Low-Altitude Low-Cost Networkable Virtual Control Tower with Localized Sensor Systems to Support Autonomous Operations.

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This report presents the findings from an FAA BAA research project that evaluated the Lighthouse Avionics Virtual Control Tower (VCT) as an innovative solution for airspace monitoring. The VCT system was designed to track and classify manned aircraft, drones, and other airborne objects, supporting Beyond Visual Line of Sight (BVLOS) drone operations and enhancing airport security. Extensive testing validated the VCT's performance across key metrics such as latency, update rate, and position accuracy, demonstrating its potential to improve safety and efficiency in complex airspace environments. While initial results confirmed the system's effectiveness, further refinement is needed for real-time automated detection. This work contributes to the FAA's mission of integrating Unmanned Aircraft Systems (UAS) by providing a scalable, cost-effective tool for modern airspace management, poised to become a pivotal component in future aviation infrastructure.

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I. Introduction

The rapid growth of drone operations and the emergence of Advanced Air Mobility (AAM) have introduced significant challenges to the National Airspace System (NAS). Traditional air traffic management infrastructure, particularly control towers, is primarily designed to support manned aircraft at established airports, offering limited functionality for non-towered airports and low-altitude airspace where much of the Unmanned Aircraft Systems (UAS) activity occurs. This gap in airspace management has highlighted the need for innovative solutions capable of addressing the dynamic and complex demands of modern aviation.

Lighthouse Avionics developed the Virtual Control Tower (VCT) system to address these challenges. The VCT system provides a scalable, cost-effective, and comprehensive solution for localized airspace management. Unlike traditional control towers, the VCT system can be deployed in various locations, offering enhanced situational awareness and airspace management capabilities, particularly in supporting Beyond Visual Line of Sight (BVLOS) operations for drones and enhancing security around airports.

This report presents the findings from an FAA BAA research project that evaluated the VCT system's effectiveness as a critical tool for modern airspace management. The significance of this work lies in its potential to advance the integration of UAS into the NAS, a key priority for the Federal Aviation Administration (FAA). By addressing the current limitations in airspace management, the VCT system could play a pivotal role in supporting the safe and efficient operation of both manned and unmanned aircraft in increasingly crowded airspace.

II. Project Objectives

The primary objective of this project was to validate and demonstrate the capabilities of the Virtual Control Tower (VCT) system developed by Lighthouse Avionics as a comprehensive solution for modern airspace management. The VCT system is intended to address the growing needs of the aviation industry, particularly in supporting Beyond Visual Line of Sight (BVLOS) drone operations, enhancing airport security, and facilitating the integration of Advanced Air Mobility (AAM) systems into the National Airspace System (NAS). To achieve these goals, the project focused on the following key objectives:

A. Validation & Verification

Before the VCT system could be considered for broader adoption, its capabilities, functionalities, and robustness required rigorous validation. The project aimed to verify that the system operates as designed, meeting or exceeding established benchmarks. This involved collecting and analyzing data to confirm that the VCT system could reliably track and classify manned aircraft, drones, and other airborne objects across various airspace volumes.

B. Safety Assurance

Safety is the cornerstone of any aviation-related project. A primary objective of this project was to ensure that the VCT system aligns with established safety standards, minimizing risks and ensuring secure operations in the airspace. The data collected during the tests was crucial in validating that the system could safely manage air traffic, particularly in complex environments involving both manned and unmanned aircraft.

C. Operational Efficiency

Beyond ensuring safety, the project sought to enhance the operational efficiency of the VCT system in managing airspace. This involved analyzing key performance metrics such as latency, update rate, and position and velocity accuracy to identify areas for improvement. The goal was to ensure that the VCT system could optimally support aviation operations by providing timely and accurate information to air traffic controllers and other stakeholders.

D. Performance Metrics Development

To comprehensively evaluate the VCT system's performance, the project focused on developing a statistical profile for several critical metrics. These metrics were analyzed within the largest relevant airspace volumes defined by RTCA DO-381 [1] (for manned aircraft) and RTCA DO-396 [2] (for small unmanned aircraft systems, sUAS). See table 2-4 from DO-381 [1] for the metrics and the description of the confidence level required. As presented in there the system must ensure that 95% of the reports compared against ground truth meet the standard, both from the raw system output and the tracker projection system placed on top. The key performance indicators (KPIs) are included here:

- **Latency:** The time from image capture to the update of the integrated system state was measured to determine the system's responsiveness. The objective was to achieve a mean latency of 100ms for manned aircraft and 300ms for sUAS.
- **Update Rate:** The frequency at which the VCT system analyzed the 360-degree camera set was measured, with a target update rate of 1Hz.

- **False Track (False Positive):** The project aimed to minimize false detections of manned aircraft entering the declaration volume, with a goal of less than 0.3 false tracks per hour per square mile.
- **Missed Track (False Negative):** The system's ability to detect all manned aircraft entries into the declaration volume was assessed, with an objective to minimize missed tracks.
- **Position and Velocity Accuracy:** The accuracy of the VCT system in determining the horizontal and vertical positions and velocities of detected objects was evaluated. The target accuracies were set to within 175m horizontally and 105m vertically for manned aircraft, and 10m for both dimensions for sUAS.

E. Stakeholder Communication

Transparent and consistent communication with stakeholders was vital throughout the project. The data analysis provided stakeholders with clear, actionable insights into the VCT system's performance. This informed decision-making and helped guide the strategic development of the VCT system.

F. Strategic Development

The insights derived from the data analysis did not only serve the immediate needs of the project but also informed future developments. Recognizing patterns, challenges, and opportunities through the collected data was key to guiding the strategic evolution of the VCT system. The project aimed to ensure that the VCT system remains aligned with the long-term goals of integrating AAM and supporting UTM developers and city/state governments.

G. Regulatory Compliance

A critical objective of the project was to demonstrate the VCT system's compliance with relevant regulatory standards. The aviation industry is governed by a myriad of regulations, and by analyzing the data from the operational tests, the project aimed to build a strong case for the VCT system's widespread adoption. The data collected was used to validate that the system meets the necessary performance and safety standards outlined in RTCA DO-381 [1] and DO-396 [2], ensuring its readiness for integration into the NAS.

III. Project Structure

The project titled "Low-Altitude Low-Cost Networkable Virtual Control Tower with Localized Sensor Systems to Support Autonomous Operations," led by Lighthouse Avionics, was a comprehensive effort spanning several critical phases. This project aimed to develop, validate, and demonstrate a Virtual Control Tower (VCT) system capable of providing scalable, cost-effective airspace management, particularly for supporting Beyond Visual Line of Sight (BVLOS) drone operations and enhancing overall airspace safety.

A. Project Initiation

The project began with a structured initiation phase, where the key project elements were defined, and the foundational planning took place. This phase included participating in a contract kickoff meeting with the UAS Integration Office (AUS), attending training sessions for FAA deliverable submittal tools, and creating an Integrated Master Schedule (IMS) that outlined the timeline for all subsequent project tasks.

B. Development and Planning

During the development and planning phase, the focus was on establishing the necessary framework for the VCT system's validation and testing. A Data Analysis Plan was created to explain how the VCT performance would be evaluated. Additionally, a Requirements Traceability Verification Matrix (RTVM) was developed, defining the technical and operational requirements that the VCT system needed to meet. This matrix was refined through stakeholder feedback and subsequently presented to the FAA for review and acceptance.

C. Hardware and Software Updates

This phase involved finalizing the design modifications required to ensure the VCT system's optimal performance during testing. The hardware and software were updated, and the final digital designs and architectures were presented to the FAA for approval. This step was crucial in ensuring that the VCT system was built on a solid foundation, capable of meeting the project's ambitious objectives.

D. System Preparation

The system preparation phase was extensive, involving the assembly of two VCT units to be used for testing and evaluation. These units were equipped with embedded and localized control systems, computer vision, communication networks, and artificial intelligence components. A series of component and system-level tests were conducted to ensure that the hardware and software operated harmoniously. Field testing was performed both at Lighthouse Avionics' facility and at the City of Hilliard to verify the VCT's operational specifications. Network connectivity and data communication tests were also carried out, with results documented in interim reports.

E. Installation and Initialization

With the system prepared, the VCT units were installed at the Griffiss International Airport. This phase included site visits to determine optimal placements for the VCTs, followed by the installation and initialization of the units. Initial connectivity tests with the operations center and local UTM/DAA software were performed to ensure the system's readiness for subsequent flight testing.

F. Flight Testing

The flight testing phase was divided into two key stages:

- **Flight Test #1**: Passive data collection and evaluation of ongoing operations were conducted at the NY UAS Test Site. This stage focused on assessing the effectiveness of the onboard computer vision, artificial intelligence, and processing systems.
- **Flight Test #2**: A series of controlled tests were executed to evaluate the VCT system's performance under specified conditions. Data collected during these tests was analyzed for accuracy and efficacy, with results documented in detailed test reports.

G. Data Analysis and Final Reporting

The final phase of the project involved a comprehensive analysis of all the data collected during the previous tasks. This analysis was conducted in accordance with the Data Analysis Plan and focused on validating the VCT system's performance against the project objectives. The findings from this analysis were compiled into the final report submitted to the FAA. The report includes an executive summary, background information, project objectives, methodology, results and discussion, and recommendations for future work.

H. Focus of This Report

This report specifically covers the methodology and results of the flight testing performed during the final phase of the project structure. The team designed and executed tests to validate the VCT system's performance, focusing on critical metrics such as latency, update rate, and position accuracy. The findings presented in this report represent the culmination of extensive hardware and software development, system integration, and rigorous testing, providing insights into the VCT system's current capabilities and areas for future improvement.

IV. Methodology

The methodology for this project involved a series of steps designed to evaluate the performance of the Virtual Control Tower (VCT) system installed at Griffiss International Airport. The primary goal was to assess the system's ability to track and classify airborne objects, particularly manned aircraft and drones, as well as analyze the accuracy of its projections compared to actual position data.

A. VCT Installation and Data Collection

Three VCT units were installed at Griffiss International Airport in early June 2024. Each VCT unit was equipped with 42 fixed cameras and a Pan-Tilt-Zoom (PTZ) camera. Additionally, a Ping Station 3 unit was installed on one of the VCTs to capture the transmitted positions of aircraft in the vicinity. Following the installation, the system underwent calibration, tuning, and debugging to ensure optimal operation.

Video data was collected passively from June through August 2024. This data, including video feeds from all cameras and ADS-B data captured by the Ping Station, was stored on a central server for subsequent analysis. The original plan to utilize automated detection and tracking for direct comparison with ADS-B data was revised due to limitations in the detector's performance. Specifically, the automated detection algorithms did not consistently meet the accuracy and reliability benchmarks necessary for fully automated operation. These limitations included challenges in detecting small or distant objects, accurately classifying objects under varying environmental conditions, and differentiating between closely spaced objects. As a result, we adopted a more manual approach to validation, where the analysis focused on evaluating the performance of individual system components rather than relying on end-to-end automated processing. The team believes the detection model issues can be resolved, but just ran out of time on the project to perform the adjustments necessary to get the system fully operational. The details of this manual analysis will be presented in subsequent sections.

Figure 1: VCT Across the Runway from Hangar

Figure 2: VCT at North End of Runway

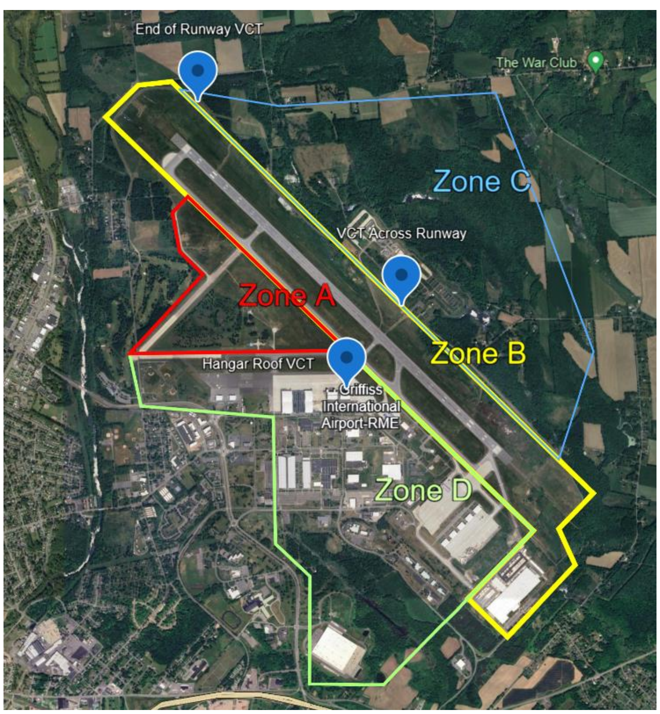

Figure 3: VCT Placement Map

Figure 4: VCT on Hangar Roof

B. Data Set Creation and Manual Object Identification

Given the detector's limitations in accurately differentiating between different types of objects, a manual analysis of system's ability to meet the stated objectives was performed by analyzing the different system subcomponents that would contribute to the fully integrated systems ability to meet the objectives. In order to perform this manual analysis, the team constructed a data set that would be useful specifically for validating the triangulation accuracy for position and velocity, as well as for performing an analysis of the current detector performance. This dataset creation process began with identifying time periods when aircraft were near the VCT units by reviewing logs and video feeds. A specific dataset was then created by linking video feeds with ADS-B data for identified aircraft, allowing for targeted analysis. The dataset consisted of 10 hours and 11 minutes of ADS-B data and the associated video feeds for 11 aircraft across 25 flights. This totaled around 20,000 total ADSB reports.

To streamline the manual identification process, custom software was developed to parse stored ADS-B data alongside the video recordings from the VCT units. Due to storage constraints, video data was only captured during specific times of day with a higher likelihood of aircraft activity. The software predicted which cameras on the VCT units the aircraft would likely be visible on based on the ADS-B data and the VCTs' known orientation.

The resulting video feeds were then presented to manual operators. These operators were tasked with identifying the aircraft within the video frames, assisted by bounding boxes indicating the projected location of the aircraft based on the ADS-B data and the camera's intrinsic and extrinsic parameters. Operators marked the center location of the aircraft or indicated if the aircraft was not visible. This data associated a particular ADSB report with the pixel location of the aircraft in all the cameras in which it was visible. The subsequent sections describe the utilization of this dataset to perform an analysis of whether the system subcomponents indicate that automated system, once developed, will be capable of meeting the objectives.

C. Position Accuracy Calculation

The manually identified positions from the dataset were then used to triangulate the aircraft's location in 3D space whenever the object was visible in more than one camera feed. This triangulation data was compared to the ADS-B positions to evaluate the system's position accuracy. The reports utilized in this analysis consisted primarily of NACp values greater than 9 and NIC values greater than 9. The data collected through this process was first utilized to refine the VCT system's orientation. Software was developed to analyze the average angular error by comparing the object's bearing vector with the ADS-B reported bearing vector. Adjustments were then made to the orientation settings of each fixed camera that had recorded data during the tests. The necessary rotations around relevant axes were calculated using vector math to align the VCT's object bearing vectors with the ADS-B bearing vectors.

Once the orientation settings were updated, the data purged any reports on the high side that were more than 5 standard deviations above the mean with the assumption that these reports resulted from situations where the user had selected the wrong object for triangulation in at least one of the cameras. Following this, the horizontal and vertical errors were plotted against the ADS-B reported object distance, averaged across the distances from the three VCT units. Separate scatter plots were created for triangulation using data from all three VCTs versus data from only two VCTs. It was observed that errors were largest when the VCTs and the object of interest were nearly collinear (within approximately 5 degrees). To address this, data where the objects were nearly linear with the VCTs were filtered out from the dataset. The team plans to use differential sizing in conjunction with the angle based triangulation in the future, but since this feature wasn't yet developed before performing the analysis, no 2 VCT linear alignments were included in the position calculations. This filtering process significantly improved the accuracy of the position calculations.

Future work will explore augmenting this dataset by incorporating object size differentials to enable trilateration, particularly in scenarios where the VCTs and the object are nearly collinear. By adding relative object sizes as an input to the positioning system, the team expects to enhance accuracy, especially as the VCTs and objects approach close to linear alignment. Following the refinement and filtering steps, the data was analyzed to calculate metrics such as the mean and standard deviation of horizontal and vertical errors. These metrics were further binned by distance to identify viable spots for accurate positioning. The final metrics were calculated for mean, standard deviation, and percentage of the data points meeting the standards were calculated of all bins of 1.5 km between 0 and 15 km from the center point of the VCTs.

Figure 5: Demo of VCT 4 Sector 6 Camera 2

Figure 6: Demo of VCT 4 Sector 6 Camera 4

Figure 7: Demo of VCT 6 Sector 5 Camera 0

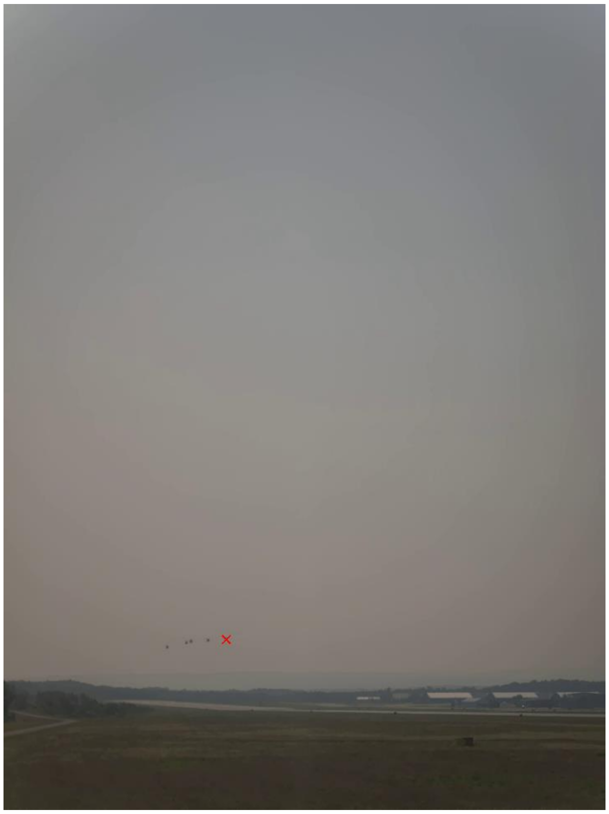

Figure 8: Demo of VCT 3 Sector 3 Camera 0

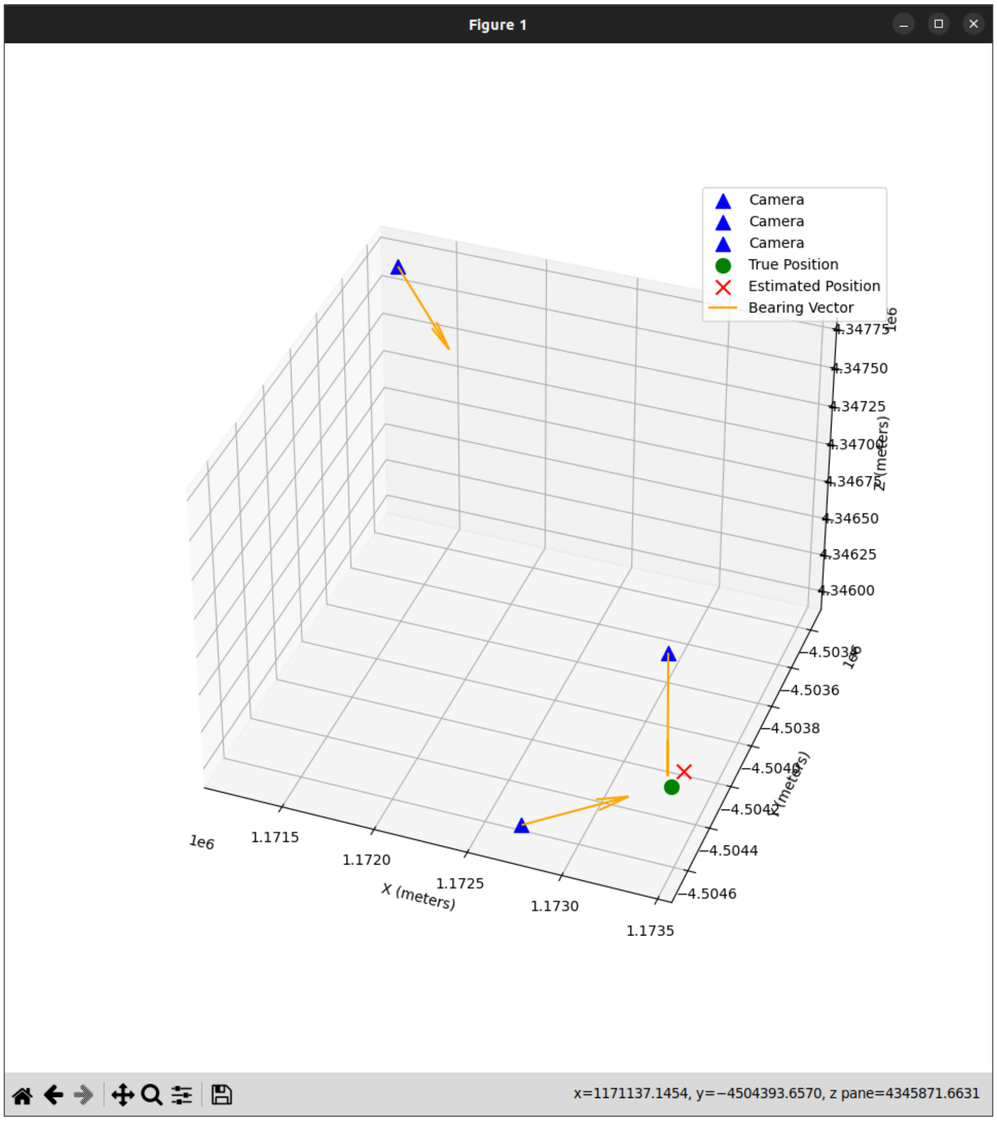

Figure 9: Demo of Triangulation Script Output Plot

D. Detection Model Evaluation

Following the manual validation of aircraft positions, the collected data was used to evaluate the performance of several detection models developed by the team. These models varied in their training data and the specific classes they were designed to detect. The evaluation focused on determining each model's ability to accurately detect and bound the aircraft in the manually labeled images.

Each detection model was run on the manually labeled images, and the output was analyzed to determine whether the model successfully detected the aircraft. A detection was considered successful if the model correctly placed a bounding box around the pixel location identified by the user. This simplistic metric was applied to give a general measure of each model's capability.

The detection results were then categorized into distance bins, representing the distance of the aircraft from the VCT unit at the time of detection. These bins were used to generate histograms that displayed the accuracy of each model as a function of distance. As expected, detection accuracy typically decreased as the distance between the aircraft and the VCT increased, reflecting the challenges of detecting smaller, more distant objects. An exception to this rule was for planes from 0 to 1 kilometer from the VCTs. This anomaly is likely due to the underrepresentation of instances in the training dataset involving planes flying below the horizon, particularly as they approached a runway. Consequently, the model struggled to accurately detect planes within this proximity. In support of this theory, the drone which flew mostly above the horizon at close distances shows the expected behavior of better performance at closer distances with the same detection models.

To control the rate of false positives, a subset of the detection results was manually reviewed. The subset reviewed included a separate sample for each analyzed aircraft. Each sample consisted of all the frames associated with 10 randomly selected ADS-B reports, resulting in 1 to 6 frames per report, depending on how many cameras had the aircraft within their field of view. Due to the overlap in airspace coverage between adjacent cameras, an aircraft could be captured by up to 6 cameras simultaneously. During this review, any images containing more than one false detection were flagged, and the model's confidence rate filter was adjusted accordingly. The models were tested at confidence levels of 0.005, 0.01, 0.03, and 0.05, where only 0.05 passed the false positive test for all the samples. This adjustment ensured that the data metrics reflected a more realistic detection accuracy, balancing between correctly identifying aircraft and minimizing false positives. Other than the tuning of the confidence threshold, there was no tuning or training of the model on the dataset gathered at Griffiss; it served purely as a validation dataset for the model. The performance of each model was assessed using several key metrics:

- **Bin Detection Accuracy**: The primary metric for each model was the percentage of correctly detected objects within each distance bin. These results were presented as histograms to illustrate how detection accuracy varied with distance from the VCT.
- **Overall Detection Accuracy**: A summary metric was calculated for each model, representing the overall percentage of correctly detected objects across all distance bins.
- **Relative Runtime**: The relative runtime of each model was also recorded, providing an indication of the computational efficiency of each model. While the raw timing data was collected on desktop computers, the relative differences in runtime are expected to hold across different platforms, even if absolute timings differ.

This analysis is crucial for determining which detection model offers the best balance of accuracy and efficiency. The results will guide future development efforts, helping the team decide whether to pursue a simpler detection model focused exclusively on manned aircraft or larger objects that could potentially be manned aircraft. Such a model might trade off some detection range for improved reliability and simplicity, which could ultimately enhance the system's overall performance.

Additionally, the team is considering reducing detection frame rates to further improve accuracy, a strategy that will be explored in more detail in the future work discussion. The plots provided in the results section will include histograms showing detection accuracy percentages for each model across different distance bins, as well as overall accuracy metrics and relative runtimes for each model.

E. Velocity Accuracy

Velocity accuracy was a critical metric for evaluating the performance of the VCT system in tracking moving aircraft. The accuracy of the system's velocity estimates was determined by comparing them to the known velocities reported by ADS-B data. The following steps outline the process used to calculate and assess velocity accuracy.

The team utilized the manually positioned and triangulated objects to calculate velocity vectors based on changes in position over time. Specifically, the following procedure was applied:

1. **Triangulation and Position Changes:** For each object that was successfully triangulated at least twice in a 1-second window, the relative position changes between each successive triangulation was recorded.
2. **Velocity Vector Creation:** From these recorded position changes, velocity vectors were created. These vectors represent the estimated velocity of the aircraft over the given timeframe.
3. **Comparison with ADS-B Data:** The calculated velocity vectors were then compared to the corresponding velocity data reported by ADS-B. This comparison was performed separately for horizontal and vertical components of the velocity.

The accuracy of the velocity estimates was assessed by calculating the mean and standard deviation of the errors between the VCT-estimated velocities and the ADS-B-reported velocities. These errors were analyzed both as a global metric across all distances and within specific distance bins to understand how velocity accuracy varies with the distance from the VCT units.

- **Global Metrics:** The overall mean and standard deviation of the velocity errors were calculated, providing a broad measure of the system's performance across the entire dataset.

- **Binned Analysis:** The data was also divided into distance bins, and the mean and standard deviation of the velocity errors were calculated within each bin. This binned analysis helped to identify any trends in accuracy relative to the distance from the VCT units.
- **Error Distribution Plots:** A plot of the raw velocity error values versus the distance from the VCT units was generated, illustrating how velocity accuracy changes with distance. This plot, along with the binned metrics, provides a comprehensive view of the system's velocity estimation capabilities.

The velocity accuracy metrics will be presented similarly to those reported for position accuracy, allowing for direct comparison and providing insights into the VCT system's overall performance.

F. Latency and Update Rate Testing

The latency and update rate of the VCT system were critical metrics for evaluating the system’s ability to process and respond to real-time data effectively. These metrics were analyzed using a combination of bench-top tests and live operations, focusing particularly on the performance of the detection models running on Jetson Orin AGX units. Given that the automated triangulation system was not fully functional by the end of the project, the approach to testing these metrics was adapted to estimate their potential in a fully developed system.

The latency and update rate targets were based on industry standards set by RTCA DO-381 [1] and DO-396 [2]. The key performance indicators (KPIs) are as follows:

- **Latency:** The system aimed to achieve a latency of 100 ms for compliance with DO-381 [1] and 300 ms for compliance with DO-396 [2].
- **Update Rate:** The system aimed to achieve an update rate of 1 Hz for compliance with both DO-381 [1] and DO-396 [2].

Latency was measured by combining several factors, including the ping times between the central server (or cluster) and the various components within the VCTs, as well as the processing times recorded by the Jetson Orin AGX units during detection operations.

1. **Ping Latency Analysis:**
    - The team first measured the latency of the network communications between the central server and each VCT component by analyzing ping times. These measurements provided a baseline understanding of the communication delays within the system.

- Ping latency data was collected over multiple sessions, and the mean and standard deviation of these times were calculated. The average ping latency across the three VCTs was then determined to provide an overall estimate.

2. **Detection Pipeline Latency:**
   - To estimate the latency introduced by the detection pipeline, a specific test was designed where the VCT computer ran the currently selected detection model. This test measured the time elapsed between the moment the detection data hit the Redis database and the moment the corresponding image was captured by the sensor.
   - An additional fixed 50 ms buffer was added to these measurements to account for the time required by the tracking methods to utilize the raw detection data for updating tracking states. This buffer was based on estimations of future system requirements as discussed in the future work section.
3. **Overall Latency Estimation:**
   - The overall system latency was estimated by combining the average ping latency measurements with the detection pipeline latency. This combined metric provided a reasonable estimate of the system's response time in a fully operational state.
   - The results were analyzed by calculating the mean and standard deviation of the overall latency, using the average performance across all VCT units to ensure a comprehensive assessment.

The update rate, defined as the frequency at which the VCT system processed detection data across all pixel locations within the captured images, was another essential metric for evaluating the system's real-time capabilities.

1. **Live Detection Rate Monitoring:**
   - The update rate was primarily determined by the detection rate of the currently implemented model running live during the tests. As the model processed data, it generated detections that were continuously sent across Redis channels.
   - The team listened to the Redis channels to retrieve the rate of data generation from each VCT over the test period. This provided a direct measure of how frequently the system was able to update its detection states.
2. **Update Rate Calculation:**

- The data retrieved from the live detection runs was analyzed to calculate both the mean and standard deviation of the update rate across the system. This analysis highlighted the consistency and reliability of the detection process in maintaining real-time awareness of the airspace.
- The update rate was converted from seconds per detection report to Hertz (Hz) to align with the target performance metrics.

These metrics, while reflective of the system's current state, also provided insights into areas where further development and optimization are needed, as detailed in the future work section. The results of these tests, along with relevant plots and charts, will be presented in the subsequent section.

G. Limitations and Challenges

Throughout the course of this project, several limitations and challenges were encountered that impacted the overall performance and outcomes of the Virtual Control Tower (VCT) system. These limitations highlight the areas that require further development to achieve a fully optimized and operational system capable of meeting the project’s initial objectives.

1. Detection Model Performance

One of the most significant limitations was the underperformance of the detection models. The models struggled to accurately differentiate between manned aircraft, drones, birds, and other airborne objects, which hindered the system's ability to reliably track and classify targets. We think this was some combination of model size and/or amount of data provided to the system, since similar large models have worked well in the past. This limitation necessitated a shift from the original plan of fully automated detection and tracking to a more manual approach to validating the system’s possible performance. Instead of characterizing the fully integrated system performance we had to fall back to analysis of subcomponent performance using the manual validation methods.

However, this pivot to manual validation was not merely a workaround but a strategic decision aimed at providing crucial validation of the system’s positioning capability. By manually identifying and triangulating objects, the team was able to assess the accuracy of the VCT system’s orientation and the validity of its triangulation processes. This manual approach allowed the team to validate that, once properly configured, the system could achieve the desired accuracy in positioning, even though the automated detection models were not fully functional.

Moving forward, the team plans to improve the detection models to reach the level of performance necessary for automated operation. The insights gained from the manual validation will guide these improvements, ensuring that the automated system, once fully developed, will meet the stringent accuracy and reliability requirements.

2. Automated Object Triangulation

Another major challenge was the limited performance of the automated object triangulation and tracking scripts. These scripts, which were intended to automatically correlate and calculate the 3D positions of detected objects based on bearing data from multiple VCT units was not performing sufficiently. This was mostly hindered by the detection model performance as described above. Since detection was inconsistent development of the tracking model was hindered and thorough performance analysis couldn't really be tested on real data, since the real detection data did not meet the standards expected. This led to inaccuracies in positioning and required manual intervention to validate and correct the triangulated positions.

The shift to manual triangulation allowed the team to rigorously test and refine the system's orientation settings and validate the underlying positioning algorithms. While this manual process was more labor-intensive, it provided a necessary foundation for validating the system's capability to accurately determine object positions. The lessons learned from this process will be instrumental in enhancing the triangulation scripts for future automated use.

3. Field of View (FOV) Limitations

The height and positioning of some VCT units also presented challenges, particularly in terms of field of view (FOV). The limited FOV reduced the system's ability to effectively triangulate objects, especially at greater distances or lower altitudes. This limitation affected the overall coverage area of the VCT system and its ability to provide comprehensive airspace monitoring.

Addressing this challenge will require careful consideration of VCT placement and potentially adjusting the height or angle of the cameras to maximize FOV and improve triangulation capabilities. Additionally, future work may explore alternative mounting solutions to make sure placement of VCT's is always above the local tree line.

4. Latency and Update Rate Constraints

The project successfully measured latency and update rates, but these metrics had to be estimated based on the performance of individual subcomponents rather than the full system. Due to the fact that the fully integrated tracking and triangulation scripts were not yet operational as originally planned, it was not possible to calculate a comprehensive latency and update rate for the entire system. Instead, the team estimated these values by analyzing the performance of key subcomponents, such as the network communication latency (ping times between the central server and VCT units) and the detection pipeline latency on the Jetson Orin AGX units.

By summing the latencies of these subcomponents, the team was able to provide an estimated value for the overall system latency and update rate. Although these estimates were within acceptable ranges for the current state of the system, further optimization is necessary to meet the stringent requirements of real-time airspace management. Future work will focus on optimizing both hardware and software components, reducing communication delays, and improving the integration of detection, tracking, and triangulation processes to achieve more accurate and reliable real-time performance.

V. Results and Discussion

The results of this study provide critical insights into the current capabilities and limitations of the VCT system. The following sections discuss the key findings from the analysis of position accuracy, detection performance, velocity accuracy, and system latency and update rates.

A. Position Accuracy

The position accuracy of the Virtual Control Tower (VCT) system was evaluated by comparing the triangulated positions of detected manned aircraft against the known positions provided by ADS-B data. This analysis aimed to determine whether the system could meet the stringent positioning requirements outlined in the RTCA DO-381 and DO-396 standards.

The VCT system's performance in terms of horizontal and vertical positioning accuracy was assessed across various distances. The key performance indicators (KPIs) set by DO-381 and DO-396 standards require the system to achieve a horizontal position accuracy within 175 meters and a vertical position accuracy within 105 meters for manned aircraft, with even more stringent requirements of 10 meters for both horizontal and vertical accuracy under DO-396 for small unmanned aircraft systems (sUAS).

Table 1. Vertical Position Errors

Start of Bin (m)	End of Bin (m)	Number of Data Points	Mean Error (m)	Standard Deviation (m)	Percent of Data Meeting DO-381	Percent of Data Meeting DO-381
0	1500	393	11.47	5.75	100.0%	44.8%
1500	3000	619	10.56	9.11	99.5%	59.8%
3000	4500	407	11.55	9.43	100.0%	41.0%
4500	6000	421	8.19	13.25	98.8%	77.0%

6000	7500	465	14.15	23.81	98.7%	50.5%
7500	9000	114	64.25	68.63	78.9%	34.2%
9000	10500	24	19.71	5.67	100.0%	0.0%
10500	12000	178	28.21	4.61	100.0%	0.0%
12000	13500	91	36.18	4.39	100.0%	0.0%
13500	15000	52	47.00	5.62	100.0%	0.0%

Table 2. Horizontal Position Error

Start of Bin (m)	End of Bin (m)	Number of Data Points	Mean Error (m)	Standard Deviation (m)	Percent of Data Meeting DO-381	Percent of Data Meeting DO-381
0	1500	393	6.5	8.4	100.0%	87.0%
1500	3000	619	17.2	70.2	98.9%	75.8%
3000	4500	407	14.8	26.5	99.0%	50.6%
4500	6000	421	20.4	46.6	98.3%	51.3%
6000	7500	465	50.9	170.4	97.8%	9.9%
7500	9000	114	546.5	625.4	34.2%	10.5%
9000	10500	24	58.6	36.2	100.0%	8.3%
10500	12000	178	52.2	25.9	100.0%	9.0%
12000	13500	91	68.8	27.4	100.0%	0.0%
13500	15000	52	90.8	65.1	94.2%	0.0%

1. *DO-381 Compliance:*

The analysis shows that the VCT system meets the DO-381 horizontal and vertical position accuracy requirements out to approximately 7.5 km. This is a significant achievement, demonstrating that the system can provide reliable positioning for manned aircraft within this range. The charts included in this section illustrate that both the horizontal and vertical position errors remain within the specified limits of 175 meters and 105 meters, respectively, up to this distance.

2. *DO-396 Compliance:*

However, the system does not meet the more stringent position accuracy requirements set by DO-396. The horizontal and vertical errors exceed the 10-meter threshold well before reaching 5 km, indicating that the current VCT configuration is not suitable for applications requiring sUAS-to-sUAS deconfliction or other operations governed by DO-396. This outcome was anticipated, as the DO-396 positioning accuracy goals were ambitious given the current capabilities of the VCT system.

3. Position Accuracy Results Discussion

It is important to note that the position accuracy analysis did not account for potential errors in the ADS-B data used as a reference. ADS-B accuracy can vary depending on various factors, and any inherent inaccuracies in this data could influence the results. For example, a NIC of 9 represents a VPL of < 112 m error. Using ADSB as our ground truth will not allow us to demonstrate accuracies required for DO-396 since it is an order of magnitude lower error required than our reported ground truth source would provide. Consequently, the VCT system's actual performance might be better than reported here if ADS-B errors were factored into the analysis. Future investigations could explore the impact of ADS-B data accuracy on the system's performance and adjust the analysis accordingly.

Additionally, while the VCT system in its current configuration does not meet the DO-396 standards, the team recognizes that placing VCT units closer together or adjusting their configuration could potentially improve positioning accuracy. However, based on the current data, such a setup may still struggle to achieve the 10-meter accuracy required by DO-396, and this limitation should be considered in future planning and development efforts.

In summary, the VCT system has demonstrated compliance with the DO-381 horizontal and vertical positioning requirements out to distances beyond 7.5 km, affirming its suitability for supporting manned aircraft operations within this range. However, the system does not meet the more stringent DO-396 positioning requirements, which limits its applicability for certain sUAS operations. These findings are critical for guiding the future direction of VCT development, particularly in refining its application scope and considering potential enhancements to improve positioning accuracy further.

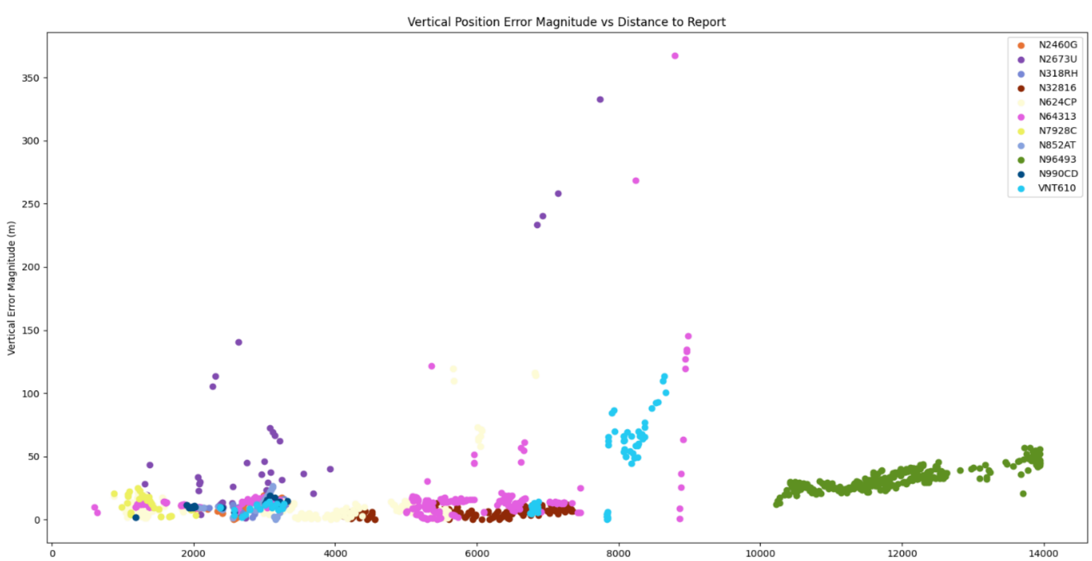

Figure 10: Scatter plot of vertical positioning error

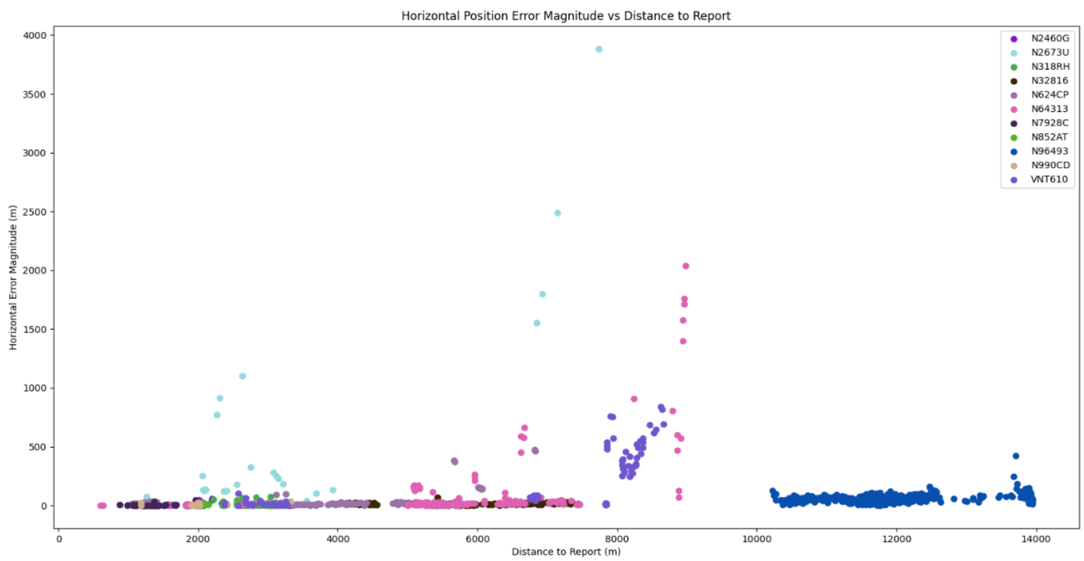

Figure 11: Scatter plot of horizontal positioning error

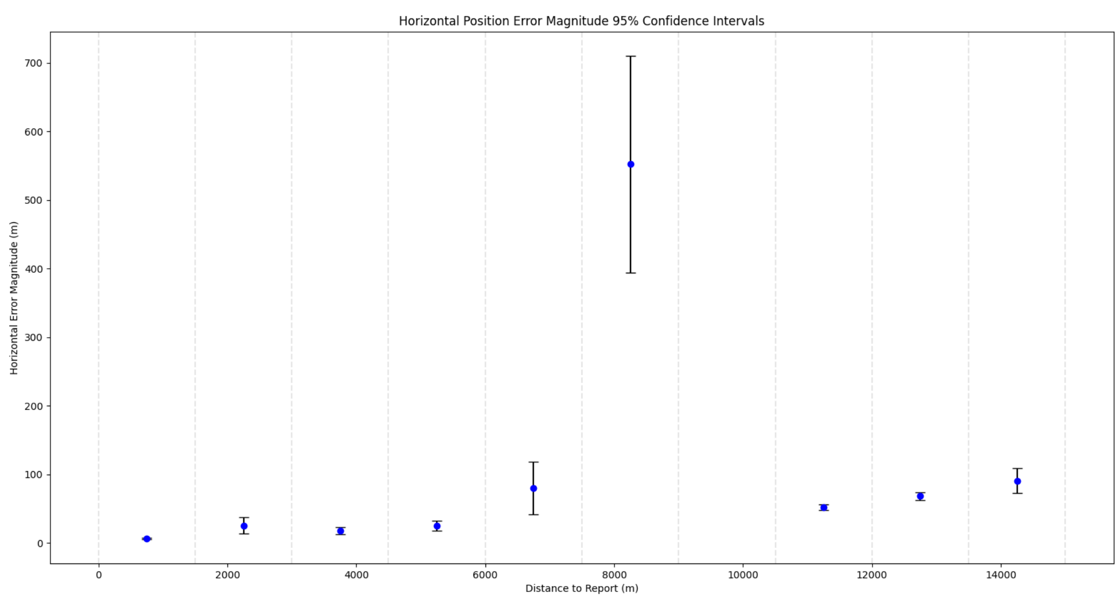

Figure 12: Horizontal Error Distribution by Distance

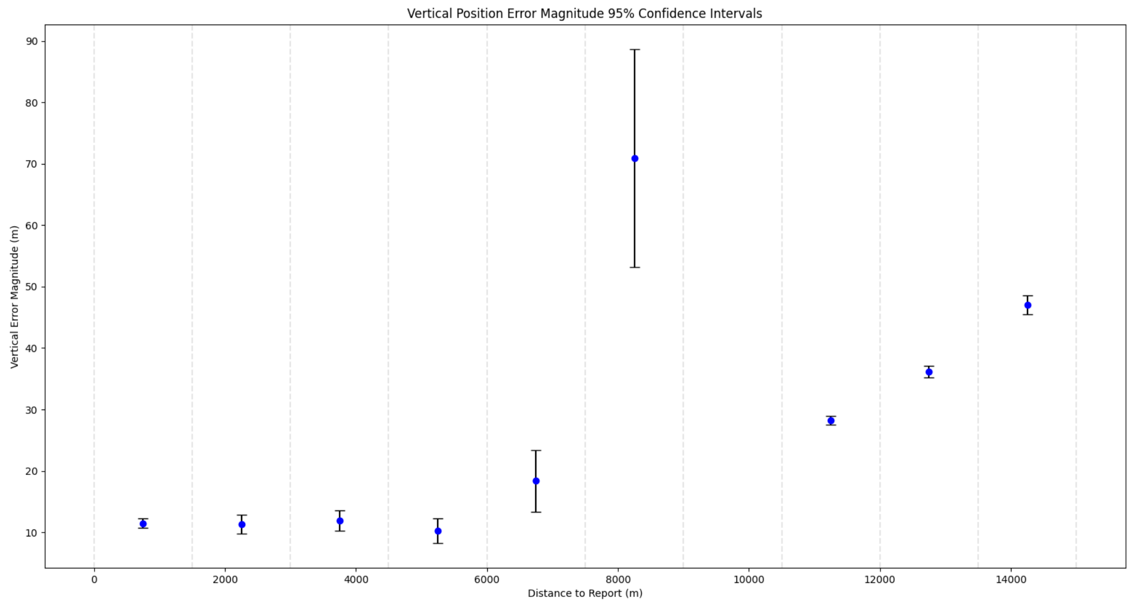

Figure 13: Vertical Error Distribution by Distance

B. Velocity Accuracy

The velocity accuracy analysis indicated that while the system could reasonably estimate the velocity of aircraft over short periods, discrepancies with the ADS-B data were observed. These discrepancies were more pronounced in scenarios with rapid changes in aircraft speed or direction, suggesting the need for more sophisticated filtering techniques.

Table 3: Vertical Velocity Errors

Start of Bin (m)	End of Bin (m)	Number of Data Points	Mean Error (m)	Standard Deviation (m)	Percent of Data Meeting DO-381	Percent of Data Meeting DO-381
0	1500	524	22.8	19.9	0.0%	0.0%
1500	3000	660	24.2	12.5	0.5%	0.5%
3000	4500	510	32.2	8.6	0.0%	0.0%
4500	6000	673	35.8	37.9	6.7%	2.4%
6000	7500	607	34.3	25.9	1.8%	1.3%
7500	9000	136	130.4	79.6	0.0%	0.0%
9000	10500	54	62.1	67.4	27.8%	16.7%
10500	12000	529	67.0	62.6	6.8%	4.0%
12000	13500	287	65.7	66.6	11.1%	8.4%
13500	15000	151	92.0	73.4	2.0%	0.0%

Table 4: Horizontal Velocity Errors

Start of Bin (m)	End of Bin (m)	Number of Data Points	Mean Error (m)	Standard Deviation (m)	Percent of Data Meeting DO-381	Percent of Data Meeting DO-381
0	1500	520	2.1	4.7	94.2%	85.2%
1500	3000	660	4.3	8.3	84.1%	59.4%
3000	4500	510	6.2	6.0	65.9%	36.3%
4500	6000	671	10.4	34.3	73.8%	49.2%
6000	7500	607	10.0	23.3	66.9%	37.6%
7500	9000	139	74.9	94.6	10.8%	10.8%
9000	10500	54	44.8	59.8	5.6%	5.6%
10500	12000	529	48.6	57.5	7.0%	4.0%
12000	13500	287	49.5	65.3	12.9%	4.9%
13500	15000	151	70.4	76.9	21.2%	16.6%

C. Latency and Update Rates

1. Latency Results

The latency measurements across the three VCT units yielded the following average results:

- **Ping Latency**:
    - **VCT6: Mean**: 1.86 ms, **Std Dev**: 0.51 ms
    - **VCT4: Mean**: 0.682 ms, **Std Dev**: 0.076 ms
    - **VCT3: Mean**: 0.738 ms, **Std Dev**: 0.048 ms
    - **Average Ping Latency Across VCTs**: 1.0933 ms
- **Detection Pipeline Latency**:
    - **Average Latency**: 99.60 ms
    - **Std Deviation**: 30.84 ms
    - **Max Latency**: 173.93 ms
    - **Min Latency**: 43.74 ms
- **Triangulation and Tracking Estimated Latency**: 50 ms
- **Total Estimated Latency**: 150.6933 ms

Comparing these results with the KPI targets:

- **DO-381 Target (100 ms) [1]:** The estimated latency of 150.6933 ms does not meet the 100 ms target for DO-381 [1] compliance.

- **DO-396 Target (300 ms) [2]:** The system's latency comfortably meets the 300 ms target for DO-396 [2] compliance.

While the latency results fall short of the DO-381 [1] standard, the team is not overly concerned. In a BVLOS application, it may be possible to implement other mitigations, such as reducing the declaration volume under the current standards, to maintain a similar level of safety. Additionally, the team plans to explore methods for reducing latency, such as decreasing the image size coming off the sensor or optimizing the queuing procedures to expedite data processing.

2. Update Rate Results

The update rate for the system was measured as:

- **Mean Update Rate:** 3.02 Hz
- **Standard Deviation:** 0.113 Hz

The target update rate of 1 Hz, as specified in both DO-381 [1] and DO-396 [2], was easily met by the system's performance.

3. Update and Latency Results Discussion

The results indicate that while the update rate metric was comfortably met, the latency metric for DO-381 [1] compliance presents a challenge. The team will need to consider various approaches to optimize latency, such as adjusting image resolution or improving data handling processes. Despite not fully meeting the DO-381 [1] latency requirement, the system's performance under DO-396 [2] is promising. The ability to achieve the 300 ms latency target under DO-396 [2] suggests that the VCT system can be effectively utilized in contexts with less stringent latency requirements or where additional mitigations can be employed to ensure safety. Overall, the system shows strong potential for real-time airspace management, and the insights gained from these results will guide future development efforts to further refine and optimize the system.

D. Latency and Update Rates

1. Model Differences

Model 1 was trained at a higher resolution than Model 2, 1152x2048 compared to 576x1024. The size differential of the models is apparent in the runtime differences shown below. Also, the training dataset for Model 1 was augmented with more drone images than Model 2.

2. Detection Results

For manned aircraft, the models performed similarly, with the most notable difference being model 1 overperforming overall while model 2 performed better within a kilometer, likely due to model 2 being of a smaller size. This performance is interesting because the runtime of model 2 is one third of model 1 with only a 13 percent difference in accuracy for manned aircraft. For pursuing improvements in latency, the team will explore if the difference in accuracy could be overcome while retaining the latency improvement for manned aircraft applications. For drones however, model 1 markedly outperforms model 2 by 43.7 percent. Most of this performance difference is likely due to the difference in training datasets.

The detection of drones by model 1 significantly outperforms model 1 for manned aircraft, particularly at distances less than 1 kilometer. This difference is likely due to the drone flying close and above the horizon compared to the manned aircraft which mostly entered the 1 kilometer range approaching the runway at low altitude. This hypothesis for the cause of poor manned aircraft detection is further supported by the fact the drones would appear smaller than the manned aircraft at a given distance but were detected more consistently regardless.

The performance differences suggest as the team expands the training dataset with new contexts and instances of different manned aircraft and drones, the unreliable detection models will greatly improve their performance. The team will work on expanding the training dataset and exploring other methods such as increasing the network size to improve the accuracy to a functional level.

Table 5: Detection Model Performance Metrics

	Accuracy % Manned Aircraft	Accuracy % Drones	Model Runtime (ms)
Model 1	63.93	82.6	30.33
Model 2	50.82	38.9	10.02

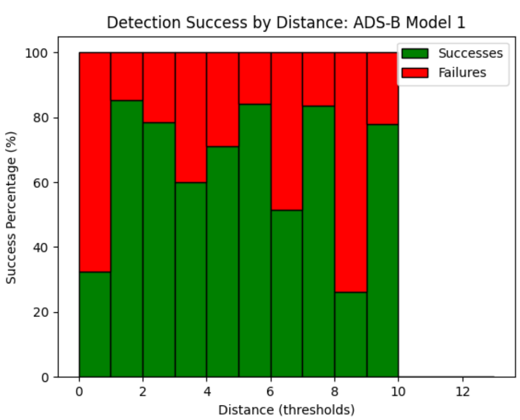

Figure 14: Detection Model 1 ADS-B Results

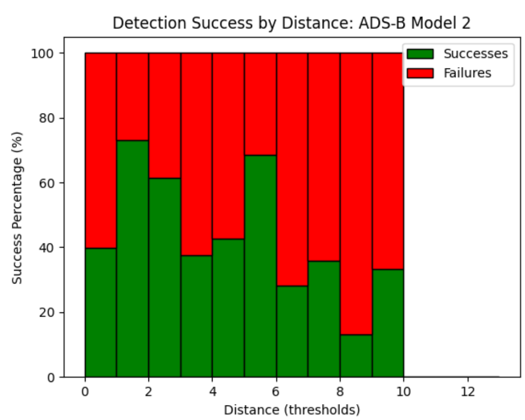

Figure 15: Detection Model 2 ADS-B Results

Figure 16: Detection Model 1 Drone Results

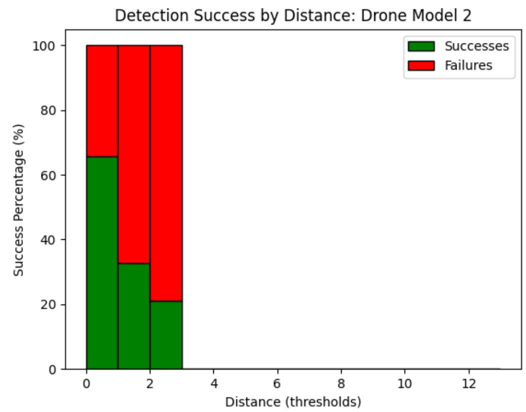

Figure 17: Detection Model 2 Drone Results

VI. Future Work

As the VCT project progresses, several key areas for improvement have been identified to enhance system performance and achieve the project's long-term goals. These areas will be the primary focus of future work, with the objective of refining the system to meet the stringent requirements of real-time airspace management, particularly in BVLOS applications.

A. Detection Model Performance

The foremost priority in future work is to significantly improve the detection model's accuracy, particularly in identifying "potential manned aircraft." The current detection model struggles with distinguishing between relevant and irrelevant objects, leading to a high rate of false positives for smaller, less critical objects such as bugs, birds, and distant aircraft that do not require immediate attention.

The team plans to develop a more specialized detection model optimized exclusively for manned aircraft. This model will prioritize detecting larger objects more likely to be manned aircraft, particularly those closer to the VCT units. The goal is to enhance performance for detecting nearby manned aircraft while deprioritizing the processing of distant or insignificant objects.

To achieve this, the team will regroup, using the detection rate data from this project to fine-tune and significantly upgrade the detection model. Sacrifices may be made in detection rate in favor of accuracy, and the team will explore the potential of using video clips instead of single frames to improve detection performance by leveraging motion information.

Additionally, a reporting filter may be implemented to require detection data to meet a minimum pixel size threshold before being considered for tracking. This will help the tracking systems focus on more likely objects that are closer and thus more relevant to airspace management. The team remains confident that, with these improvements, a sufficiently accurate and reliable detection model can be developed to meet the project's needs.

B. Triangulation and Tracking Enhancement

The performance of the triangulation and tracking stages is closely linked to the quality of the detection data. As the detection model is improved, the team will review and refine the object detection aggregation process to ensure accurate and consistent tracking.

Future work will focus on continuing the development of the triangulation and tracking systems, particularly through the use of simulated data. This parallel development approach will allow the team to make progress on tracking and triangulation even as the detection model is being improved. With better detection data, the tracking system is expected to perform more effectively, with fewer false objects and dropped tracks. Larger detected objects will be easier to track consistently across frames, reducing the likelihood of objects disappearing and reappearing unexpectedly.

C. Field of View and Placement Considerations

The effectiveness of the VCT system is heavily influenced by the placement and height of the VCT units. In future installations, the team will prioritize placing the system above the local tree line to maximize the field of view (FOV) and ensure optimal system performance and coverage.

To facilitate higher installations, the team will explore hardware improvements that make the VCT system easier to mount at elevated locations. This may involve reducing the weight and size of the units or potentially splitting the system into smaller subsections that can be more easily integrated at non-crown positions on towers or other high structures. By enhancing the system's physical design, it will be easier to secure placement on top of water towers, cell towers, radio towers, and similar structures, where space is often limited.

These improvements in system placement and design will significantly enhance the VCT system's overall capability, making it more adaptable and effective in a wider range of environments.

VII. Conclusion

The Virtual Control Tower (VCT) system developed by Lighthouse Avionics has demonstrated significant potential in providing accurate and reliable airspace monitoring capabilities, particularly in the context of supporting Beyond Visual Line of Sight (BVLOS) drone operations and enhancing overall airspace safety. Through extensive testing and analysis, the VCT system has proven effective in terms of its orientation accuracy, successfully meeting the required horizontal and vertical accuracy specifications for both position and velocity determination. This validates the core functionality of the system's triangulation process, confirming that the VCT units can provide precise positional data essential for modern airspace management.

However, while the foundational capabilities of the VCT system have been validated, the project has also highlighted the need for further development in the areas of automated object detection, tracking, and triangulation. The current detection models require significant refinement to improve their accuracy, particularly in distinguishing between relevant and irrelevant airborne objects. The automated tracking and triangulation scripts, which are dependent on the accuracy of the detection data, will also need to be enhanced to achieve the fully integrated system performance originally envisioned.

Despite these challenges, the VCT system's demonstrated ability to meet the stringent position and velocity accuracy requirements is a promising step forward. With continued development, the system holds substantial potential to support BVLOS operations and ensure that Unmanned Aircraft Systems (UAS) can operate safely within complex airspace environments. The successful integration of this system into the National Airspace System (NAS) could provide a scalable, cost-effective tool for modern airspace management, contributing to the FAA's mission of safely integrating UAS into the broader aviation ecosystem.

The insights gained from this project will guide the next phases of development, focusing on enhancing the system's automated capabilities to meet the safety and efficiency standards necessary for widespread adoption. The VCT system is poised to become a pivotal component in future aviation infrastructure, offering a robust solution for the dynamic and evolving needs of airspace management.

VIII. Acknowledgments

We would like to extend our sincere gratitude to AX Enterprize for their invaluable support in the on-site installation of the VCT units at Griffiss International Airport and their assistance in conducting drone flight tests as part of this project. Their collaboration was instrumental in the successful execution of the testing phases.

We also acknowledge Cal Analytics for their expert consulting services, which significantly contributed to the development and refinement of our project.

Special thanks go to the City of Hilliard, Ohio, for their ongoing support of our local testing efforts. The city provided a crucial testing ground, enabling us to refine our systems and processes before deployment at Griffiss International Airport.

We are also grateful to the Griffiss International Airport UAS Test Site for providing the facilities and support necessary for conducting our tests. Their collaboration has been essential to the project's progress.

Finally, we would like to thank the FAA UAS Integration Office for their guidance and oversight throughout the project. Their support has been pivotal in steering the project towards its goals.

IX. References

[1] RTCA, "Minimum Operational Performance Standards (MOPS) for Airborne Collision Avoidance System X (ACAS X)," RTCA DO-381, Washington, DC, June 2017.

[2] RTCA, "Safety, Performance and Interoperability Requirements Document (SPIRD) for Airborne Collision Avoidance System Xu (ACAS Xu)," RTCA DO-396, Washington, DC, December 2018.