

A Digital Twin Framework for New Generation FTI Management Processes

Ali Tahsin KAYMAK¹, Mehmet KEKEÇ², Selma AYDIN²

¹ Turkish Aerospace, Ankara / TÜRKİYE,

² Turkish Aerospace, Ankara / TÜRKİYE

alitahsin.kaymak@tai.com.tr^[1], mehmet.kekec@tai.com.tr^[2], ses@tai.com.tr^[2]

Abstract

In 2024, our study proposed a framework to integrate Flight Test Instrumentation (FTI) Configuration Records -Numbered Parameter Lists (NPL)- with Flight Test Database to establish a ground for an FTI Digital Twin development. This paper aims to present the operational outcomes to date. FTI Configuration Management is evolving into an advanced ecosystem where NPL and flight test big data are merged in one medium, OPTIMUS. Supported with Inventory Management Sub-Module to track assets such as sensor or equipment from warehouse to aircrafts. FTI Digital Twin in its current form features a 3D visualization and within its infrastructure, it communicates with Teamcenter, JIRA and Document Management System to ensure an accessible and traceable configuration management and data integrity.

A key point in FTI Digital Twin development is to integrate Artificial Intelligence algorithms and models to support pre-flight operations. System now performs autonomous pre-condition checks for FTI data according to sensor-based rules, such as full-scale or fixed-data validations for sensors. Multiple Deep Learning and ML models are deployed in a selectable model pool to try to identify possible anomalies in real-time sensor data and are re-trained if needed in a feedback loop when necessary. Progressing to the next phase of the project, to analyze similar data characteristics between sensors across flight test campaigns, the software architecture is being established and is progressing through to support predictive maintenance on preparation for flight test campaigns.

Key words: FTI, Digital Twin, Big Data, Configuration Management, Artificial Intelligence

1 - Introduction

Flight test instrumentation (FTI) is a multi-disciplinary field in the aviation industry that involves the dynamic and controlled management of core responsibilities such as design, procurement, planning, maintenance, documentation, configuration tracking flight-by-flight from projects' T0 moment to the completion of the test and evaluation phase and situationally beyond. Across multiple experimental platforms and projects, maintaining configuration integrity, data traceability, and operational continuity required significant engineering effort in multi-system framework and tools. In our previous work presented at ETTT 2024 ^[1], we proposed a unified FTI management platform to serve as an architectural foundation to manage configuration management of FTI system in one place. FTI Digital Twin.

The development roadmap is planned across three phases. Phase 1 addresses the grounds for the configuration management. Establishing

the data infrastructure, internal TUSAŞ system integrations, FTI inventory management, and 3D modelled twin versioning mechanisms on which all these capabilities depend on. Phase 2 introduces machine integrated pre-flight sensor health monitoring through a rule-based pre-condition checks and a multi-algorithm anomaly detection framework. Phase 3 extends the system toward flight test maneuver analysis across platforms for inconsistent sensor behavior detection and estimation of sensor behavior under planned conditions for flight test campaigns.

This paper reports on the progress of developments in the project's phases, the current capabilities on pre & post flight data and defines the next steps in the ongoing development.

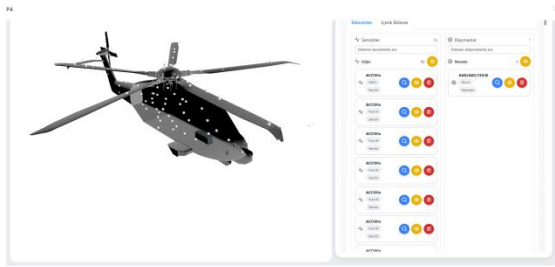


Fig. 1. 3D FTI Digital Twin.

2 - The Unified FTI Management Platform

The unified FTI management platform is being built in OPTIMUS, Turkish Aerospace's in-house flight test data management system, as a sub-module. The goal of the integration is not to replace existing internal company tools or systems. It is rather to create a single flow that allows the contents of the said systems accessible on a single medium. This aims to effectively optimize the time spent on manual processes that divide personnel attention between time-demanding configuration management and operational FTI work.

The platform consists of three layers.

- The OPTIMUS Numbered Parameter List (NPL) is a core layer for data and configuration tracking, being the bridge between flight data and instrumentation. It is the authoritative source for sensor and FTI architecture configurations installed on each experimental aircraft. Migrated from manually tracked version based spreadsheet form, the NPL now aims a complete flight-by-flight traceability record for each sensor, reflecting its metadata, calibration history and documentation in one place.
- At the integration layer, external systems communicate with FTI Digital Twin via NPL on a sensor and aircraft basis. Jira provides access to current or closed findings at the sensor level. The Electronic Document Management System (EDMS) and Teamcenter enable access to and referencing of documents, depending on how a particular project manages its documentation. Currently a dedicated digital twin test server operates as a submodule of Optimus, brings these integrations together and forms the basis for the twin's visualization and management interface.
- The twin management layer, much like in NPL, a version-controlled 3D model framework provides FTI personnel with

the ability to independently handle helicopter, sensor and equipment models with libraries and convert them into prototype specific twin configurations. Any activity affecting the FTI Digital Twin, such as sensor additions or removals, equipment modifications, structural or avionics changes to an aircraft is tracked and recorded at this layer on a version-by-version basis.

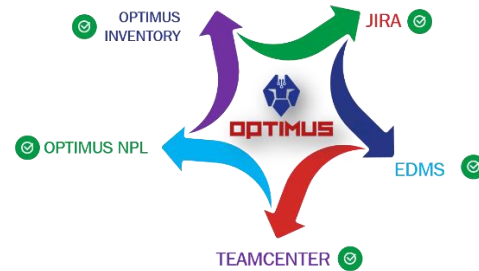


Fig. 2. Internal Systems in One Media.

3 - Development Progress and Implementation

Phase 1: Configuration Management Infrastructure

As mentioned in the previous chapter, Phase 1 development focused on internal systems integrations and building a website friendly 3D model framework to integrate the aircraft and the FTI system components. During the project development phase, extra internal systems were developed under OPTIMUS and integrated to manage sensors and equipment requiring recalibration, as well as track and record the FTI inventory via OPTIMUS, and to communicate with the FTI Digital Twin.

System Integrations

The transfer of NPL from spreadsheets to Optimus was the first and most fundamental step. With Jira, EDMS, Teamcenter, and now the FTI Inventory as a sub-module in OPTIMUS, an FTI engineer reviewing a sensor in the prototypes can access the instrumentations complete NPL record and its attachments, all documentation released for that sensor or its installed helicopter. JIRA findings are visible within the sensors metadata stating if its an open one or a closed one. Most critical information to manage a sensors story from the start to finish is accessible in a single interface. Configuration reviews and post-flight anomaly investigations for fault monitoring requires the use of these disconnected systems. With FTI Digital Twin, they are now united in one.

Calibration Management & Formula Generation

When a sensor or a tools re-calibration procedure is complete, calibration department logs the new calibration reports in a separate network. FTI engineer must manually find the new report and attach it to the sensor, update the due date and sensitivity data in NPL which is critical for engineering formula generation. The new automated connection established between OPTIMUS and the Calibration Management System allows the calibration reports to be added to the sensor attachments within the NPL and update the changes in the sensor metadata like due date with one click. There is also another development underway to automate the sensitivity value to be updated as well found in the reports.

The automation of sensitivity data within the NPL also directly advances engineering formula generation. Formula generation for sensors previously depended on an external tool [2] that consumed the XIDML file, a DAU configuration file with channel definitions, gain values, excitation parameters etc. and NPL to automatically produce engineering unit formulas for each sensor. With the NPL now managed in OPTIMUS and sensitivity values updated automatically within the close future, a formula generator module has been integrated into OPTIMUS as well. Sensor specific formula templates are defined within the platform with parameters mapped to their corresponding NPL or XIDML fields. The system then generates the required engineering formulas based on the user chosen versions of NPL and XIDML without manual parameter lookup or transcription. A formula comparison tool [2], previously also external, has been brought into OPTIMUS alongside the generator. Engineering formula management, calibration data, engineering formulas and version comparison are now being handled within a single environment. When an engineer selects a sensor in the Digital Twin, the NPL metadata, calibration history and the engineering formulas used to convert that sensors signal to a meaningful data are all accessible in one place.

Inventory Management

Inventory tracking is a critical process for FTI management. Accessibility to inventory history and count is essential for the accurate and reliable operations such as preparing for new projects, maintaining sensors in prototypes undergoing flight testing, planning helicopter maintenance processes and sensor/tool calibrations, and arranging materials needed for field missions.

An inventory system was developed within OPTIMUS to track FTI items through their lifecycle. For assets with serial numbers every logistical transition or calibration procedure is automatically logged. The NPL link provides location changes to log automatically. A sensor present in an active NPL is recorded as installed on the corresponding helicopter. When a sensor moves between prototypes, for example when a sensor moves from T625 P1 prototype to T625 P2, the system detects the NPL change and updates the location record. Sensors absent from any NPLs are assigned a default warehouse location, reflecting the operational logic that a sensor removed from an aircraft is in storage unless a location change is implemented manually. Consumables are tracked by quantity rather than serial number, such as cabling and gauges.

3D Twin Versioning

FTI Digital Twin mirrors the NPL version logic. Each physical configuration or systematic data change on an experimental aircraft must trigger a new version of the twin, maintaining the ability to reflect history. This is foundational for FTI configuration management. Flight test data must be in correlation with the exact instrumentation configuration during projects life cycle. Once the helicopter model library is established, FTI personnel will be able to import an instrumentations 3d model from product life cycle management (PLM) system and define their installed location within the twins environment in inline with their NPL data. Since instrumentations PLM data does not reflect the FTI naming rule or dynamic flight changes, this ability is critical.

Phase 2: Sensor Health & Condition Monitoring

The second phase of the project is where the infrastructure built in phase 1 meets preflight data. Preflight operations, which is carried out within the personnel's experience, are subject to optimization with increasing prototype and instrumentation count respectively. Management of preflight operations are taken in two stages. First data of sensors are subjected to specific rule-based controls. Second step is to check the sensors that complied with these rules using multiple machine learning and/or deep learning based algorithms.

Pre-Condition Rule Checks

Sensor data is evaluated through a set of rules designed to identify sensor or zonal based conditions. These include full-scale output, constant data output or high-mean deviations. For some sensors, environmental or physics

based rules are applied. An accelerometer not giving ~1g on its z-axis during the pre-flight checks or a thermocouple not reading the ambient temperature of hangar indicates the sensor is faulty and doesn't require any analysis with AI based algorithms. The rules are definable per sensor types and will be configurable in FTI Digital Twin's UI.

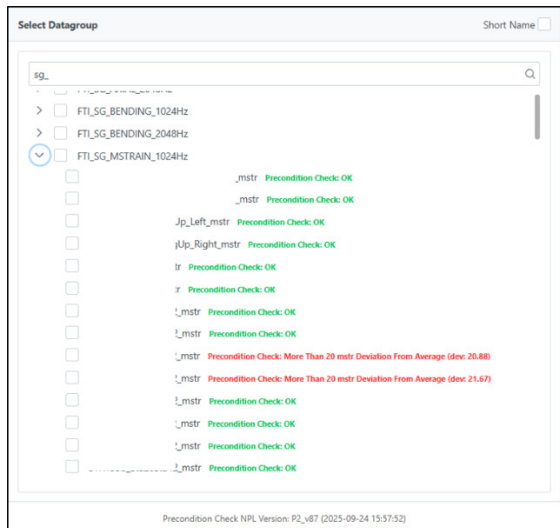


Fig. 3. Pre-Condition Rule Checks.

Multi-Algorithm AI Analysis Pool

The platform integrates a library containing more than ten anomaly detection algorithms, including Prophet, VANILLAVAE and various additional AI Models. Prophet performs well for anomaly detection in relatively smooth signals like thermocouples and potentiometers but less

suitable for vibration data where low-amplitude oscillation is normal. For that matter an FTI Engineer might want twin to use IQR model to detect sudden spikes. New algorithms or methods an FTI engineer might find suitable through literature review or researches can be integrated to the algorithm pool. For better analyses or detections, AI team re-trains the models with fault labeled data based on sensor types.

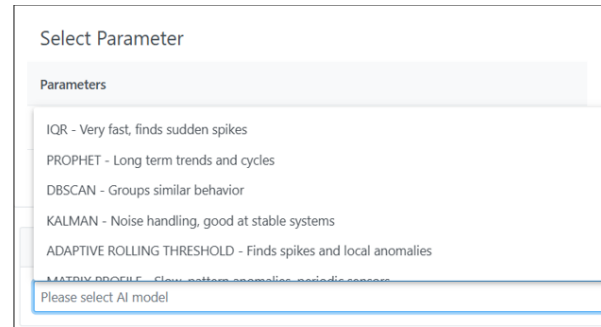


Fig. 4. AI Model Pool.

Analyses are presented in a standardized format that reports the count of anomaly (candidate) samples, their timestamps, anomaly sample percentage within the whole data. By selecting multiple sensors (such as zones or similar character expectations), the user can run a broad analysis of the similar sensors data and examine characteristics that might not be observable visually. In that matter we have seen re-configured DBSCAN model is a good choice to group similar behavior.

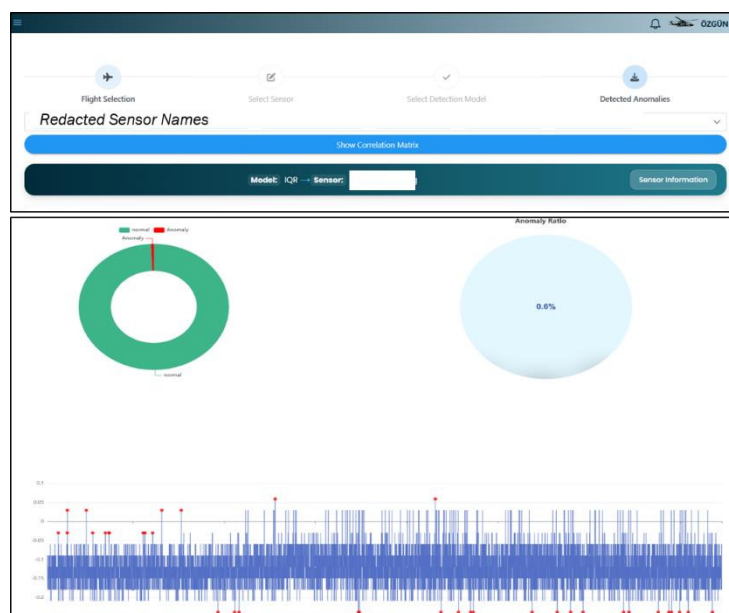


Fig.5.AI Analyses Result on an Accelerometer Pre-flight Data.

Whether a sensor is reported as faulty or unhealthy in the pre-flight report after rule-based and AI-based checks, the final decision will always be given by the FTI engineer. The system is able to generate the relevant report at the end of the operation and send it via email to the teams participating in the telemetry for the flight test.

Operational Impacts

FTI Team will no longer perform these checks by eye with thanks to real-time data flowing into Twin. The system handles pre-condition evaluation automatically and surfaces results for engineer review. This improves time management for the personnel, particularly on aircrafts where manual review of hundreds of instrumentations is the primary time cost.

The ML/DL layer introduces a different category of improvement beyond time savings. An experienced FTI engineer reviewing pre-flight data can recognize patterns that deviate from what they have learned to expect for a given sensor type or aircraft zone. That knowledge is accumulated over years and does not transfer automatically to teammates. The algorithms can operate simultaneously on multiple sensor data and aims to apply the same analytical criteria on every check, regardless of who is on the job. Anomalies that would require a specific observation to notice become detectable. Cross-sensor and cross-zone relationships across hundreds of channels is now accessible. Engineering judgement is still the final interpretation of results but it will not be bounded by individual experience and the practical limits of manual review anymore.

Phase 3: Predictive Maintenance with Sensor Behavior

Phase 3 work has begun with analytical checks rather than ML/DL methods. Focus is mainly establishing a reliable behavioral base from historical flight test data before introducing more complex AI integrated processes.

Test Point Analysis Across Platforms

A set of test points or maneuvers common across flight tests were selected as the test cases. Some of these maneuvers are engine off to idle and idle to flight test points. Using sensor type and zone as primary filters, the system compares sensor behavior across the selected flights and identifies where a sensor has shown inconsistent characteristics in a particular flight relative to the collective data. The inconsistent sensor data for that flight can then be plotted directly from the same interface. The fact that relevant JIRA findings, flight data, information on NPL and related systems enabling sensor

traceability are now accessible from a single location. A solid starting point for troubleshooting.

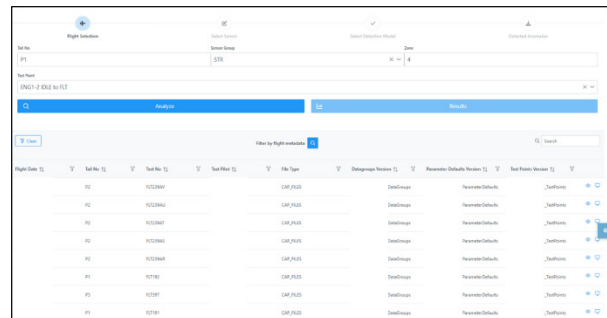


Fig. 6. Flight, Maneuver, Sensor Type & Zone Choice Window.

4 - Early Findings and the Path Forward Configuration Management (Phase 1)

The most tangible outcome of Phase 1 is that the instrumentation history of an experimental aircraft, its installed equipment and sensors, calibration records, documentation, JIRA findings and engineering formulas are now accessible in one place and navigable through a web-based 3D environment. Sensors and equipment are reflected with their real locations on the helicopter. Selecting a sensor in the twin interface reveals its full metadata, not as a lookup in a separate system but as a native part of the same UI. This is the foundational step toward a genuine digital twin. The upcoming sensor cloud import feature addresses one of the remaining critical point in digital twin development for configuration management. FTI layout is currently managed in Teamcenter. Transferring an already positioned sensor and equipment layout from Teamcenter into the FTI Digital Twin requires exporting and importing models individually. Instead of repeatedly installing FTI layout in two separate environments, importing sensors collectively will reduce the repetitive feel of the process. The planned capability will allow an instrumentations position and orientation to be exported from PLM media and imported into the twin in a single step. This will preserve location data without manual re-entry.

Conditional Health Monitoring (Phase 2)

The pre-condition rule engine has been applied to preflight post data and it started to produce the intended effect. Sensors with saturation, constant output, physics-violating readings etc. are flagged automatically before the deeper AI integrated reviews begin. On large prototypes where thermocouple and strain gauge counts exceed 600, this step itself ensures reduction in preflight activity workload for the engineers and technicians. In the ML/DL analyses layer, the

clearest result is that algorithm suitability has to be sensor type dependent. FTI preflight data has specific characteristics that prevent ready to use AI models from being used. Prophet flags the normal low-amplitude oscillations of a healthy vibration sensor as anomalous. IQR and VanillaVAE perform more appropriately on vibration outputs. Across sensor types, a potentiometer check illustrates the next step. Technicians apply a sinusoidal input via a pot wire to verify sensor response. Resulting transition is treated as an anomaly by nearly every algorithm in the pool despite it being the confirmation that the sensor is actually working correctly. The conclusion is that every algorithm in the framework must be trained against labelled characteristic FTI data before AI analyses responses can support operational decisions with reliability. This the primary next step for Phase 2, alongside advancing the analysis pipeline from post preflight data to real-time execution in OPTIMUS directly. Currently FTI team records the preflight activity data and then uploads it to Digital Twin framework. By implementing real time big data parsing capability to OPTIMUS and installing the necessary equipment to send FTI data directly to TUSAS internal network where OPTIMUS is located, preflight activity will be done entirely in FTI Digital Twin. Average FTI configuration outputs around 80 Mbps data. To parse all these packets and converting to a meaningful engineering data to make it ready for pre-condition rule check and AI model reviews with minimal delay is another big workload.

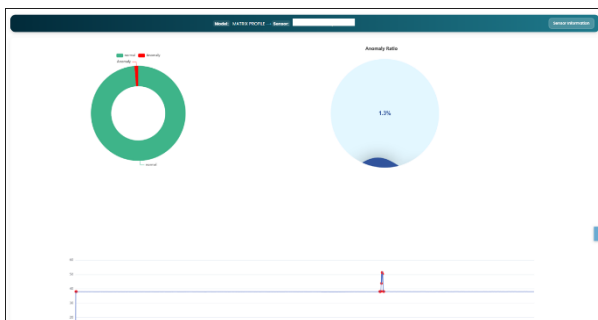


Fig. 7. Potentiometer Signal False Positive Anomaly.

Predictive Maintenance (Phase 3)

The underlying objective of Phase 3 is predictive maintenance. The goal is to assess whether a sensor is expected to perform healthy during the planned sorties. Based on the environmental conditions of those flights and the behavioral profiles built from old testpoints. Preflight signal characteristics will be also part of this procedure. A sensor showing drift signs in ground checks is a risk that should be looked at before the flight test campaigns. Reducing flight test aborts by

FTI is the operational target for this capability. The comparative maneuver analysis currently in semi-use runs against a limited set of common test points. It has demonstrated that the approach is viable for detections. The system identifies sensors that behaved anomalously in a specific flight or maneuver relative to the same set of sensors for the same testpoints. The limitation is that the current analysis does not account for environmental conditions. Same maneuver under different wind speed, altitude or temperature conditions might produce different sensor responses. We believe that approaching these differences as if they were the expected characteristics (rather than directly calling them anomalies) would be a more realistic approach for simulating testpoints in future campaigns. That is why incorporating environmental parameters into the comparison framework is the next step and it will be followed by building a Phase 3 algorithm pool along the same lines as Phase 2 but calibrated to the post-flight data instead of preflight data. Which differs from the static ground data Phase 2 algorithms are being trained against. The same labelled data re-training requirement will be applied for different types of testpoints and sensors before algorithm outputs or synthetic data can carry reliable operational weight.

5 - Conclusion

The work presented here represents a significant and tangible advancement towards the next-gen FTI management platform or FTI Digital Twin proposed in our previous publication. Phase 1 infrastructure is semi-operational and has already begun to digitally transform daily FTI workflows in active prototypes. Phase 2 introduced a scalable algorithm framework for automated sensor health monitoring and anomaly detection. Phase 3 began to provide structured outlier sensor data analysis for common maneuvers in flight testing. Taken together, the three phases create a system where configuration management tracking, sensor health monitoring, and behavioral prediction are maintained in a single 3D environment. Reducing workload on dynamic instrumentation management which can be described as babysitting. Decreasing the reliance of routine operations on experience and providing FTI Team with a significantly more data driven view of instrumentation health throughout a projects T0 moment to certification.

6 - Acknowledgements

The authors would like to thank the Artificial Intelligence and Big Data teams at Turkish Aerospace for their contributions to the on-going development of the FTI Digital Twin project presented in this work.

References

- [1] Kaymak, A. T., Kekeç, M., Uzun, R., & Aydın, S. (2024). Integration of FTI Configuration Management with Flight Test Database for an Enhanced Digital Twin Development. In Proceedings of the European Test and Telemetry Conference (ETTC 2024) (pp. 195–199). AMA Service GmbH.
<https://doi.org/10.5162/ETTC2024/B2.3>
- [2] Hacıömeroğlu, F., Uzun, R., Kekeç, M., & Kaymak, A. T. (2024). Automating Data Conversion. In Proceedings of the European Test and Telemetry Conference (ETTC 2024) (pp. 175–179). AMA Service GmbH.
<https://doi.org/10.5162/ETTC2024/B2.1>