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Digital Twin Architecture with EKF Sensor Fusion for RadAlt Faults

RadAlt Arızaları için EKF Sensör Füzyonlu Dijital İkiz Mimarisi

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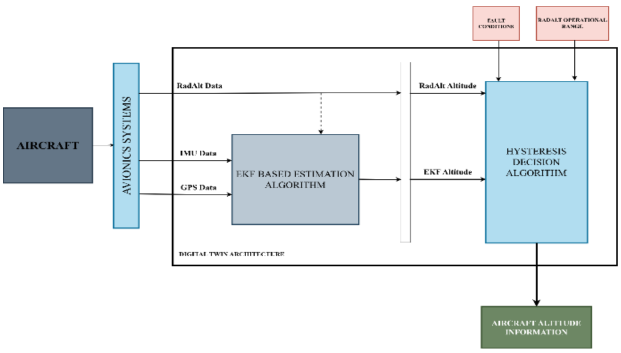
Highlights

A digital twin architecture using EKF-based sensor fusion was developed to provide real-time altitude estimation for RadAlt fault scenarios. The proposed system runs the prediction algorithm with IMU and GPS data while performing validation using valid RadAlt measurements. Simulation results demonstrate that the digital twin system ensures stable and seamless transitions during RadAlt fault scenarios and maintains altitude deviations within the ±50 ft range.

Graphical Abstract



Abstract

This This study aims to develop a digital twin of an altimeter system to provide a real-time backup altitude solution in the event of possible Radar Altimeter (RadAlt) failures. RadAlt systems may occasionally fail due to reasons such as electromagnetic interference, technical malfunctions, or operational range limitations. During the design of the digital twin architecture, a virtual simulation of the physical system was created using an Extended Kalman Filter (EKF)-based sensor fusion scheme. In line with the defined fault scenarios, the digital twin architecture incorporates a hysteresis-based decision mechanism that ensures the prediction algorithm runs continuously in the background but only outputs the digital twin data when a RadAlt fault scenario occurs, thereby maintaining system stability. A flight profile was designed with realistic sensor models and fault conditions, and the system was tested under various simulation scenarios. Simulation results showed that, in the event of a RadAlt failure, the digital twin system functioned as a virtual altimeter providing reliable altitude estimation and accurate altitude information.

Özet

Yapılan bu çalışma, bir altimetre sisteminin dijital ikizini oluşturarak olası radar altimetre (RadAlt) arızalarında gerçek zamanlı yedek bir irtifa sistemi sağlamayı hedeflemektedir. RadAlt sistemleri zaman zaman elektromanyetik girişimler, teknik arızalar ve çalışma aralığı gibi sebeplerden dolayı başarısız olabilmektedir. Dijital ikiz mimarisi tasarlanırken, genişletilmiş kalman filtre (EKF) tabanlı sensör füzyon tasarımı ile fiziksel bir sistemin sanal bir simülasyonu oluşturulmuştur. Tanımlanan arıza senaryoları doğrultusunda histerezis bir karar mekanizmasına sahip olan dijital ikiz mimarisi, tahmin algoritması arka planda sürekli çalışmasın rağmen sadece RadAlt arıza senaryosu gerçekleştiğinde sistemin dijital ikiz çıktısı vermesini sağlayarak sistemin kararlılığını sağlamaktadır. Gerçekçi sensör modelleri ve arıza koşulları ile bir uçuş profili tasarlanarak farklı test senaryolarında simülasyon test edilmiştir. Simülasyon sonuçları, RadAlt verisinin arıza senaryosunda dijital ikiz sisteminin güvenilir irtifa tahmini sağlayan sanal bir altimetre görevi gördüğü ve doğru irtifa bilgisi verdiği gözlemlenmiştir.

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1. INTRODUCTION

A digital twin is defined as a virtual system that models the real-time behavior of physical systems and operates in parallel with them [1]. This digital system technology processes sensor data and historical system data to simulate and predict the future behavior of the physical system. In doing so, it also supports system optimization processes. In the event of a failure of the physical system, the digital twin continues to operate as an alternative system. The digital twin approach, initially employed by the National Aeronautics and Space Administration (NASA) for space missions, is now applied across a wide range of industries from aerospace to automotive [2].

Digital twin systems are utilized in a wide range of aerospace and industrial applications. Their primary use cases include: (i) fault detection and tolerance by comparing real-time outputs with modeled predictions, (ii) real-time redundancy to provide outputs in case of sensor failure, (iii) performance optimization by evaluating operational parameters.

Holler and colleagues have suggested that the digital twin architecture mentioned in the literature are scattered across various industrial applications, and that standard architecture needs to be updated to enhance these structures. Furthermore, they published a review article aiming to introduce a new concept of digital twin to the industrial sector and to provide meaning to the term [3].

This study contributed to topics such as predictive maintenance, system performance enhancement, and fault detection in digital twin applications. In particular, the study focuses on flight-critical altimeter systems in the aviation industry. A digital twin of an avionic system, such as the Radar Altimeter (RadAlt), has been developed and implemented as a backup system to address fault conditions.

Recent developments in sensor fusion and fault-tolerant control systems have enabled digital twin technologies to be effectively used in real-time critical systems. This paper aims to contribute to this growing body of knowledge by proposing a digital twin architecture for altitude estimation under RadAlt failure scenarios.

Table 1 presents a comparison between conventional altimeters and a digital twin-based altimeter [4–6]. It compares the main types of altimeters with the digital twin architecture. It provides a detailed examination of technical specifications such as fundamental operating principles, error margins, response times, advantages, and disadvantages. The limitations of the radar altimeter, which constitutes the focus of this study, define the fault scenarios in which the These limitations include electromagnetic interference, low-reflectivity surfaces, reduced reliability at higher altitudes, and hardware malfunctions. In this context, the digital twin architecture presented in this paper aims to provide an alternative and reliable altitude estimation under radar altimeter failure conditions, thereby improving the continuity and safety of the system.

Table 1: Comparison of altimeter systems and digital twin architecture.

Feature / System	Barometric Altimeter	Radar Altimeter	GPS Altimeter	Digital Twin Architecture
Operating Principle	Atmospheric pressure measurement	Microwave signal reflection	Satellite-based position data	IMU + GPS data and modeling
Output Type	Altitude (MSL)	Altitude (AGL)	Altitude (MSL)	Estimated Altitude (AGL)
Typical Error Margin	±10–30 m	±0.3–3 m	±5–10 m	±1–5 m
Response Time	Medium	Fast (10–20 ms)	Slow (≥500 ms)	Medium (Kalman filter-based)
Dependencies	Atmospheric conditions	Altitude and terrain	Satellite and GNSS quality	Sensor data and model accuracy
Application Area	Commercial aviation	Low-altitude military flights	GNSS-assisted flights	Backup system / fault scenarios
Advantage	Simple, low-cost	High accuracy	Global coverage,	Flexible, fault-tolerant
Disadvantage	Sensitive to pressure, requires calibration	Errors on reflective surfaces, range, EMI/EMC	Weak signals, delayed data	Accuracy depends on model quality

Among altimeters, the radar altimeter (RadAlt) was preferred instead of conventional altimeters to incorporate various fault scenarios into the analysis. RadAlt can occasionally produce errors due to factors such as electromagnetic interference (EMI), hardware malfunction, or limited range. A study published by AIRBUS in 2022, shown in Figure 1, demonstrated that 5G mobile networks activated in certain countries caused electromagnetic interference in radar altimeter systems due to operating at frequencies close to those of radio altimeter bands. This highlights the critical importance of the proposed digital twin architecture in providing a real-time backup altitude system in the event of potential RadAlt failures. This system is not designed to replace altimeters, but rather to function as an alternative software-based digital twin system.

This study aims to provide a real-time backup altitude system by developing a digital twin of an altimeter system for potential radar altimeter (RadAlt) failures. The developed digital twin is a simulation model based on actual flight data, estimating the aircraft’s altitude through sensor fusion and automatically activating when the RadAlt becomes inoperative.

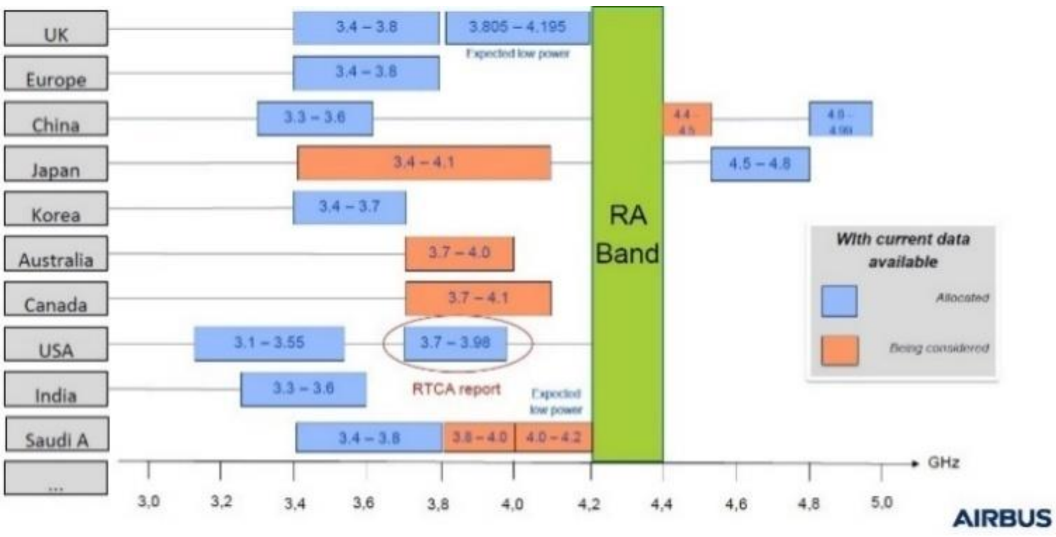

Figure 1: 5G Telecommunication and Radar Altimeter frequency band [7].

RadAlt systems may fail from time to time due to electromagnetic interference, technical malfunctions, or operational range limitations. Therefore, RadAlt was preferred instead of a barometric altimeter for alternative fault scenarios. While designing the digital twin architecture, a virtual simulation of the physical system was created using an Extended Kalman Filter (EKF)-based sensor fusion framework. This architecture operates as an alternative digital twin system that is activated in the event of a failure. During the system design, a simulation study was carried out using EKF-based sensor fusion with input parameters from the Inertial Measurement Unit (IMU), accelerometers, Global Positioning System (GPS), and RadAlt.

Based on the defined fault scenarios, the digital twin architecture incorporates a hysteresis-based decision mechanism, ensuring system stability by triggering the digital twin output only when a RadAlt failure occurs, even though the prediction algorithm runs continuously in the background.

For the test scenario, a flight profile was designed using realistic sensor models and failure conditions, and the system was tested via simulation. In the study, the real-time altitude estimation performance of the model was evaluated under different scenarios. Simulation results showed that in RadAlt failure scenarios, the digital twin system functioned as a reliable virtual altimeter, providing accurate altitude information.

The concept of a digital twin, which is limited in current literature, was addressed through the simulation of a specific digital twin architecture, offering both a scientific and technical perspective for real-time applications. With this study, the foundation was laid for future research by paving the way for direct testing of the digital twin altimeter system on an actual aircraft. Within this context, it was concluded that digital twin models can serve as an effective solution in aviation applications.

2. RELATED WORKS AND CONCEPTUAL BACKGROUND

In this section, the foundational literature necessary for the application of digital twin systems to avionic systems is reviewed.

Additionally, the focus is placed on surveying published studies to enhance the understanding of the technical concepts mentioned in this work.

2.1 Altimeter Systems and Altitude Measurement

Altimeter systems are used to determine the altitude of aircraft either above ground level (AGL) or mean sea level (MSL). There are essentially three main types of altimeters:

2.1.1 Barometric Altimeter

Barometric altimeters calculate altitude by measuring changes in atmospheric pressure. This system uses sea level pressure as a reference, according to International Standard Atmosphere (ISA) conditions, and calculates altitude using the following equation [4]:

$$h = \frac{T_0}{L}\left[\left(\frac{P_0}{P}\right)^{\frac{R.L}{g_0}} - 1\right] \quad (1)$$

Where:
h: Altitude [m]

T_0: Sea level temperature (≈ 288.15 K)

L: Temperature lapse rate (≈ 0.0065 K/m)

P_0: Sea level pressure (101325 Pa)

P: Measured atmospheric pressure [Pa]

R: Gas constant (287.05 J/kg·K)

g_0: Gravitational acceleration (9.80665 m/s²)

This calculation may sometimes yield low accuracy due to variations in weather conditions (e.g., temperature, pressure). Therefore, its use in critical operations is limited [7].

2.1.2 GPS-based Altimeter

GPS-based altimeter systems calculate altitude by correcting the height data obtained through satellite positioning relative to the geoid surface. During this altitude calculation, a difference arises between the geoid—which represents the shape of the Earth's surface—and the reference ellipsoid. To account for this difference in the calculation, the following transformation formula is used.

$$h_{MSL} = h_{GPS} - N \quad (2)$$

Where:
h_{MSL}: Height above mean sea level

h_{GPS}: Ellipsoidal height (GPS-derived)

N: Geoid height (e.g., EGM96 model)

The accuracy of these systems is affected by factors such as signal quality and data latency. GPS altimeters have limited applicability in time-critical missions due to delayed data in real-time scenarios [6].

2.1.3 Radar Altimeter (RadAlt)

RadAlt systems operate based on the reflection of electromagnetic waves and exhibit the characteristics of radio waves. They are particularly accurate at low altitudes. The system relies on the reflection process of electromagnetic waves transmitted from antennas mounted on the aircraft. The time-of-flight calculation is performed using the fundamental equation given below:

$$h = \frac{c.\Delta t}{2} \quad (3)$$

Where:
h: Height above ground [m]

c: Speed of light (≈ 3×10⁸ m/s)

Δt: Round-trip time of the electromagnetic wave [s]

In general, Frequency Modulated Continuous Wave (FMCW) and pulse radar principles form the operational basis of RadAlt systems [8].

Using the frequency difference, Equation (3) is rewritten as follows:

$$h = \frac{\Delta f . c}{2 . S} \quad (4)$$

Where:

Δf: Frequency difference between signals

S: Radar modulation slope [Hz/s]

The RadAlt system provides high accuracy within its operational range at low altitudes (h ≤ 2500 ft). Factors such as electromagnetic interference, increased altitude, and low-reflectivity surfaces negatively affect system performance [9]. The optimal operating range is specified as 0–2500 feet (AGL), within which the system achieves its highest accuracy. At altitudes beyond this range, signal loss and "no return" conditions may occur; therefore, the system is either not utilized or not presented to pilots as reliable data. The operational limits defined by leading companies in the aviation industry fall within this specified range for such devices.

2.2 Digital Twin and Avionics Systems

The concept of the digital twin refers to the creation of a digital counterpart of physical systems, enabling real-time simulation and analysis of the system. In other words, it is a virtual representation of a physical system that continuously analyzes input parameters and updates its behavior accordingly. Grieves and Vickers, in 2002, stated that this architecture involves bidirectional data exchange between the physical system and its digital model. Tao and Zhang define the digital twin as a modeling approach that encompasses the entire lifecycle of a system [10].

With current technology, digital twins are utilized across various sectors such as cyber-physical systems, the Internet of Things (IoT), big data technologies, and industry. The aviation sector has also found applications for digital twins. Leading companies in the industry, such as Boeing and Airbus, employ this technology in critical systems like engines and structural components [11].

In the aviation domain, the primary functions of digital twin applications include condition monitoring, fault tolerance, performance optimization, and decision support. Especially in the event of a failure in the physical system, the activation of the digital twin contributes to mission continuity of the aircraft, which is critical for flight safety [12].

Various studies exist in literature. Napolitano et al. employed a virtual sensor-acceptable as a digital twin based on EKF/UKF algorithms-to address Pitot tube failures [13]. Hazbon et al. referred to this approach as an aviation digital twin [14]. In this study, a similar method is applied to a critical system such as the Radar Altimeter, specifically in scenarios where it becomes inoperative or provides incorrect data. The proposed digital twin system is intended to ensure the operational continuity of the aircraft.

Unlike the studies in the literature that focus on predicting maintenance intervals of specific systems during flight or enabling predictive maintenance planning, this study will test fault scenarios directly [15].

2.3 Kalman Filter and Sensor Fusion

The Kalman filter is a Bayesian-based estimation algorithm used to predict the instantaneous state of a system using noisy measurements. In this study, it is utilized in the analysis and fusion of IMU, GPS, and, when applicable, RadAlt parameters within navigation systems [16]. Kalman defines the state and observation models as follows:

State Transition Model:

$$x_k = F_{k-1}x_{k-1} + B_{k-1}u_{k-1} + w_{k-1} \tag{5}$$

Observation Model:

$$z_k = H_k x_k + v_k \tag{6}$$

Where:

x_k: State vector of the system

u_k: Control input

z_k: Observation/measurement vector

F_k: State transition matrix

H_k: Observation matrix

w_k: Process noise (Q ~ N (0, Q_k))

v_k: Measurement noise (R ~ N (0, R_k))

The Kalman filter applies two fundamental steps to the system: it predicts the next state and compares it with the measurement parameters, correcting errors to update the algorithm.

While the classical Kalman Filter is sufficient for linear systems, the Extended Kalman Filter (EKF) is used in nonlinear scenarios. EKF performs prediction and correction by linearizing the state transition and measurement models using Taylor series expansion. The following equations represent the application to the state and observation functions:

$$x_k = f(x_{k-1}, u_{k-1}) + w_{k-1} \tag{7}$$

$$z_k = h(x_k) + v_k \tag{8}$$

The Jacobian matrices are used for linearization of nonlinear equations:

$$F_k = \left.\frac{\partial f}{\partial x}\right|_{x=\hat{x}_{k-1}} \tag{9}$$

$$H_k = \left.\frac{\partial h}{\partial x}\right|_{x=\hat{x}_k} \tag{10}$$

EKF has been preferred for the fusion of IMU and GPS data, which include nonlinear parameters. With the implemented sensor fusion technique, nonlinear GPS and IMU measurements (acceleration, velocity, and position) are processed using EKF [17].

Since the digital twin system receives input from multiple sensors, a literature review was also conducted on the term sensor fusion. Sensor fusion is a technique that ensures the correct and reliable interpretation of data obtained from avionic equipment (IMU, GPS, and RadAlt). Selecting a structure compatible with the digital twin architecture through data fusion is critical to the system [18].

Loosely Coupled Fusion: Each sensor produces its own output, and these outputs are combined at the end of the process. The fusion is performed in a separate integration layer where sensors operate independently.

Tightly Coupled Fusion: Sensor data is directly connected to the filter algorithm. This structure enables estimation even if one of the sensors fails.

Centralized Fusion: All sensor data is integrated into a common filter directly. Although this structure is comprehensive, it has computationally intensive architecture.

In avionic systems, each sensor has its own error profile. The direct use of system data such as

GPS, IMU, barometric, and radar altimeters would be insufficient for the digital twin system. Therefore, Kalman filter–based sensor fusion will produce the most optimal estimate by processing the incomplete and noisy outputs of these sensors [16].

The Kalman filter is a linear estimator (as in Equation 5). By integrating sensor fusion into the Extended Kalman Filter formulation (Equation 7), the difference between model and measurements can be validated even in a nonlinear system. The equations used for estimation and minimizing the error in sensor measurements are presented below.

Prediction:

$$\hat{x}_{k|k-1} = F_{k-1}\hat{x}_{k-1|k-1} + B_{k-1}u_{k-1} \qquad (11)$$

$$P_{k|k-1} = F_{k-1}P_{k-1|k-1}F^{T}{}_{k-1} + Q_{k-1} \qquad (12)$$

Correction:

$$K_k = P_{k|k-1}H^{T}{}_{k}(H_k P_{k|k-1}H^{T}{}_{k} + R_k)^{-1} \qquad (13)$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - H_k\hat{x}_{k|k-1}) \qquad (14)$$

$$P_{k|k} = (I - K_k H_k)P_{k|k-1} \qquad (15)$$

Where:

$\hat{x}$: State estimate vector

F: State transition matrix

K: Kalman gain

Q, R: Process and measurement noise covariance matrices

z: Measurement vector

These equations are used to evaluate the residuals (innovations) and subsequently update the filter output based on system reliability. If sensors fail, the filter detects this condition through deviations in the output and reduces the data update frequency to minimize computational load [17].

3. METHODOLOGY

3.1 EKF-Based Sensor Fusion Architecture

The developed digital twin system models the altitude information of an aircraft using an EKF-based architecture. To simulate physical flight data, mathematical models of IMU, GPS, and RadAlt equipment were created. An Extended Kalman Filter (EKF)-based sensor fusion architecture was designed to integrate the data from these sensor models. The altitude estimation obtained via EKF functions as a real-time virtual system; thus, when RadAlt provides erroneous measurements, this software-based virtual system activates to continue delivering altitude information [14]. When the aircraft performs climbing or descending maneuvers, it changes altitude along the z-axis. The change in the z-axis measured by the IMU is fed into the EKF, and the system updates its altitude estimate based on the incoming parameter. A hysteresis-based decision algorithm determines whether the output comes from the digital twin or the RadAlt, depending on the equipment failure condition. In this way, the system provides uninterrupted altitude information. The system architecture is illustrated in the following figure.

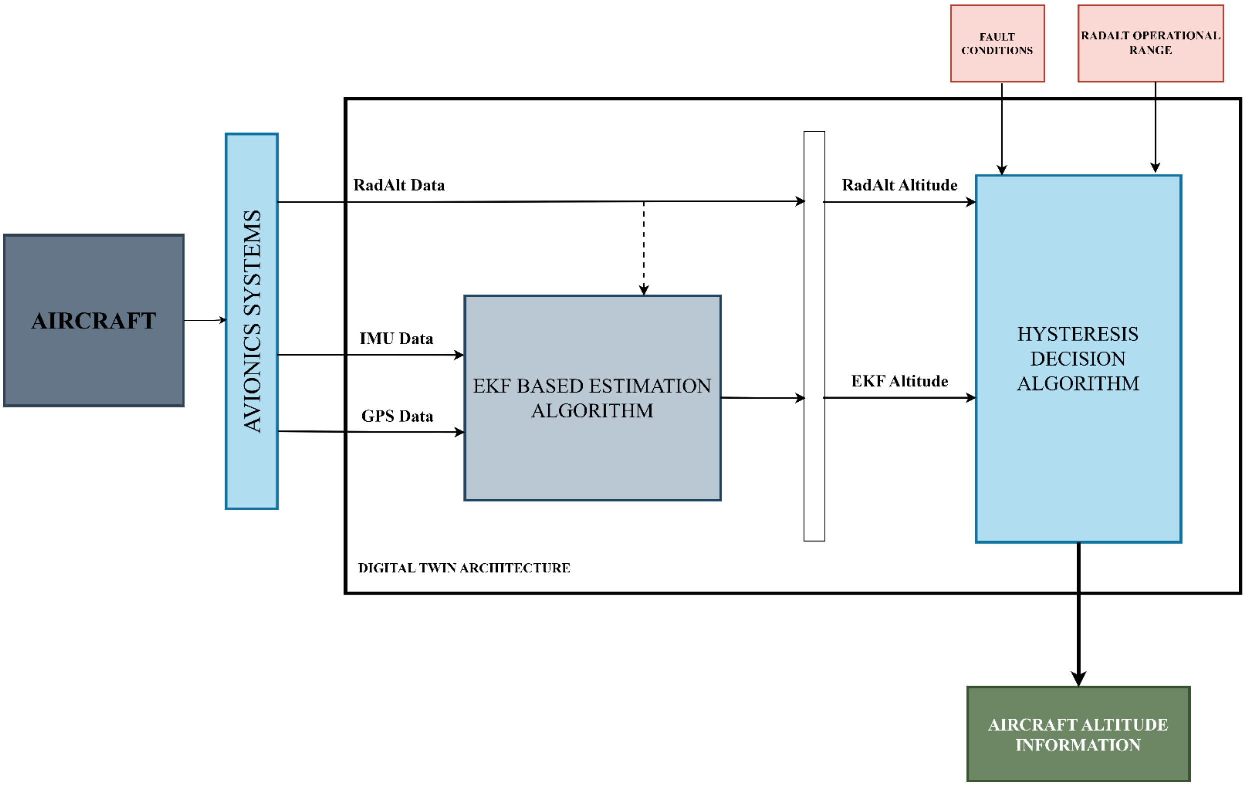

Figure 2: The proposed digital twin architecture.

As illustrated in Figure 2, the general structure, input, and output of the designed digital twin architecture can be observed. Two primary data sources are utilized for aircraft altitude estimation. The model predicts instantaneous altitude variation using IMU data. This prediction is performed by integrating acceleration to obtain optimal altitude estimation is achieved by combining the high-frequency but drift-prone IMU data with the low-frequency but high-accuracy GPS data. The RadAlt input is included as a discrete reference for comparison purposes when the system is functioning correctly, in order to enhance algorithm stability. In fault scenarios, the prediction algorithm disregards RadAlt data as input. This approach provides a new perspective on GPS and IMU-based prediction algorithms found in the literature, aiming to improve system robustness. The overall operational algorithm of the proposed system is illustrated in the figure below.

As shown in Figure 3, the foundation of the digital twin architecture is built upon an EKF-based sensor fusion algorithm. Although the algorithm appears to follow a basic state-observation framework, it entails a highly complex structure that requires intensive computations. At each step, multidimensional matrix multiplications are required for the prediction of the nonlinear state vector, along with the computation of Jacobian matrices for the measurement update and the update of covariance matrices.

Additionally, the system and sensor models must be statistically parameterized to ensure accurate modeling of process and measurement noise. Advanced mathematical procedures such as minimizing linearization errors and maintaining a consistent error covariance management strategy are essential. EKF performs an iterative estimation to minimize errors in altitude and vertical velocity. For this nonlinear model, linearization is conducted using a Taylor series expansion [13].

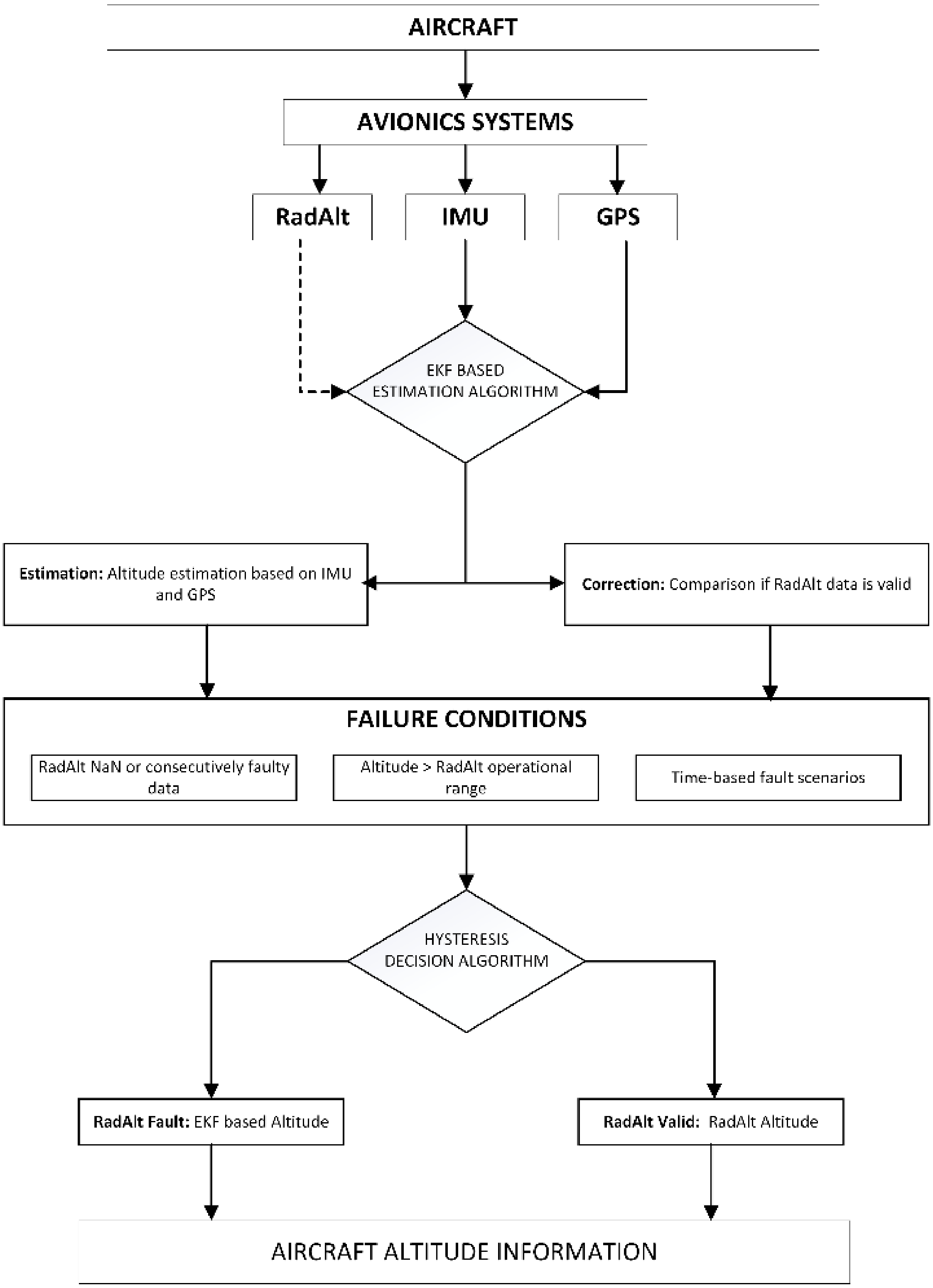

Figure 3: The proposed digital twin algorithm.

State Vector:

$$x = \begin{bmatrix} h \\ v \\ b_a \end{bmatrix} \tag{16}$$

Where:

h: Altitude

v: Vertical velocity

b_a: IMU bias

$$\dot{h} = v,\ \dot{v} = a - g,\ \dot{b}_a = 0 \tag{17}$$

In Equation (17) above, a represents the acceleration measured by the IMU, and g denotes the gravitational acceleration. To convert this system into a discrete-time format using a sampling period Δt, the prediction formulas (11) and (12) referenced in the literature are applied [19].

Discrete-Time Transition:

$$x_{k|k-1} = Ax_{k-1|k-1} + Ba_k \tag{18}$$

$$A = \begin{bmatrix} 1 & \Delta t & -\frac{1}{2}\Delta t^2 \\ 0 & 1 & -\Delta t \\ 0 & 0 & 1 \end{bmatrix}, \qquad B = \begin{bmatrix} \frac{1}{2}\Delta t^2 \\ \Delta t \\ 0 \end{bmatrix}$$

In this linear transition, the bias is assumed to be constant, and the state transition matrix A linearizes the process by estimating altitude and velocity from the previous state. Vector B incorporates the IMU input into altitude and velocity predictions. To filter the noisy altitude measurements received by the EKF, the update equations (13), (14), and (15) mentioned in the literature are used.

In the digital twin system, the high-frequency IMU acceleration output is used in every prediction step. GPS altitude measurements are used as inputs to correct long-term drift ($\sigma_{GPS} \approx$ 1.5m). RadAlt provides highly accurate measurements ($\sigma_{RadAlt} \approx$ 0.02m) but is subject to signal loss in fault scenarios. Both RadAlt and GPS provide their respective error covariance values as feedback inputs to the EKF. As a result, the high-frequency characteristics of the IMU are fused with the long-term accuracy of the GPS and RadAlt systems. Furthermore, the correction and rejection capabilities of the Kalman filter are effective in handling fault tolerance. During normal operation (i.e., in the absence of faults), including RadAlt measurements in the EKF have been observed to improve altitude estimation accuracy at low altitudes. The EKF-based sensor fusion constitutes the backbone of our digital twin approach. When RadAlt data is unavailable or faulty, the digital twin functions as a virtual altimeter, providing a reliable altitude estimate.

3.2 Fault Detection and Digital Twin Activation

A robust fault detection algorithm is intended to be integrated into the sensor fusion architecture described above. The system detects RadAlt failures and switches to the digital twin mode in the event of a fault. The algorithm continuously compares the RadAlt measurements with the EKF estimates at a specified frequency and evaluates them under multiple conditions.

3.2.1 Signal Loss or Invalid Data

The algorithm flags an error when the RadAlt output provides measurements (NaN) or when the output deviates negatively or positively beyond physical altitude limits. RadAlt outputs are considered unreliable when the altitude exceeds 2500 ft [20].

3.2.2 Large Residual Analysis

A residual calculation is performed between the RadAlt measurement and the EKF altitude estimate using the following formula:

$$r_k = z_{h,RadAlt,k} - \hat{h}_{k|k-1} \quad (19)$$

Here, $z_{h,RadAlt,k}$ represents the RadAlt altitude measurement, while $\hat{h}_{k|k-1}$ notes the EKF's prior altitude estimate at time step k. If $|r_k|$ exceeds the statistically expected RadAlt noise threshold, a fault scenario is triggered. Both relative and absolute thresholds are employed in the fault detection algorithm:

$|r_k| > 0.5\hat{h}_{k|k-1}$: Acts as a relative threshold.

$|r_k| > 50$ ft: Acts as an absolute threshold.

Additionally, the predicted altitude and the RadAlt measurement are compared. If the absolute residual exceeds a minimum defined threshold, a fault flag is raised. This enables the detection of sudden drops or physically implausible spikes.

3.2.3 Predefined Fault Windows

In the designed simulation, intentional large errors are injected into the RadAlt system at predefined time intervals. The aim is to observe how the system responds under unexpected fault conditions. For evaluation purposes, these windows are labeled as "RadAlt Fault" in Figure 3. Each logical condition is combined through a logic gate and defined in the design as:

$$faultFlag = (isNaN) \cup (isOutofRange) \cup (isLargeError) \cup (isInFaultTime) \quad (20)$$

Thus, even a single active fault condition is sufficient to trigger a fault scenario. EKF provides $\hat{h}_{k|k-1}$ as a high-accuracy virtual sensor to the system, serving as an example of analytical redundancy.

3.2.4 Hysteresis Mechanism

System accuracy and smooth transitions are critical for reliable switching logic. In the initial design phase, even minor RadAlt noise caused immediate switching to the digital twin mode. A study in the literature proposed the use of a fault persistence counter to avoid rapid mode transitions [21]. When a fault is detected, the counter is incremented by one. If RadAlt starts providing valid measurements again, the counter is decremented by one. To activate the digital twin mode, at least three consecutive fault detections are required (0.1s for a ~0.3s cycle). Similarly, returning to the normal mode requires the counter to decrease back to zero. This results in a stable switching algorithm that prevents transitions caused by transient noise or short-term anomalies, thereby maintaining system robustness.

3.2.5 Digital Twin Mode

When the counter-based algorithm is satisfied, the system identifies a RadAlt fault scenario. The system output switches to the digital twin mode, and the EKF altitude estimate is used as the output in place of the RadAlt measurement. In this scenario, EKF operates solely with IMU and GPS data. Since it has been continuously estimating altitude from previous steps, the transition is observed to be seamless. The digital twin mode continues to provide output until RadAlt resumes delivering reliable data. This strategy also falls within the framework of Sensor Fault Detection, Isolation, and Accommodation (SFDIA) [22].

3.3 Simulation and Performance Analysis

To validate the proposed method, a realistic simulation including sensor models and fault scenarios was carried out in the MATLAB/Simulink environment. The block diagram of this implementation is shown in Figure 2, which visually presents the simulation structure used during the test scenarios. The aircraft scenario includes a real flight profile with climb (0 ft), cruise (maximum ~5000 ft), and descent phases. IMU, GPS, and RadAlt data feed EKF. RadAlt was programmed to fail in four separate 30-second intervals, and the response of the digital twin system was examined.

In Figure 3, this condition is shown in light pink as “RadAlt Error.” Prior to the first fault (~0–60s), RadAlt successfully tracks the true altitude. Similarly, the digital twin continues this tracking in parallel. During the 60–90s interval, although RadAlt output is faulty, the EKF activates, and the blue line continues to track the true altitude despite the RadAlt data loss. As observed during the transition, there is no instantaneous jump. This is due to the continuity of the filter prediction. When the fault ends (~90s), RadAlt recovers after a short hysteresis delay, and RadAlt output is once again provided. This is illustrated in Figure 4. The same scenario is repeated in the other fault intervals.

The graph presented in Figure 4 compares the true altitude (black line) with RadAlt measurements (red) and the digital twin's altitude outputs (blue). Observing the RadAlt data, it is seen that correct measurements are provided between 0 and 2500 ft. Only at specific intervals are there data interruptions, which result from the intentionally defined RadAlt faults. The system state graph given in Figure 5 shows the transition between modes. A value of 0 represents RadAlt mode, while a value of 1 represents digital twin mode. Each time a fault condition is satisfied, the status flag rises to 1; after the fault clears, the system returns to 0 a few seconds later. This shows that the hysteresis transition works as intended.

The digital twin is able to track the true altitude (black) smoothly even during fault scenarios, maintaining deviations within approximately ±2% of the altitude range. For example, when examining the 260–290s interval, despite RadAlt being in a fault condition, the digital twin follows the true curve continuously. Considering GPS noise and IMU drift, the expected ±50 ft threshold operates in accordance with the transition logic [15]. At low altitudes where RadAlt functions properly, both the blue and red curves converge toward the black line. This is due to the EKF optimally fusing high-frequency IMU data with RadAlt and GPS inputs.

Throughout the simulation period, the RMS error of the EKF prediction during fault intervals remains low. This demonstrates that the advanced sensor fusion limits deviation effectively. Consistent with the report by Hazbon et al., who achieved similar accuracy for Pitot tube faults [8], the altitude estimation provided by the digital twin remains within acceptable performance limits.

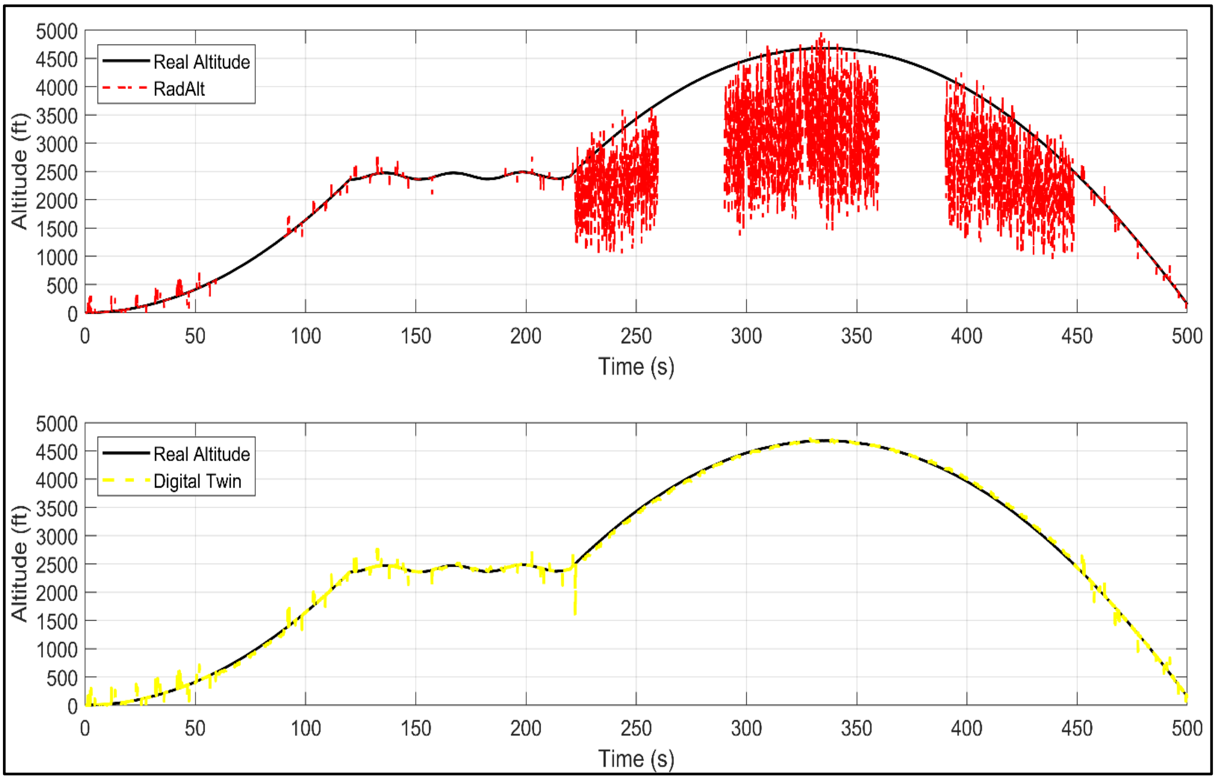

Figure 4: Altitude estimation vs. time – comparison of RadAlt and digital twin during fault scenarios.

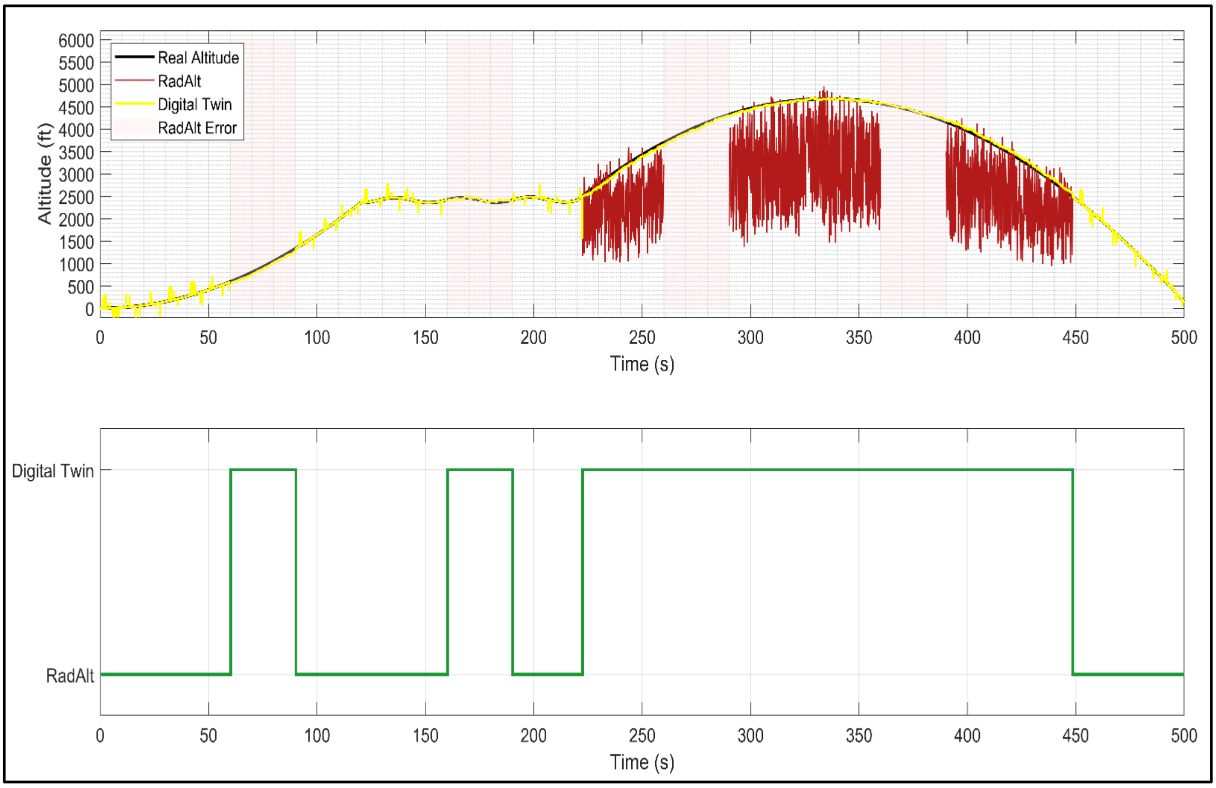

Figure 5: System mode etc. time – transition between RadAlt and digital twin states during fault events.

To summarize the methodology section, this approach forms a digital twin for the RadAlt system by combining an EKF-based sensor fusion architecture with a fault-tolerant control logic. In future work, this approach will be compared with other filtering techniques and validated through actual flight tests.

3.4 True Altitude Reference Data

The actual altitude profile used in the simulation was created as a reference flight profile to compare RadAlt measurements with digital twin predictions. This profile included the trajectory, climb, cruise and descent phases. The altitude profile equation used during the climb and descent phases is:

$$h_{true}(t) = h_0 + r.t \tag{21}$$

Where:

h_{true}: *True Altitude*

h_0: *Initial Altitude*

r: Vertical Rate in ft/s

t: Elapsed Time

This approach generates a clean, kinematically coherent altitude reference that underpins an exacting assessment of system performance. While the model omits certain real-world effects—such as turbulence and wind shear—it nevertheless captures the characteristic flight profile of a regional jet, as exemplified by the Embraer E190. To ensure its validity, the synthetic trajectory was compared against publicly available ADS-B altitude records for comparable aircraft [23], demonstrating mean absolute deviations of less than 0.5 percent across the 0–5000 ft operating envelope. Future works will integrate authentic flight recordings such as ADS-B feeds and Flight Data Recorder logs to assess the digital twin's performance within realistic atmospheric environments and operational scenarios.

4. CONCLUSIONS

This study presents an EKF-based sensor fusion architecture that effectively mitigates RadAlt failures. The proposed system functions as a digital twin altimeter by seamlessly taking over altitude estimation when RadAlt data becomes erroneous, using an Extended Kalman Filter to fuse IMU and GPS outputs.

Simulation results (see Figure 4 and Figure 5) show that during RadAlt fault conditions, the EKF altitude estimation closely converges to the true altitude, maintaining deviations within approximately ±2% of the typical operating altitude range (equivalent to ±50 ft in a 0–2500 ft flight segment). It is essential to note that the hysteresis-based decision algorithm improves system stability by preventing unnecessary mode transitions. Thus, instantaneous sensor errors do not immediately trigger a switch to the digital twin.

The aircraft's altitude information is provided continuously and without interruption through the prediction and decision algorithms of the digital twin architecture. This architecture reliably detects RadAlt faults and allows transition to the digital twin mode only when necessary. In this way, the digital twin continues to provide stable altitude output until the RadAlt system recovers from the failure.

The primary contribution of this study to the literature is the development of a real-time RadAlt digital twin architecture that enables accurate and reliable altitude estimation under all conditions. Once real-time flight data testing is completed, this approach will be applicable across a wide range of platforms, including commercial aircraft and unmanned aerial vehicles (UAVs). As a result, a safer aviation ecosystem supported by digital twin technology will be realized. In addition, considering current aviation digital twin applications, this study is expected to make a significant contribution.

Several topics stand out for future work. First, the EKF-based sensor fusion architecture will be evaluated using real flight data to test its accuracy and robustness. Second, the system will be implemented as embedded flight hardware using a microprocessor or avionic computer, and its integration with aircraft systems will be verified. Finally, the architecture will be developed into real-time test and validation software for RadAlt fault scenarios within flight safety operations, contributing to safer flight activities.

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AUTHOR CONTRIBUTIONS

Mustafa Enes AKÇAY: Conceptual Design, Literature Review, Data Acquisition, Analysis Evaluation, Data Curation, Software, Visualization Writing.

Seyfettin VADİ: Supervision, Literature Review, Methodology, Project Administration, Validation, Review & Editing.

CONFLICTS OF INTEREST

The author(s) has/have no competing interests to declare.

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