Investigating Fundamental Issues in Lateral Conformance Monitoring Using a Fault Detection Approach

Tom G. Reynolds, R. John Hansman & Hong Li

International Center for Air Transportation, Department of Aeronautics & Astronautics

Massachusetts Institute of Technology, Cambridge, MA 02139, USA

***Abstract**:* Conformance monitoring is an essential function in air traffic management and control to ensure that aircraft adhere to assigned trajectories that maintain efficient traffic flows, secure airspace and safe aircraft separation. Many modern automation systems are incorporating conformance monitoring functions into their design to assist controllers in this task, while the introduction of new surveillance technologies will make more information available for conformance monitoring. There is therefore a need to identify important conformance monitoring issues and effective conformance monitoring approaches. This paper presents a technique for investigating conformance monitoring using fault detection methods. This approach is used to investigate conformance monitoring in the lateral domain under several representative ATC environments and to assess the implications of using more aircraft-derived state information.

Introduction

Conformance monitoring in air traffic control (ATC) describes the process that determines whether an aircraft is following its assigned trajectory so that corrective action can be taken if non-conformance is detected. "Flight Path Monitoring" and "Route Adherence Monitoring" are also used to describe this general process.

There is currently much interest in this topic since the ability to detect aircraft non-conformance in a timely fashion has implications for overall ATC system security, safety, capacity and efficiency. This function can be performed by controllers who compare radar data with the assigned trajectories on flight strips or from knowledge of commands that have been issued. Conformance monitoring functions with varying degrees of sophistication are also being included in many modern ATC automation systems to support the controller, including the US User Request Evaluation Tool (URET) [1], the European Flight Path Monitor (FPM) [2], the Canadian Automated Air Traffic System (CAATS) [3] and The Australian Advanced Air Traffic System (TAAATS) [4]. Most of these systems use a "threshold" approach based primarily on position such that non-conformance is flagged when the observed position deviation of an aircraft from the assigned trajectory exceeds some predetermined threshold. New technologies such as Automatic Dependent Surveillance (ADS) and Controller Pilot Data-Link Communication (CPDLC) may enable more effective conformance monitoring to be undertaken by making more aircraft-derived information available to the conformance monitor, whether it is an automated system or a human controller [5].

In this paper, a previously-developed analysis framework [6] is briefly described and then used to analyze conformance monitoring in a number of representative ATC environments. By drawing parallels across other ATC environments, the results from these analyses allow general conformance monitoring issues to be discussed and allow consideration of the impact that new technologies may have on the task.

Conformance Monitoring Analysis Framework Development

Conformance Monitoring as Fault Detection

In order to provide a context for discussing conformance monitoring issues and to investigate the impact of future ATC technologies, a Conformance Monitoring Analysis Framework has been developed [6]. By posing the conformance monitoring task as a fault detection and isolation (FDI) problem (where non-conformance of an aircraft is considered a "fault" to be detected in the

ATC system), the framework utilizes a general model-based fault detection technique [7] as illustrated in Figure 1.

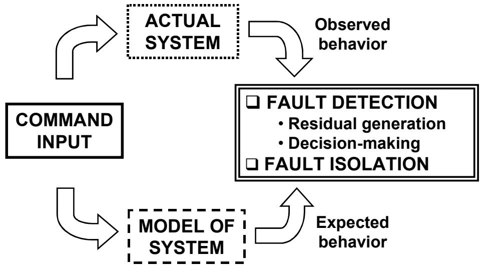

Figure 1: General Model-Based Fault Detection

In the generalized case, the actual system of interest receives command inputs and the resulting system response available to an observer is characterized by those system states that are measured from sensors or surveillance systems. A model of the actual system being monitored is used to develop an expectation of the behavior of the states of interest given the same command input and other knowledge of the system. The resulting observed and expected behaviors at any given time are used as input to the three FDI processes of:

- **Residual generation**: the difference between the observed and expected state behaviors is quantified by a residual. The residual is generated in such a way that the larger the difference between the observed and expected behaviors, the larger is the residual.
- **Decision-making**: once a residual has been generated, a decision-making function determines whether it indicates a fault exists in the system or not. One simple approach is to declare that a fault exists if the residual exceeds some pre-determined threshold. Signal detection theory can be used to set thresholds based on performance metrics of interest, such as time-to-detection or false alarm targets.
- **Fault isolation**: after a determination of non-conformance has been made, fault isolation techniques can be used to determine where the fault may have occurred so that system reconfiguration can be attempted to compensate for the detected fault.

Model-based Conformance Monitoring

The various elements of the general model-based fault detection concept illustrated in Figure 1 can be customized for the conformance monitoring application as shown in Figure 2.

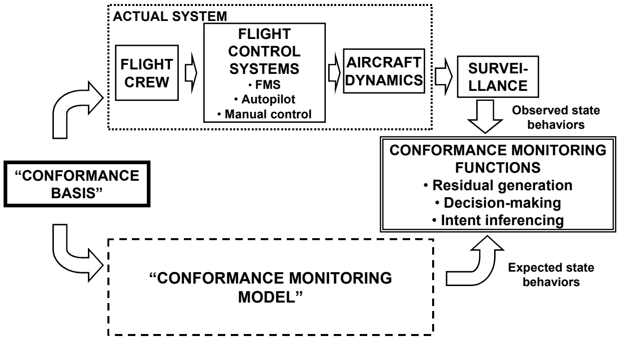

Figure 2: Model-based Conformance Monitoring

The command input is now considered the "Conformance Basis", i.e. the basis against which the conformance of a subject aircraft is being compared, such as the assigned trajectory.

The pilots make appropriate inputs to the aircraft systems (flight automation or manual control) to manage the aircraft trajectory in a manner consistent with the active Conformance Basis. These actual system processes are shown by the upper box in Figure 2 and some of the states are observable through the available surveillance system(s).

The expected state behaviors are based on a "Conformance Monitoring Model" (CMM) shown in the lower box. This can be an explicit model of the actual system being monitored, or based upon more abstract knowledge of the expected behavior of the system. Either way, the model requires sufficient form and fidelity to determine expectations on the states that are to be used in the residual generation task.

The "Conformance Monitoring Functions" block at the right receives the observed states and determines at any given time whether they are consistent with the expected behaviors being output from the CMM by using the FDI-inspired techniques of residual generation, decision-making and fault isolation. In the context of a conformance monitoring application, the fault isolation task attempts to identify what the aircraft *is* doing if it *is not* conforming and this is therefore termed "intent inferencing".

Each of these aspects will be discussed in the context of the Conformance Monitoring Analysis Framework that has been developed.

Conformance Monitoring Analysis Framework

The model-based conformance monitoring representation of Figure 2 is the basis for the Conformance Monitoring Analysis Framework shown in Figure 3. The four main components of the framework (i.e. Conformance Basis, Actual System Representation, Conformance Monitoring Model and Conformance Monitoring Functions) are discussed next in greater detail.

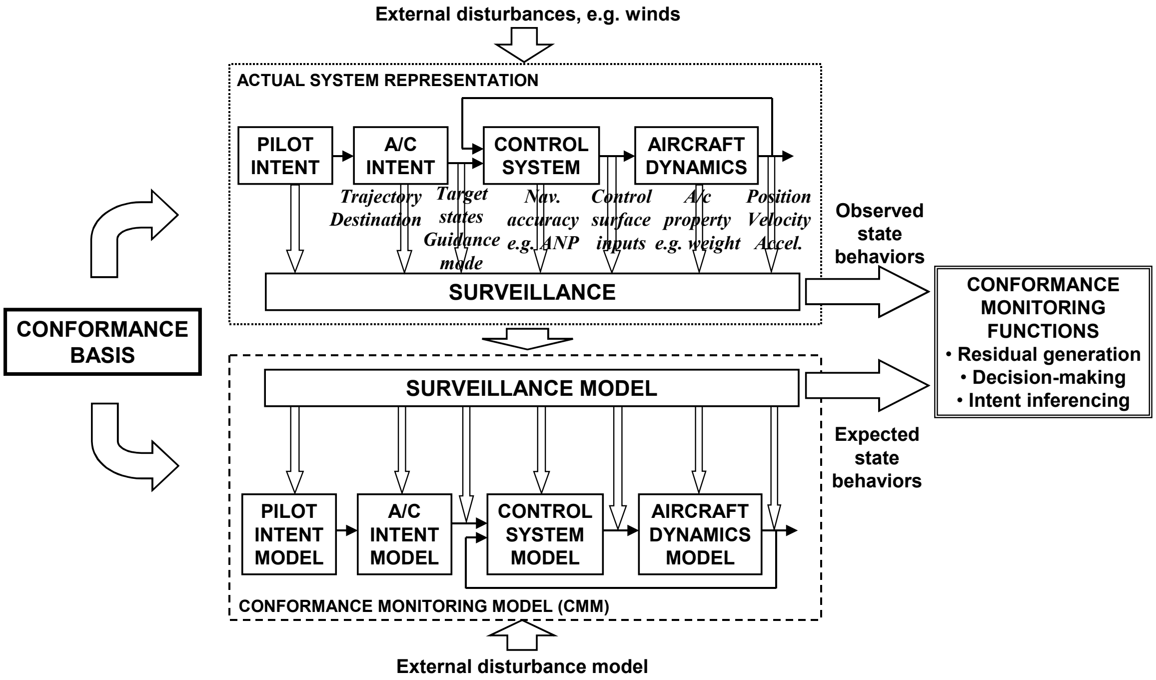

Figure 3: Conformance Monitoring Analysis Framework

Conformance Basis

The Conformance Basis is typically the currently-active set of clearances for the aircraft, including (but not necessarily limited to) the initial Flight Plan plus any amendments, standard procedures (such as departure and arrival procedures) and ATC vectors or constraints which are communicated to the flight crew (e.g. descend at pilot's discretion to cross fix at assigned altitude).

Knowledge of the Conformance Basis is of paramount importance in conformance monitoring since it defines the baseline from which the expected state behaviors are generated and against which the observed behaviors are compared. Without it, therefore, accurate expectations of aircraft behavior cannot be generated and this degrades the value of enhanced surveillance of aircraft states (i.e. improving the quality of the observed behaviors).

Actual System Representation

The Actual System processes of Figure 2 are represented in Figure 3 by the key elements that are involved in executing the clearance or other instructions forming the communicated Conformance Basis. This is shown as a classical feedback representation of the aircraft control system supplemented with upstream flight crew and aircraft "intent" components which define the future trajectory of the aircraft. A definition of intent consistent with the way future trajectories are communicated in the operational ATC environment has been proposed in the form of a Surveillance State Vector [8]. Here, intent states comprise "current target", "planned trajectory" and "destination" states. In this way, each element in the actual system representation generates appropriate control system target states for the downstream elements. The downward arrows in Figure 3 represent where actual system states could be surveilled. These states include traditional dynamic states such as position and velocity, along with intent and supporting states such as aircraft properties and navigation capabilities which help to define characteristics of the model blocks and to better understand their outputs. The surveillance block provides the actual system observed state behaviors to the Conformance Monitoring Functions block.

Conformance Monitoring Model (CMM)

The states surveilled from the actual system can be used to help populate or provide inputs to the appropriate Conformance Monitoring Model elements, as shown by the downward arrow in Figure 3 from the Actual System Representation to the CMM. There are many potential forms that the Conformance Monitoring Model could take, for example it could be a simple "mental model" of expected behavior in a controller's mind [5] or a more explicit functional model implemented in a decision support tool. These latter types could exist at many different levels depending on the conformance monitoring performance requirements. Reflecting standard FDI approaches [9], they could be based on simple "signal-based" techniques where no system dynamics are considered; "knowledge-based" techniques that incorporate heuristics and qualitative descriptions of dynamics; explicit dynamic "model-based" techniques or a combination of all of these. One of the greatest challenges in implementing the framework is the development of the Conformance Monitoring Model at an appropriate level. It requires sufficient fidelity to undertake effective conformance monitoring (e.g. to meet time-to-detection targets), but not be so detailed that modeling uncertainty and sampling issues introduce too much noise into the residual (thereby increasing false alarm rates). A tradeoff is therefore required to determine what level of fidelity is required in the Conformance Monitoring Model in the ATC environment being monitored. Some of these issues will be demonstrated in the results presented later.

Conformance Monitoring Functions: Residual Generation

The residual generation scheme should utilize as many states as required (or are available) to build up the best measure that describes whether the aircraft being monitored is behaving in a conforming fashion. One example approach to this process is presented here in terms of a "Conformance Residual", ***CR***, defined as:

$$\boldsymbol{CR} = \frac{\sum \boldsymbol{WF_x} \left| \boldsymbol{x_{obs}} - \boldsymbol{x_{CMM}} \right|}{\boldsymbol{n}} \qquad \text{Eqn. 2}$$

where $\boldsymbol{x}$ is a useful observed state, $\boldsymbol{WF_x}$ is a weighting factor for each state, $\boldsymbol{x_{obs}}$ is the observed value for each state, $\boldsymbol{x_{CMM}}$ is the expected value of the state from the Conformance Monitoring Model (annotated as *CMM*) and $\boldsymbol{n}$ is the total number of states used to define the Conformance Residual. Thus, the individual state components add to ***CR*** in proportion to the magnitude of the difference between the observed and expected values of the state $\boldsymbol{x}$.

The weighting functions are used to normalize each state component to acceptable conforming behavior limits and to reflect each state's relative importance. The concept of placing limits on acceptable deviations from assigned values is already well established. For example, the Required Navigation Performance specifications [10] define cross-track containment limits within which an aircraft must remain for 95% of the time to be RNP-compliant (see Figure 4).

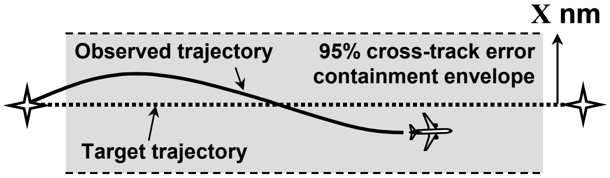

Figure 4: RNP-X Specifications Bound Cross-track Error

As such, an RNP specification is a reasonable basis for normalizing an aircraft's cross-track position error. Under this assumption, a cross-track position error weighting function in the Conformance Residual formalism would be the reciprocal of the RNP value.

The philosophy of using confidence containment limits as the basis for developing weighting functions can also be used for other states that might be observable. A weighting function that is the reciprocal of a suitable range defining the confidence containment interval (annotated as $\boldsymbol{\Delta x_{CI}}$) is then appropriate.

Overall normalization of a residual is desirable so that a comparison can be made between surveillance environments where differing amounts of state information may be available. In the example used here, this is achieved by simply dividing the sum of the various weighted components by the number of components used in the summation. As an example, the Conformance Residual for an environment containing surveilled position (from which cross-track position error, ***L***, can be determined if the planned trajectory intent state is also known), heading angle (ψ) and roll angle (ϕ) information would be:

$$CR = \frac{\left[\frac{|L_{obs} - L_{CMM}|}{RNPspec} + \frac{|\psi_{obs} - \psi_{CMM}|}{\Delta\psi_{CI}} + \frac{|\phi_{obs} - \phi_{CMM}|}{\Delta\phi_{CI}} \right]}{3} \qquad \text{Eqn. 3}$$

It should be noted that many other approaches to generating residuals could also be developed. For example a vector residual could be defined where each component of the vector is the difference between the observed and expected values of a state.

Conformance Monitoring Functions: Decision-Making

Once the residual has been generated, the decision making process involves a determination of whether the residual behavior is characteristic of a conforming aircraft or not. One approach is to compare the Conformance Residual to an appropriate threshold at any given time:

- ***CR(t) < threshold(t)*** implies a conforming aircraft at time *t*
- ***CR(t) > threshold(t)*** implies a non-conforming/deviating aircraft at time *t*
- ***CR(t) = threshold(t)*** implies an aircraft at its conformance limit at time *t*

It is often a challenge to determine the appropriate threshold to use with different implementations of the Conformance Monitoring Analysis Framework, under different ATC environments and at different times in that environment. However, their placement can be based on a trade-off of figures of merit such as false alarm and time-to-detection values, as illustrated conceptually in Figure 5. For example, a small threshold implies rapid detection of a deviation if one occurs, but would be susceptible to false alarms created by nominal variations in state behavior due to navigational tracking or ground surveillance system limitations. On the other hand, a large threshold reduces the number of false alarms but at the expense of a longer time-to-detection of a true deviation. This representation is similar to the System Operating Characteristic (SOC) curve [11] that is often used in alerting system design.

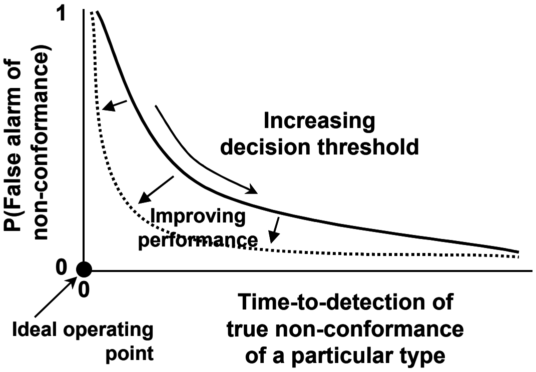

Figure 5: Schematic False Alarm/Time-To-Detection Tradeoff

It is the job of the designer of the conformance monitoring system to determine appropriate target values for the figures of merit within the environment being considered. These target values will determine appropriate threshold settings for a given implementation of the elements of the Conformance Monitoring Analysis Framework.

Conformance Monitoring Functions: Intent Inferencing

In the event of non-conformance, fault isolation techniques can then be employed to help perform intent inferencing, i.e. inferring what the aircraft *is* doing given that it *is not* following the intended Conformance Basis. This can be achieved by running alternate Conformance Bases or Conformance Monitoring Models (e.g. to represent different aircraft operating modes) until the residual is minimized. Even if the real behavior cannot be accurately determined, this approach enables certain behaviors to be excluded or a set of possible behaviors to be identified. This approach to intent inferencing will not be demonstrated in this paper, but examples can be found in [6].

Examining Lateral Conformance Monitoring Issues in ATC

Methodology

In order to investigate conformance monitoring issues, the analysis framework has been used to demonstrate conformance monitoring in various representative ATC scenarios and under different surveillance environments. The experimental methodology used is summarized in Figure 6.

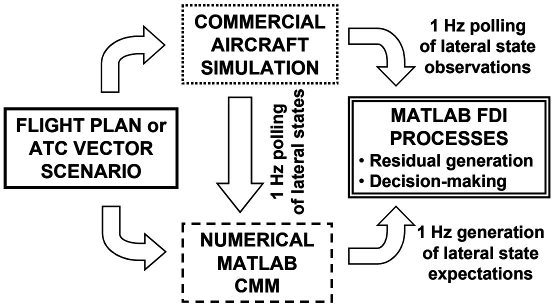

Figure 6: Experimental Methodology

The chosen scenarios had Conformance Bases represented by a section of a Flight plan and by an ATC vector. Future surveillance environments were simulated where position; heading angle (equivalent to track angle in a no-wind environment); roll angle and heading target states in the autopilot were made available to the monitor at 1 second intervals. For simplicity, only the lateral aspects of the conformance to the trajectories were considered. Altitude and speed were constant at 25,000 ft and 300 knots throughout. Future papers will discuss vertical issues.

For these demonstrations, the Actual System of the analysis framework was represented by an 'off-the-shelf' commercial flight simulation program (running on a standard PC) of a Boeing 767 aircraft equipped with an FMS/Mode Control Panel (MCP). Weather settings of zero-mean-wind and occasional turbulence were implemented in the simulation.

The states to be observed, x_{obs}, (position, heading, roll and heading target in this case) were 'surveilled' from this aircraft simulation by polling them at 1 second intervals and sending them to MATLAB® in real-time using application software developed in-house at MIT.

Expectations for each of these states, x_{CMM}, were developed from the Conformance Monitoring Model residing within MATLAB® workspace. A simple point mass Conformance Monitoring Model was assumed which defined the expectations of how the position, heading angle, roll angle and heading target would evolve along the defined lateral Conformance Basis of each scenario if no disturbances or system noise were present. This form of conformance monitoring model does not model the aircraft with very high fidelity but has the advantage of being the simplest. Much higher fidelity models could be implemented and future papers will examine when this is appropriate.

Conformance Residuals were generated (also in real-time) according to the form proposed in Eqn. 3 using different combinations of the observed states and weighting factors depending on the scenario. Explicit Time-To-Detection / False Alarm trades are not presented here in the interest of space, but general discussion of the Conformance Residual behaviors are included.

Flight Plan Conformance Basis Scenario

With the flight plan Conformance Basis, the aircraft simulation FMS was programmed to fly a segment of a flight plan containing direct-to clearances from JFK to BDL and from BDL to BOS, as illustrated in Figure 7. At the start of the simulation run, the aircraft was directly over JFK at 25,000 ft altitude and traveling at 300 kts IAS. Three cases of aircraft behavior were considered:

- "Conforming aircraft" flew the trajectory as planned with the autopilot engaged throughout
- "Rogue aircraft 1" executed an unscheduled turn off the flight plan between JFK and BDL
- "Rogue aircraft 2" failed to execute the transition at BDL, instead remaining on a heading of 032°.

These cases are also illustrated in Figure 7.

The CMM point mass model flew directly along the legs of the defined trajectory until a standard rate turn of 1.5°/sec was initiated at the appropriate time to accomplish the leg transitions in the scenario. The roll angle required to achieve this rate of heading change was calculated to give the CMM roll state.

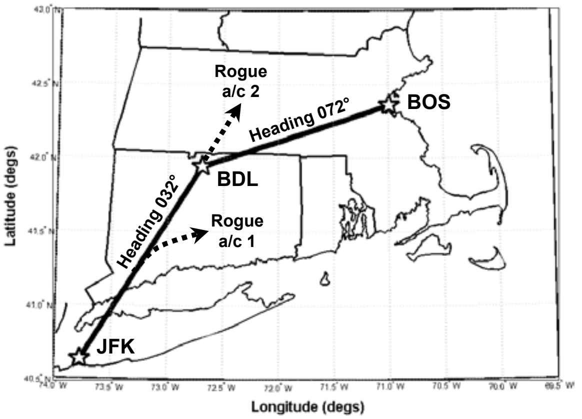

Figure 7: Flight Plan Scenario and Aircraft Behavior Test Cases

Conformance Residuals were calculated according to the form proposed in Eqn. 3 with example weighting factors as given in Table 1.

Table 1: Flight Plan Scenario Example Weighting Factors

Weighting Factor	Assumed value
$WF_L = 1 / RNP\ spec$	1 / 0.5 nm
$WF_\psi = 1 / \Delta\psi_{CI}$	1 / 5°
$WF_\phi = 1 / \Delta\phi_{CI}$	1 / 10°

An RNP 0.5 specification was assumed (similar to the performance expected from a modern commercial aircraft) while the confidence intervals on the other states were estimated for this preliminary investigation to generate results for discussion purposes. More care over these parameters would be required for detailed analysis of specific environments. Conformance Residuals were calculated for various state combinations of cross-track error only; cross-track & heading errors and cross-track, heading and roll errors according to:

$$CR_L = WF_L |L_{obs}|$$

$$CR_{L\psi} = \frac{WF_L |L_{obs}| + WF_\psi |\psi_{obs} - \psi_{CMM}|}{2}$$

$$CR_{L\psi\phi} = \frac{WF_L |L_{obs}| + WF_\psi |\psi_{obs} - \psi_{CMM}| + WF_\phi |\phi_{obs} - \phi_{CMM}|}{3}$$

Eqns. 4

The resulting observed/expected state behaviors and Conformance Residuals for the three aircraft behavior test cases are presented in the following figures.

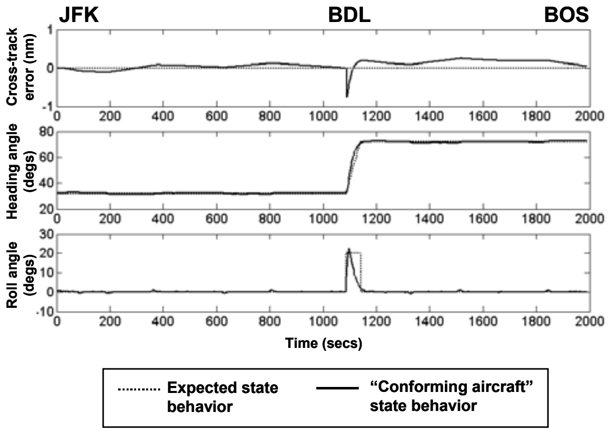

Figure 8: "Conforming Aircraft" State Behaviors

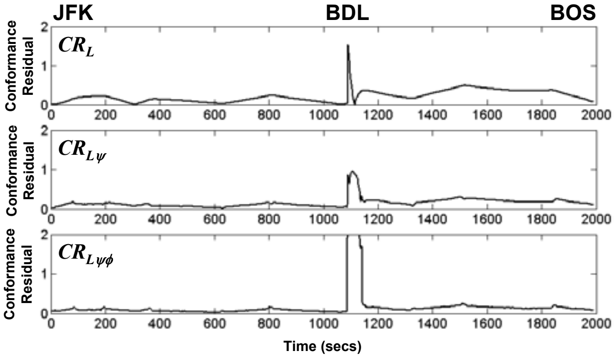

Figure 9: "Conforming Aircraft" Conformance Residuals

Some important conformance monitoring issues are demonstrated by these results. When the aircraft is flying along a flight plan leg, the observable states shown in Figure 8 are relatively predictable. The cross-track error is bounded within the expected RNP value, while the heading and roll states also behave in a predictable fashion given the planned trajectory. Similarly, the Conformance Residuals shown in Figure 9 are low when the aircraft is flying along a flight plan leg. However, at the transition point of BDL, there is a spike (approximately ten times larger than away from the transition) in all the forms of the Conformance Residual indicating a significant difference between the observed and expected states used in the residual. This is the case even though the aircraft is nominally conforming. These spikes are caused by the differences between the observed and expected states that can be seen in Figure 8 at the transition point due to the lack of fidelity in the point mass CMM, as well as small timing and logic differences between the actual and expected transition points. These differences become more pronounced in the higher order states (especially the roll angle) due to their greater dependence on proper modeling of the aircraft dynamics and autoflight system logic. Given that small differences will always exist between the real world dynamics/environment and the model of these being used to generate the expected state behaviors, these residual spikes can always be expected to exist to some degree at transition points. As a result, the decision threshold placement will generally need to be larger at transition points than away from them to reduce false alarm rates.

In order to investigate the impact of guidance mode on the results, the "conforming aircraft" case was also flown manually using flight director and map displays for guidance, as shown in Figure 10.

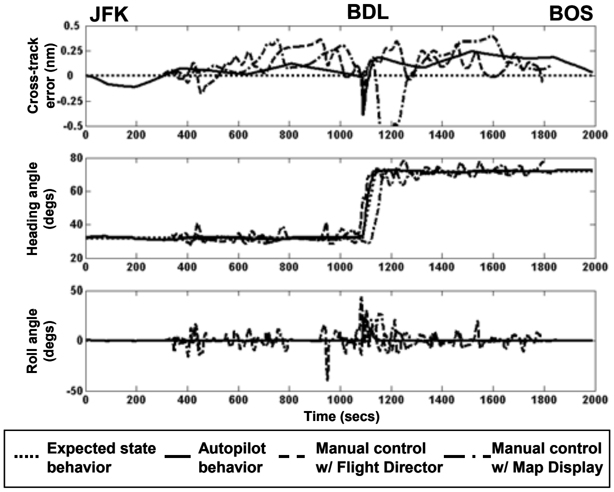

Figure 10: Effect of Guidance Mode on State Behavior

This caused significantly more noise in all of the observable states even though the pilot was attempting to conform to the trajectory as well as he could. If this dependence on guidance mode is not accounted for either in the generation of the residual (e.g. by changing the weighting factors in ***CR***) or in the setting of the decision threshold, false alarms can result. Figure 11 demonstrates the larger Conformance Residuals associated with the same weighting factors as used above, even though the aircraft is still nominally conforming.

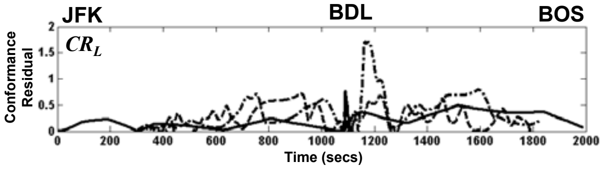

Figure 11: Effect of Guidance Mode on Cross-track Error Conformance Residual

The two "rogue aircraft" case results are presented in Figure 12 and Figure 13.

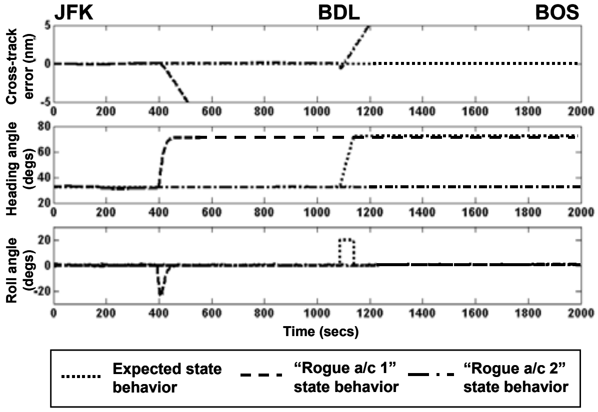

Figure 12: "Rogue Aircraft" State Behaviors

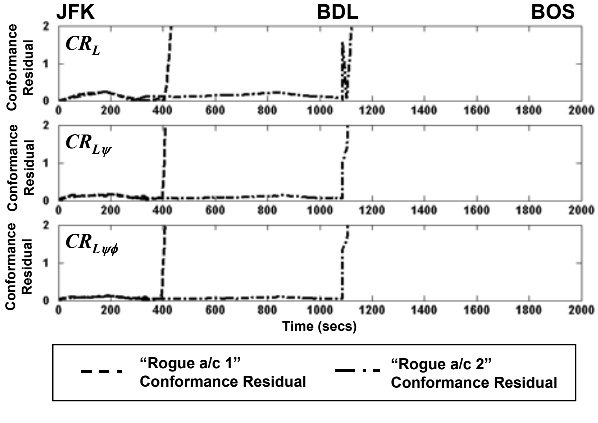

Figure 13: "Rogue Aircraft" Conformance Residuals

"Rogue aircraft 1" makes an unscheduled turn away from its expected flight plan leg. As discussed, a conforming aircraft has well behaved states and Conformance Residuals at this time, so any deviation from this conforming state can be easily detected. This is evident in the rapid increase in the Conformance Residual plots of Figure 13 for this aircraft after it makes the unscheduled turn and the high signal-to-noise ratio. Here, the benefits of using additional states (other than just cross-track error) are also evident. The Conformance Residual based purely on cross-track error exceeds unity 29 seconds after the unscheduled turn was initiated, compared to 13 seconds with cross-track & heading errors and 9 seconds with cross-track, heading and roll errors. In this case, the use of higher order dynamic states reduces the time-to-detection of a non-conforming aircraft.

"Rogue aircraft 2" fails to make the expected transition at BDL. It has already been demonstrated that larger decision thresholds are required around transition points to account for the increase in Conformance Residual noise, even for a conforming aircraft. True non-conformance at transition points, such as in this case, are therefore much harder to detect. Larger decision thresholds are required in these regions to reduce false alarm rates but this adversely affects non-conformance detection times. This difficulty in detecting non-conformance at transition points is entirely consistent with the effort being expended on "critical maneuver detection" in NASA's new Automated Airspace Concept [12].

The results from the "rogue aircraft 2" case can also be used to illustrate the problems with inconsistent or ambiguous Conformance Bases. In today's US ATC system, the conformance monitoring tasks conducted by the tactical controllers rely on the accuracy of the active flight plan in the Host Computer System (HCS) compared to the Conformance Basis communicated to the aircraft. However, a preliminary study based on observations in ATC sectors [13] indicated that it was common to observe route amendments that were issued by voice but not entered into the HCS and that significant position deviations from the active HCS route resulted. Although most of the route clearances not entered in to the system were likely to have been self-contained within the controller's own sector (and therefore the controller would have a mental model of the "correct" Conformance Basis), downstream controllers could encounter an aircraft flying to a different trajectory Conformance Basis than that indicated on their flight strip. To the controller (or an automation system using the "incorrect" flight plan), this aircraft would appear non-conforming.

The "rogue aircraft" in the previous examples could have been conforming if the monitor was using an incorrect Conformance Basis. For example, assume that "rogue aircraft 2" had been given a heading hold command by a controller prior to BDL but which was not communicated to a downstream controller responsible for airspace around BDL or was not entered into the conformance monitoring automation system. The Conformance Residuals to the "old" (i.e. invalid) and "new" (i.e. valid) Conformance Bases are given in Figure 14. When the valid Conformance Basis is used, rogue aircraft 2 now appears conforming as evidenced by the small Conformance Residuals.

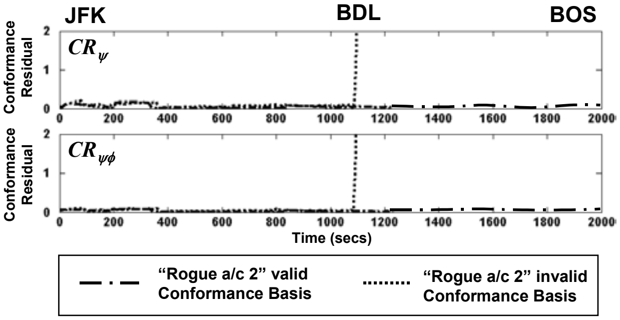

Figure 14: Impact of Conformance Basis on "Rogue Aircraft" Conformance Residuals

These results indicate the essential role of proper surveillance and communication of the Conformance Basis. Without a valid and complete Conformance Basis, conformance monitoring may be ineffective.

ATC Vector Conformance Basis Scenario

In the ATC vector scenario, a command requesting a left turn to 030° was assumed to have been issued by ATC to the aircraft as it approached BOS, as illustrated in Figure 15 below.

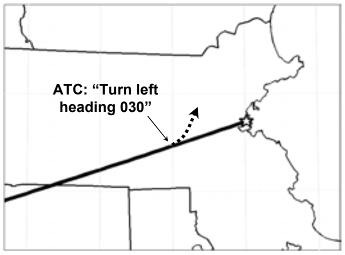

Figure 15: ATC Vector Scenario

Flight crew typically implement a tactical command such as a vector by disengaging LNAV mode and engaging heading select mode with the appropriate heading target state on the autopilot MCP. Variability in aircraft response time to the ATC vector Conformance Basis can be expected since the flight crew are involved in the control loop (dialing the heading target into the MCP). Figure 16 below shows the aircraft state behaviors over three separate runs of this scenario with a human pilot inputting appropriate commands to the MCP in the simulation. The human-induced variability in the states is clearly evident. A 'standard response' time of 10 seconds was assumed to generate the 'nominal expectation' state values in this case.

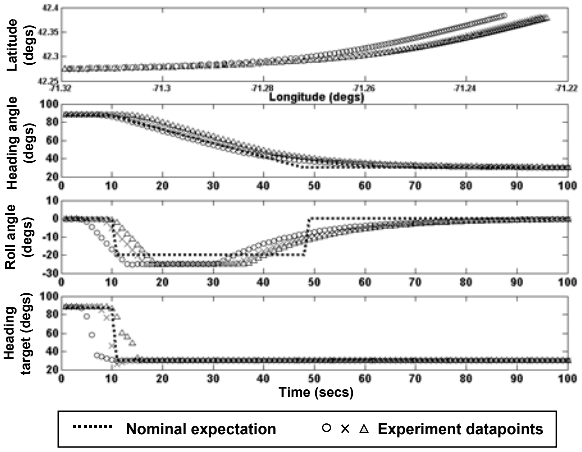

Figure 16: ATC Vector Scenario State Behaviors

The importance of higher fidelity modeling of aircraft dynamics at transitions is again evident. Since the model used for the CMM in this example is simple, another way to use the higher order states while reducing the effect of modeling uncertainty is to reduce the weighting factors. A selection of Conformance Residuals using combinations of heading, roll and heading target (i.e. MCP) states are presented in Figure 17. These were calculated using the reduced weighting factors in Table 2.

Table 2: Conformance Residual Parameters for 95% Confidence in ATC Vector Scenario

Weighting Factor	Assumed value
$WF_{\psi} = 1 / \Delta\psi_{CI}$	1 / 10°
$WF_{\phi} = 1 / \Delta\phi_{CI}$	1 / 25°
$WF_{\psi Target} = 1 / \Delta\phi_{TCI}$	1 / 10°

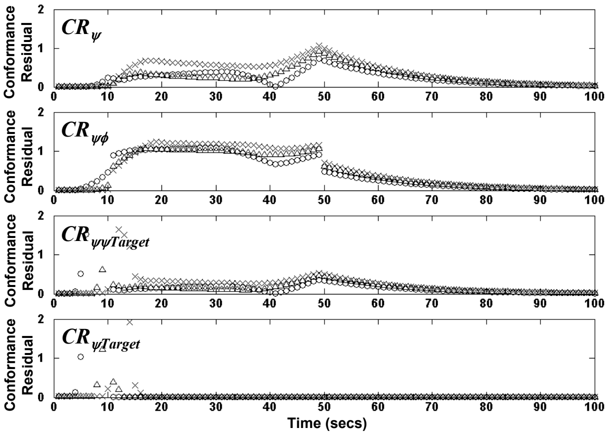

Figure 17: ATC Vector Scenario Conformance Residuals

In the case of a vector, there is no positional component to the Conformance Basis, so there is no cross-track error component to the Conformance Residuals used here. Even with the reduced weighting factors, the Conformance Residuals that use higher order dynamic states are relatively large due to the poor modeling fidelity in this example, even though the aircraft was conforming to the vector. The best indication of conformance under this scenario comes from the heading target state: it is a state that is directly comparable to the active Conformance Basis.

Conclusions

Conformance monitoring is of fundamental importance in ATM/ATC operations. An analysis approach based on fault detection techniques has been developed and implemented using a flight simulator and MATLAB®. This has proven useful for identifying and analyzing conformance monitoring issues. The critical importance of knowledge of the Conformance Basis (e.g. a detailed and accurate description of the trajectory an aircraft is expected to be following) has been demonstrated. This suggests that enhanced surveillance of the Conformance Basis is just as important (or even more so) than improving the surveillance of traditional dynamic states such as position or heading. When an accurate Conformance Basis is available, limitations to effective conformance monitoring still exist at transition points due to the inability to accurately predict nominal state behaviors and exact timing and logic parameters during a transitioning flight regime. In addition, although higher order dynamic states (which may be surveillable in future, such as roll angle) provide more lead-time of aircraft behavior, they also add significant noise to the conformance residual. The current guidance mode also has a large impact on the conformance monitoring approach.

The ability to perform effective conformance monitoring depends on the ability to predict expected aircraft behaviors to an appropriate fidelity and to have access to the proper surveillance states. The level of fidelity required in the model to generate the expected behaviors, the specific states that are required and decision threshold placements are all functions of the application domain in which conformance monitoring is being conducted.

Finally, although this paper has focused on the lateral domain, vertical conformance monitoring issues can also be examined using the approach presented here. Comparable issues exist in the vertical domain, although vertical transition conformance monitoring is more problematic due to the challenges associated with modeling vertical transition trajectories to generate expected states. Future papers will address these issues.

Acknowledgements

This work was supported by NASA Langley Research Center under grant NAG1-02006. Thanks to Richard Barhydt & Mark Ballin of NASA Langley, and to Franck Billarant & Josh Pollock of MIT for help with the simulation/MATLAB® link.

References

[1] Celio, J. C. *et al.*, 2000, “Free Flight Phase 1 Conflict Probe Operational Description”, Mitre Tech Report MTR 0W00000100, McLean, VA.

[2] Jansen, R. B. H. J., H. J. Kremer & W. C. Vertegaal, 1999, “PHARE Advanced Tools: Flight Path Monitor Final Report”, Eurocontrol DOC 98-70-18/6, Brussels, Belgium.

[3] Troutman, K. & G. Pelletier, 2002, “CAATS—New Generation ATM Automation”, *Journal of Air Traffic Control*, Vol. 44, No. 1, pp. 3-7.

[4] Scott, W. B., 2001, “Technology is Key to Australia’s ATC”, *Aviation Week & Space Technology*, Vol. 155, No. 17 (Oct. 22), pp. 72-75.

[5] Reynolds, T. G., J. M. Histon, H. J. Davison & R. J. Hansman, 2002, “Structure, Intent & Conformance Monitoring in ATC”, *ATM2002*, Capri, Italy.

[6] Reynolds, T. G. & R. J. Hansman, 2002, “Conformance Monitoring Approaches in Current and Future Air Traffic Control Environments”, *21st Digital Avionics Systems Conference*, Irvine, CA.

[7] Frank, P. M., 1992, “Principles of Model-Based Fault Detection”, *IFAC/IFIP/IMACS Symposium on Artificial Intelligence in Real-Time Control*, Delft, Netherlands, pp. 213-220.

[8] Reynolds, T. G. & R. J. Hansman, 2000, “Analysis of Aircraft Separation Minima Using a Surveillance State Vector Approach”, *3rd FAA/Eurocontrol Air Traffic Management Conference ATM2000*, Naples, Italy.

[9] Frank, P. M., 1996, “Analytical and Qualitative Model-Based Fault Diagnosis—A Survey and Some New Results”, *European Journal of Control*, Vol. 2, No. 1, pp. 6-28.

[10] RTCA, 2000, *Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*, DO-236A, Washington DC.

[11] Kuchar, J. K., 1996, “Methodology for Alerting-System Performance Evaluation”, *Journal of Guidance, Control & Dynamics*, Vol. 19, No. 2.

[12] Erzberger, H., 2001, “The Automated Airspace Concept”, *4th FAA/Eurocontrol Air Traffic Management Conference ATM2001*, Santa Fe, NM.

[13] Lindsay, K. S., 2000, “Currency of Flight Intent Information and Impact on Trajectory Accuracy”, *FAA/Eurocontrol Technical Interchange Meeting on Shared Flight Intent Information*, Atlantic City, NJ.

Key Words

Conformance monitoring, Conformance Basis, intent, surveillance, model-based fault detection.

Author Biographies

Tom G. Reynolds is a Ph.D. student in the International Center for Air Transportation of the Department of Aeronautics & Astronautics at MIT. He obtained his Master of Science degree in Aeronautics & Astronautics at MIT in 1998 and a Bachelor’s degree in Aeronautical Engineering from the University of Bristol, UK in 1995. He was selected as a UK Fulbright Scholar in 1996 and has worked in aircraft operations at British Airways

Engineering and on advanced cockpit displays for the Defence Evaluation and Research Agency, UK.

R. John Hansman has been on the faculty of the MIT Department of Aeronautics & Astronautics since 1982. He obtained his A.B. in Physics from Cornell University in 1976, his S.M. in Physics in 1980 and his Ph.D. in Physics, Meteorology, Aeronautics & Astronautics and Electrical Engineering from MIT in 1982. He is the Head of the Humans and Automation Division and the Director of the International Center for Air Transportation at MIT. He conducts research in many areas related to flight vehicle operations and aviation safety.