# WHITE PAPER

## Institute for Materials, Manufacturing, and Sustainment's

# SCIENCES FOR AVIATION PLATFORM SUSTAINMENT (SAPS)

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## EXECUTIVE SUMMARY

The purpose of this strategic plan is to: (1) detail the IMMS' initiative in an integrated academic program called *Sciences for Sustainment* to support aviation research; (2) present the need to establish the Sustainment System Integration Laboratory (SIL); and (3) convey the Lubbock Economic Development Alliance's (LEDA) willingness to support the establishment of the Sustainment SIL in Lubbock, Texas.

The Sciences for Aviation Platform Sustainment (SAPS) white paper presents a holistic approach to explore, demonstrate, develop, and transition futuristic concepts, which can then be matured to enable ultra-reliable designs, "fatigue-free" platforms, and the desired capabilities needed to sustain the next generation of vertical lift aircraft with little or "zero-maintenance" over a significant useful life. The initiative is inspired by the U.S. Army's "Aviation 2050 Vision –Technology for Tactics" [1].

There are two major benefits to stakeholders. First, creating a unique national asset for the development and demonstration of futuristic concepts and technologies in support of existing and next generation aviation platforms, including fully autonomous and unmanned aerial systems (UAS), Future Vertical Lift (FVL) platforms, and the next technical demonstrator (TD). Second, creating high-quality jobs and a well trained, next generation of scientists and engineers based on the development of strong bonds and networks within research communities and government laboratories.

In collaboration with the U.S. Department of Defense (DOD), aviation industry, and other non-profit institutions, IMMS pursues the following opportunities and initiatives:

1. **Integrated Academic Program of the Sciences for Sustainment:** In 2016, TTU established IMMS. The IMMS team has well over 100 years of experience from the basic and applied research to technology demonstration, test and evaluation, and transition. IMMS has an adequate resource, which consists of faculty members, postdoctoral researchers, and a selected group of graduate students. These researchers are conducting the integrated basic and applied research and advanced aviation platform concept and technology demonstrations needed to achieve the *Sciences for Sustainment* paradigm-shifting goals and results.

2. **Establishment of the Sustainment SIL:** Consistent with the U.S. Army's aviation development objective, IMMS's commitment to the academic program of the *Sciences for Sustainment*, and the City of Lubbock's goal to promote economic growth, TTU strongly encourages the establishment of the Sustainment SIL in Lubbock, Texas. This major initiative is aimed at enabling the exploration, demonstration, development, and transition of futuristic sustainment concepts and technologies in support of the existing fleet and next generation aviation platforms for the year 2048 and beyond. The proposed Sustainment SIL, engrained with the IMMS *Sciences for Sustainment*, will:

    a. Demonstrate a holistic approach and an integrated and networked sustainment capability to: (1) design platform systems/sub-systems upfront for a common optimized reliability; (2) enable a total system for predictive health monitoring; and (3) model and simulate the full platform sustainment process with virtual and augmented realities.

    b. Provide initiatives to produce well-planned research and theses development with high value for potential integration, fielding, and commercialization. Train and develop world-class scientists and engineers well positioned to achieve paradigm-shifting scientific results and create a path for entrepreneurial students who are ambitious to support the nation's economic growth.

3. **LEDA's Support of the Establishment of the Sustainment SIL:** The City of Lubbock actively fosters opportunities to promote economic growth. LEDA supports the City of Lubbock goal to promote economic growth by creating high-quality jobs, investing in new capital improvements, and enhancing Lubbock's quality of life. During the April 3, 2017 meeting between the U.S. Army and TTU, LEDA expressed their strong willingness to support the establishment of the Sustainment SIL in Lubbock, Texas.

## 1. AVIATION SUSTAINMENT CHALLENGES AND SHORTFALLS

Former Army Chief of Staff General Dennis Reimer stated that a revolution in military affairs cannot take place without first having a revolution in military logistics. However, a revolution in military logistics will not take place without significant improvements in logistics automation and information technology capabilities [2].

The U.S. Army sustainment functions consist of related tasks and systems that provide support and service to ensure freedom of action, extended operational reach, and prolonged endurance [3]. Endurance refers to the ability to maintain, protect, and sustain forces regardless of where they are deployed, how austere the environment, or how much land power is required [4]. One of the sustainment functions is logistics, which is the planning and execution of the movement and support of forces and the maintenance of Army assets, including platforms.

Due to increasing operational and usage demands, the design of complicated machines like air platforms is far from perfect. Air platforms are prone to catastrophic failures, which substantially increase operation and sustainment (O&S) and life cycle costs. In FY13, Operation and Maintenance (O&M) accounted for $47B or 35% of the U.S. Army-based budget of $135B. Since FY13, O&M funding has grown approximately 4.4% [5].

Catastrophic failures and frequent maintenance practice increase platform downtime, reduce platform availability, and impact the U.S. forces' ability to fight and win precisely and effectively, particularly in expeditionary missions.

In 2007, emerging data showed that during operational testing, a significant number of U.S. Army systems were failing to demonstrate established reliability requirements [6]. In 2011, based on historical data, approximately four out of five U.S. Army systems still failed to achieve their reliability requirements, resulting in significant penalties associated with system availability, life cycle costs, and scheduled delays [7]. The reliability measurement is based on the U.S. Army's developed reliability scorecards, reliability growth planning, tracking, projection models, and reliability test planning tools.

According to the *Study on Rotorcraft Safety and Survivability* conducted by the Institute for Defense Analyses and Joint Aircraft Survivability Program Office [8], during Operation Enduring Freedom and Operation Iraqi Freedom (October 2001 to September 2009), there were 375 rotorcraft losses with 496 fatalities. Mishaps accounted for 81% of all losses, with combat losses accounting for the remaining 19%. Based on the Congressional and Secretary of Defense (SECDEF) goal of 0.5 mishaps per 100,000 flight hours, the rotorcraft in-theater mishap loss rate was ten times worse, and the out-of-theater loss rate was four times worse.

UAS are rapidly evolving to meet the increasing needs for civil and military applications. However, the utilization of these systems poses concerns in the areas of safety, maintainability, airspace traffic, regulatory needs, societal perception, economics and others, all of which must be addressed and resolved for a successful integration of UAS into civil airspace and military operations. Since UAS were introduced into service, historical data reported an average failure rate of about 40%. According to the *Navy Times* [9], most of the problems encountered are associated with reliability failures and ineffective maintenance, resulting in a direct loss of several billion dollars and substantial UAS maintenance costs.

The U.S. Navy, Marine Corps, and Air Force are currently fielding F-35 aircraft. According to the Defense Aerospace [10], the number of F-35s in service will reach 597 by FY18 and 760 by FY19. The worldwide in-service fleet of F-35s will require 17 million maintenance man-hours (MMH) in FY18 and FY19. This equates to about 1,043 MMH per aircraft per month. The U.S. Navy expects the F-35 combat aircraft to fly approximately 250 hours per year, which results in an average of 50 MMH per flight hour.

The U.S. Army operates more than 4,000 helicopters, the largest fleet in the world. A helicopter has approximately 200 to 400 flight critical parts, and a failure from one of them will result in a catastrophic crash. As a result, many flight critical components have been replaced well before having fully consumed their design life. The U.S. Army imposes a phase time-based maintenance program, which includes preventive maintenance inspections (PMIs). For example, the U.S. Army maintenance team conducts two PMIs for the UH-60 Black Hawk helicopter. The first PMI is conducted at 360 flight hours and lasts for seven days. The second PMI is conducted at 720 flight hours and lasts approximately fourteen days. These PMIs are required even during the platform deployment. When the Black Hawk helicopter returns to the states, it goes through a complete overhaul, resulting in additional down time and reduction of aircraft availability.

With the introduction of the Health and Usage Monitoring Systems or HUMS, the civil and military rotorcraft communities have begun to move toward the condition-based maintenance as well as time-based maintenance. HUMS offer some safety benefits and maintenance credits. However, HUMS technologies may have been saturated and require substantial improvement to reliably detect impending mechanical failures or to provide credits for reducing scheduled maintenance. Super Puma helicopters, flown in the North Sea to transport oil workers to and from the oil platforms, are equipped with HUMS. From 2009 to 2014, mechanical problems resulted the crashes of numerous Super Puma helicopters, including the April 1st, 2014 accident, which killed 16 passengers and crew [11].

*Optempo* is the ability to provide critical resources required to conduct and support full-spectrum operations training, maintain unit equipment, and sustain routine, day-to-day operations. The previously described challenges and shortfalls result in low *optempo*, increasing the need for large, complex maintenance infrastructures and resources and significantly impacting U.S. military campaigns and expeditionary operations. These challenges also impact the successful development and execution of the Third Offset Strategy, e.g., series of strategic capabilities that must be developed to give the U.S. forces a decisive military-technological offset that generates lasting asymmetrical advantages over potential adversaries for the next 25 to 50 years [12].

## 2. IMMS ACADEMIC PROGRAM OF THE SCIENCES FOR SUSTAINMENT

### 2.1 Enterprise Goals and Strategies for Aviation Sustainment Sciences

In 2016, TTU established IMMS and integrated an academic program of the *Sciences for Sustainment*. The overarching goal of the *Sciences for Sustainment* is to develop a scientific foundation in support of the concept and advanced technology demonstration and maturation needed to significantly increase the U.S. defense's platform operational readiness and substantially reduce O&S costs. The ultimate goal of the *Sciences for Sustainment* research is aimed at providing paradigm-shifting results to support the development of the next generation vertical lift platforms, including FVL and UAS, while enhancing the current sustainment capabilities of the existing platforms.

To address the aviation sustainment challenges and shortfalls, SAPS is built around the science and technology (S&T) perspectives developed by the Aviation and Missile Research, Development and Engineering Center (AMRDEC) – Aviation Development Directorate (ADD) "2014 Aviation Science & Technology (S&T) Strategic Plan (ASSP)" [13]. Particularly, the *Sciences for Sustainment* research is based on the system engineering approach and aimed at Platforms and Sustainment Focus Areas to bridge S&T gaps. Since the *Sciences for Sustainment* encompasses diverse aspects of S&T, it is also addressing other foci wherever there is an overlap, including Mission Systems and Power, to ensure a comprehensive integrated solution for platforms and sustainment.

TTU has a formal Collaborative Research and Development Agreement (CRADA) with the Army Research Laboratory (ARL) and is a part of the established ARL South ecosystem. Additionally, TTU is currently integrated in the ARL South Power and Energy program, in which ARL scientists and engineers work at TTU and conduct research side-by-side with TTU's postdoctoral researchers, graduate students, and faculty members.

On April 6, 2017, IMMS met with the ARL Assessment and Analysis (A&A) Campaign leaderships at Aberdeen Proving Ground, MD, to discuss the establishment of a TTU-ARL A&A team under the ARL South ecosystem. The objective of the proposed collaboration is to foster and accelerate collaborative research in the multi-scale/discipline A&A of rotorcraft survivability, healing, and resilience. Particularly, the collaboration can provide opportunities for government, industry, and academia to develop holistic A&A solutions to: (1) reduce vertical lift, including rotorcraft vulnerability to failures and battle damage, (2) enhance rotorcraft resilience and survivability, and (3) enable self-healing so rotorcraft can survive in extreme operation environments.

The IMMS academic program of the *Sciences for Sustainment* is also currently integrated with the existing research collaborations and has solid relationships with the National Rotorcraft Technology Center (NRTC) – Vertical Lift Consortium (VLC), in which TTU is a member, and Vertical Lift Center of Excellence (VLCOE). The program is also built on existing collaborations and partnerships with other agencies including the U.S. Navy (Naval Air System Command (NAVAIR), Office of Naval Research (ONR), and Naval Research Laboratory (NRL)), Marines, Defense Advanced Research Project Agency (DARPA), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and the Federal Aviation Administration (FAA).

On March 24, 2017, IMMS also met with the DARPA Program Office to discuss potential collaborations and advancement of the *Sciences for Sustainment*, particularly the *Fabrics of Artificial Intelligence-informed Technology for Healing* (FAITH) research. FAITH is aimed at enabling the demonstration of the ARL and AMRDEC's conceptualized "big idea" entitled "Virtual Risk-informed Agile Maneuver Sustainment" or VRAMS. According to the National Academies of Sciences and Engineering (NAS/NAE) Technical Assessment Board, who conducted a peered review of the VRAMS concept in July 2016, "*VRAMS is a holy grail of integrated material system behavior … a paradigm change in design, operation, and sustainment for all structural platforms. The program has a grand and ambitious vision with huge industry-wide impact*" [14].

Additionally, IMMS is also aggressively forming numerous collaborative research alliances with the rotorcraft industry as well as with non-profit research organizations to provide enterprise solutions addressing ultimate goals, defined in the AMRDEC-ADD ASSP, which include reducing the platform footprint and O&S costs and increasing platform affordability, availability, survivability and safety, and mobility.

Finally, the IMMS academic program of the *Sciences for Sustainment* is built on the existing supports of the multiscale and multi-disciplinary expertise from the TTU faculty members as well as state-of-the-art facilities from the Edward E. Whitacre Jr. College of Engineering (e.g., mechanical engineering, manufacturing and systems engineering, and electrical and computer engineering) and the College of Arts and Sciences (e.g., mathematics and statistics).

## 2.2 IMMS Sciences for Sustainment Team and Focus Areas

a. **Location:** TTU is located in the City of Lubbock, Texas, a mainstream city of 250,000 citizens. TTU is committed to excellence and was founded in 1923 by residents to create an "Oxford in the desert." It educates a very diverse student body of nearly 37,000 students who are committed to honor, integrity, and service. The leadership of TTU consists of mathematicians, scientists, medical professionals—women and men from a diverse set of academic disciplines.

b. **Management Team:** The IMMS team has well over 100 years of experience from basic and applied research to technology demonstration, test and evaluation, and transition. The IMMS leaderships have directly served the nation for many years and held numerous prestigious positions from NAS/NAE, Office of the Scientific and Technology Policy (OSTP), NAVAIR, Department of Transportation (DOT), FAA, and ARL. As a part of the *Sciences for Sustainment* initiative, in 2016, TTU recruited and hired Professor Satya N. Atluri, Mr. Dy D. Le, and Dr. Oliver McGee.

Professor Atluri is a Presidential Chair and University Distinguished Professor. He is nationally and globally recognized for his contributions to the core of the *Sciences for Sustainment* including fracture, fatigue, materials, mechanics, aerospace engineering, and data science. He is a 1969 doctoral graduate of aerospace engineering from the Michigan Institute of Technology (MIT). He was elected to membership in NAE/NAS in 1996, for his contributions to sustainment sciences. He served on the National Academies of Sciences and Engineering committees on Aging Aircraft and on the Research Engineering and Development Advisory Committee (REDAC) to the FAA Administrator for five years. Over the past 30 years, he has received prestigious national and global awards in the *Sciences for Sustainment*. Professor Atluri founded numerous forums, including the *Global Forum on Structural Longevity (FSL) and International Conference on Computational Experimental Engineering and Sciences (ICCES)*, and journals, including *Structural Durability & Health Monitoring (SDHM), Computer Modeling in Engineering & Sciences (CMES)*, and *Computer Materials and Continua (CMC), Mechanics and Chemistry of Biosystems (MCB).*

Mr. Dy D. Le is Director of the newly established IMMS. Mr. Le is a Vietnam veteran, a military helicopter pilot trained and commissioned at Fort Rucker, Alabama, and a former Prognostics and Diagnostics researcher lead at NAVAIR, Program Manager at the FAA William J. Hughes Technical Center (WJHTC), and Chief of the Mechanics Division at ARL. While at FAA WJHTC, he led the research and development of HUMS technologies, which enabled the FAA certification of the first HUMS to address the civil rotorcraft safety. At ARL, he worked closely with AMRDEC-ADD research teams in numerous S&T focus areas including sustainment and platforms to advance the widely-acclaimed paradigm of a newly developed concept (e.g., VRAMS) for the sustainment of military platforms. Within eight months of the establishment of IMMS, Mr. Le conceptualized the FAITH architecture designed to enable a comprehensive integrated solution for sustaining military platforms with little or "zero-maintenance". A provisional patent application for FAITH has been filed and is currently being reviewed for approval by the U.S. Patent and Trademark Office.

Another impressive investment in the *Sciences for Sustainment* was the addition of Dr. Oliver McGee as the Chair of the Mechanical Engineering (ME) Department, the largest ME department in the country. Dr. McGee is one of the foremost African-American educators in the country. He was a Fellow in the White House OSTP and the Deputy Assistant Secretary of Transportation under President William J. Clinton. Dr. McGee is a subject matter expert (SME) in aircraft catastrophic failures and provides U.S. television news networks with SME opinions on air disasters, including that of the Germanwings Flight 9525 crash.

Dr. McGee and Professor Atluri will take the lead in recruiting eight new faculty members in diverse disciplines of engineering to support the academic program of the *Sciences for Sustainment*. IMMS currently has an adequate resource, which consists of faculty members, postdoctoral researchers, and a selected group of graduate students.

**c.** **Research Focus Areas:** In addition to the integrated academic program of the *Sciences for Sustainment*, IMMS is also integrating the *Sciences for Rotorcraft Assessment of Survivability and Healing*. Additionally, Center for Advanced Research in Engineering Science (CARES) is now also directly supporting the IMMS research. The IMMS research addresses not only the basic and applied research but also the advanced aviation concept and technology demonstration.

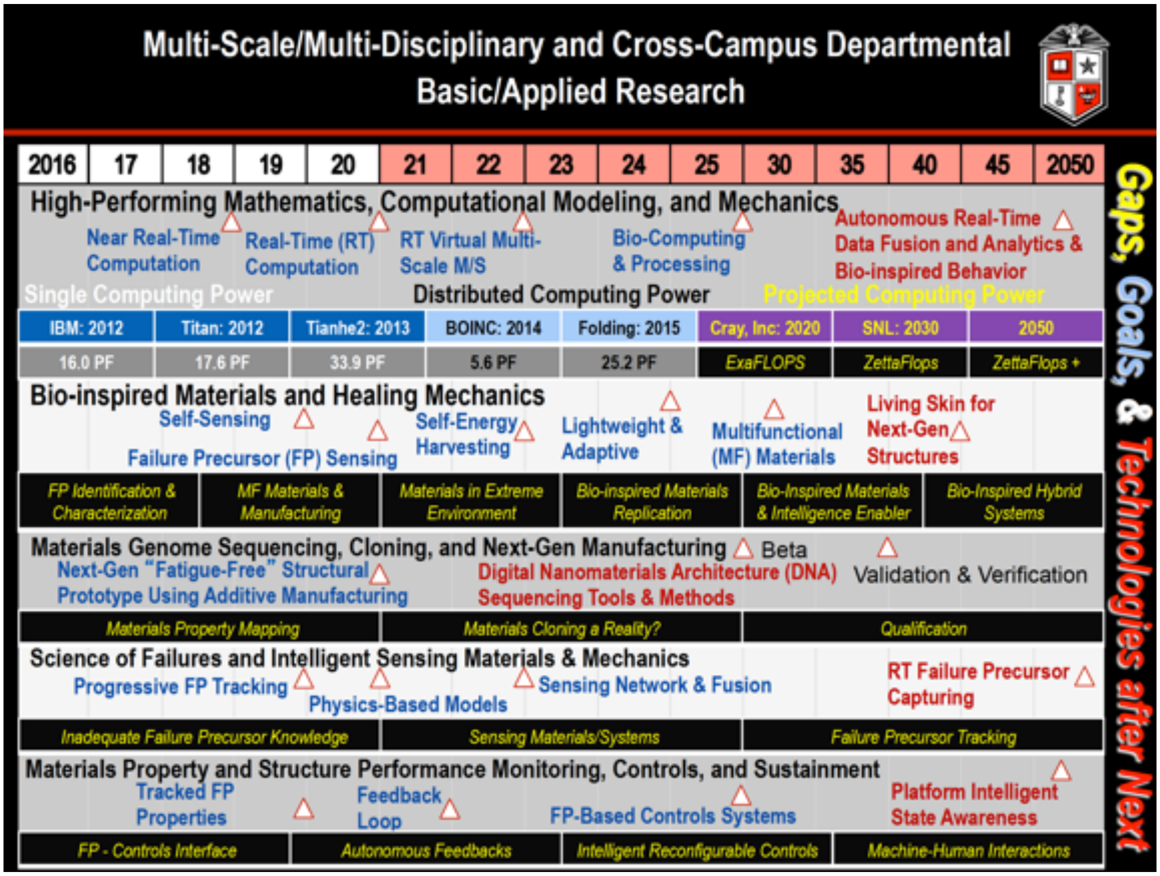



**Figure 1:** Cross-Campus Department *Sciences for Sustainment* Research

As shown in **Figure 1**, the IMMS research focus areas are:

1. *High-performing Mathematics, Computation Modeling, and Mechanics:* Establish scientific foundation and capabilities for real-time computational modeling, artificial intelligence; cognitive and direct feedback; learning; virtual and augmented reality, and bio computing and processing. The ultimate outcome is to enable the bio-inspired and adaptive behavior for self-healing.

2. *Bio-inspired Materials and Healing Mechanics:* Establish the scientific foundation and capabilities for self-sensing of failure precursors, self-energy harvesting, lightweight and adaptive, multi-scale design of materials for sustainment, design-in reliability, and multifunctional materials mechanics. The ultimate outcome is to enable the development of living skin for next generation platform structures.

3. *Materials Genome Sequencing, Cloning, and Next Generation Manufacturing:* Enable a holistic capability or tools, similar to those used by the Human Genome community to sequence the human DNA, for use in engineering the most desirable materials performance properties. Use the additive manufacturing technique to fabricate a prototype of the extremely lightweight, adaptive, durable, and damage-tolerant structures, which also exhibit "fatigue-free" characteristics.

4. *Science of Failures and Intelligent System Sensing Mechanics:* Establish capabilities for progressive failure precursor tracking, model of models, and sensing network and data fusion.

The ultimate goal is to enable a capability for tracking and capturing precursors prior to the onset of progressive failure of systems in real time.

5. *Materials Property and Structure Performance Monitoring, Controls, and Sustainment:* Establish capabilities for tracking system precursor properties, enable feedback loop, and facilitate the change of platform or system behavior via a damage-based controls system to sustain platforms with little or "zero-maintenance". The ultimate outcome is the enabling of the platform intelligent state awareness at system, subsystem, and material levels.

## 2.3 Sciences for Sustainment Basic and Applied Research

SAPS presents a holistic approach to exploring, demonstrating, developing, and transitioning futuristic concepts, which can then be advanced and matured to enable ultra-reliable designs and "fatigue-free" platforms, and to sustain the next generation vertical lift aircraft with little or "zero-maintenance" over a significant useful life for the year 2048 and beyond.

The focus areas, as generally outlined in **Figure 1**: Multi-Scale/Multi-Disciplinary and Cross-Campus Departmental Basic/Applied Research, are aimed at producing paradigm-shifting results to advance capabilities through technology development for existing and future platforms. Engrained with the Sustainment SIL, the *Sciences for Sustainment* research efforts are:

a. *Sciences for Autonomous Prognosis and Healing for Longevity Sustainment:* The research mimics the human ability to heal certain injuries or adapt to extreme conditions to survive. Bio-inspired platforms, **Figure 2**, are enabled with integration of artificial intelligence and multifunctional systems, e.g., multifunctional structures, which not only can carry loads but also can sense, characterize, and be aware of their own structure's health. The ultimate outcome is to enable the bio-inspired system adaptive behavior for self-healing and the accurate determination of the platform system, subsystem, and component's remaining useful life.

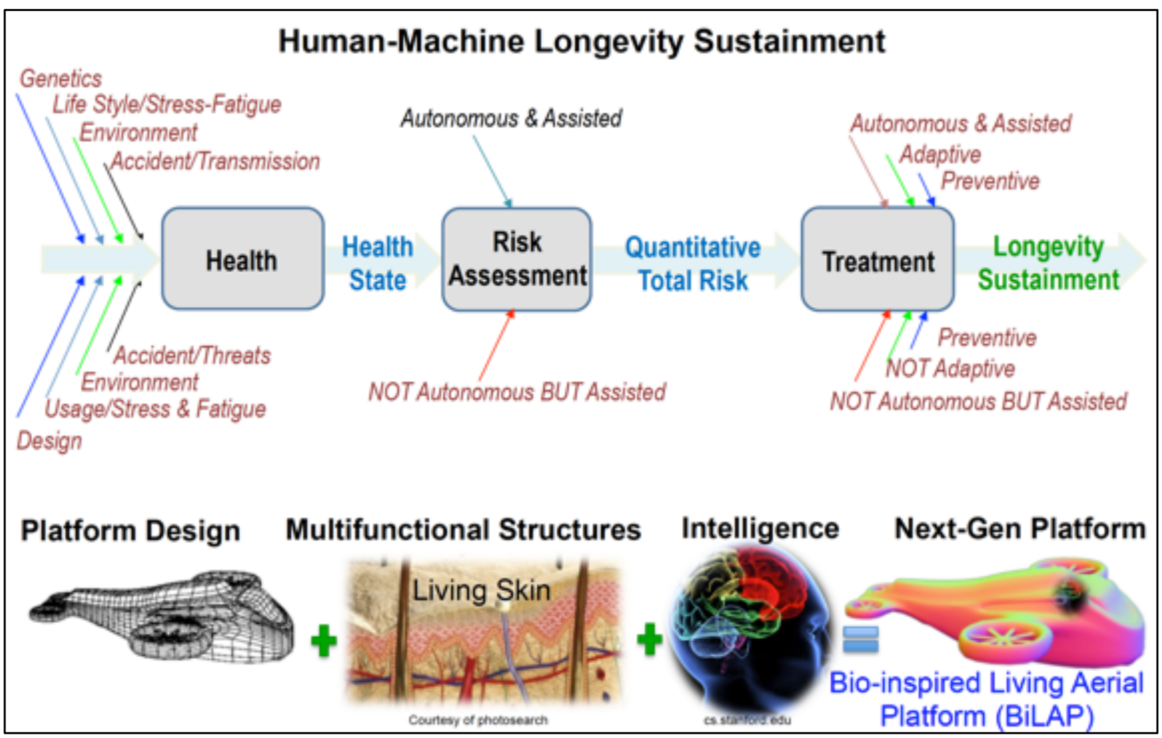



**Figure 2:** Sciences for Autonomous Prognosis and Healing for Longevity Sustainment

b. *Sciences for Bio-inspired Living Aerial Platforms:* The research, as illustrated in **Figure 3**, is aimed at enabling the aviation platform to feel and assess its own health condition (as a human does), automatically quantify risks, autonomously repair the complications (e.g., damage or inoperative system), and if not repairable, adapt to the existing condition and successfully complete its mission and safely return to its base or friendly territory. The research outcomes can provide the scientific foundation for the platform to be integrated with an intelligent state awareness capability at system, subsystem, and material levels. The ultimate goals are to increase platform survivability, extend operational usages, and effectively sustain aviation platforms with little or "zero-maintenance".

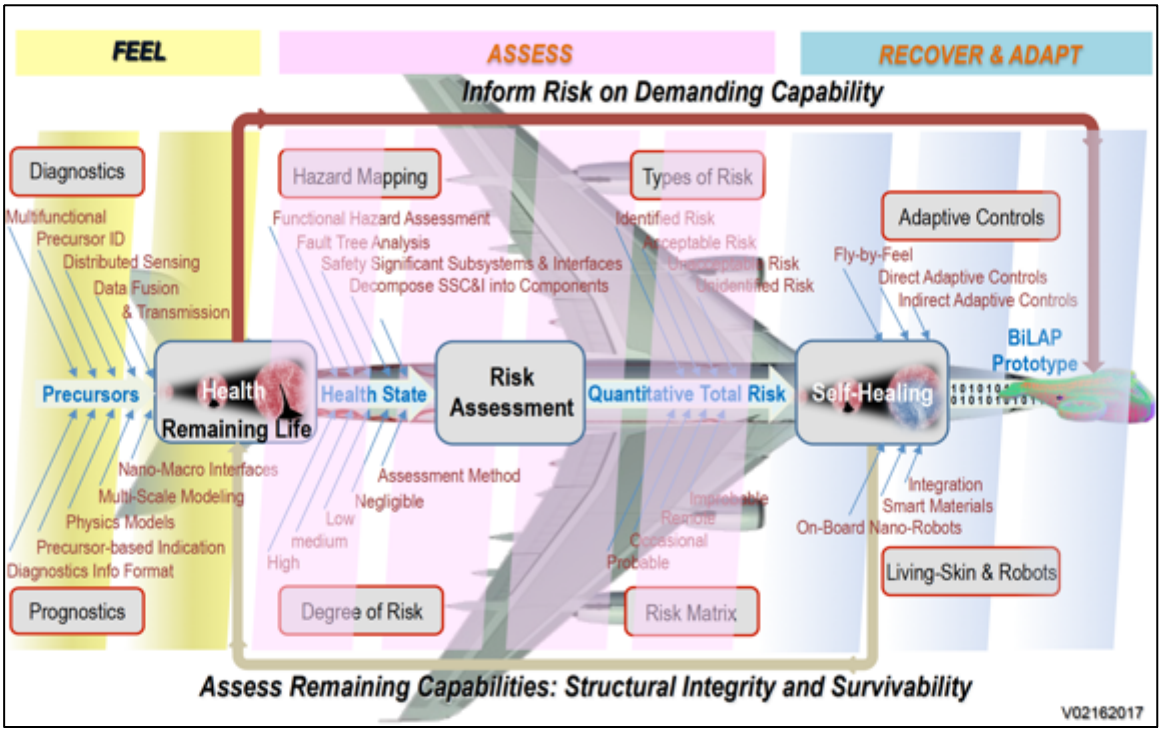



**Figure 3:** Sciences for Bio-inspired Living Aerial Platforms

## 2.4 Sustainment Sciences and Technology for Platforms

For the past several years, AMRDEC-ADD has focused on developing, demonstrating, and maturing individual systems' health assessment and sustainment technologies. These programs included Operations Supports and Sustainment Technologies, Capability-Based Operations and Sustainment Aviation, Autonomous Sustainment Technologies for Rotorcraft Operations, and Adaptive Vehicle Management System (AVMS).

The proposed Sustainment SIL and its integrated *Sciences for Sustainment* research intend to support efforts built upon AMRDEC-ADD past sustainment technology achievements and current research and development (R&D) efforts. While advancing the scientific foundation in the *Sciences for Sustainment*, the R&D efforts supported by the proposed Sustainment SIL are intended to demonstrate, mature, and integrate the scientific foundation and AMRDEC-ADD developed autonomous sustainment technologies, which can enable informed; intelligently determined; real-time comprehensive system controls; mission planning; and the "zero-maintenance" philosophy based on the actual platform health condition and usage. Particularly, the proposed Sustainment SIL will accommodate the development, maturation, and integration of health assessment technologies, methodologies, and systems to provide platforms with the ability, as illustrated in **Figure 3**, to feel and assess their own health condition, automatically quantify risks, autonomously repair the complications (e.g., damage or inoperative system), and if not repairable, adapt to the existing condition, successfully complete its mission, and safely return to base or friendly territory.

2.4.1 *Sustainment Concept and Technology Demonstration*: As previously mentioned, the National Academies of Sciences and Engineering strongly support the advancement of the VRAMS concept. As noted in their final report, "*VRAMS is a holy grail of integrated material system behavior … a paradigm change in design, operation, and sustainment for all structural platforms. The program has a grand and ambitious vision with huge industry-wide impact.*" [14]

Additionally, the IMMS *Sciences for Sustainment* has recently developed a sustainment software-oriented architecture entitled "*Fabrics of Artificial Intelligence-informed Technology for Healing*" or (FAITH), which once fully developed, can enable a holistic capability for a comprehensive integrated health management approach to encompass platform engines, drives, structures, AVMS, electrical and wirings, and rotor systems to support the AMRDEC-ADD "zero-maintenance" philosophy.

a. *FAITH Concept Framework:* The original VRAMS concept is only focused on structural state awareness at the materials level. It does not encompass other platform systems and subsystems. FAITH evolves VRAMS to provide a holistic state awareness capability that encompasses platform systems and subsystems, including structures.

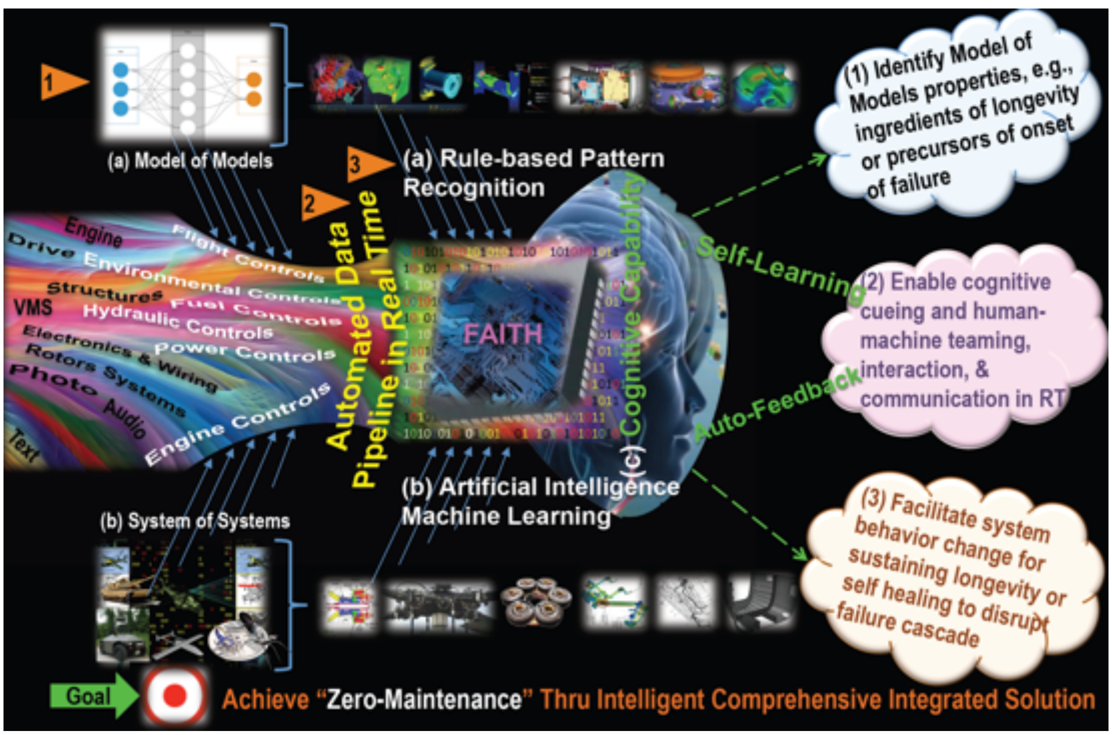



**Figure 4:** FAITH Concept

FAITH, **Figure 4**, is a revolutionary and paradigm-shifting state awareness technology integrated with the VRAMS concept. We theorize that if we can (1) develop an intelligent model of expert models, which represents a meaningful real world and complex entity containing materiel and human interdependent and independent properties that are ingredients of system longevity or precursors of the onset of failure; (2) automate the data collection and data pipeline flow in real time to update the models; and (3) devise an artificial intelligence (AI) to learn and recognize system behavior patterns and enable the cognitive capability for self-learning and direct feedbacks, then platforms, by themselves, can: (1) identify the ingredients of system longevity or precursors of the onset of a particular failure, (2) enable the cognitive cueing and human machine teaming, interaction, and communication in real time, and (3) facilitate system behavior changes to disrupt the failure cascade.

Through learning and feedbacks, FAITH can build a comprehensive databank of knowledge about platform integrity, performance, and behaviors. The knowledge can then be used to develop a transformative design and build the next generation of ultra-reliable vertical lift and bio-inspired living platforms, which are more affordable and do not require substantial operation and maintenance costs to sustain.

FAITH is scalable, based on open architecture, and intended to be Future Airborne Capability Environment (FACE™) standard compliant. Integrated with AI and machine learning, FAITH provides the autonomous descriptive, predictive, and prescriptive analytics to enable the self-state awareness in real time as shown in **Figure 5**.

*Descriptive:* Aggregate data so that relationships, meaningful patterns, and/or insights of anomaly might emerge.

*Predictive:* Quantify, forecast, and prognosticate the likelihood of future events.

*Prescriptive:* Optimize hindsight into the past, insight into the present, and foresight into the future, assess the effect of future decisions and projected outcomes, and inform course of actions.

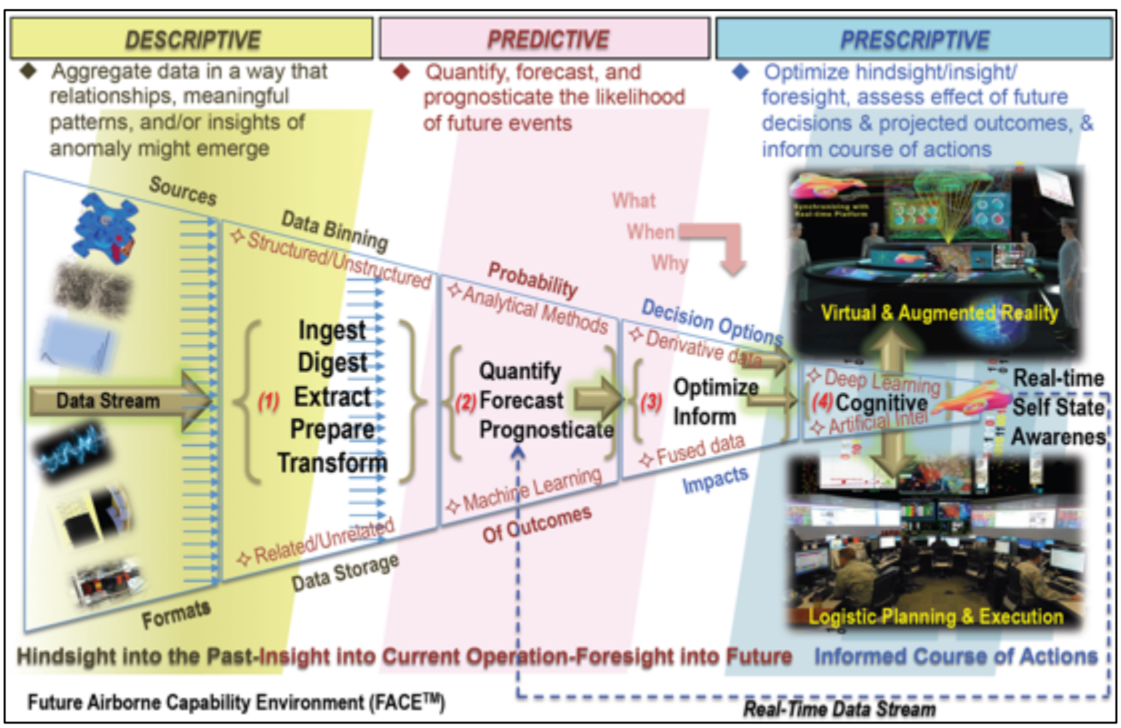



**Figure 5:** FAITH Overall Capabilities

FAITH consists of four modules:

1. *Automated Data Collection and Management of Data Pipeline in Real Time (Module 1):* Automating data collection and managing the data pipeline in real time is an extremely complicated process, particularly for complex systems such as rotorcraft. There are three critical tasks for automating data collection and pipeline flow in real time, **Figure 6**.

   First, FAITH enables the ability to ingest, digest, and extract data from multiple sources containing a high volume of data that is complicated and unstructured. It is critical to capture not only transient sensor data, but also other forms of data including maintenance information, human communication and feeling (communication between flight crews during flight), and data from integrated monitoring systems on board aircraft.

   Second, FAITH enables advanced methods capable of streaming, filtering, aggregating, and transforming data clusters into useful patterns and models so anomalies can emerge. The patterns and models will be analyzed by advanced analytics and analytical methods to provide hindsight into the past, insight into the current, and foresight into the future health condition of platform systems and subsystems including structures.

   Third, FAITH enables an AI machine learning capability to maintain the data pipeline flow to critical chains of the network and enterprise and provide cognitive, ad-hoc queries of data and information for big data, in-memory processing, which enables the AI machine to have immediate access to relevant information and formulate informed decisions in real time.

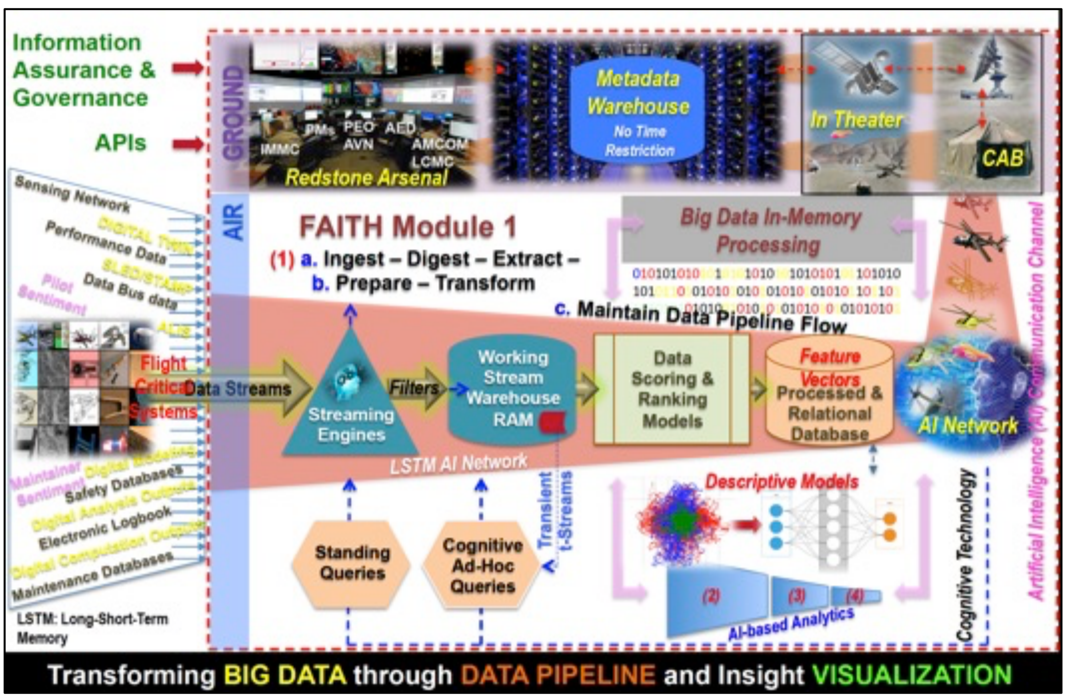



**Figure 6:** Automated Data Collection and Management of Data Pipeline in Real Time

2. *Autonomous Prognostics via Machine Learning:* Modules 2 and 3 (**Figure 7)**, enable the rule-based methods integrated with complex models to perform predictive analytics and provide the hindsight into the past and insight into the current platform operations and states. In parallel, Modules 2 and 3 also enable the AI capability: particularly, with reinforcement machine learning for dynamic events and knowledge discovery in databases to provide pattern recognition, data mining, statistics, and neurocomputing. The knowledge discovered or obtained will be used to provide the cognitive capability to provide direct feedbacks and self-learning.

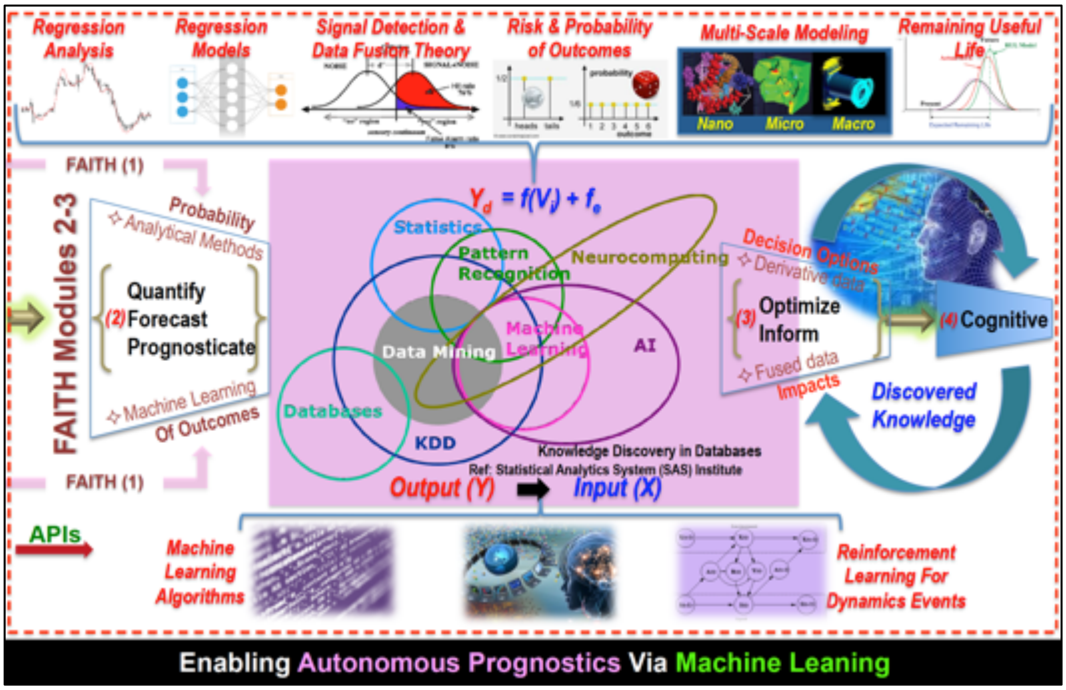



**Figure 7:** Autonomous Prognostics and Artificial Intelligence Machine Learning

3. *Deep Learning Network for Self-learning Platforms:* Module 4 as shown in **Figure 8**, enables the cognitive capability to predict the future and provide direct feedbacks and self-learning. The use of reinforcement machine learning involves the application of a deep neural network. The applicable deep learning network is a neural net with several hidden layers that need to be solved.

   Building a deep learning network model is complex, and the training process is an important step. To start the training, we use a training dataset, which contains actual data and its associated labels. At the end of every cycle through the neural network, we compute the difference between the actual label and the predicted network output. This difference is quantified as the error of the network (also known as the cost function). The weights and biases of the neural network are updated to reduce this error before the next cycle. This process is repeated until the error and uncertainty become negligible.

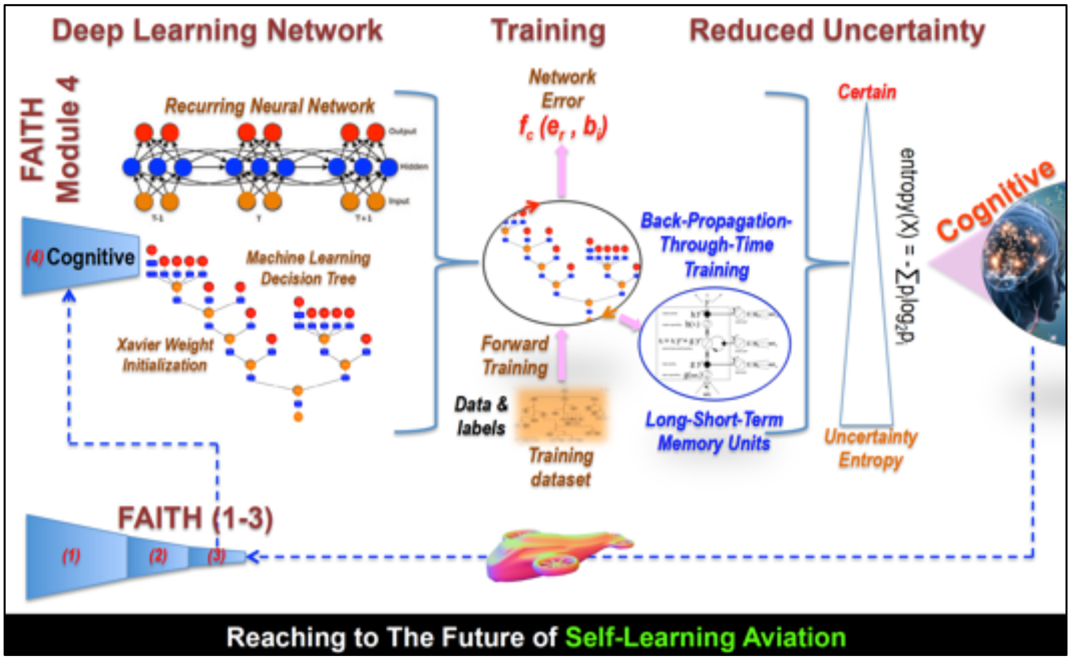



**Figure 8:** Deep Learning Network for Self-learning Platforms

FAITH, if developed and matured, can enable the following technologies and capabilities for existing and future aviation platforms:

1. *Self-Sustaining Capabilities:* Enable the development of "fatigue-free" platforms, achieve the Maintenance-Free Operating Period goal, and provide a capability for automated maintenance and optimization of "Big Data" to build the knowledge database of aviation platforms.
2. *Self-Maneuvering Technologies:* Enable the development of reconfigurable controls technologies and automated autorotation capability for rotary wing platforms, allow teaming of autonomous manned/unmanned systems, and enable fully autonomous human-machine interactions and mission.
3. *Self-Adapting and Survivability:* Facilitate self-healing behaviors, allow self-informing parts replacement demands and schedules, and enable the ability for self-informing about remaining capability to achieve demanding tasks and maneuvers.

## 3. PROPOSED ESTABLISHMENT OF THE SUSTAINMENT SIL

### 3.1 Sustainment SIL Mission:

In order to meet the milestone "*Sustainment Prototype SIL/FVL Integrated Sustainment Network Demos*", as planned in the AMRDEC Joint Aviation Sustainment S&T Roadmap [15] and shown in **Figure 9**, the establishment of the Sustainment SIL is required.

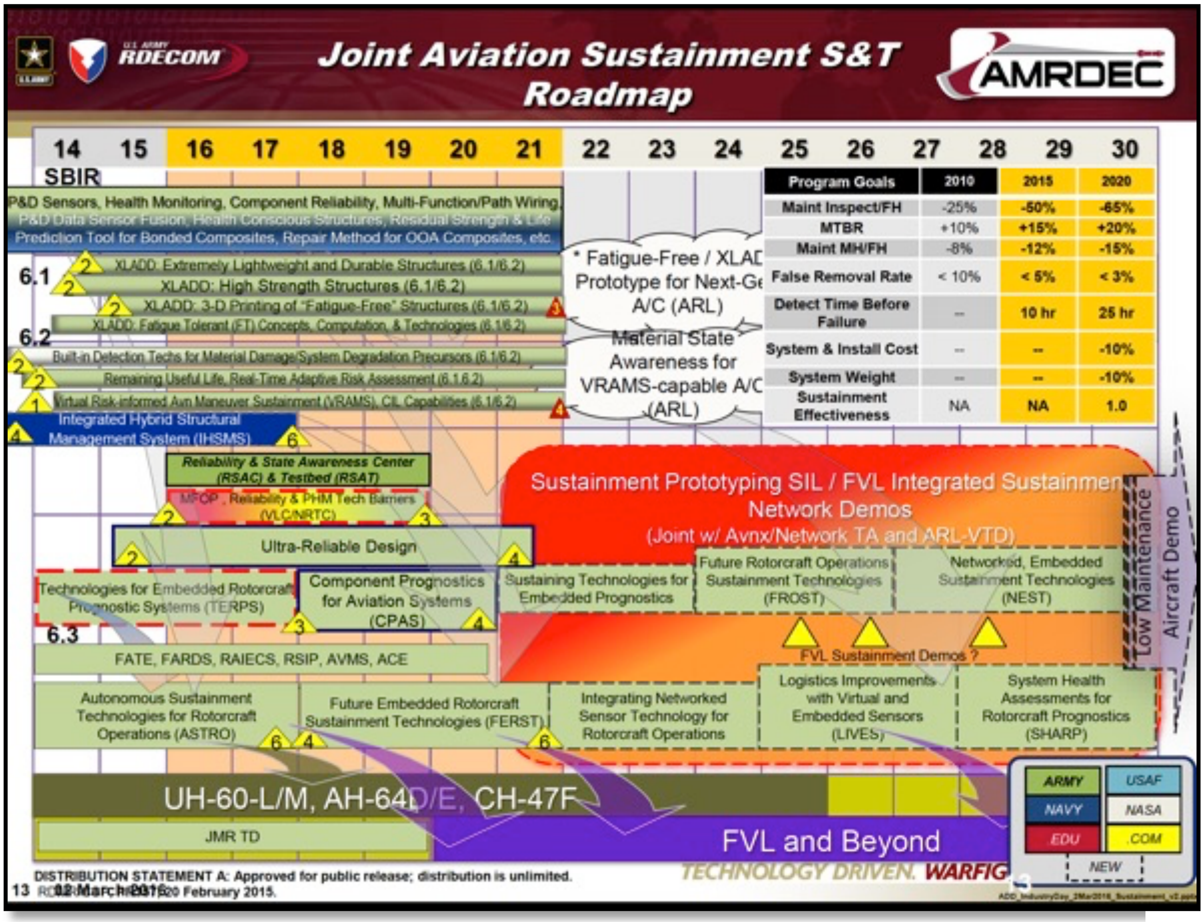



**Figure 9:** AMRDEC Joint Aviation Sustainment S&T Roadmap

The *Sustainment Prototyping SIL* aims at enabling an enduring capability to explore, demonstrate, and transition futuristic sustainment concepts and technologies in support of next generation aviation platforms for the year 2048 and beyond. The proposed Sustainment SIL, engrained with the IMMS academic program of the *Sciences for Sustainment* and AMRDEC-ADD advanced aviation development efforts, is to:

a. Demonstrate a holistic approach and an integrated and networked sustainment capability to: (1) design platform systems/sub-systems upfront for a common optimized reliability; (2) enable a total system for predictive health monitoring; and (3) model and simulate the full platform sustainment process with the virtual and augmented realities.

b. Provide initiatives to produce well-planned research and theses development with high value for potential integration, fielding, and commercialization. Train and develop world-class scientists and engineers well positioned to achieve paradigm-shifting scientific results and create a path for entrepreneurial students who are ambitious to support the nation's economic growth.

## 3.2 Sustainment SIL Capabilities:

The proposed Sustainment SIL is intended to provide:

a) A unique integrated computation, modeling, and assessment and analysis with prototype in the loop to enable the live testing and virtual and augmented reality environment

b) Test-bed for platform and sustainment technologies

c) Joint Common Architecture-based sustainment capability

d) Integrated network for predictive health monitoring and assessment to enable adaptive and reconfigurable controls, assess efficacies at the total level system, and provide health and usage assessment inputs to the Adaptive Vehicle Management System (AVMS)

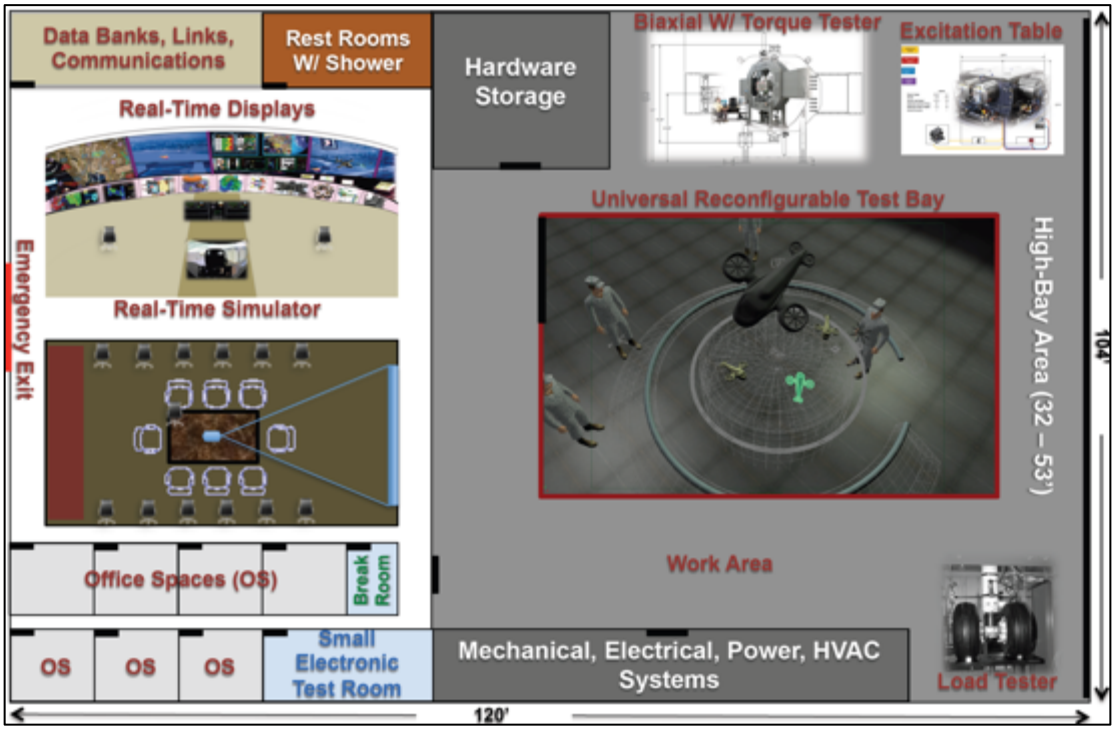



**Figure 10:** Notional Sustainment SIL (Not Proportionally Scaled)

## 3.3 Sustainment SIL General Space Requirements and Specifications:

To enable the capabilities highlighted above, the following building requirements and configurations are projected and shown in **Figure 10**.

a. *General Building Space Requirements:*

1. Total Building Area: 17,472 square feet (sq. ft.)
2. Approximate Length (L) and Width (W) of the building: 120' (L) X 104' (W)
3. Test Bay Area: 72' (L) X 104' (W), minimum ceiling height of 32' and maximum of 53'
4. Office and Control Room (OCR) Areas: 48' (L) X 104' (W) with two stories
5. OCR Areas Ceiling: Minimum height of 12' (first floor) and minimum height of 9' (second floor)

b. *Office and Controls Area:*

1. The first floor accommodates real-time data displays and panels, real-time simulation, data banks; links; and communication systems, seven offices/cubicles, small electronic test room, a break room, and a conference rom with an occupancy capacity of at least 18 people.

2. The second floor accommodates an additional space for offices for potential government, resident contractor, and TTU students and employees.

c. *High-Bay Test Area:*

1. *Universal Reconfigurable Test Bay*: It is envisioned that the universal reconfigurable test bay as shown in **Figure 11** will accommodate both tethered and untethered platform and system/sub-system testing. It will allow add-on integrated hardware, embedded sensors, software, and seeded fault for tethered test-bed testing or hovering in safe air space. It will also support live and virtual and indoor (hovering mode only) and outdoor flight-testing and demonstration.

   A detailed engineering conceptual design is needed for the universal reconfigurable test bay, safe air space, impact-tolerant and noise suppression walls.

   Additional capabilities for concept and technology demonstrations using test specimens and sub-scale components can be accommodated with the optional biaxial with torque tester, 6-degree-of-freedom excitation apparatus, and helicopter landing gear test system for operational load determination and monitoring as shown in **Figure 10**.

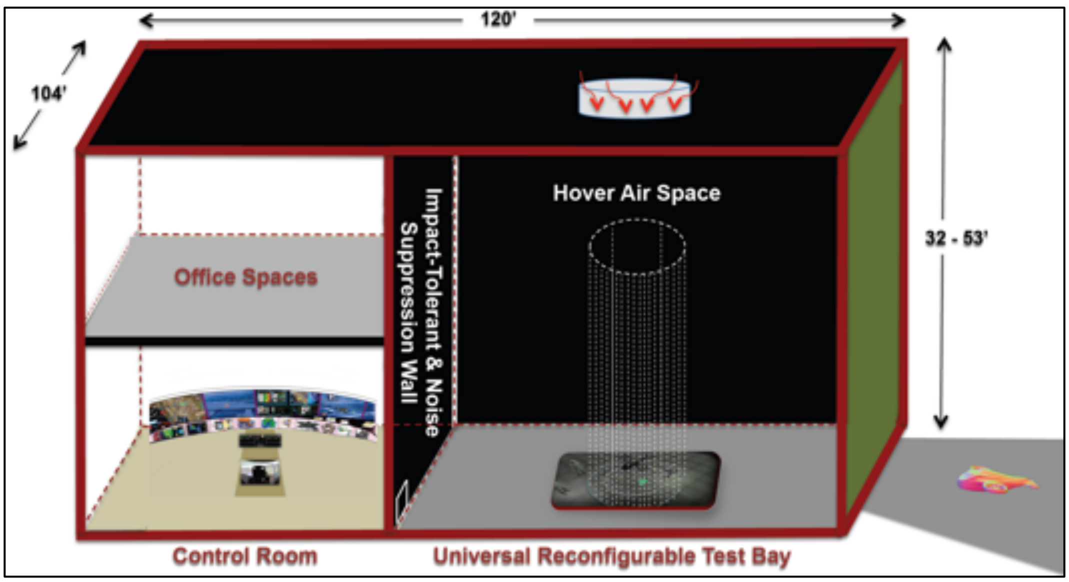



**Figure 11:** Notional 3D Sustainment SIL (Not Proportionally Scaled)

d. *Control Rooms:*

1. *Real-Time Displays*: The Sustainment SIL control room accommodates curved panels as shown in **Figure 12**. It utilizes a new technology to enhance the peripheral vision and autonomously draw the viewer deeper into the event being displayed. It appears to be 3D even though it is a 2D event. The curving of image display edges toward the viewers enhances their visual perception of the depth of the event being watched.

   The curved panels are integrated with a suite of software and algorithms, which provide live event monitoring and tracking as well as displays of multi-scale modeling of models and parameter tracking and monitoring of system of systems; all are in real time.

Simulated data can be used to create virtual reality, and actual data be used to create the augmented reality environment to view the entire sustainment or the potential augmented repair capability process during flight or when grounded.

2. *Reconfigurable Fix-based Motion Flight Simulator (RFMFS):* RFMFS plays a critical function in the platform sustainment design, study of human-machine interactions, and testing of damage-based maneuvers and controls. RFMFS will be integrated with reconfigurable flight control algorithms to accommodate damage and failure precursor information or data to provide intelligent solutions for adaptive maneuvers to ensure longevity sustainment.


**Figure 12:** Sustainment SIL Panels and Reconfigurable Fixed-based Motion Flight Simulator

### 3.4 Milestones to Support Sustainment SIL and Technology Development for FVL and UAS:

SIL can support the development and demonstration of sustainment technologies for FVL (e.g., FVL Sustainment Demo – FY26), UAS, and next generation platforms. The proposed Sustainment SIL and IMMS *Sciences for Sustainment* are capable of conducting the following AMRDEC-ADD R&D efforts, as planned in the AMRDEC Joint Aviation Sustainment S&T Roadmap [15], **Figure 9**.

1) Sustainment Technologies for Embedded Prognostics
2) Future Rotorcraft Operations Sustainment Technologies (FROST)
3) Network, Embedded Sustainment Technologies (NEST)
4) Integrated Networked Sensor Technology for Rotorcraft Operations
5) Logistics Improvements with Virtual and Embedded Sensors (LIVES)
6) System Health Assessment for Rotorcraft Prognostics (SHARP)

Additionally, in collaboration with S&T communities including AMRDEC and ARL, the proposed Sustainment SIL is intended to demonstrate concepts; technologies; and capabilities, which can then be used to develop an extremely lightweight, adaptive, durable, and damage-tolerant structure prototype to be integrated into the next generation aircraft, as well as into the VRAMS-operated prototype per ARL milestones (FY22-24), as planned in the AMRDEC Joint Aviation Sustainment S&T Roadmap.

a. *Sustainment SIL Construction and VRAMS-integrated FVL and UAS Milestones:* **Figure 13** provides milestones and a comprehensive program plan to support the establishment of the Sustainment SIL and demonstrations of FVL, UAS, and next generation platforms after next. The timeframes are aligned with the milestones as planned in the AMRDEC Joint Aviation Sustainment S&T Roadmap, **Figure 9**. The Rough Order of Magnitude (ROM) provides an estimate of costs and time given in the early stages of the Sustainment SIL and will be revised as needed. Based on the FY18 start (Milestone 1), the Sustainment SIL architecture and design, construction, checkout, and verification and validation can be completed by FY22 (Milestone 5).

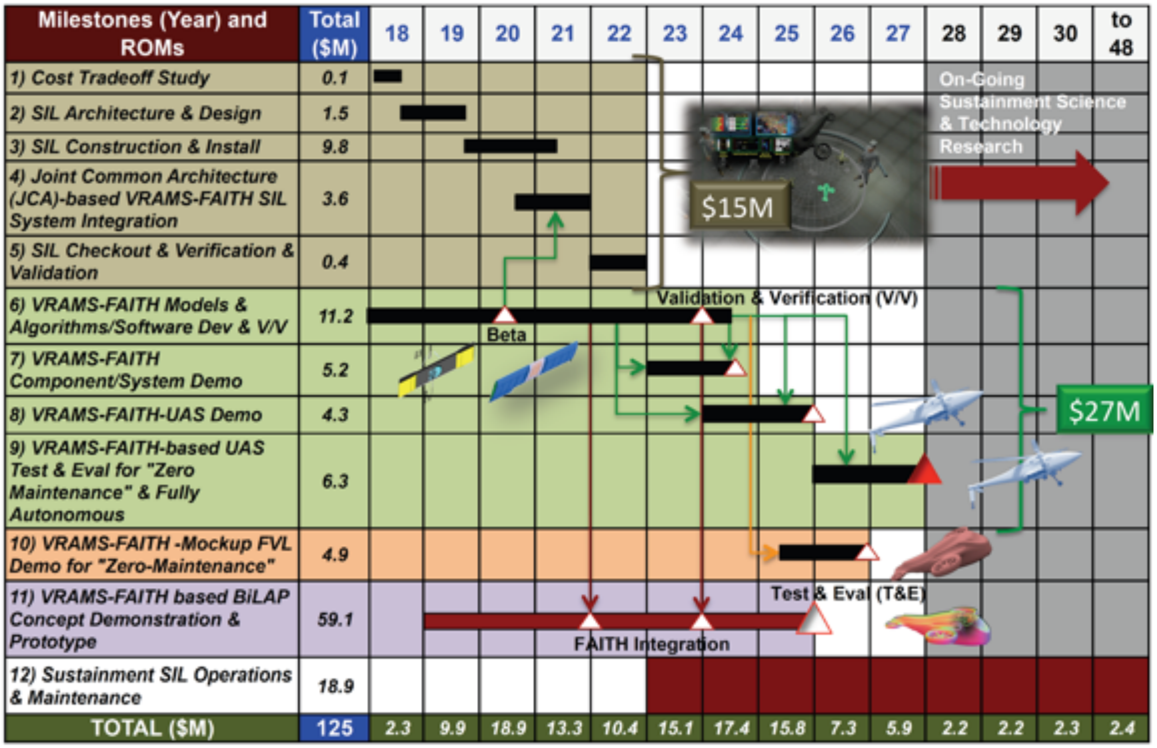


**Figure 13:** Sustainment SIL Milestones

b. *Future Aviation Sustainment Research and Development Prospects:* To support the IMMS *Sciences for Sustainment* basic and exploratory research and the aviation platform sustainment technology development, we can integrate VRAMS with the FAITH technology for the development and demonstration of the next generation vertical lift platforms including FVL and UAS to meet the sustainment metrics. Milestones 6 through 10 list major tasks to achieve the FVL and UAS platform sustainment goals, ranging from test specimens and scaled components/systems through prototype test, evaluation, and demonstration.

The projected estimate for milestones 6 through 10 is approximately $32M and includes:

1. *Milestone 6, VRAMS-FAITH Models & Algorithms/Software Development and Verification and Validation:* Develop the VRAMS-FAITH Beta algorithm suite (FY20) and verify and validate its capability against aviation platform sustainment metrics using simulated test or actual data (FY18-FY24).

2. *Milestone 7, VRAMS-FAITH UAS Component/System Demonstration:* Demonstrate VRAMS concept and FAITH capability using test specimens, sub-scaled configurations, and selected platform components and systems (FY23-FY24).

3. *Milestone 8, VRAMS-FAITH-UAS Demonstration:* Demonstrate VRAMS-FAITH technology and capability on a selected UAS for meeting Maintenance-Free Operating Period requirement (FY24-FY25).
4. *Milestone 9, VRAMS-FAITH UAS-based UAS Test and Evaluation for "Zero-Maintenance" and Full Autonomy:* Conduct test and evaluation of VRAMS-FAITH technology and capability on a selected UAS platform to achieve "Zero-Maintenance" philosophy and fully autonomous capability (FY26-FY27).
5. *Milestone 10, VRAMS-FAITH Mockup FVL Demonstration for "Zero-Maintenance":* Conduct VRAMS-FAITH integrated FVL prototype demonstration for achieving "Zero-Maintenance" philosophy (FY25-FY26).
6. *Milestone 11, VRAMS-FAITH-based BiLAP Concept Demonstration and Prototype:* As previously mentioned, through learning and feedbacks as a human does over the time, FAITH can build up a comprehensive databank of knowledge on platform integrity, performance, and behaviors. The knowledge can then be used to develop a transformative design to build the next generation ultra-reliable vertical lift and the bio-inspired living platforms, which are more affordable and do not require substantial operation and maintenance costs.

   To develop a Bio-inspired Living Aerial Platform or BiLAP (UAS) prototype with integrated VRAMS-FAITH to demonstrate the platform ability to feel its own health condition, assess the risks, and recover from or adapt to damages and system health complications, it is estimated that funding of about $59M with a duration of approximately seven years is needed (FY19-FY25).

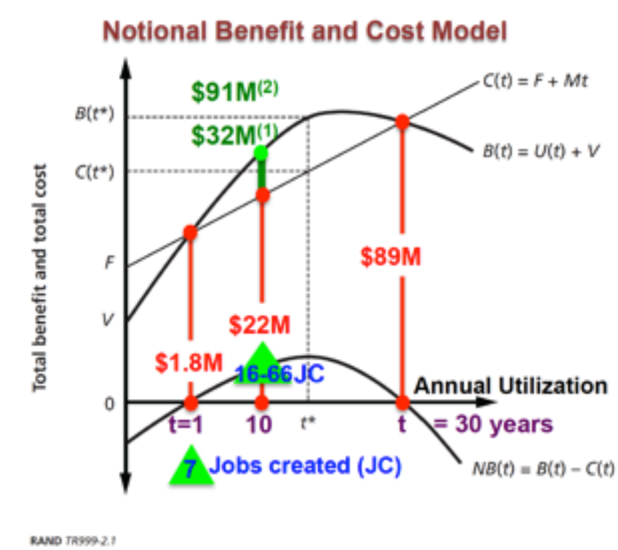
## 3.5 Projected Sustainment SIL Operations & Maintenance Team and Overhead Costs

**Figure 14** includes the proposed Sustainment SIL Operations and Maintenance (O&M) team and highlights general expenses required to operate the Sustainment SIL (approximately $1.8M/Year). This is an approximation and still needs to be updated with the most current labor and miscellaneous overhead expenses.

In an attempt to estimate the potential benefits versus costs, we use the model described in the Technical Report entitled "*Pricing Strategies for NASA Wind-Tunnel Facilities*", developed by RAND Corporation [16]. The displayed "total benefit and total cost" curves and fitted figures as shown in **Figure 14** are notional and will require in-depth trade benefits-costs analysis to be done when required.

Based on the *Future Aviation Sustainment Research and Development Prospects* and assuming that the Sustainment SIL and *Sciences for Sustainment* can support Milestones 6 through 12, approximately 66 high-quality new jobs can be created when the Sustainment SIL is fully operational.

**Warning:** Notional. Required more data and in-depth analysis




**Projected Operation/Maintenance Team Expenses**

| SIL Operations and Maintenance (O&M) | MY | Salary/Yr | Cost/Year | Overhead | TOTAL |
|---|---|---|---|---|---|
| O&M Team | | $685,000 | | $274,000 | |
| Overhead Rate | | | | 40% | |
| Electro-Mechanical Technician | 1 | $70,000 | | $28,000 | |
| Instrumentation Technician | 1 | $75,000 | | $30,000 | |
| Electronics Technician | 1 | $80,000 | | $32,000 | |
| Test Engineer | 1 | $110,000 | | $44,000 | |
| Software Engineer | 1 | $115,000 | | $46,000 | |
| Design Engineer | 1 | $115,000 | | $46,000 | |
| Flight Engineer/Test Pilot | 1 | $120,000 | | $48,000 | |
| | | | | | |
| | | | | | |
| Misc Equipment & Software Maint | | | $350,000 | | |
| SIL | | | $300,000 | | |
| Software | | | $50,000 | | |
| | | | | | |
| Misc Utilization | | | $149,000 | | |
| Utilities | | | $100,000 | | |
| HPC | | | $49,000 | | |
| | | | | | |
| Misc Utilization | | | $350,000 | | |
| Lease | | | $350,000 | | |
| | | | | | |
| TOTAL: | 7 | $685,000 | $849,000 | $274,000 | $1,808,000 |

**Notional Programs & Projected Jobs**

| | UAS/FVL | UAS/FVL/BiLAP |
|---|---|---|
| | | |
| Projected Funding in 10 Years | $31,900,000 | $91,000,000 |
| Projected Funding per year (AVG) | $3,190,000 | $9,100,000 |
| Projected Annual SIL OPM cost (10 Years AVG) | $2,134,849 | $2,134,849 |
| Research Budget | $1,055,151 | $6,965,151 |
| Projected Researcher Fully Burden Salary/MY | $117,444 | $117,444 |
| OPM Team | 7 | 7 |
| Research Team | 9 | 59 |
| Total Jobs Created | 16 | 66 |

(1) Projected figures for UAS and FVL Sustainment programs

(2) Projected figures for UAS, FVL, & BiLAP programs

**NOTE:** Does not include other potential non-Army Sustainment programs

**Figure 14:** Notional Model of Benefits-Costs to Operate and Manage the Sustainment SIL

## 4. LEDA'S SUPPORT AND THE SUSTAINMENT SIL LOCATION AVAILABILITY

4.1 **LEDA's Support in the Establishment of the Sustainment SIL:** The City of Lubbock actively fosters opportunities to promote economic growth. Consistent with the City of Lubbock's goal, the LEDA's mission is to promote economic growth by creating high-quality jobs, investing in new capital improvements, and enhancing Lubbock's quality of life. From 2015-2016, the LEDA's goals include the new capital investment (NCI) of $30M, new jobs announced (NJA) of 650, and workforce development value added impact (WDVAI) of $40M. By the end of FY16, LEDA exceeded the goals with NCI of $172M, NJA of 1,191 jobs, and WDVAI of $55M. From 2016-2017, the LEDA goals are: NCI of $30M, NJA of 700, and WDVAI of $62M [17].

During the April 3, 2017 meeting between TTU and the U.S. Army, LEDA expressed their strong willingness to support the establishment of the Sustainment SIL in Lubbock, Texas.

4.2 **Sustainment SIL Location Availability:** During the meeting, attendees toured two potential building sites: former Reese Air Force Base and Lubbock Preston Smith International Airport, which are being proposed and considered for the installation of the Sustainment SIL.

a. *Former Reese Air Force Base (RAB)*: It is located six miles west of Lubbock, Texas, 10 minutes' drive from the TTU main campus, **Figure 15**, 314 miles from the Bell Helicopter located in Forth Worth, Texas, and 100 miles from Amarillo, Texas, **Figure 16**, where V-280 Joint Multirole (JMR) is being developed. The former RAB's primary mission was pilot training.

**Figure 15:** TTU Administration Building

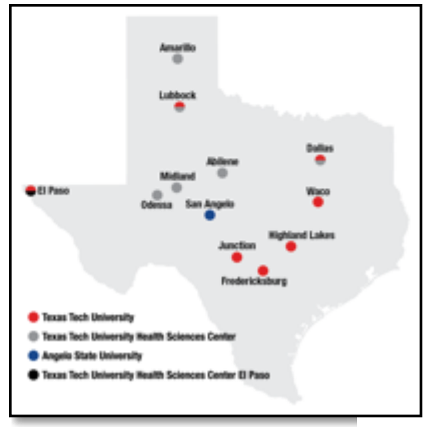



**Figure 16:** TTU System

The former RAB was closed on September 30, 1997 after being selected for closure by the Base Realignment and Closure Commission in 1995. Since then, it has become a research and business park called Reese Technology Center (RTC). RTC has three operational runways: one 6,500 feet in length and two 10,500 feet in length, **Figure 17**, as well as an air traffic control tower, which is still operational, **Figure 18**.

**Figure 17:** RTC Runways


**Figure 18:** Air Traffic Control Tower

During the RTC tour, attendees visited the former Flight Simulator Building (B930), which was built in 1976, **Figure 19**. It has three stories (first floor: 35,184 sq. ft.; second floor: 22,264 sq. ft.; and third floor: 12,572 sq. ft.), with a cargo elevator, eight simulator bays with 35' ceilings, loading dock, and two overhead bay doors. The building has space for offices, conference rooms and classrooms. There is a large parking area in front of the building, **Figure 20**.


**Figure 19:** Former Flight Simulator Building

**Figure 20:** B930 Walkway to Parking

*b. Lubbock Preston Smith International Airport (LBB)*: It began as the Lubbock Municipal Airfield in 1929. The U.S. Government's War Department took over the airport in 1942 and created the South Pains Army Airfield to train combat glider pilots. These "Silent Wings" were used extensively during D-Day to free Europe, as well as in Pacific Theater operations. After World War II, the City of Lubbock regained the airport and began commercial airline service on July 1, 1945. Currently, the airport is accommodating a number of general aviation service providers, freight airline operations, industrial parks, and four commercial passenger airlines, **Figures 21 and 22**.

The airport has a 24-hour communications center and full-time police department. In the event of a medical emergency, a mutual aid plan is in place with the local Emergency Medical Services, city fire department, and ambulance services.

**Figure 21:** LBB

**Figure 22:** LBB Runway

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