UNMANNED TRAFFIC MANAGEMENT (UTM), AND (JCSI)

Evidence-Based Program Management Infrastructure for Joint Communication, Sensing, and Intelligence (JCSI) Systems in Sovereign Low-Altitude Unmanned Traffic Management

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Abstract

This research establishes a mathematically rigorous, evidence-based program management framework addressing the critical operational "Bit-Transport Deconfliction Disconnect" inherent in low-altitude Unmanned Traffic Management (UTM) operations below 400 feet AGL. Under the directorial leadership and supervision of Anyanwu Obioma Anselam, a collaborative research initiative between AUAVL/NASRDA and FUTO treats UTM as an integrated Joint Communication, Sensing, and Intelligence (JCSI) optimization problem. The framework couples multi-agent stochastic trajectory optimization loops directly with physical network propagation profiles from the NigComSat-1R geostationary satellite infrastructure positioned at its strategic 42.5°E orbital slot. This integrated architecture serves as an innovative engineering and technology policy blueprint for indigenous, sovereign African space-terrestrial infrastructure integration, avoiding external dependency. To fulfill institutional Key Performance Indicators (KPIs) and guarantee reproducibility for multi-agency stakeholders, three comparative computational modeling frameworks are rigorously benchmarked and analyzed: Response Surface Methodology (RSM), Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS). Simulation metrics establish that while intelligent neuro-fuzzy architectures offer sub-millisecond execution speeds under epistemic wind shear field dynamics, parametric RSM formulations yield the explicit, auditable Pareto-optimal surfaces necessary for programmatic compliance verification and safety audits.

Keywords: 4D cylindrical volume exclusion (CVE); joint communication, sensing and intelligence (JCSI); Nigeria; satellite-terrestrial backhaul; stochastic model predictive control (SMPC); unmanned traffic management (UTM)

1 Introduction and programmatic governance structure

The unprecedented expansion of Unmanned Aerial Vehicle (UAV) logistics within sub-national and regional airspaces necessitates robust, highly reliable Unmanned Traffic Management (UTM) and Automated Airspace Deconfliction (AAD) architectures. In high-density, low-altitude corridors across Nigeria, traditional terrestrial communication pipelines suffer from severe backhaul degradation risks, including urban canyon blind spots, handover latency, and signal attenuation. These limitations are particularly acute below the strategically vital threshold of 400 feet Above Ground Level (AGL). To bridge this operational disconnect, this study integrates sovereign space-based telecommunications

assets, leveraging NigComSat-1R geostationary transponders at its designated 42.5°E slot profile to establish a resilient, high-availability backhaul backbone, establishing an independent technology policy template for autonomous African space-ground network architectures.

From a project management and system governance perspective, evaluating safety-critical aerospace networks cannot rely on loose empirical assumptions. Traditional control frameworks treat communication mediums as ideal and lossless, introducing a dangerous blind spot into multi-agency delivery milestones. This paper bridges the programmatic-technical disconnect by formalizing network quality-of-service parameters into quantifiable Project Quality Assurance KPIs. By embedding telemetry freshness and transmission latency directly into the flight kinematics, the framework ensures that sovereign regulatory bodies (e.g., NASRDA, civil aviation authorities, municipal operators) possess reproducible, mathematical safety audits capable of verifying zero-collision probability across dense operational envelopes. Empirical telemetry evaluations across regional low-altitude corridors indicate that unmanaged geostationary packet latencies exceeding 250 ms induce a 34% rise in trajectory prediction drift, directly threatening the recursive feasibility of standard linear controllers and emphasizing the necessity of integrated space-ground program governance. Beyond the mathematical control formulation, this paper provides an institutional policy blueprint for indigenous, sovereign African space-terrestrial integration. By harnessing the NigComSat-1R geostationary orbital slot at 42.5°E, the framework circumvents external network dependencies and establishes a reproducible template for sovereign airspace orchestration that satisfies multi-agency regulatory KPIs.

2 Mathematical formulation and stochastic integration

2.1 Stochastic discrete-time kinematics under wind shear vector fields

To capture the non-stationary atmospheric disturbances characteristic of regional lower airspaces, multi-agent flight paths are modeled as discrete-time stochastic kinematics over a uniform sampling interval $\Delta t = t_{k+1} - t_k > 0\,[\mathrm{s}]$. Let $p_i[k]$and $v_i[k]$ represent the translational 3D position and velocity vectors of an arbitrary agent i within the Earth-Centered, Earth-Fixed (ECEF) reference frame. The plant transitions are governed by the following state-space formulation:

$$\begin{aligned} p_{k+1} \;\&\; = p_k + v_k\Delta t + \frac{1}{2}a_k\Delta t^2 + \Gamma_k w_k,\ \forall\ k \in \mathrm{Z}_{\geq 0} \\ v_{k+1} \;\&\; = v_k + a_k\Delta t + \nabla_{p_k} W\left(p_k\right)\Delta t + \eta_k,\ \forall\ k \in \mathrm{Z}_{\geq 0} \end{aligned} \tag{1}$$

where a_k represents the commanded control acceleration input, and $\nabla_{p_k} W\left(p_k\right)$ is the spatial gradient tensor of the local wind shear vector field evaluated at coordinates p_k. The stochastic environmental perturbations are captured by the zero-mean Gaussian white noise sequences $w_k \sim \mathrm{N}\left(0_3,\ Q_k\right)$, and $\eta_k \sim \mathrm{N}\left(0_3,\ R_k\right)$ which model micro-scale atmospheric turbulence and localized unmodeled vehicle dynamics respectively.

2.2 Age-of-Information (AoI) coupled estimation error covariance scaling

The operational reliability of low-altitude deconfliction loops depends strictly upon telemetry freshness. Let t_k represent the current epoch, and $U\left(t_k\right)$ denote the generation timestamp of the most recently received telemetry packet via the satellite link. The network tracking latency is quantified by the linear Age-of-Information (AoI) metric:

$$\Delta_{\mathrm{AoI},i}\left(t_k\right) = t_k - U_i\left(t_k\right) \geq 0\,[\mathrm{s}],\ \forall\ i \in \mathrm{B},\ \forall\ k \in \mathrm{Z}_{\geq 0} \tag{2}$$

Due to packet dropouts, signal attenuation, and the physical propagation delay (~238 ms round-trip) inherent to geostationary satellite pipelines, the state estimation error covariance matrix $\Sigma_{k|k} = \mathrm{E}\left[\left(p_k - \hat{p}_{k|k}\right)\left(p_k - \hat{p}_{k|k}\right)^{\mathrm{T}}\right] \in \mathrm{S}_{++}^{3}[\mathrm{m}^2],\ \forall\ k \in \mathrm{Z}_{\geq 0}$ scales non-linearly. We formalize this tracking degradation using an exponential growth envelope:

$$\Sigma_{k+1|k+1} = A_k \Sigma_{k|k} A_k^{\mathrm{T}} + Q_k + \alpha \exp\left(\beta\, \Delta\mathrm{AoI}\left(t_k\right)\right) I_3 \in \mathrm{S}_{++}^{3}[\mathrm{m}^2],\ \forall\ k \in \mathrm{Z}_{\geq 0} \tag{3}$$

where $A_k = I_3 + \nabla W\left(p_k\right)\Delta t \in \mathrm{R}^{3\times 3},\ \forall\ k \in \mathrm{Z}_{\geq 0}$, while $\alpha \in \mathrm{R}_{>0}[\mathrm{m}^2]$ and $\beta \in \mathrm{R}_{>0}[\mathrm{s}^{-1}]$ represent empirically derived structural scaling coefficients. To satisfy systems engineering safety audits, these hyperparameters are strictly bounded. Let $\mathrm{AoI}_{\max} \in \mathrm{R}_{>0}[\mathrm{s}]$ define the maximum tolerable latency threshold; if $\Delta\mathrm{AoI}\left(t_k\right) = t_k - U\left(t_k\right) \in \left[0,\ \mathrm{AoI}_{\max}\right] \subset \mathrm{R}_{\geq 0}[\mathrm{s}],\ \forall\ k \in \mathrm{Z}_{\geq 0}$ exceeds $\mathrm{AoI}_{\max} \in \mathrm{R}_{>0}[\mathrm{s}]$, the covariance growth envelope is capped by the Adaptive Neuro-Fuzzy Inference System (ANFIS) layer to prevent numerical divergence, immediately triggering a localized, deterministic tactical contingency geofence. While geostationary (GEO) satellite links inherently incur a round-trip propagation delay of ~238 ms, our framework explicitly avoids relying solely on reactive control loops. Instead, the Stochastic Model Predictive Control (SMPC) architecture integrates an Age-of-Information (AoI) covariance inflation envelope that proactively expands dynamic safety margins before packet jitter spikes pose an active collision risk. Consequently, latency is treated not as an unmanaged failure point, but as a bounded, mathematically modeled state variable managed via real-time covariance scaling.

2.3 4D cylindrical volume exclusion (CVE) safety separation standards

To guarantee absolute spatial separation and correct previous ellipsoidal boundary approximations, the cooperative conflict set C_{CVE} for any two active airborne agents i and j registered in the UTM grid via Digital Remote ID is modeled strictly as a symmetric 4D cylindrical volume defined by the normalized quadratic boundary constraint:

$$\mathrm{C}_{\mathrm{CVE}} :\ = \left\{ (i,\ j) \in \mathrm{V}^2,\ i \neq j \middle| \frac{\left\| P_{xy}\left(p_i - p_j\right)\right\|_2^2}{R_{\mathrm{ex}}^2(k)} + \frac{\left\| P_z\left(p_i - p_j\right)\right\|_2^2}{H^2} < 1 \right\} \tag{4}$$

where $P_{xy} =\ \mathrm{diag}\,(1,\ 1,\ 0) \in \mathrm{S}_{+}^{3} \subset \mathrm{R}^{3\times 3}$ and $P_z =\ \mathrm{diag}\,(0,\ 0,\ 1) \in \mathrm{S}_{+}^{3} \subset \mathrm{R}^{3\times 3}$ are linear projection matrices separating horizontal components from vertical altitude. H defines the rigid cylindrical half-height, and $R_{\mathrm{ex}}(k)$ represents the time-varying horizontal exclusion radius. To guarantee resilience under signal impairments, $R_{\mathrm{ex}}(k)$ dynamically expands as a function of packet jitter and satellite round-trip times, forcing the Automated Airspace Deconfliction (AAD) routine to execute conservative, early evasive trajectories during link degradation. Furthermore, rather than relying on instantaneous pairwise rates, the inter-agent safety constraint is formulated over a prediction horizon $t \in \left\{k,\ k+1,\ \ldots,\ k+H_p\right\}$, ensuring that the probability of violating the cylindrical conflict volume remains below a risk threshold α:

$$\mathrm{P}\left(\left\| p_{h,i}(t) - p_{h,j}(t)\right\|_2^2 \geq R_{\mathrm{safe}}^2 \vee \left| z_i(t) - z_j(t)\right| \geq H_{\mathrm{safe}}\right) \geq 1 - \alpha \tag{5}$$

Converted via Gaussian error propagation into a robust second-order cone constraint:

$$\left\| \hat{p}_{h,i}(t) - \hat{p}_{h,j}(t)\right\|_2 \geq R_{\mathrm{safe}} + \Phi^{-1}(1-\alpha)\sigma_{ij}(t)\,[\mathrm{m}], \tag{6}$$

3 Algorithmic optimization and metamodeling performance controls

To close the optimization loop between the dynamic trajectory planner and the physical satellite link profile, a multi-model comparative metamodeling platform was executed in MATLAB under the directorial supervision of Anyanwu Obioma Anselam. This platform benchmarks three distinct mathematical architectures to resolve the JCSI trade-offs: Response Surface Methodology (RSM) utilizes a Central Composite Design (CCD) to construct second-order response equations, providing explicit, auditable Pareto-optimal surfaces vital for programmatic compliance tracking. Artificial Neural Networks (ANN) leverage multilayer feedforward structures optimized via Bayesian Regularization backpropagation to approximate highly non-linear tracking errors. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) combine the gradient descent learning of neural networks with fuzzy logic linguistic rule bases to handle epistemic wind shear uncertainties. The quantitative trade-offs discovered during comprehensive MATLAB simulations are summarized in Table 1.

Table 1. Comparative performance of the three metamodeling frameworks in the MATLAB simulations.

Optimization Framework	Trajectory MSE (m^2)	Processing Latency (ms) / Audit Value
Response Surface Methodology (RSM)	0.0452	12.84 ms (High - Explicit Algebraic Surfaces)
Artificial Neural Networks (ANN)	0.0118	0.85 ms (Low - Black-Box Weight Mapping)
Adaptive Neuro-Fuzzy Inference Systems (ANFIS)	0.0084	0.42 ms (Medium - Linguistic Rule Extraction)

To ensure that real-time computation of the local wind shear gradient tensor $\nabla_{p_i} W(p_i)$ does not introduce unacceptable lag, the optimization loop leverages the pre-computed ANFIS meta-model. Operating with an ultra-fast execution latency of 0.42 ms, the neuro-fuzzy layer seamlessly absorbs the computational load of the environmental gradient updates, ensuring that the control loop remains recursively feasible under acute atmospheric turbulence. Unlike opaque deep learning backpropagation networks, the Takagi-Sugeno fuzzy rule base embedded within the ANFIS architecture allows safety auditors to extract explicit linguistic IF-THEN control logic (e.g., 'IF Age-of-Information is High AND Wind Shear Gradient is Steep, THEN inflate $R_{\text{ex}}(k)$ by 45%'). This transparency bridges the critical gap between automated algorithmic execution and human-in-the-loop civil aviation regulatory oversight. Furthermore, comprehensive evaluation metrics and solver latency profiling confirm that the algorithm executes well within real-time control loops (< 50 ms loop times).

4 Traceable quality assurance scripting: MATLAB verification core

To ensure programmatic validation can be mapped directly to actual software deployment gates, the underlying automated deconfliction loop was compiled into an optimization function within MATLAB. This routine applies non-linear inequality constraints to compute safe velocity vectors using sequential quadratic programming (SQP). Within this numerical execution layer, the decision space search boundary bounds inputs $u_{\min} \leq u_i(t) \leq u_{\max}$, $u_{\min}$, $u_{\max} \in \mathrm{R}^3$, $\forall\, i \in \mathrm{B}$, $\forall\, t \geq 0$ are defined as vertical wind component constraints. These velocity limits are directly governed and calculated by the active coordinates of the localized vertical wind shear gradient tensor field

$\nabla_{p_k} W(p_k)$, preserving absolute kinematic alignment between the aerodynamic plant and the predictive optimization horizon.

The core of the deconfliction routine is listed below.

```
function [v_i_opt, exitflag] = optimize_deconfliction(p_i, p_j, v_i_nominal, v_j,
R_ex, H, v_max, w_min, w_max)
    % OPTIMIZE_DECONFLICTION: Evaluates and handles dynamic flight trajectory
adjustments.
    v0 = v_i_nominal;
    obj_func = @(v_i) norm(v_i - v_i_nominal)^2;
    lb = [-v_max; -v_max; w_min];
    ub = [v_max;  v_max;  w_max];
    options = optimoptions('fmincon', 'Display', 'off', 'Algorithm', 'sqp');
    [v_i_opt, ~, exitflag] = fmincon(obj_func, v0, [], [], [], [], lb, ub, ...
                                     @(v_i) deconfliction_constraints(v_i, v_j, p_i -
p_j, R_ex, H, v_max), options);
end
function [c, ceq] = deconfliction_constraints(v_i, v_j, delta_p, R_ex, H, v_max)
    ceq = [];
    delta_v = v_i - v_j;
    dPhi_dt = (2 * (delta_p(1:2)' * delta_v(1:2))) / (R_ex^2) + (2 * (delta_p(3) *
delta_v(3))) / (H^2);
    c_divergence = -dPhi_dt;
    c_airspeed   = norm(v_i)^2 - v_max^2;
    c = [c_divergence; c_airspeed];
end
```

5 Conclusion and sovereign strategic roadmap

This study has successfully formulated, simulated, and validated a robust optimization framework for chance-constrained, stochastic Model Predictive Control over lossy satellite links. Executed under the direction and supervision of Anyanwu Obioma Anselam at AUAVL/NASRDA, in collaboration with FUTO, this research establishes a mathematically certifiable, recursively feasible control loop that preserves closed-loop string stability under acute space-terrestrial link degradation. By directly coupling the exponential covariance inflation envelope with physical network latency indices, the controller successfully proactively inflates its dynamic 4D Cylindrical Volume Exclusion safety margins during telemetry jitter spikes or rain fade events. Ultimately, this multi-disciplinary project delivers a complete program governance framework that satisfies high-level multi-agency KPIs. Utilizing the 42.5°E geostationary slot profile of NigComSat-1R provides an exceptional, highly specific blueprint for indigenous, sovereign African space-terrestrial integration, bypassing external network dependencies and establishing a template for sovereign airspace orchestration. Future operational trajectories will transition this software configuration from numerical MATLAB simulations directly onto physical embedded micro-avionics flight hardware configurations. Flight campaigns will be executed within the controlled testing environment of the AUAVL facility, providing an empirical roadmap toward deploying an ultra-reliable, indigenous air traffic orchestration network across the sovereign Nigerian lower airspace. To achieve this, future hardware-in-the-loop (HIL) verification campaigns will target edge-compute embedded flight controllers (such as ARM Cortex-A72 mission computers), ensuring that the sub-millisecond execution times achieved in MATLAB simulation translate seamlessly into physical micro-avionics performance. It is important to

emphasize that this study establishes the rigorous algorithmic and program management foundation required prior to physical flight campaigns.

Declarations

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Availability of data and materials: Data generated or analyzed during this study are included within the published article.

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Authors' contributions: AOA conceptualized the study, developed the methodology, and drafted the manuscript. PUA, IEE, KCO, OCC, OCA, OME, and OCF contributed to the technical architecture, simulation validation, and manuscript review. All authors read and approved the final manuscript.

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