FTIEs: The Instrumentation of Safety

Tim Evans
Flight Test Instrumentation and Test Controls Engineer SME
AeroTEC, Inc.
Seattle, WA
tevans@aerotec.com

Abstract

As Flight Test Engineers, we always operate to a set of requirements. These requirements define our scope, hazard levels, mitigation techniques, etc. with the help of the Flight Test Instrumentation Engineers (FTIE) to visualize and show compliance (or not) to said requirements. The FTIE also designs measurement components to build confidence in reliability, helping mitigate risks and limitations associated with the test. But what do FTIEs do with our requests? This paper will pull back the curtain on the FTIE as part of a flight test team. We will focus on the proper selection of tools and equipment that help understand the difference between test and safety parameters and how to organize those on a display for clear observation.

Introduction

It is the intent of this paper to define, describe and visualize the actions of an instrumentation engineer in relationship to designing safe and reliable instrumentation in the form of data acquisition systems. The principles and details involved with the decisions will familiarize you with how they identify requirements, measurements, and parameters that allow for clear identification of the safety related test conditions.

Defining Instrumentation

The words and definitions of instrumentation, measurement, and parameters can be conflated and misunderstood, which generally can lead to confusion for what is being asked for and the actual purpose. Clearly conveying ideas, intentions and requirements is essential to effectively and safely designing instrumentation.

Definitions

Instrumentation

Measuring instruments regarded collectively.
"the controls and instrumentation of an aircraft"
- the design, provision, or use of measuring instruments.

Measurement

The action of measuring something.
"accurate measurement is essential" ·
- the size, length, or amount of something, as established by measuring.
  "his inseam measurement"
- a unit or system of measuring.
  "a hand is a measurement used for measuring horses"

Parameter

A numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation.
"the transmission will not let you downshift unless your speed is within the lower gear's parameters"

- *mathematics*
  a quantity whose value is selected for the particular circumstances and in relation to which other variable quantities may be expressed.
- *statistics*
  a numerical characteristic of a population, as distinct from a statistic of a sample.
- (in general use) a limit or boundary that defines the scope of a particular process or activity.
  "they set the parameters of the debate"

Example

The instrumentation systems fuel quantity gauging system measurements and water ballast indication measurements can be useful in creating a derived parameter to determine aircraft center of gravity.

Flight Test Instrumentation Engineers

Through the history of instrumentation engineering, instrumentation as well engineers have evolved. During the 1960s and 70s simple instruments like steam gauges were mounted on a panel. These panels were filmed in high speed during flight or ground test and played back post test frame by frame while a room of analyst would transpose and graph individual instrument readings into a plot and using a French curve to create the parameter time histories. These were known as photo panels (see Figure 1). Into the late 70s and mid 1980s electronics allowed us to now create data acquisition systems. These systems would electronically quantify and record the exchange of physical properties. Much like the earlier used photo panels these systems were hand built, from the circuit boards to the chassis ending with the results being displayed on a monochrome monitor.

Figure 1 Early Flight Test Photo Panel

Fast forward to the year 2010. With the advancement of electronics and measurements technology private industry took shape and created modular components that were compact, smaller in size with more efficient processing while requiring less power. From the earlier years of having to hand fabricate data acquisition systems now Commercial Off The Shelf (COTS) equipment was available. Instrumentation engineers also took a new shape. From the days of designing systems from a component level they moved into an integration role.

Similar in history to the slide rule and TI60, the fundamentals of Instrumentation transformed from how they build measurement devices into what devices do they integrate and how do they safely make these devices work together to meet the requirements and scope of work for their customers.

Today the instrumentation engineer is challenged to integrate an instrumentation data acquisition system that is composed of three fundamental sections: data acquisition, data reduction, data management and display with a market of competing complexed instruments and computers with varying data analysis tools.

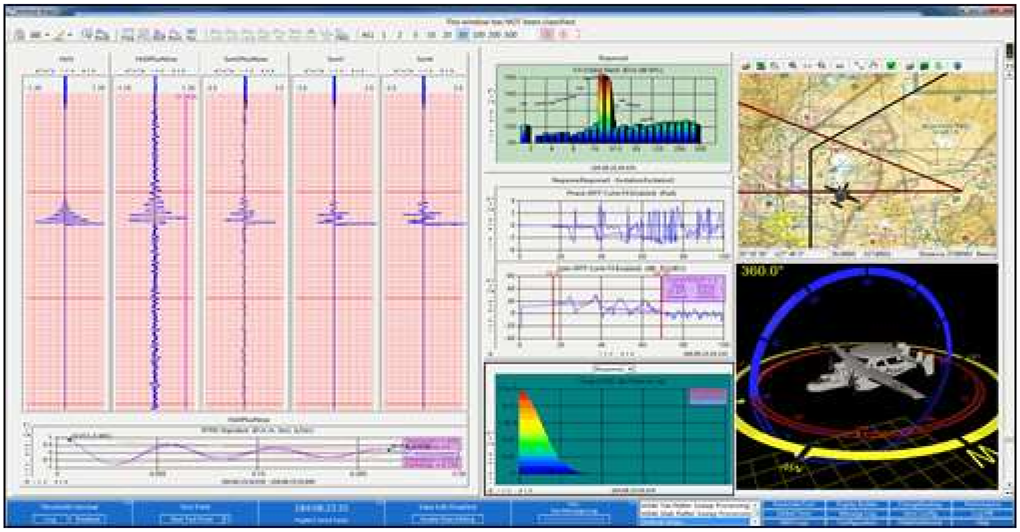


Figure 2 Modern Day FTE Test Data Display

FTIE Team Member

When organizing a flight test team, one could draw a similarity to the construction industry and the building of a house. There are many skill sets required to safely construct a quality, good value house within a reasonable time.

Starting with the general contractor then comes the architect, marketing, sales, subcontractors licensing and inspection. This is not intended to be an entire list however a very high-level view to show the structure which we understand. This is as well the same general structure as many flight test teams with aerospace skillsets. When a new product is identified the administrative portion begins and then it is transferred to an engineer to make that vision become reality. The flight test team is then given the responsibility to test the article. Testing can and often does quantify the mechanical, structural, aerodynamic and performance aspects within established rules and regulations of certification authorities.

Flight test and the engineers that support the team should be mindful their mission is to test a prototype or product to meet the specifications or intent of the designer with reliable data that accurately quantifies the results. The role of a flight test engineer within the test team should be interactive and understanding of the testing requirements providing sensors, signal interface, data recording, data storage and data reduction.

Scope

To start the process the instrumentation engineer will need to define the scope of the project. This can be achieved by collecting all the crucial project information, building out a project schedule and tailoring the scope to the project and organization. Once this is complete and compiled it can be reviewed with the stakeholders to insure it meets the expected results and deliverables.

Requirements

Once the scope has been defined and is agreed upon, requirements begin. Understanding requirements at times could be a bit overwhelming, however, staying with the fundamentals has proven that sometimes less truly is better. What is the desired outcome? Are the requirements starting from a clean sheet design or expanding an existing system? If expanding does the existing system have the capability to meet the measurements intent?

These and many more questions will lead to defining how the final system should be structured. Using an outlined definition system and the 4W's creates an organized repeatable flow that is consistent and sets the boundaries to design within.

As an example:

What – Transferable Ballast

Why – To safely support takeoff and landing performance with controllable CG locations to expedite the testing schedule by reducing maintenance activities to reconfigure solid ballast

Where – Forward and aft locations to control the longitudinal CG without affecting lateral positions

When – Design, fabrication, installation, functional test, calibration, handover within 16 weeks of project kick off

Design – Considerations, resolution, accuracy, repeatability, frequency of interest, derived equations, automation process, display format

Safety – Critical, un-commanded exceedances in forward and after center of gravity limits can result in departure from normal flight.

Differences in Test and Safety Measurements

From our example we have identified a safety critical measurement. Let's further discuss various types of measurements and what defines them in their classification.

When building a master parameter index, measurements can be classified within three distinct categories.

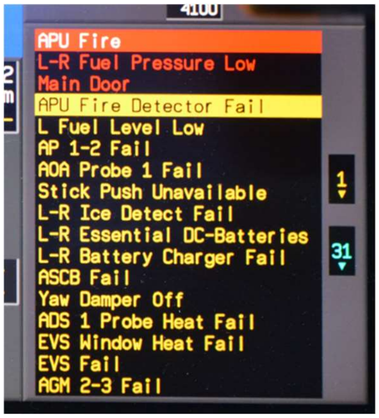
Test Measurements

1. Certification – measurements that are required for certification or test validation and requires specific measurands with traceability. These measurements can be specific to a test card or as a general certification measurement that is required across the program as identified during the scope and requirements research. These measurements as an example could be airspeed, altitude, control surface positions and for more specific testing ECS, hydraulics, pneumatics

2. Nice to have – a byproduct or subset of the original measurement. These measurements or parameters typically exist within digital data buses where collecting airspeed, altitude from a digital air data computer offers additional information like barometric pressure, impact and static pressure is available however not required.
3. Developmental - evolutionary measurements that are required during a flight or test campaign to identify root cause of deficient or failing test results. As a result, these measurements should be reclassified after the deficiency has been reconciled into certification, nice to have for monitoring and trend analysis or is a safety related item.

Safety Measurements

Safety measurements fall under the same structure as a crew advisory system (CAS). These measurements represent warning, caution, and information. Safety related measurements require an action in order to avoid an adverse or unintended consequence. An aircraft fire warning CAS message would be an example of a situation that would require an action from the flight crew where a data acquisition system may monitor unknown zonal conditions of uncertified areas that could ignite or lead to equipment failure. Critical safety items can be defined as measurements such that if the limitations are exceeded can result in catastrophic failure of a component.



APU Fire
L-R Fuel Pressure Low
Main Door
APU Fire Detector Fail
L Fuel Level Low
AP 1-2 Fail
AOA Probe 1 Fail
Stick Push Unavailable
L-R Ice Detect Fail
L-R Essential DC-Batteries
L-R Battery Charger Fail
ASCB Fail
Yaw Damper Off
ADS 1 Probe Heat Fail
EVS Window Heat Fail
EVS Fail
AGM 2-3 Fail

Figure 3 CAS Messages on a Cockpit Display

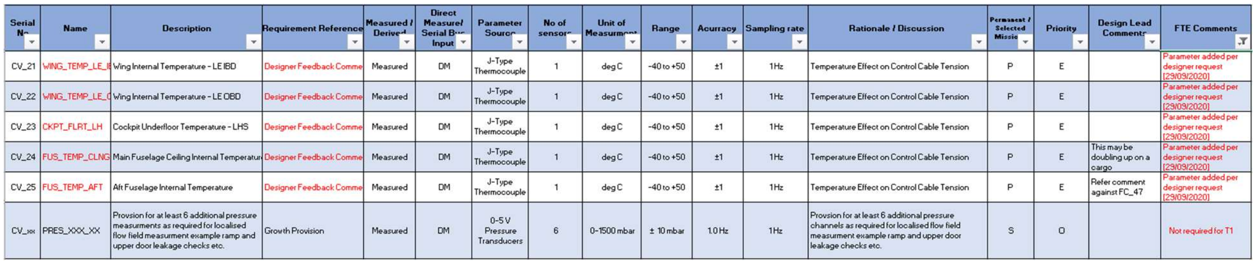
Measurement Design

As you can see in the example, requirements set the parameters for completing the design. The system must first be looked at holistically understanding the elements and the requirements of a safe system versus safety and risk mitigation as they can be vastly different. As previously mentioned, the three systems integrated that define instrumentation are data acquisition, data reduction, and data management and displays.

Starting with the data acquisition system it can be further broken down into separate elements of its own. There are sensors, signal interfaces and output formatting. These systems can be built either on data or network centric platforms. The one that is generally selected is based on availability and one's experience with those systems. Building a safe system can start with robustness of the sensors and environmental compatibility. We can take that further to expected reliability of the sensor. Once those parameters are set then we can look at the signal interface and data acquisition system to determine if it has the capacity and specifications to support the sensors requirements. If starting with the data system and signal interface working outwards concessions are often made in order to accommodate lesser sensor specifications which results in not acquiring the necessary data.

Moving inwards to design the signal interface considerations continue with again matching the article to be tested and the primary engineers design requirements. These requirements will allow the instrumentation engineer to select interfaces that support the necessary sample rates and filters for the frequency of interest including gain and offset for the sensor selected. Along with these specifications it is important that the instrumentation engineer also understands the accuracy and resolution of a particular measurement. Systems come in all different shapes and sizes particularly in the Analog to Digital Conversion (ADC) circuitry. When converting analog to digital we go from an analog input to a digital representation of that input and now the resolution of the measurement is decided by the number of bits an ADC can support. As an example, a 10 bit ADC converts an input to 1023 counts. If you are measuring altitude to 45,000ft you get a useful resolution of 44ft. Not so useful if testing Vmca however the configuration my work well for a door position of 0-30deg giving a resolution of .03deg.

The intent here is not to deep dive designing instrumentation signal interface parameters however demonstrate through example to a flight test engineer or test conductor all the elements of the system that need to be considered and evaluated. This evaluation should conclude that the data being acquired or monitored will fit within constraints of safety.



Serial N	Name	Description	Requirement Reference	Measured / Derive	Direct Measure/ Serial B Input	Parameter Source	No of sensor	Unit of Measurm	Range	Acurracy	Sampling rate	Rationale / Discussion	Permanent / Selected Missio	Priority	Design Lead Comment	FTE Comments
CV_21	WING_TEMP_LE_	Wing Internal Temperature - LE IBD	Designer Feedback Comme	Measured	DM	J-Type Thermocouple	1	deg C	-40 to +50	±1	1Hz	Temperature Effect on Control Cable Tension	P	E		Parameter added per designer request [29/09/2020]
CV_22	WING_TEMP_LE_	Wing Internal Temperature - LE OBD	Designer Feedback Comme	Measured	DM	J-Type Thermocouple	1	deg C	-40 to +50	±1	1Hz	Temperature Effect on Control Cable Tension	P	E		Parameter added per designer request [29/09/2020]
CV_23	CKPT_FLRT_LH	Cockpit Underfloor Temperature - LHS	Designer Feedback Comme	Measured	DM	J-Type Thermocouple	1	deg C	-40 to +50	±1	1Hz	Temperature Effect on Control Cable Tension	P	E		Parameter added per designer request [29/09/2020]
CV_24	FUS_TEMP_CLNG	Main Fuselage Ceiling Internal Temperatur	Designer Feedback Comme	Measured	DM	J-Type Thermocouple	1	deg C	-40 to +50	±1	1Hz	Temperature Effect on Control Cable Tension	P	E	This may be doubling up on a cargo	Parameter added per designer request [29/09/2020]
CV_25	FUS_TEMP_AFT	Aft Fuselage Internal Temperature	Designer Feedback Comme	Measured	DM	J-Type Thermocouple	1	deg C	-40 to +50	±1	1Hz	Temperature Effect on Control Cable Tension	P	E	Refer comment against FC_47	Parameter added per designer request [29/09/2020]
CV_xx	PRES_XXX_XX	Provsion for at least 6 additional pressure measurments as required for localised flow field measurment example ramp and upper door leakage checks etc.	Growth Provision	Measured	DM	0-5 V Pressure Transducers	6	0-1500 mbar	± 10 mbar	1.0 Hz	1Hz	Provsion for at least 6 additional pressure channels as required for localised flow field measurment example ramp and upper door leakage checks etc.	S	O		Not required for T1

Figure 4 Data Requirements

Selection of Tools and Equipment

Tools of the trade? Tools as well can be classified into many categories depending on the trade and the use. The most apparent being software and test controls. Software can range from data display and analysis to the ability to control test parameters (test controls).

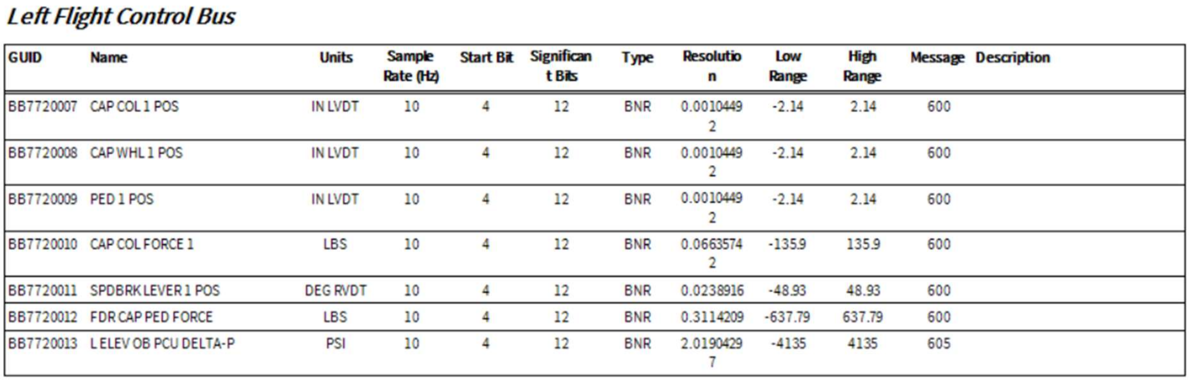
The instrumentation engineer and flight test engineer's tools can vary differently however do share one common tool and that is data display. To create those displays the instrumentation engineers' tools calculate the measurements parameters into polynomials or look up tables that when converted displays information in an understandable engineering unit.

Those tools are generally in the background and not seen by the flight test engineer however are important to ensure that when multiple components are selected, they can work seamlessly together to create an output, an alarm, time history or the other elements to create a display that provides situational awareness of a test component or the test conditions.

Starting with the basics a typical set of measurements may include temperature, frequency, pressure, stress, and position. These are the fundamentals of measurement and propagate into many different areas and the criticality of the measurement's parameters fall under one of the previous mentioned categories as certification or safety. During the design evolution of a measurement the type of measurement and its category will be made and documented by an instrumentation calibration report which is commonly referred to as a "cal sheet".

Confidence and Reliability

The main parameters of interest in a calibration sheet that will help the flight test engineer better understand and have confidence in their display are not necessary in the numbers however understanding how they work together. The interaction of these parameters may not be apparent at first so let's take a look at them and how they influence the perceived performance.



Left Flight Control Bus

GUID	Name	Units	Sample Rate (Hz)	Start Bit	Significant Bits	Type	Resolution	Low Range	High Range	Message	Description
BB7720007	CAP COL 1 POS	IN LVDT	10	4	12	BNR	0.00104492	-2.14	2.14	600	
BB7720008	CAP WHL 1 POS	IN LVDT	10	4	12	BNR	0.00104492	-2.14	2.14	600	
BB7720009	PED 1 POS	IN LVDT	10	4	12	BNR	0.00104492	-2.14	2.14	600	
BB7720010	CAP COL FORCE 1	LBS	10	4	12	BNR	0.06635742	-135.9	135.9	600	
BB7720011	SPDBRK LEVER 1 POS	DEG RVDT	10	4	12	BNR	0.0238916	-48.93	48.93	600	
BB7720012	FDR CAP PED FORCE	LBS	10	4	12	BNR	0.3114209	-637.79	637.79	600	
BB7720013	L ELEV OB PCU DELTA-P	PSI	10	4	12	BNR	2.01904297	-4135	4135	605	

Figure 5 Example Calibration Sheet

Those parameters are:

Upper and lower limits - the bookends of the measurement and are often referred to as useful range which we will discuss next. Upper and lower limits tell you where the measurement begins and ends. This does not indicate that the measurement no longer exists it only indicates the instrumentation systems ability to capture its performance. For this example, let's use look at Pitot or impact pressure used to derive airspeed. Airspeed is the delta P of static and impact pressure and is measured in knots. This measurement can also be used in calculating Mach Number when the Delta P is combined with temperature. As you see it can be a measure independently or used as part of a derived equation. Depending on the measurement the upper and lower limits are selected to capture the outer boundaries.

Useful Range –the limits to which a measurement can be considered accurate to fulfil the objective of its intended purpose. This can be a result of design, sensor selection or the elements being measured. A pneumatic airspeed indicator is an instrument which can advertise upper and lower limits of let's say 0-150 knots. In application the instrument may not come alive until 30 knots due to aerodynamics which gives a useful range of 30-150 knots. When reviewing a measurement Upper and Lower limit it is equally as important to recognize the useful range.

Resolution – the smallest unit of measurement. Often like useful range it is overlooked. In the earlier example of altitude, we seen where the analog to digital converter determined the minimum resolution. This can easily be overcome by selecting the correct ADC to accomplish the parameters requirements. As in all data systems the opportunity exists to over resolute the measurement as well. Is too much resolution a bad thing? Not necessarily however it can distract from the measurements intent and take focus from observation.

Sample rate – The time or period at which a measurements results are current. Although a consideration that should not be overlooked this is not latency of the circuit or processing time. Sample rate determines the rate of change for the measurement. The minimum period of a measurement should be looked at not only independently but in the strategy of the measurement. What is the intent of the temperature? Most are not dynamic in nature but can be. If measuring a surface temperature or thermal shock an engine you understand a measurement as independent and the data is used to monitor or analyze.

The purpose of this topic is to not only bring awareness to rate the of change but also recognize that the sample rate of the individual measurements in a derived parameter needs to be considered. Again, using airspeed and an extreme example to show relationship, if the impact pressure is measured at 1s/s and the static air pressure is measured at 10s/s with the derived equation updated at 10s/s the result will be 1 true reading per second with 9 shewed readings consisting of the current altitude with a stale impact pressure. This is an extreme example however gives the foundation for thought and why to review a measurements sample rate independently and holistically.

Filtering – The removal of unwanted data points. Filtering in essence removes data that can corrupt the intent of the measurement. Filters come in different types. Analog and Digital start the conversation which extents out into High Pass, Low Pass and Notch. This is only the surface and how they are calculated as well comes in many types. There are many great books written on this subject and if you would like to know more invest the time to read those.

From the measurement index it is important to acknowledge not only the signal you will be observing but what you don't see as well. In the case of a hydraulic pressure measurement a flight engineer may observe the mean or average pressure of 3000 psig. If a filter was used to observe the pressure and it were removed and the sample rate were increased, you would typically start to see the observed pressure has ripples created from a pump. Is this data important also? Yes, it is to the hydraulic engineering for analysis but not to the flight test engineer who's using it for observation however, the ripple does exist.

Accuracy - the degree to which the result of a measurement, calculation, or specification conforms to the correct value or a standard. This number needs to be fully understood and what it represents. Accuracy is measured with different expressions. Some of which are percentage of full scale, best strait line, average, or even drift over time or temperature. Know your requirements and how the value pertains to your expectations. Accuracy should also be evaluated by how it was determined as it will be a product of calculations, calibrations, or both.

Calibration - the action or process of calibrating an instrument or experimental readings to a standard will determine its accuracy. Although typically not mentioned in the Master Measurement Index this can be a factor when determining confidence and reliability.

Most common calibrations can be separated into three categories. Although the methods differ the end results combinate into the calibration report.

End to End, these calibrations are performed in circuit and represent a high degree of confidence. This is where a known input is applied to a sensor and converted to an electrical signal. This electrical signal follows its path to the signal interface where it is converted to a digital representation. This digital representation is then calculated with the known inputs engineering units to create a calibration. All the circuit's inaccuracies are there for accounted and compensated for. The circuit has also been tested for functionality.

Component Calibration is composed of multiple components then being mathematically calculated to combine the results. Like the end-to-end calibration known inputs are applied to the individual components of a measurement. The sensor can be calibrated in a metrology lab and the signal interface on aircraft and the results merged together to create a final calculation. Unlike the end-to-end calibration other variables exist and if not compensated for will induce error into the calibration. Wire length causing excitation and signal drop and the combined error of the multiple standards used, where in the end-to-end only the accuracy of the source needs to be considered.

Digital, these are instruments at the component level that produce a digital output in relation to an analog input. Although sometimes referred to as a calibration it is more in line with a conversion. This sensor has many advantages. It can be calibrated in a metrology lab, installed in the system being tested without having to compensate for the variables found in component calibrations. Although straight forward and seemingly easy the calibration of the sensor and digital conversion should be understood. Is the ADC in the sensor linear or does it contain an internal calibration record to correct the output, and does it have an internal regulated power supply?

Flight test engineers should work with the instrumentation engineer and have these sheets available for review with an understanding of the background for the display they are building.

Mitigate risks and limitations

Until now we have discussed the fundamentals of measurements, the parameters of the measurement and how an instrumentation engineer uses this knowledge to build the requirements that design an instrumentation system. Let's now take a closer look at how we perceive the monitoring of the measurement, mitigating risk and lessening the opportuning for misinterpretation.

Data display and analysis programs have matured at the same pace and in some cases exceeded the engineer, analysist, and data acquisition system. For every one end user being an instrumentation, test, or flight engineer there are multiple if not teams of software programmers creating data reduction and display systems. Starting from the input or backend of the software, developing an executable that will recognize and de-commutate the data format can be a challenge. Equally another team is writing modules to display the information. These programmers may not have the experience to interpret your intentions, they are only building tools for you to create a display. There is no liability for the outcome and only that it represents your intentions. With this in mind it is the Flight Test Engineers' responsibility to clearly identify and display information relevant to the test, identifying limitations and predicting outcome.

This is not an easy task given technology mixed with marketing leads us down a path that can be more informative than useful. Resist the opportunity to add more than what is necessary to comprehend what is of interest. Understanding the limitations of the measurement and using it to mitigate risk can be accomplished approaching the display or elements of the display by minimize the amount interactions between elements. Yes, there are certainly measurements that require complicated algorithms or derived equations to simplify the visualization that notify us of an exceedance, however these should be used as required and not as rule of thumb to elevate the cosmetics of the image.

Hazard levels, mitigation techniques

As previously stated, the data acquisition system display can be closely compared to the flight deck caution and advisory system. Hazard Level of the data acquisition system display should follow as an example. Data and images should be recognizable and be classified as information, caution, and warning. Images can serve multi functions in that an airspeed can turn yellow as an exceedance is approaching. The same follows for a spoiler alert. Both are acceptable however the issue surfaces when the indications are on separate screens, and you now have to scan two screens to comprehend the condition. Screens should be divided much in the same order where caution and warnings are sectioned into an easily identifiable area where muscle memory directs your attention. From organizing a basic singular sectioned tabulated display to planning multiple page multiple screen displays create a section that list caution and warning messages. This may seem redundant but will give a clear consolidated summary of the situation.

Figure 6 Example Flight Test Cockpit Display

One of the most overlooked risk mitigations when working with displays is consistency throughout an organization. Test screens have become individual and a product of personalization. The lack of consistency tends to create confusion with multiple users allowing misinterpretation. Test organizations should have an approved format that will organize information and advisories to be consistent from user to user or over multiple test campaigns.

Test control systems are those that require input to achieve results. One of the most recognizable controls systems is load banks. The results of the load applied are captured locally if the load back is small and self-contained or if larger from a remote input and the is data transferred to a data acquisition system. The organization of these input controls should follow the same structure. If contained on a panel it should be sectioned into action - response and color coded accordingly.

Visualize and show compliance

To further mitigate risk, visualize and show compliance. The technique of functional testing has proven effective. Don’t assume because the individual measurements raw data appears to be correct the derived parameter will function as programmed. These functional tests should be performed initially at the aircraft or test article’s location and be reperformed as measurements are added or edited. If during the build of a program recorded data is available initial verification can be performed using in office playback prior to transferring to the test article. This should not replace in situ functional test however it will allow multiple opportunities to adjust and reconfigure as required without tying up ground crew resources. Final verification of the test screens should exercise the individual measurements of a derived equation that are not available through playback to ensure proper operation.

Summary

By defining instrumentation, measurements, and parameters we understand their use and how they should be organized. Familiarizing ourselves with the principles, relationship to requirements and expectations we can better relate how the Instrumentation Engineer's role takes shape. As a team member their expertise and experience aids in equipment and component selection that pulls from resources historical and current.

Gathering clearly defined requirements, scope of the project and expectations are but the start of the design effort. Working with the Flight Test Engineer the Instrumentation Engineer will integrate the sensors, signal interface and other necessary components to develop an instrumentation data acquisition system.

The detailed specifications of the systems which include sampling, resolution and filtering are then worked into the design. That will ensure data acquired from the sensors will accurately reconstruct the exchange of physical properties within a reasonable amount of uncertainty as defined by the requirements.

Once the data has been collected and ready for monitoring the Instrumentation Engineer consults the Flight Test Engineer as to the parameters of the measurement for display and the category for each. These categories and information allow the Flight Test Engineer to create and organize test display screens to ensure safety and easy recognition of the measurement's intent.

To complete the process the Instrumentation Engineer often will assist in functional testing of the screens and derived measurements either in office with playback data or at the final functional check at the test article to ensure compatibility.

Conclusion

You may have notice throughout this paper dedicated to instrumentation and safety only an occasional use of the word safety. Odd you may think however, safety is a culture, a way of thinking, paying attention to detail and ensuring the use of a measurement with its display system is structured to achieve confidence in testing which leads to safety. Please use the information discussed here to start conversation with peers and your organization to be consistent in organizing displays and using proper skillsets to that provide confidence.