.

We begin by defining the problem statement associated with the customer's primary need. The beneficiary of the system is the customer's data analysts that have a need to locate substances at sites of interest to the customer. The solution neutral intent along with the system concept is shown in Figure 1. The system problem statement corresponding to the diagram is:

System Problem Statement	**To find the location of substances of interest by detecting their chemical signatures using an airborne long-wave infrared imager with geo-registering capability**

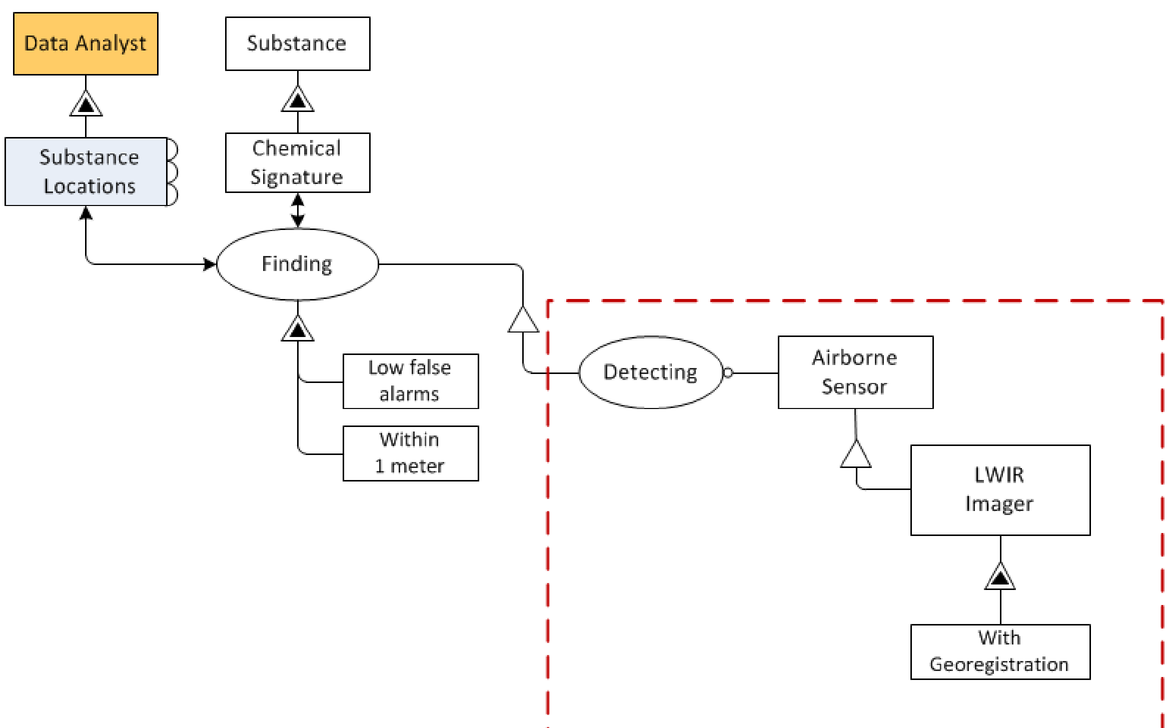

Figure 1 - Need, Intent, Concept diagram for the LWIR System

We next consider all stakeholders and their needs for the LWIR system. Table 3 shows an extensive but not comprehensive list of stakeholder needs and associated derived goals. Note that the cells shaded in gray purposely do not have a goal associated with a stakeholder need. This is due to the fact that the

LWIR system is not directly responsible for meeting these particular needs, and therefore assigning a goal and metric does not make sense. However, this class of needs is relevant to the architecture of the whole product system and therefore belongs in the table because these needs are satisfied indirectly via a chain of interacting stakeholders.

Table 4 tabulates the scores of the LWIR system successfully achieving each goal and highlights those goals (magenta) that are not being adequately met. It is important to point out that the table is intended to emphasize those goals that are not being met and therefore gives the appearance that the system is worse off than what is actually the case in reality. This is due, in part, to the fact that access to the original system requirements was not possible. The goals were reconstructed by soliciting input from the stakeholders. And, the emphasis of the survey was on what issues the stakeholders had with the current system. The goal weight refers to a scoring from 1-3 of the importance of a specified goal to the delivery of value for that stakeholder. A score of 3, being the maximum, corresponds to a goal that could be considered unambiguously met, in absence of access to the original goals, validation metric and target value. Given the tone of the survey, list of goals in this category is not comprehensive, resulting in a goals table with a negative slant. The goal score column describes the SDM team's assessment based on all the available input from the stakeholders of how well the goal has been met in the current system. For simplicity in performing a global assessment of which goals are unmet in the current system, an attainment metric was computed to be the difference between the attaining value and the goal weight. Non-negative values indicate goals that have been met, and negative values signify those that are not being satisfied.

Table 4 shows that over half of the goals are adequately being fulfilled. In fact, the meeting of Goal 3.1 is significant in that it indicates that the fundamental operational objective for the LWIR system is being attained consistently. The sensor system is rarely down and performs its function consistently. If the sensor had not been reliably working, the entire system would be called into question with the possibility of an alternative technology taking its place.

The goals that have not been satisfied appear in magenta in Table 4 and all fall under the area of operations. These goals map back to the needs of the Sensor Operator and the Service Personnel and are associated with efficiency, reliability and complexity (3.2, 3.3, and 4.5). Use cases for the system have not been adequately defined, and some documentation does not exist (4.1 and 4.3). Note that some feedback is currently provided, but additional information is needed so that the operator can correct issues quickly and is aware of performance degradation. In addition, it is desirable for the sensor system to feed back to the Data Analysts some information about the "health" of the sensor in the form of some meta-information to measure "the confidence of the confidence metric". Both the LLNL team and the Data Analysts have indicated that this is an emerging, high-priority need for the continued performance and success of the system (1.6, 3.2, and 5.3).

Goal 1.4 is currently an unsatisfied objective that relates to the reliability of the confidence metric for detection. This goal pertains more to details of the analysis algorithm versus the system architecture as a whole, but we point out this unmet need for completeness. Feedback from the Data Analysts indicate that the confidence metric provided to them for each measurement has a higher false alarm rate than is desired making it more difficult to assess the credibility of the data.

In going through the process of identifying needs and goals, a latent need has been identified. That is the tactical and strategic goals of LLNL, the Sensor 2 OEM. Although a hierarchical distinction was not made, goals 5.3-5.5 could be thought of as level 2 goals of the level 1 goal 5.2. LLNL seeks to solidify the success of this sensor system as well as to enable future LLNL projects with this and other customers. To achieve this goal, LLNL seeks to more easily gather information about the sensor's performance in order to find ways to improve it. Further, value can be added to the primary beneficiary by increasing their access to LLNL analysis & metrics.

Stakeholders	Needs	Goal #	Goals
Data Analysts	Hyperspectral image data and associated geo-registration data	1.1	The System shall provide hyperspectral image data and geo-registration
	Data format specification	1.2	The data shall be formatted as specified
	Detect and ID of substances with associated confidence metric	1.3	The data package should provide detection and ID of substances and detected substances should be associated with a confidence measure
	Few false alarms on ID'd substances	1.4	False alarms should be less than 5% of substances detected
	Receive results same day as data collection	1.5	Processed sensor data results should be available for delivery at end of each flight.
	Metrics of system performance	1.6	The sensor data product should include metrics of system performance.
System Integrator	Sensor meets "fit and fly" req's	2.1	The system shall not weigh more than XX pounds and the system shall survive aircraft transport
	Sensor has a compatible physical and electrical interfaces	2.2	The system shall comply with approved Interface Control Document
	Sensor does not consume more power than budgeted	2.3	Sensor shall operate consistently under the max power level indicated in ICD
	Remote sensor triggering	2.4	The sensor should accept trigger commands as described in ICD
Sensor Operator	Sensor operates reliably	3.1	Sensor system shall be ready for use >95% of time in service
	Sensor UI clearly indicates problems	3.2	Sensor device failures and performance issues will be indicated in UI
	Simple pre and post flight operations	3.3	Pre/post flight ops should be < 15 minutes
Service Personnel	Clearly stated routine maintenance requirements	4.1	A maintenance manual with procedures and intervals should be provided
	Spares for long lead or failure prone components	4.2	Needed spares will be identified and delivered with the sensor systems
	Maintenance procedures	4.3	See goal 4.1
	Ease of maintenance	4.4	The sensor system design should consider ease of maintenance
	System can be secured easily	4.5	The system shall be delivered in compliance with first tier information system policies
	Easily removable data drives	4.6	A RAID unit with removable drives shall be employed
LLNL (Sensor 2 OEM)	Safe operation	5.1	The sensor system shall be "man safe"
	Market share and strategic programmatic positioning	5.2	LLNL should meet emerging needs of the customer while under contract
	Metrics of system performance	5.3	See goal 1.6
	Use context details	5.4	
	Processing configuration	5.5	Sys. data output should include processing config.
Sensor 2 Data Processor Provider	Market share and strategic programmatic positioning	6.1	
	Use context details	6.2	
	Sensor output data format spec.	6.3	The data shall be formatted as specified
	Processing configuration	6.4	
	Low data delivery latency	6.5	Sensor data will be delivered to processor <15 sec
Other Sensor	LLNL sensor does not interfere with	7.1	Sensor shall pass system integrator's EMI tests3

OEMs	other sensors		

Table 3: LWIR stakeholders and their needs. Goals derived from those needs are also shown.

Goal #	Weight	Goal Score	Attainment Metric	Reason for Score
1.1	3	3	0	Current system provides correct data types and associated information
1.2	3	3	0	Data complies with specification
1.3	2	2	0	Confidence metric provided
1.4	2	1	-1	Confidence metric is not discriminating enough
1.5	2	2	0	Data processor meets this goal nearly all flights
1.6	2	1	-1	Some basic metrics provided, better performance metrics needed
2.1	3	3	0	
2.2	3	3	0	
2.3	2	3	1	Meets this goal with considerable margin
2.4	2	2	0	
3.1	3	3	0	This goal has been recently achieved
3.2	2	1	-1	Some feedback is currently provided but additional information is needed so that operator can correct issues quickly and is aware performance degradation.
3.3	2	1	-1	Overly complex - multiple desktop sessions and applications to manage
4.1	2	1	-1	Service personnel trained in maintenance but no documents delivered
4.2	1	1	0	
4.3	2	0	-2	Few procedures provided
4.4	1	1	0	
4.5	2	1	-1	Systems are complex and maintaining compliance is often difficult
4.6	3	3	0	
5.1	3	3	0	
5.2	2	1	-1	Sensor system has been somewhat successful, but there are some unmet customer needs
5.3	2	1	-1	Some basic metrics provided, better performance metrics needed
5.4				
5.5	2	2	0	
6.1				
6.2				
6.3	3	3	0	
6.4				
6.5	2	3	1	Data delivery is typically <10 seconds after acquisition
7.1	3	3	0	EMI tests passed

Table 4: Within stakeholder priority weight is shown on a scale of 1-3 with 3 being highest priority. A measure of successful attainment of the goals is also shown on a scale of 0-3 with 3 indicating high success. The attainment metric is the difference between weight and goal score and indicates which goals are not being adequately met.

Level 1 System Architecture

Having presented the system goals along with a coarse measure of stakeholder satisfaction for each, analysis of the architecture continues with a discussion of the structure of the architecture and the emergent behavior from processes. The LWIR architecture will show how the fundamental objectives of sensor data acquisition and analysis are achieved. We will also identify those processes which deserve a Level 2 look in order to make a connection with the shortcomings identified with the goals analysis.

The top level architecture (Level 1) of the LLNL LWIR sensor system is illustrated below in Figure 2 as an object-process model (OPM) diagram. The LLNL system is shown as part of the customer's whole product system which is the three-sensor aircraft produced by companies 4 and 5. The primary value path is highlighted with blue arrows on the left side of the diagram. Airborne scenes are imaged by the LWIR spectrometer which produces a stream of image data. The image data is captured and stored by custom software on the sensor computer system. Concurrent with the LWIR image data capture, GPS and payload attitude data, produced by the sensor systems inertial navigation system (INS), is captured and stored. Sensor software produces geo-registration data to accompany the LWIR images using the INS data. The LWIR and geo-registration data are copied to the DPP system for exploitation. The exploitation process detects and identifies substances in the LWIR images based on their chemical long-wave infrared signatures. The output of the DPP system, calibrated geo-registered images, and detect and identification results are copied to a network attached storage (NAS) device where they are aggregated with other sensor data. The data from all sensors is delivered to the customer's data analysts by IT personnel from Company 5, who physically carry the data on removable disks from the aircraft to the analyst office.

Down the right side of Figure 2, an ad hoc value path is shown. This path was created to address issues that data analysts have brought to the attention of LLNL regarding the sensor B data product.

From a Level 1 point of view, the diagram of the architecture confirms why over half of the needs are being met. There is a clear value path culminating with the delivery of the data plus analysis report, the value-related operand. The shortcomings of the architecture pertain to operations associated with the software and hardware supporting the acquisition of the LWIR data and its subsequent processing in the LLNL system. The analysis of the architecture continues with a Level 2 look at those elements. These processes and the object attached to them have been highlighted in yellow in Figure 2.

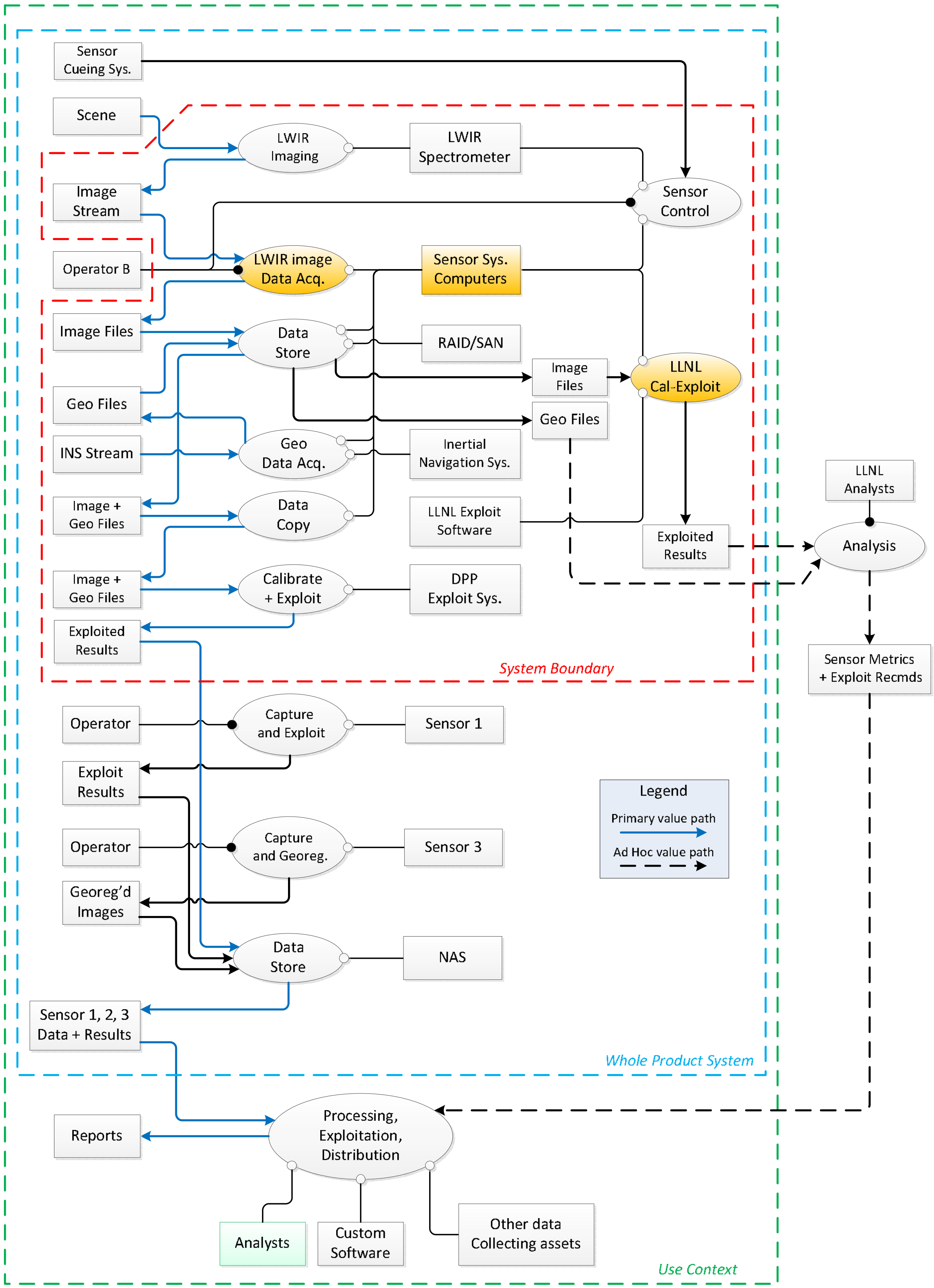

Figure 2 - LLNL LWIR System OPD

Level 2 Data Acquisition and Analysis Architecture

The architecture for LWIR data acquisition and analysis is shown below in Figure 3. The objective here is to consider the distribution of the processes across elements of form, both hardware and software, and the data flow between them. It can be seen across the top of the figure that sensor image data and geo-registration data are the main inputs. The bottom of the figure shows that there are 9 computers.

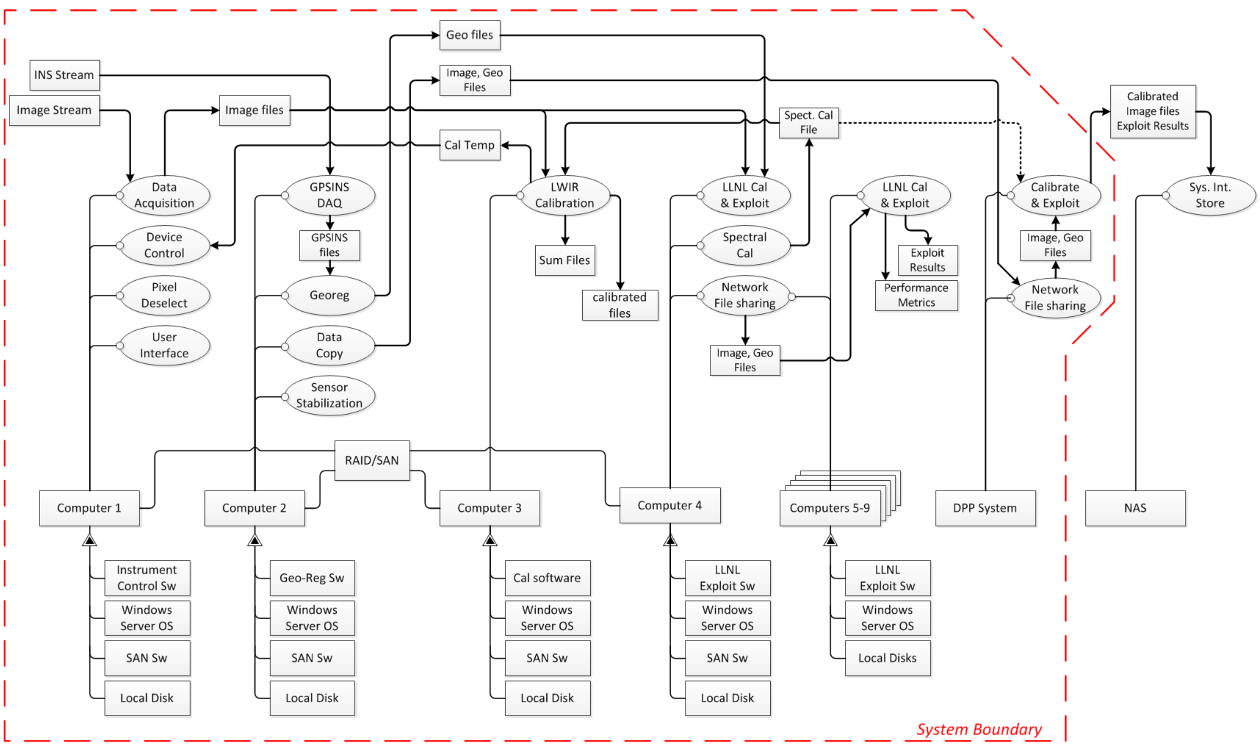

Figure 3: Current LWIR Data acquisition and analysis architecture

Computer 1 is associated with image data acquisition, provides controls for configuring the instrument, and has the user interface. Computer 2 runs an application that captures the INS data, saves it in GPSINS files, and then produces geo-registration metadata to go with the LWIR data. Computer 3 runs an application for calibrating the LWIR data and produces some signal-to-noise metrics. Computers 4-9 run the Calibrate-Exploit analysis application.

The calibrate process appears twice because an earlier version of the LLNL analysis software only carried out the exploit process on Computers 4-9 versus the integrated processes of calibration and exploitation. There are two calculations that are performed by the calibration software on Computer 3 which are of interest and have not been migrated to the analyses on Computers 4-9:

- diagnostic signal-to-noise metrics
- automatic calibration temperature calculation and adjustment

Even though the calculations are of interest to the primary beneficiary, they do not justify the use of an entire computer to carry the calculations out. This represents an area to look for improvement in use of resources and efficiency.

The current system employs a RAID with multiple host connections. Computers 1-4 are connected to the RAID and use software to coordinate the use of the shared disk drives. These computers and the RAID unit form a storage area network (SAN). This arrangement provides fast data access to the four directly connected computers. The other computers access the data via a network share on one of the directly attached computers (computer 4 in the diagram).   The disadvantage of the SAN system that has become apparent with frequent use is the labor involved in configuration following each drive set swap. In the current use case the service personnel swap drives every one-to-two days to archive the data. The process of setting up the SAN has been prone to error resulting in extra hours invested by IT staff to prepare the system for use.

The nine computers in this architecture all have local disks that carry the operating system and the applications they run. Nine computers is a large number of computers to separately use and maintain on an aircraft. Operator feedback seems to support this assertion.   The operator has to log into each of the computers to get the entire set of software running and those servicing the system have to maintain the operating system of each computer with patches and virus scans. These login and servicing processes certainly would introduce a feeling of complication in the user.

The computers in this system are members of a Windows domain with one of them functioning as a controller. This arrangement offers some administrative advantages, but ease of software maintainability is sacrificed with the introduced complexity of frequent software patching on multiple machines. Replace-ability is also devalued with this Windows domain configuration as replacement of computers is not easy here.

Assessment and Proposed Architecture Modification

This section proposes modifications to the Level 2 acquisition and analysis architecture described in the previous section. The aim of the modification is to reduce complexity (and therefore the user perception of a complicated system) and to increase value to the primary beneficiary. We begin with the reduction of complexity.

Based on operator feedback, we scored this architecture as not meeting the need of simple pre/post flight operations (goal 3.3) and not being easy to maintain system security (goal 4.5). The architectural decomposition reveals the reason: the multiple computers and the associated operating systems and software copies that must be managed. The complexity of the system, while delivering good performance, is perceived as complicated because of the amount of user involvement required.

We observe these possible opportunities for a reduction of complexity exposed to the system users:

- Reduce the total number of computers to six. Initial testing indicates that the exploitation can be accomplished with fewer computers utilizing the latest exploitation software.

- A further reduction in maintenance may be accomplished if only one of the computers utilizing the Linux operating system has a disk. The other systems can be configured to boot over the network from a boot image served by the first Linux computer. This configuration would reduce the maintenance of nine computers to just two: the Windows computer and the first (or master)

Linux computer. This configuration would also permit easy replacement of any of the four diskless computers without any configuration changes required.

- Configure the system to supply the LWIR image files and the GPSINS data to LLNL exploitation software via network shares. This eliminates the need for the SAN software and the frequent RAID setup, trading disk access performance for the reduction in complexity. In compensation, the LLNL exploitation software does not utilize the disk as much as the older calibration software.

- Integrate the diagnostic signal-to-noise metrics and the automatic calibration temperature control feature that are in the old calibration application into the new LLNL exploitation software. This reduces the number of applications that must be executed.

- Replace the Windows operating system on all of the computers except the one that provides the user interface. Use a minimal Linux operating system on the others. The minimal operating system will minimize the patches and virus scanning needed.

Figure 4 shows the system with the changes proposed above implemented.

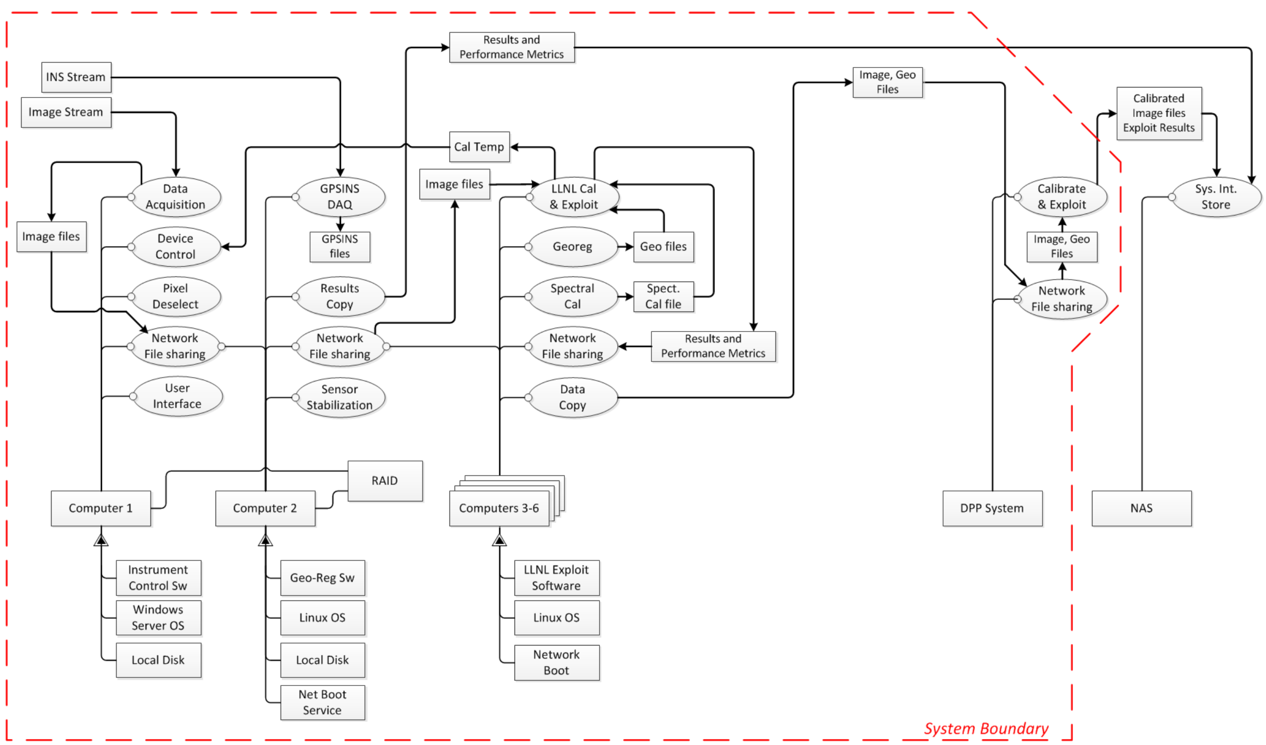

Figure 4 Proposed reduced complexity LWIR data acquisition and analysis architecture

We now discuss the one key architectural change that stands out as providing the most potential for improving value delivery. By adding a value flow path directly from the “LLNL exploit results” to the data analysts (see Figure 4), goals 1.6 and 5.3 can be satisfied simultaneously. There may be resistance to the introduction of the new value flow path due to conflicting stakeholder goals such as security or market-share/programmatic-positioning by a competitor. But, the widespread need of the systems "health" meta-information can be used as leverage to justify the creation of such a path. And, the interface requirements can and should be negotiated to maximize the quantity and variety of information through this path, thus strengthening this value flow path from LLNL to the primary beneficiary. If the delivery of value is demonstrated, this value flow path could become the primary value flow path, thus improving system performance and helping LLNL to achieve its tactical and strategic goals for market share and programmatic positioning.

Summary

In this report, we have assessed the architecture of the LLNL LWIR sensor system.

The analysis of the system began with a high-level view as outlined in the lecture by Dr. Vick Tang in which upstream and downstream aspects are considered across business, system, technology, and expression spaces. In this view we learned how LLNL interacts with other stakeholders and the impact of the LWIR sensor system on them.

We composed a system problem statement (SPS) based on the primary beneficiary need and the current architecture. Other stakeholder needs were considered and goals mapped to them. These goals were the basis for an assessment of the system's success across stakeholders. Scoring of goals was accomplished using available stakeholder feedback. The goal scores made evident that some "ilities" were not met well.

Architectural decomposition of process and associated form revealed that design decisions made for maximizing performance had resulted in a complicated system from the operation and maintenance point-of-view. We proposed some possible changes in the architecture of the LWIR system computer hardware and software to reduce complexity so that it does not seem complicated to the user.

Finally we discussed an emerging need of system performance metrics for use by the primary beneficiary that we believe warrants the integration of a new value path into the system architecture.