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Determination of the Shelf Life of MEMS Navigation-Grade Sensors through Use of Accelerated Aging Principles

April 14, 2011

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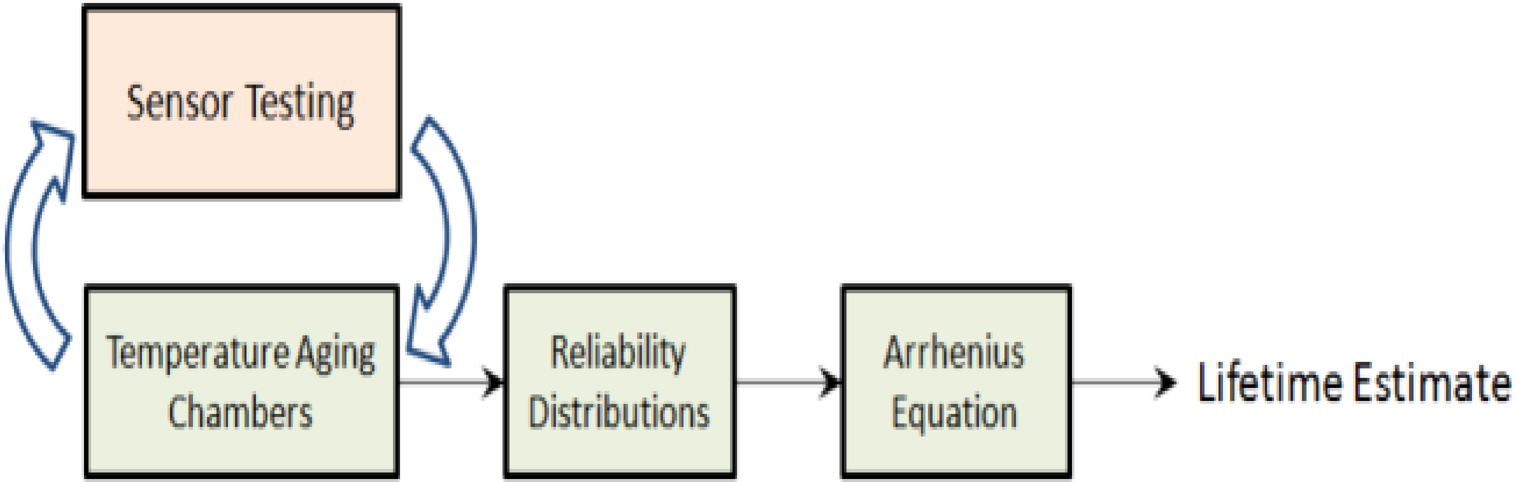
Project GOAL

- Determine the life expectancy of a generic micro electro-mechanical systems (MEMS) inertial measurement unit (IMU) designed specifically for the use in a precision munition.



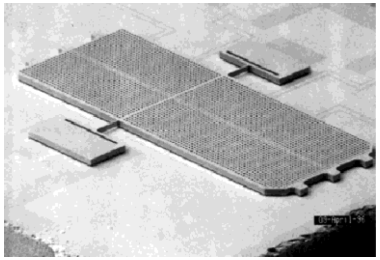
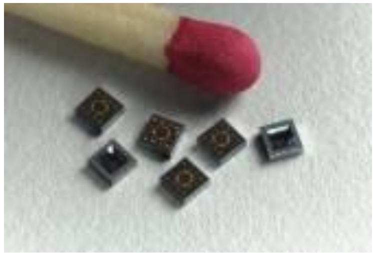
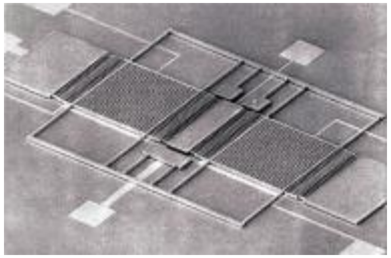
Background Information

- Degradation in performance parameters of a MEMS IMU over time is not well understood.
  - Natural aging not an option
  - Developing navigation capability

- Artificial aging is a viable option to understand product reliability.
  - Precision munitions have been expensive
  - Guidance and Control is a key cost driver

Why This Matters

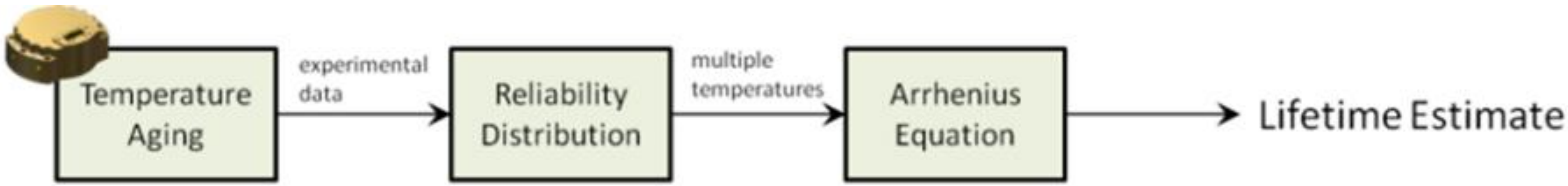
- Guided munition weapon systems are in need of extremely miniaturized, navigation-grade sensors in order to increase the lethality of the Army's precision guided products.
  - Complex environments pose a severe challenge to the warfighter, and therefore the advancement of key technology is necessary to meet stringent user requirements.
  - MEMS IMU provides full six-degrees-of-freedom triaxial motion measurements.
  - All indirect fire systems substantially benefit from precision capability.

Approach and Test Limitations

- Testing is designed to obtain the life expectancy of the inertial sensors within the inertial measurement unit system, not the life expectancy of the IMU system as a whole.
  - Performance independent of sensor integration
  - Greater sample size
- Reliability Prediction
  - A "time to failure" population distribution is required to predict shelf life
  - Weibull distribution is commonly used in reliability engineering
- Success Criteria
  - Sensors must "fail" for lifetime equations to be appropriate.
  - Sensor performance outside program goals will be considered a failure.

Accelerated Aging Principles



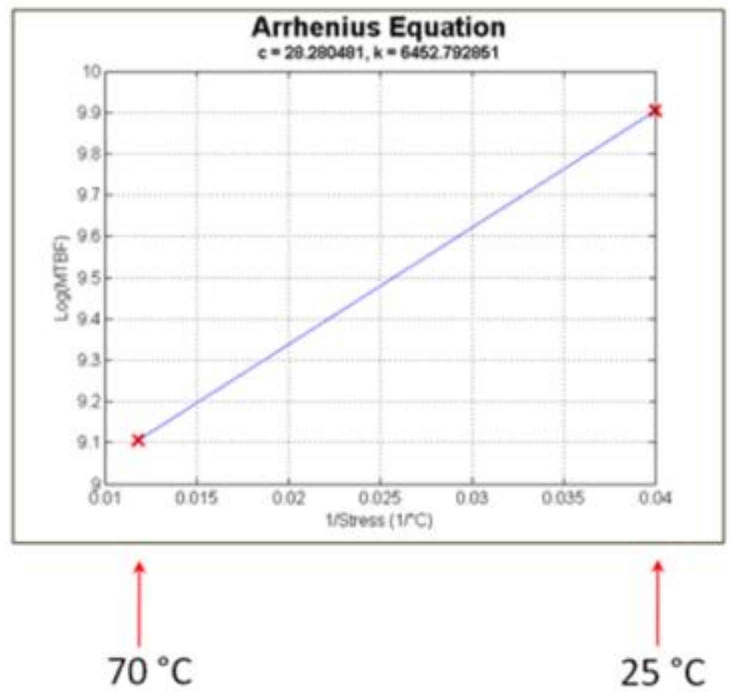
- Arrhenius equation correlates lifetime to temperature stress.

$$t = ke^{\frac{c}{S}}$$

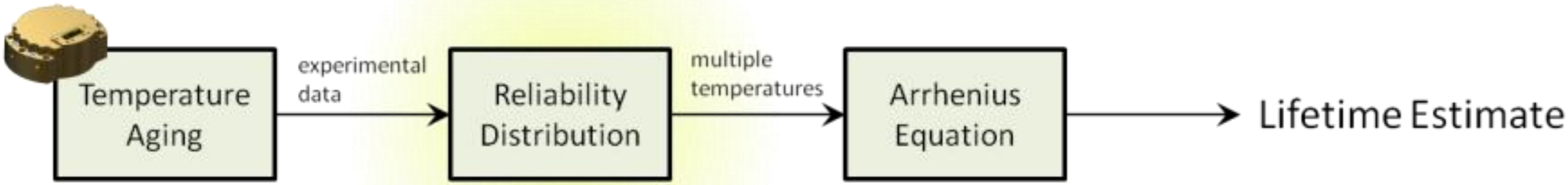
Where

t is the time to failure for a percentage of the population
k and c are constants
S is the amount of stress

- At a minimum, two temperature age estimates are needed to estimate the equation's parameters.



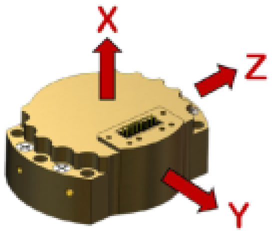
Accelerated Aging Principles



- A “time to failure” population distribution (reliability distribution) is required to use the Arrhenius equation.
- A reliability distribution is selected from a best fit to the experimental data failure times.
- The sensor parameters must fail for the reliability distribution to be determined.
- Weibull distribution will be utilized for this testing as this distribution is commonly used in reliability engineering.

IMU Performance Parameters

- Each inertial IMU contains an inertial sensor assembly (ISA) with six inertial sensors.
  - Angular rates are measured using three orthogonal MEMS gyroscopes along the x, y, and z axes.
  - Linear acceleration is measured using three orthogonal MEMS accelerometers along the x, y, and z axes.



Name	Symbol[1]	Units
Angle Random Walk (ARW)	$g_{i,ARW}$	°/√hr
Bias Error	$g_{i,Berr}$	°/hr
Bias Instability	$g_{i,Bstab}$	°/hr
Turn-on to Turn-on Bias Error Repeatability	$g_{i,Brep}$	°/hr
Self-Heating Settling Time	$g_{i,setT}$	hr
Scale Factor Error	$g_{i,SFerr}$	PPM
Scale Factor Asymmetry	$g_{i,SFsym}$	PPM
Scale Factor Nonlinearity	$g_{i,SFlin}$	PPM
In-Run Scale Factor Stability	$g_{i,SFir}$	PPM
In-Run Bias Stability	$g_{i,Bir}$	°/hr
Sensor Misalignment	$g_{\delta i}$	µrad

Name	Symbol[1]	Units
Velocity Random Walk (VRW)	$a_{i,VRW}$	m/s/√hr
Bias Error	$a_{i,Berr}$	mg
Bias Instability	$a_{i,Bstab}$	mg
Turn-on to Turn-on Bias Error Repeatability	$a_{i,Brep}$	mg
Self-Heating Settling Time	$a_{i,setT}$	hr
Scale Factor Error	$a_{i,SFerr}$	PPM
In-Run Scale Factor Stability	$a_{i,SFir}$	PPM
In-Run Bias Stability	$a_{i,Bir}$	mg
Sensor Misalignment	$a_{\delta i}$	µrad

Accelerated Aging Principles

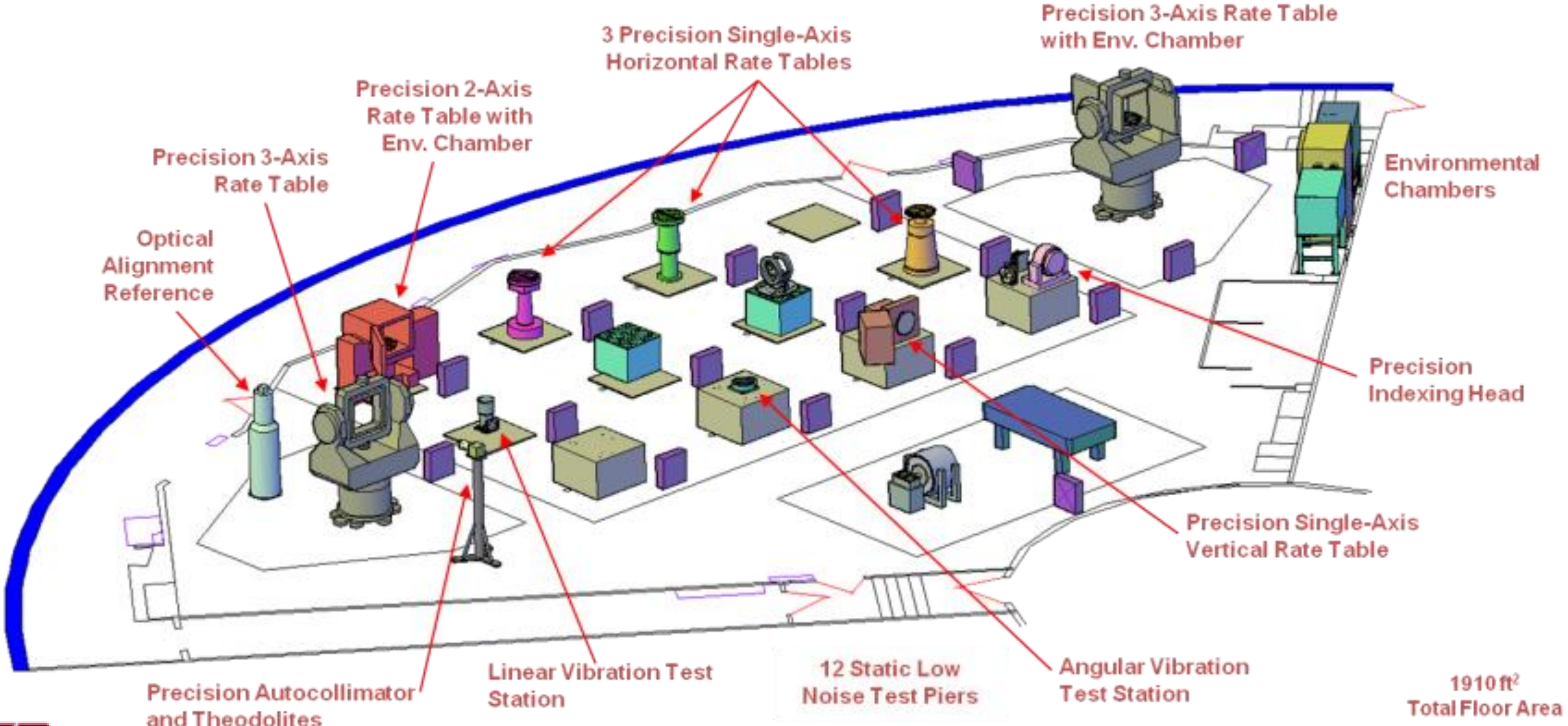
- Shape and scale parameters will be determined via linear regressions.

Gyros Parameter	Weibull Reliability Distribution Parameters	25 °C	70 °C	Arrhenius Constants
Bias Error	Shape (β)			K = , C =
	Scale (θ)			
Scale Factor Error	Shape (β)			K = , C =
	Scale (θ)			
Non-Orthogonality	Shape (β)			K = , C =
	Scale (θ)			

Accelerometer Parameter	Weibull Reliability Distribution Parameters	25 °C	70 °C	Arrhenius Constants
Bias Error	Shape (β)			K = , C =
	Scale (θ)			
Scale Factor Error	Shape (β)			K = , C =
	Scale (θ)			
Non-Orthogonality	Shape (β)			K = , C =
	Scale (θ)			

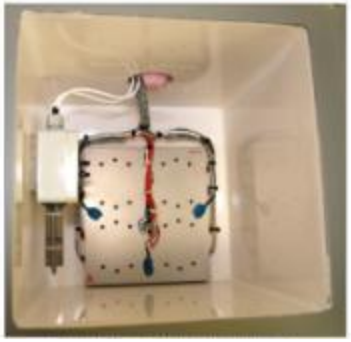
Penn State Navigation Center

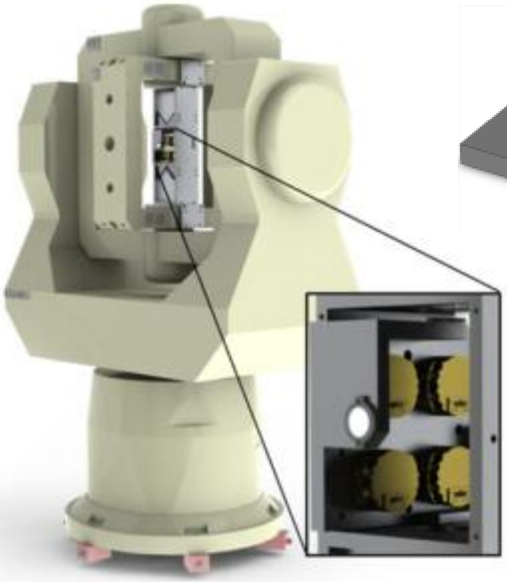
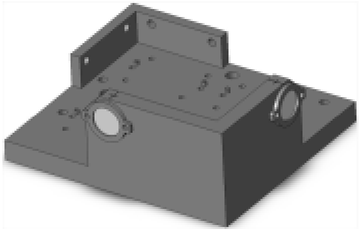
- Provides capabilities to conduct research as well as test the most precise navigation sensors and equipment
- Building design reduces noise internal to the building itself



Test Setup

- **Artificial Aging**
  - The temperature chamber provides air temperature, pressure, and humidity data.
  - Mounting fixture stabilized at target temperature during aging.
- **3-Axis Characterization**
  - Two alignment mirrors allow sensors to be precisely oriented on the fixture to the North, East, and to gravity.
  - No need to remount sensors.



Test Procedures

- Static Test
  - Sensors are powered on and held motionless for a period of 30 minutes.
- Rate Test
  - The sensor input axis of the gyros under test is positioned along the table's axis of rotation.
  - Sensor data is collected ten times according to a rate profile.
- Tumble Test
  - The sensor input axis of the accelerometers under test were positioned along north.
  - Sensor data is collected five times according to a tumble profile.

1	Static – X axis
2	Static – Y axis
3	Static – Z axis
4	Rate – X axis
5	Rate – Y axis
6	Rate – Z axis
7	Static – X axis
8	Static – Y axis
9	Static – Z axis
10	Tumble – X axis
11	Tumble – Y axis
12	Tumble – Z axis
13	Static – X axis
14	Static – Y axis
15	Static – Z axis

Rate Profile

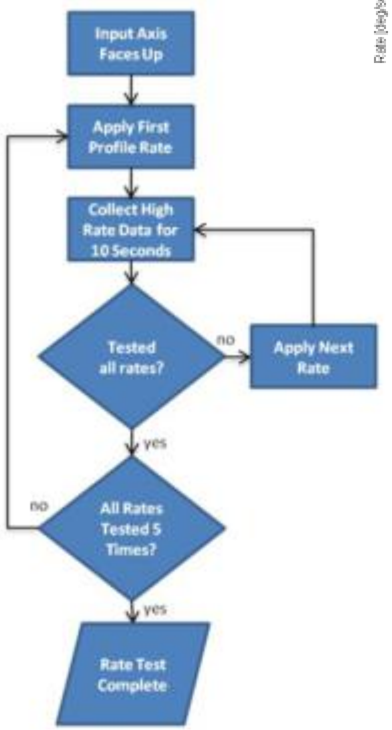
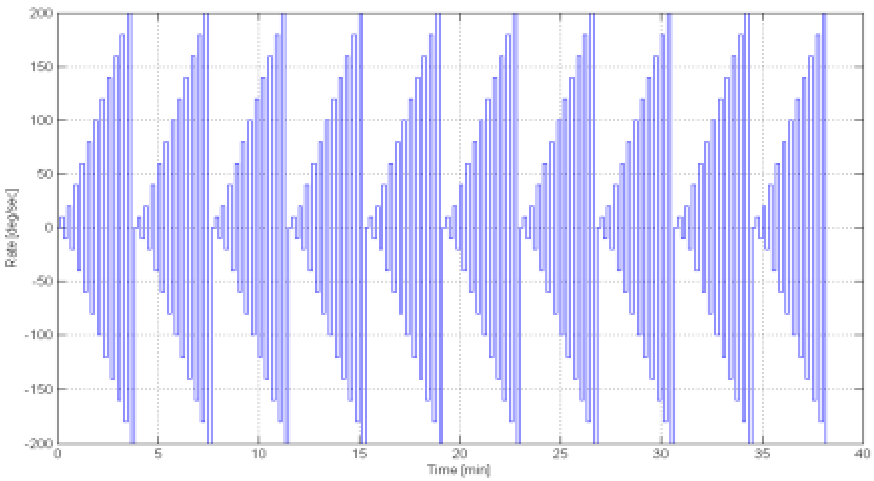


Table 16: Single Rate Profile



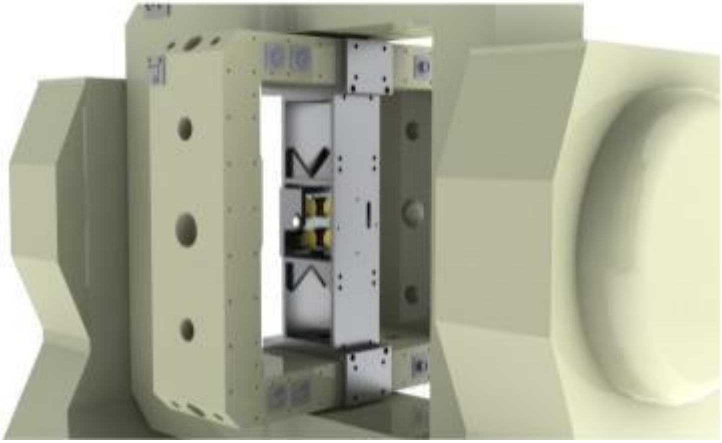
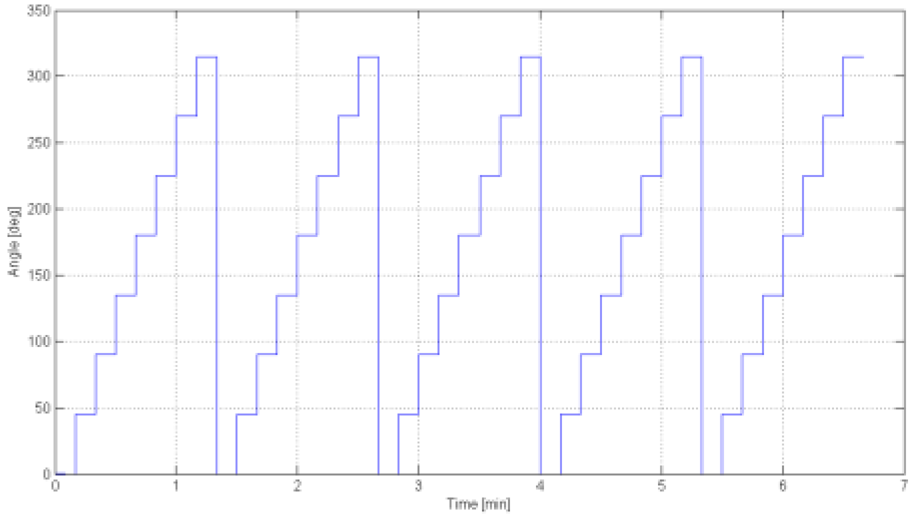
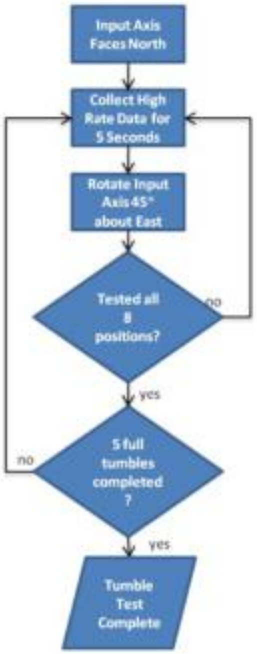


Table Rate deg/sec	Dwell Time sec
0	10
±10	10
±20	10
±40	10
±60	10
±80	10
±100	10
±120	10
±140	10
±160	10
±180	10
±200	10

Tumble Profile





	Angle deg	Input Axis Orientation
1	0°	North
2	45°	
3	90°	Up (+g)
4	135°	
5	180°	South
6	225°	
7	270°	Down (-g)
8	315°	

Test Schedule

- Initial characterization to baseline sensor performance parameters.
- Monthly characterization at the beginning of each month.
- Final characterization at the end of the 14 month period.

Year	Month	Action
2010	May	Test Setup
	June	Baseline Characterization
		Age
	July	Characterization
		Age
	August	Characterization
		Age
	September	Characterization
		Age
	October	Characterization
		Age
	November	Characterization
		Age
	December	Characterization
		Age
2011	January	Characterization
		Age
	February	Characterization
		Age
	March	Characterization
		Age
	April	Characterization
		Age
	May	Characterization
		Age
	June	Characterization
		Age
	July	Characterization
		Age
	August	Final Characterization

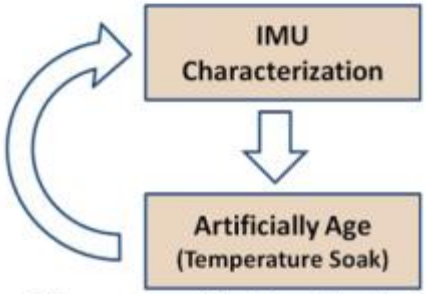


Illustration 45: Test Cycle

Path Forward

- Ongoing effort to be completed in September 2011
- Complete results are not available at this time
- Future MEMS IMU lifetime predictions can leverage off the process demonstrated in this testing program

Recommendations

- Increase the determination of reliability distributions by testing more IMUs.
  - Eight IMUs at each temperature step
- Additional temperature steps
- Further increase the aging process by increasing the aging temperature
  - More accurate lifetime prediction
- **Point of Contact**

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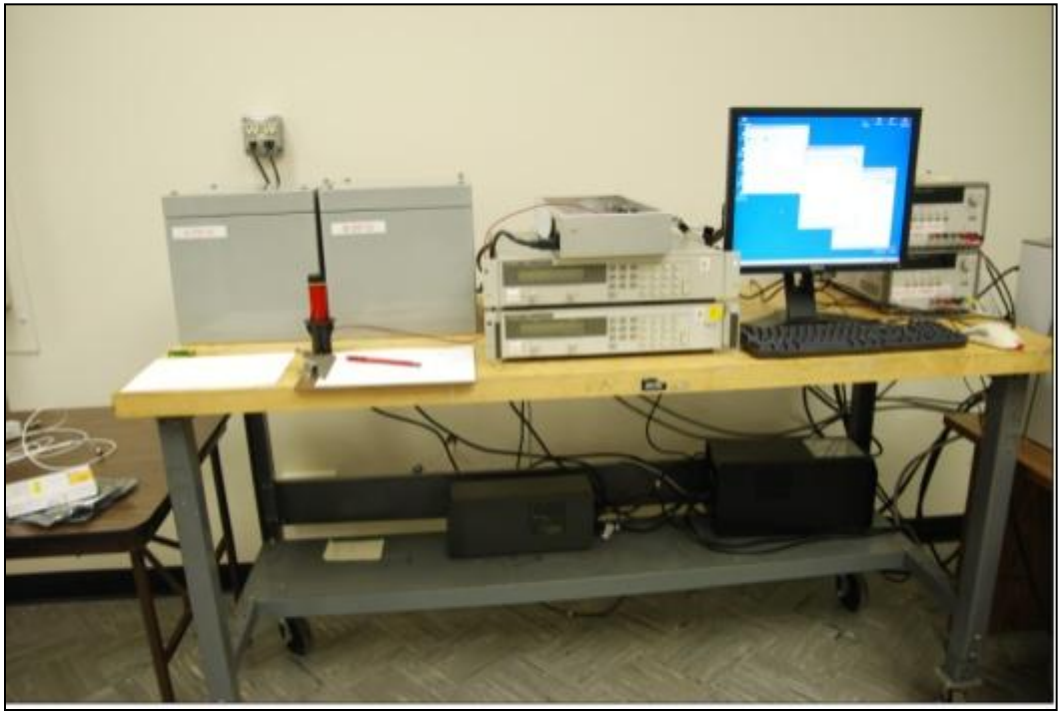
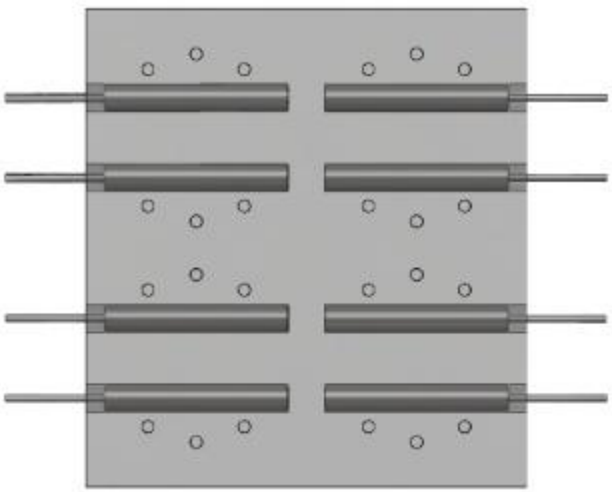
Backup – Artificial Aging Setup

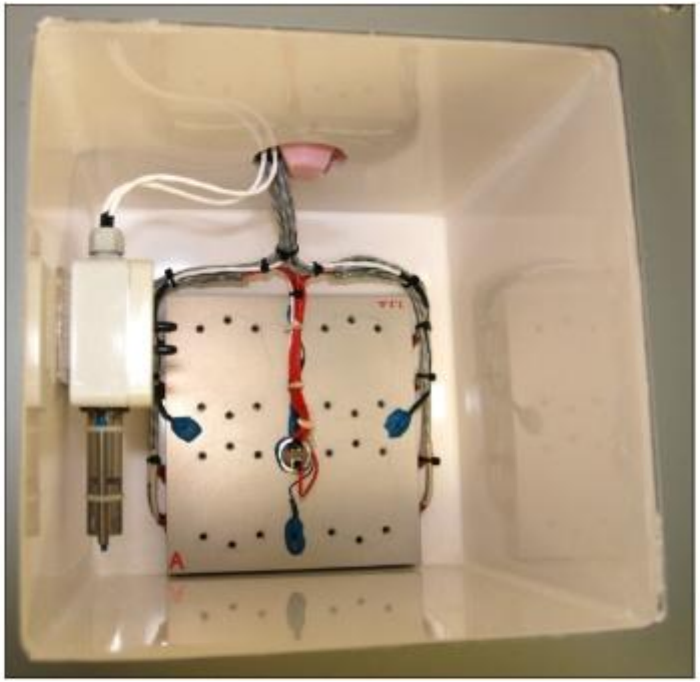
- Two thermal chambers and support electronics.
- IMUs are mounted to a custom fixture in each chamber .



Backup – Artificial Aging Setup

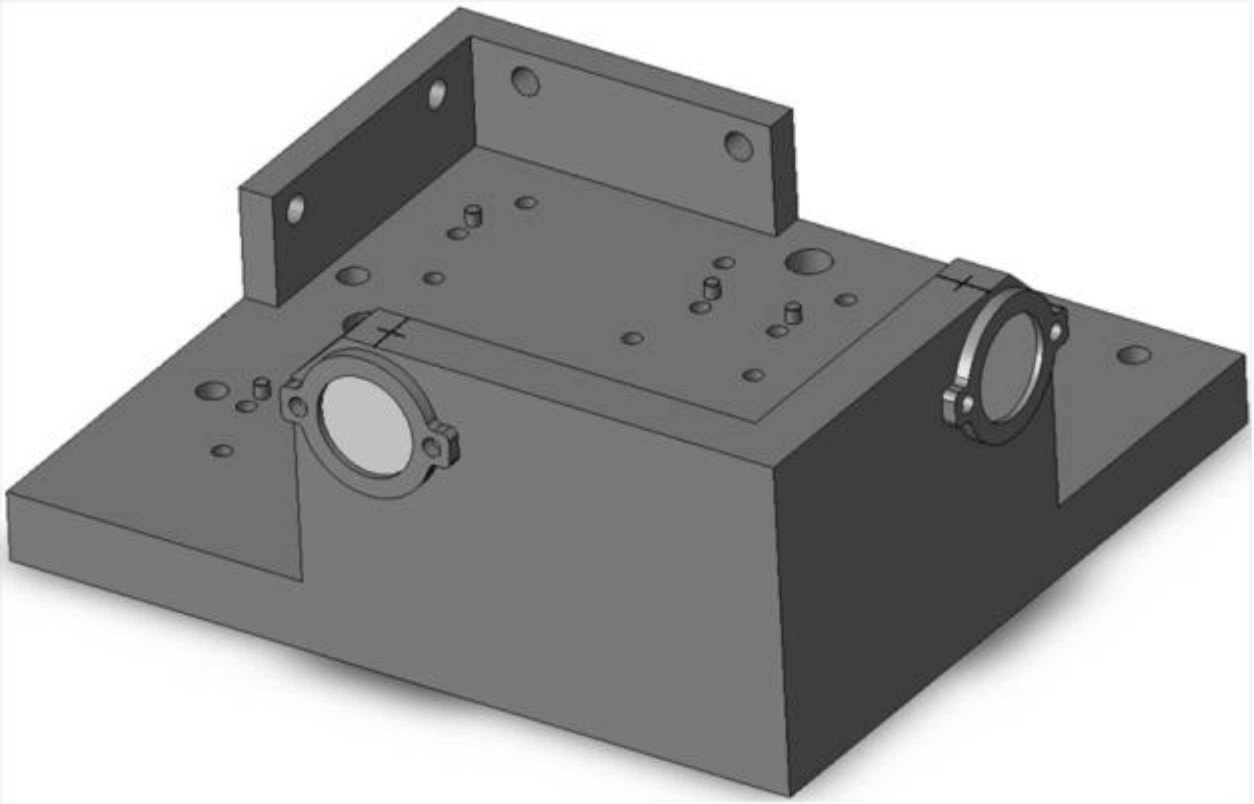
- The temperature chamber provides air temperature, pressure, and humidity control back to the support computer.



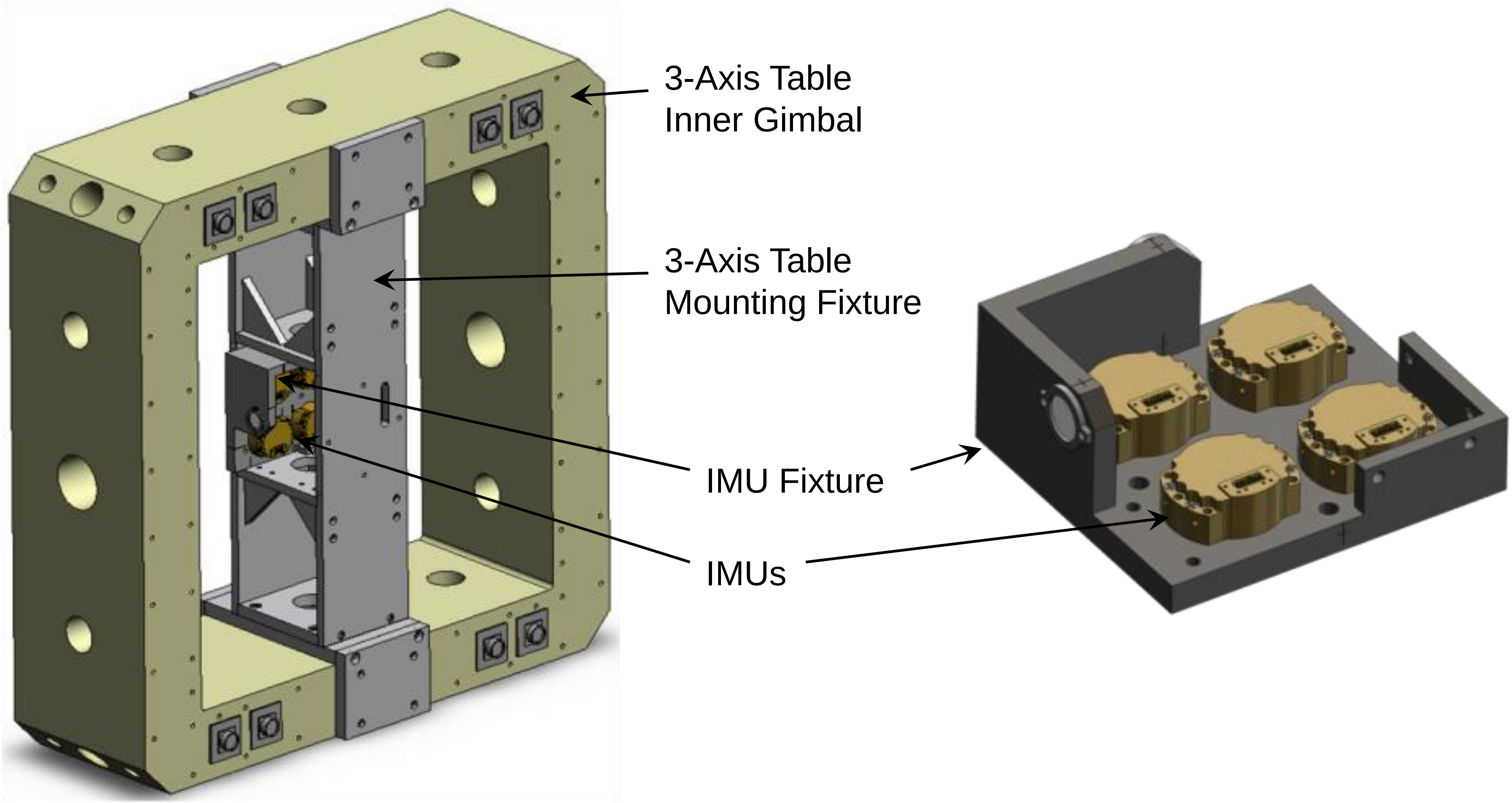


Backup – Sensor Fixture

- Two alignment mirrors allow sensors to be precisely oriented on the fixture to the North, East, and Down.



Backup – Characterization Setup



Backup - Accelerated Aging Principles

- The Arrhenius equation can be generalized to correlate any stress to a population failure.
  - At minimum, two temperature age estimates are needed to estimate the equation's parameters.

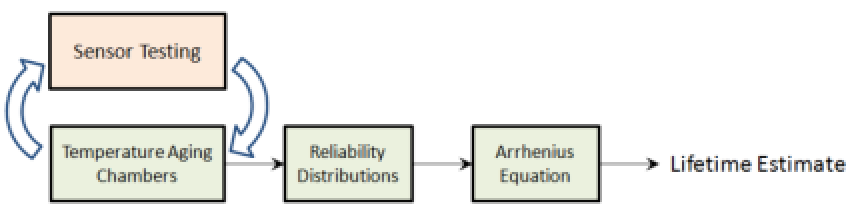
$$K = K_0 e^{-\frac{E}{BT}}$$

K_0 is the reaction rate at a known temperature

E is the activation energy of the reaction

B is Boltzmann's constant

- The devices under test do not fail simultaneously.
  - Weibull distribution used to model reliability



$$R(x) = e^{-\left(\frac{x}{\theta}\right)^{\beta}}$$

R(x) is the population reliability at time x

θ is the Scale parameter

β is the Shape parameter

Backup – Arrhenius Equation

- Direct measurements of aging degradation can take decades.
- The Arrhenius model describes the effect temperature has on chemical reactions.

$$K = K_0 e^{-\frac{E}{BT}}$$

K_0 is the reaction rate at a known temperature

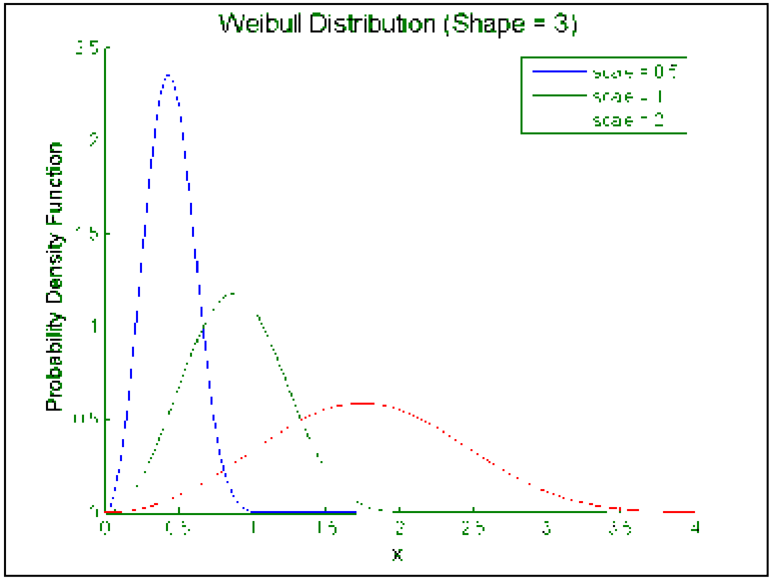
E is the activation energy of the reaction

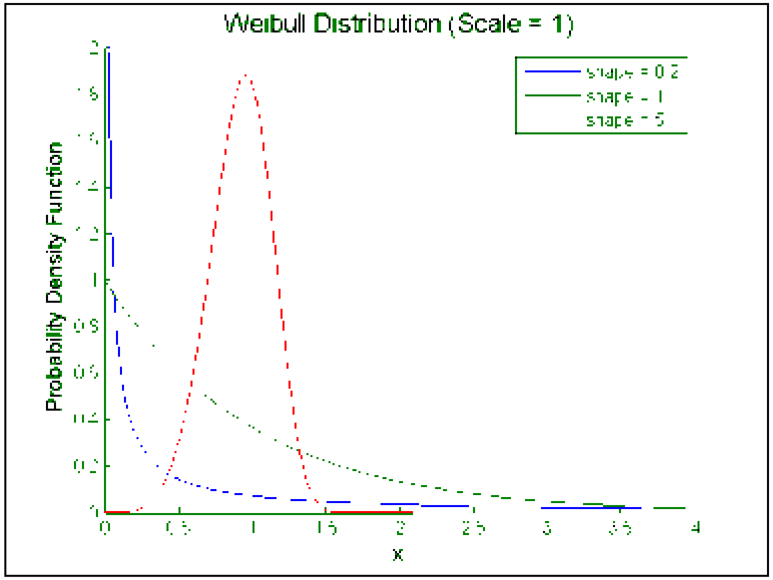
B is Boltzmann's constant

- It is possible to induce artificial aging in a material or device by applying some form of stress.
- By calculating the reliability distributions at differing stress levels, the Arrhenius model can be utilized to calculate the failure rate at intermediate stresses.

Backup – Weibull Distribution

Weibull distribution has two parameters to be calculated from the “failed” parameters data: Shape (β) and Scale (Θ)





$$f(x) = \frac{\beta}{\theta}\left(\frac{x}{\theta}\right)^{(\beta-1)} e^{-[(\frac{x}{\theta})]^{\beta}}$$

Backup – Current Results

- An appropriate out-of-spec value was chosen for each parameter
- The values are based upon the Common Guidance Common Sense (CGCS) program goals
  - Some of the sensor values were out of CGCS program thresholds at the start of the program
- Some of the gyro parameters are shown here

Gyro Parameter	Maximum Threshold
Bias Error	±100 °/hour
Scale Factor Error	±400 PPM
Non-orthogonality	±1400 μrad

Backup – Current Results

- From the extrapolated parameter failure times, the shape and scale parameter for the Weibull distributions were determined via linear regressions on the data

Gyros Parameter	Weibull Reliability Distribution Parameters	25 °C	70 °C	Arrhenius Constants
Bias Error	Shape (β)	1.04	0.97	K = 0.86, C = 70.00
	Scale (θ)	14.07	2.33	
Scale Factor Error	Shape (β)	1.18	1.34	K = 0.20, C = 94.32
	Scale (θ)	8.81	0.78	
Non-Orthogonality	Shape (β)	0.61	1.27	K = 5.28, C =1.12
	Scale (θ)	459.76	26.04	

- From the calculated Weibull distributions, the population reliability for each parameter across temperature can be computed