PART-III (A): PROJECT DEFINITION DOCUMENT (PDD)

(Detail description of PDD is attached in Annexure-1 of this document)

1 Detailed Description of Problem / Requirements

(a) Describe the problem / Requirement :

Development of Digital twin (DT) framework for Aero Gas Turbine Engine Health & Usage Monitoring System is the primary and sole requirement of this project. A hybrid aero engine Digital Twin (DT) to be developed shall be a set of high-fidelity virtual construct that shall mimic the context (purpose), functional and structural behavior of the deployed physical aero engine as an entity. It shall be a simulation platform, which can be effectively utilized to study the system behavior of the engine along with its subsystems virtually under normal and various failure modes to arrive at diagnostics / prognostics algorithms under various flight conditions. The heart of the DT framework is the models that simulate and predict the behavior of an aero engine. Physics-based thermodynamic models of major engine components form the foundation of the Digital Twin (DT), simulating the physical behavior of the engine based on its design and engineering parameters. These models include aero & thermodynamic system behaviors, providing a detailed and accurate representation of how the engine is expected to perform under various conditions. The physics-based models developed initially needs to be augmented with test data-driven models which must complement / supplement it to enhance the fidelity. Such hybrid models integrate the strengths of both physics-based and data-driven approaches to create a more comprehensive Digital twin (DT). Hybrid models are essential for ensuring that the Digital Twin (DT) remains a reliable tool for decision-making throughout the engine's lifecycle.

(b) Logical Diagram for explaining the problem:

The development of DT shall be realized by adopting following process:

- **Digital Twin (DT) frame work**: The scope of DT Frame work development shall include developing model of engine and associated subsystems using simulation tools (open-source tools / commercial tools / in-house tools). The development could be based on both physics-based models as well as data driven models to closely match the engine behavior. The scope also includes integration of various models within a frame work, execution in real time on suitably selected and mutually agreed computational platform.
- **Large Data handling**: The scope also includes handling of large sets of heterogeneous design data, simulation results data (FEM / CFD etc.) and engine test data for development and validation of simulation model.
- **Sensor management for decision making:** DT should incorporate 'virtual sensors' for both measurable states and synthesized states of the plant. The measurable states shall be validated with the measured sensor data over several engine tests. Developed frame work should have capability to perform several data integrity checks to ensure the quality of the sensed data. Further it should enhance the capability of online monitoring by identifying optimal type and numbers of parameters and associated sensor location which needs to be monitored over the life cycle of the engine.
- Architecture of hybrid DT model of Gas turbine Engine is shown in figure-1. Description of each building blocks are explained in Table-1 & 2.

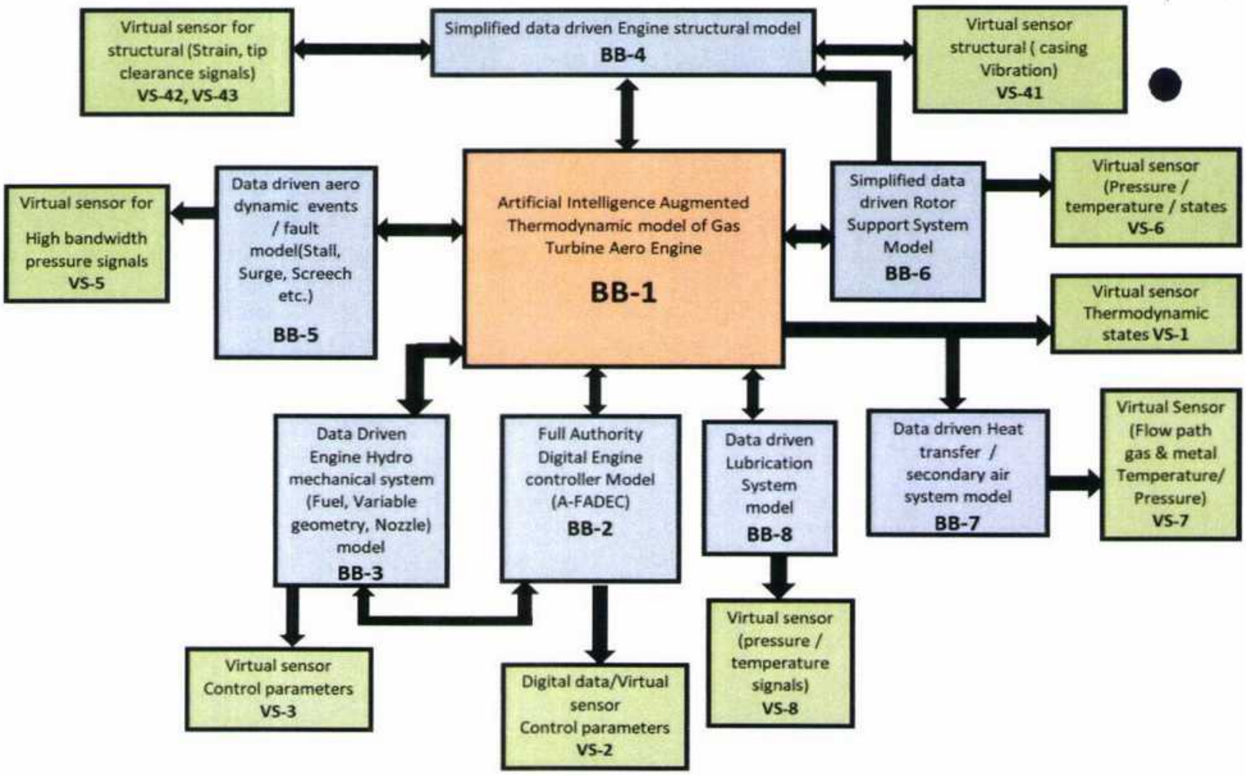

Figure-1: Architecture of hybrid DT model of Gas Turbine engine

(c) List of critical technologies involved for the solution:

i. Artificial Intelligence augmented Thermodynamic model of Aero Gas Turbine Engine
ii. Virtual Sensors for various system and control parameters of Aero Gas Turbine Engine

(d) System requirement & its description:

Development of one set of comprehensive Digital Twin (DT) framework of a user Lab specified aero gas turbine engine health & usage monitoring system along with its subsystems. Comprising of the following:

i. Hybrid Digital Twin model of aero gas turbine engine meeting user Lab specified requirement.
ii. Suitable computation hardware platform with real-time operating systems and various libraries
iii. Sensor validation and recovery systems & identification of optimal sensor set, type of sensor and location of sensor based on concepts of observability.
iv. Virtual sensor algorithms (derived & non-dimensional parameters) for aero engine performance.
v. General alarm queue by fault seeding & system response either by Synthesis /experiments.
vi. Graphical user interface with drag and drop features, data presentation pane covering all warnings and alarms detected and pictorial representations of each component & engine along with overall system data storage and retrieval methods.

2. Functionality expected from the output of the project.

Table-1: Basic Building Block

Sl. No.	Building block	Functional description	Simulation type	Remarks
1.	BB-1	The engine model is based on non-linear differential	Thermodynamic simulation with	User would be sharing various

		equations describing the thermodynamic performance of a twin-shaft, low bypass ratio gas turbine. The gas turbine engine considers two stages of compressor (LPC & HPC), combustor, two stages of turbine (LPT & HPT), shaft connecting compressor and turbine, various interduct, load on gear box, inlet & exhaust ambient conditions, heat soak effects etc.	various parameter tuned with the aid of machine learning methods based on engine test results	engine parameters required for modeling in house.
	BB-2	Full Authority Digital Engine control model (FADEC) shall constitute Control Law and various control parameters	MATLAB/SIMULINK based simulation	User would be sharing simplified control system with developer in house. This module would be replaced with detailed models later on during Phase -2 of the project (Not under the scope)
2.	BB-3	Engine hydro mechanical system model comprises of models of Fuel Control System, Variable Geometry Actuation Control System and Integrated Nozzle Actuation Control System	Data driven simplified model or Sim-Hydraulic model or Simulink model or a combination all these	User has developed detailed AMESIM based model of the fuel system. Necessary data required for arriving at a data driven model would be shared with developer in house.
3.	BB-4	Engine structural simplified model based on the FEM analysis. The model uses results of detailed FEM analysis of various structural elements of gas turbine engine to develop a Reduced Order Model (ROM).	User has detailed FEM based simulation and engine / component test results would be used to develop a simplified data driven model.	User would be sharing data derived from the user developed FEM model required for data driven modeling in house.
4.	BB-5	Aero Dynamic events/fault model for predicting Stall, Surge, Screech, Flutter response, Flame out, Combustor instability etc.	Data driven models based on test results	User would share the test results to develop the model in house.
5.	BB-6	Rotor support system model	User has detailed	User would share

		comprises of bearing and associated systems	SAMCEF based model. A data driven model has to be developed based on the simulation results, engine test results by developer	the test / simulation results for development of data driven machine learning models in house.
6.	BB-7	Heat transfer/secondary air system model	User has in-house developed models using COTS CFD / CHT tools. The test results would be used to develop a simplified data driven model	User would be sharing data required for development of simplified data driven model in house.
7.	BB-8	Lubrication system model	Data driven simplified model or Sim-Hydraulic model or Simulink model or a combination all these	User has developed detailed AMESIM based model of the Lube system. Necessary data required for arriving at a data driven model would be shared with developer in house.

Table-2: Virtual sensors emanating from basic building block Simulation models

Sl. No.	Building block	Functional description	Simulation type	Remarks
1.	VS-1	Virtual sensor for thermodynamic states / synthesized states	Data driven simulation with various parameter tuned with the aid of machine learning method based on engine test results	User would be sharing various engine parameters and test results required for modeling in house.
2.	VS-2	Digital data/virtual sensor for synthesized control parameters	Data driven simulation with various parameter tuned with the aid of machine learning methods based on engine test results	
3.	VS-3	Virtual sensor for hydro mechanical system parameters and control parameters/pressure/ temperature/vibration	Data driven simulation with various parameter tuned with the aid of machine learning	

			methods based on engine test results	
4.	VS-41, VS-42	Virtual sensor for structural (strain, tip clearance signals)	Data driven simulation with various parameter tuned with the aid of machine learning methods based on engine test results	
5.	VS-43	Virtual sensor for structural (casing / bearing housing / gear box casing vibration)	Data driven simulation with various parameter tuned with the aid of machine learning methods based on engine test results	
6.	VS-5	Virtual sensor for high bandwidth pressure signals	Data driven simulation with various parameter tuned with the aid of machine learning methods based on engine test results	
7.	VS-6	Virtual sensor for pressure/temperature/other synthesized states	Data driven simulation with various parameter tuned with the aid of machine learning methods based on engine test results	
8.	VS-7	Virtual sensor for secondary flow path gas & metal temperature and wall static pressure	Data driven simulation with various parameter tuned with the aid of machine learning methods based on engine test results	

3. **Details on expectations of Indigenous content:**
   At least 50% DT Building shall be indigenously developed for both critical technologies and should not be dependent on closed proprietary codes.

4. **Execution details and Testing / Acceptance Approach for DT Model:**
   The project involves running the models in real-time on dedicated hardware. The industry partner shall acquire the hardware and get reviewed by DRDO with respect to computational requirement including associated input/output hardware. Further the industry partner shall install the hardware at its premises to perform hardware software integration followed by proving the inter-operability of the models available in open source. The industry partner may develop those parts of the project at their premises which do not call for any data sharing or security related attributes. The testing and validation plan shall be designed to assess the performance and fidelity

of DT rigorously. It includes all phases i.e., from data pre-processing to model deployment, ensuring that the model meets predefined mutually agreed quality criteria set by user (DRDO). Once the framework along with hardware is installed at user defined location, user (DRDO) team shall share necessary experimental test results and evaluate the fidelity of the models in-house with participation of industrial partner. However, the engine run data will not be shared with the industrial partner outside the premises of DRDO. Any modification thereon shall be done within user premises in consultation with DRDO Team. The simulation results and experimental results would be compared to arrive at the evaluation metrics such as MAE, R-squared score, maximum error etc. to quantify the performance model. DT models individual BB accuracy w.r.t physical model shall be within 5% error while virtual sensors simulation accuracy shall be within 10% error.

4.1 Testing methodology for calibration/training of model.

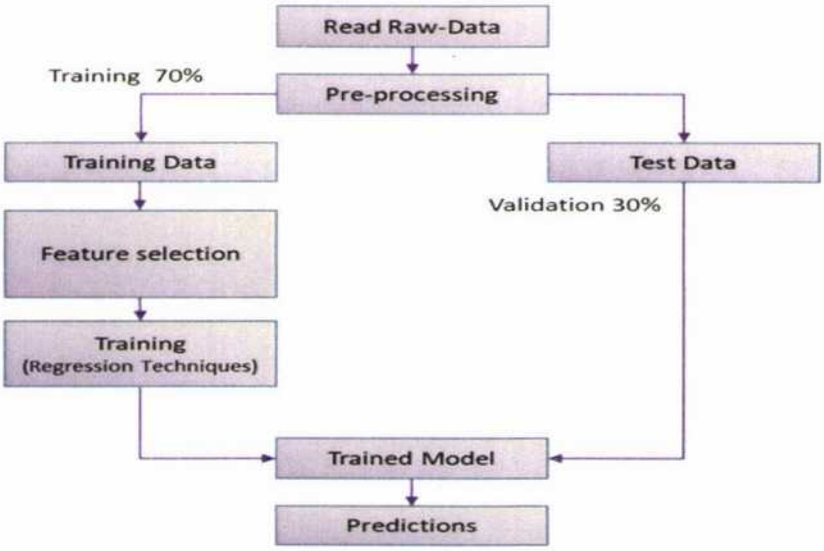

Figure-2: Testing & validation framework

About 400 test runs of the two / three engines test data obtained during various developemnt tests (ground tests, simulated altitude tests and flight tests) would be used to train models. A standard parctice of 70% of data for training and 30 % of data from validation would be adopted as depicted in figure-2, however minor variation in percentage may be permitted on basis of recommendation of review committee.

4.2 Testing methodology for Anomaly Detection and Isolation

As shown in figure-3, real aero engine & Digital Twins (DT) shall be subjected to common inputs (PLA, & flight conditions) and respective parameters shall be compared. If error between various parameters are within prescribed band then Digital Twin (DT) performance shall be declared in-sync with a real engine. However if the error is beyond prescribed limit and if it is also beyond engine to engine variation or tolerance band then the error /anomaly shall be set and declared. The anomaly information shall be fed back later to train the DT as a case of degraded model.

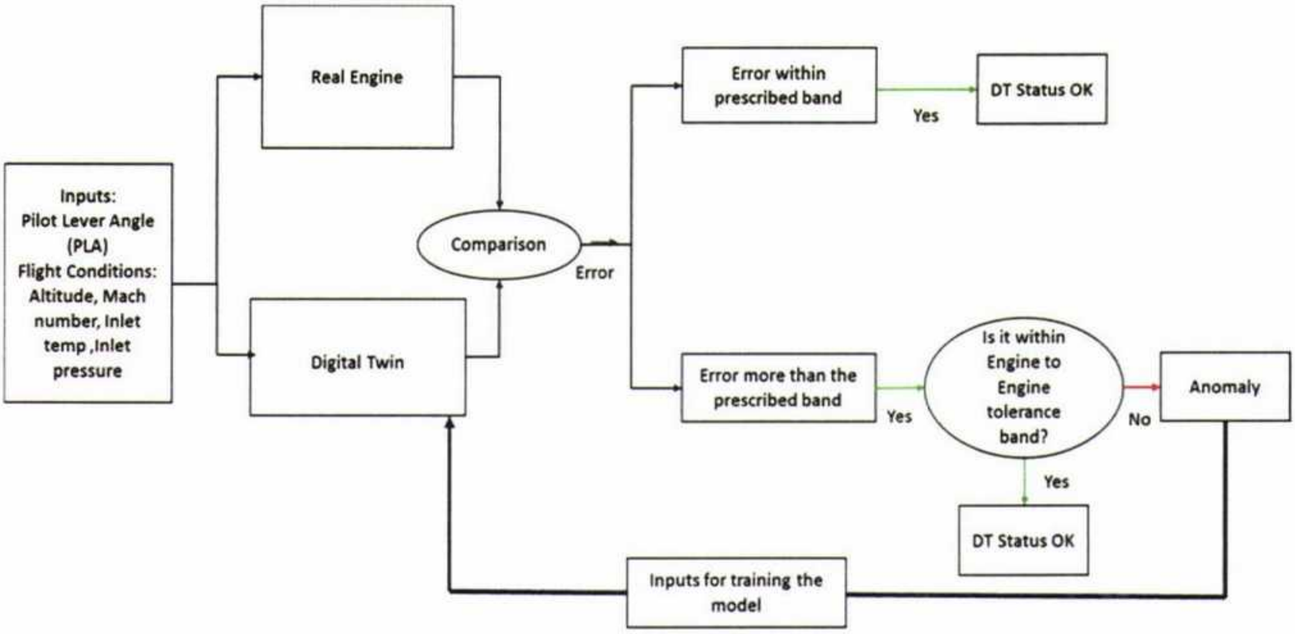

Figure-3: Approach towards anomaly detection and isolation

4.3 Acceptance based on ATP Document. Preparation of ATP document will be carried out based on functionality listed in Table-1 & 2 and will be finalized during PDR.

4.4 A formally constituted committee by user will carry out comprehensive testing using ATP document and shall recommend way forward. Besides other mandate, following shall be carried out by this committee:

a) Recording of functionality & performance measurement parameters as per ATP in the Lab.
b) Demonstration of functionality/performance of developed solution in suitable environment (hardware computational platform) to be identified by ATP committee/ finalized during PDR.
c) Valuation of Figure of Merit (FoM) / other parameters.
d) Analysis of design / solution with respect to indigenous content.
e) Analysis for closeness of the achieved FoM / other parameters values to the targeted values and identification of deviation.
f) Recommendation for way ahead based on demonstration result and achieved value FoM/ other Parameters.

5 Expected development schedule

Table-3: Phases of implementation, critical activities and milestones

Milestone & time elapsed from start of project till end of milestone (months)	Phase Activity	Deliverables for the milestone	Approximate MS wise % payment of total project cost	Approximate MS wise % payment of total project cost
	Preliminary Design Review(PDR)			
MS-1 T0+6 Months	Mutual understanding and User Interaction Finalizing System Requirement Document (SRD) **Identification of critical technology** through literature survey and study on contemporary systems and identifying the architecture of Digital Twin framework (using commercial off the shelf / open sources / In-house tools) Approval of Preliminary Design Document (PDD)	a) System Requirement Document b) Release of approved PDD document	20%	20%
	Detailed Design & Engineering Prototype			
MS-2 T0+12 Months	**Demonstration of critical technology** (a) Feasibility study to decide whether physics based or data driven based modelling for each component (17 DT blocks) Detailed design of component level (17 DT blocks) DT model (a) Collection and pre-processing of test data (50-60 engine tests) (b) Design of Integrated System with 17 DT blocks	a) System Design Document (SDD) b) Release of approved Detailed Design Document (DDD)	20%	40%

	Finalization of tentative Bill of Material (Component & sub-component level including hardware computational platform) Realization of working integrated DT model/ Engg Prototype Approval of Detailed Design Document (DDD)			
MS-3 T0+18 Months	**Critical Design Review**			
	(a) Approval of process and frame work document for prototype development (b) Approval of test reports Approval of Quality assurance plan **Realization of Prototype:** Development of prototype, Clustering of fused data into different performance regimes and computation of data through proven algorithm (a) Approval of performance of framework in offline/online integrated environment (b) Verification of prototype DT model performance with engine experimental data/synthesized data at subsystem level and integrated level. Approval of Critical Design Document (CDD)	a) Source code (initial version) b) Testing and validation report c) Approved development report of hardware computational	20%	60%
MS-4 T0+30 Months	**Production and Supply**			
	(a) Procurement of real-time supported hardware (b) Development of a	(a) Verified and validated Source code of DT and GUI and all the	20%	80%

	robust computational platform with all necessary drivers to deploy the framework (c) Integration of all the hardware and software. (d) Acceptance testing of hardware & software platform (e) Supply of Hardware & software platform to user) (f) Providing engine run data in suitable form to integrate with DT framework. (g) Software development at User premises viz-a-viz Data pre-processing (feature extractions and prediction) through machine learning model Training of the developed model through various engine tests (ground tests, simulated altitude tests and flight tests) to train the models	drivers, wherever applicable (b) Acceptance testing procedure and result report (c) Final Software Requirement Specification (SRS), Software Design Document (d) (SDD) for GUI and real time DT model (e) User manual and debugging report		
	Final production of integrated DT model developed & deployable at User premises, required quantities as per DPR and PDD			
	Acceptance test report: Verification and validation as per Para-4 of this document.			
	Acceptance of supplied item by user			

	Acceptance Test Report			
	Documentation and ToT			
MS-5 T0+36 Months	Documentation of the complete Project Project Success Report Project Completion report Execution of ToT ,if applicable as per SOP of TDF Scheme Sharing of IPR rights as per Project Definition Document of this project	(a) One set of synthesized framework of Aero Gas Turbine Engine Digital Twin making use of physics based & data based models (b)Suitable hardware [platform, operating systems and various libraries to meet real time requirement (c)Complete project documentation (d)Project success report (e)Project completion report (f) Execution of ToT Sharing of IPR rights as per T&C defined in RFP	20%	100%

6: Exemption / Waiver for Startups, if any: **nil**

7. Exemption / Waiver for MSME, if any : **nil**