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Live Blackboxes: Requirements for Tracking and Verifying Aircraft in Motion

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An intensive multi-national search for the Malaysian Airlines (MH370) aircraft that went missing somewhere over the Indian Ocean two years ago was unable to locate any first-hand evidence from the plane’s on-board flight data recorders (also known as blackboxes). To mitigate similar problems in the future, an aviation proposal was made to analyse live streamed flight data using cloud computing; however, the technological readiness of satellite telecommunications continues to be constrained by bandwidth and scalability challenges.¹

This paper proposes five requirements for addressing these challenges. These requirements frame a class of monitoring problems that share some similar quality concerns around safety, security, and accuracy. We evaluate the robustness of our sample requirements to assess the readiness of the proposed technology - which we call “live blackboxes” – by using actual global scale data and performing an analysis of different live streaming measures. Augmented with locality-sensitive hashing that reduces the bandwidth by 4.75 times, the scalability requirements for satellite communications – to track and verify all civilian aircraft in motion – could be satisfied by the results. While we focus on a particular problem in air traffic management, we draw some speculative conclusions about similar requirements for the continuous monitoring of critical systems.

I. Introduction

The last decade of aviation saw improving safety and security, until 2014, when 900 people lost their lives or remained missing.² The root causes for all the crashes except for MH370³ are already known because Flight Data Recorders, also known as the blackboxes, were eventually found at the crash sites. Such boxes contain well-protected information about the cockpit communication amongst pilots and with ground controllers, and a number of operating parameters such as longitude, latitude, altitude, speed essential for post-mortem diagnosis. As a standard practice, once the reasons are confirmed by diagnosing the data extracted from the blackboxes, the aviation industry could mitigate the failures by releasing concrete guidance necessary to the safety of future flights. However, delays and resources in recovering the blackboxes are often obstacles to timely investigation of the crashes, including the recent EgyptAir Flight 804.⁴

However, it is not yet known what has happened to the missing MH370. Its last hourly ping signals to an Inmarsat satellite suggested that the aircraft actually headed towards the southern Indian Ocean, according to the Doppler effect of drifting frequency caused by high-speed movements of the signal source. Though the international team shifted the search and rescue effort immediately towards the ocean, it was hard to locate the blackboxes under sea bed because the batteries for signalling their location lasted no longer than 90 days. As the batteries ran out, a large area was still unexplored. After spending tremendous amount of resources on search and rescue, a piece of the wings was found on 29 July 2015 at Reunion Island, which floated there from the potential crash site driven by the ocean currents.⁵,⁶ A more recent discovery of a Boeing 777 part ashore Mozambique on March 2, 2016⁷ may contain some more clues. However, without locating the blackboxes that recorded critical flight data, the search continues.

Invented in the 1950s, blackboxes are still being used widely as the primary sources of forensic information for aviation safety and security. Since the MH370 incident, the International Telecommunication Union (ITU) has adopted a live streaming proposal⁸ in its guidance for future aviation communications.⁹ With widely used remote communication capabilities, even smart-phone owners can already detect the location of their
phones and wipe data out if they are lost. It is reasonable to expect that engineers do the same for aircraft in motion by advancing the technology.

Tracking one smart-phone seems to be easy but it is not. Millions of smart-phone owners, distributed globally, may need this capability simultaneously. To be able to fulfill this simple requirement, it requires vendors to invest heavily in cloud computing, the on-demand technology to use large amounts of computation resources when needed. Additionally, for aircraft flying over the oceans, radar signals are not available and satellite communications seem to be the most reliable ways to relay location information. However, there is already a bandwidth problem concerning the need of tracking all aircraft, including those designated journeys on land: e.g., the MH370 aircraft was destined from Kuala Lumpur to Beijing, rather than above the Indian Ocean. Here, we propose five “live blackbox” requirements, namely, tracking, prediction, verification, scalability, and liveness, to enhance aviation safety and security.

The research challenge on current technology is to achieve all these requirements together. We attempt to show their feasibility, using continuously captured time-series of radar data of 21,616 globally operating aircraft, in a duration of 3 weeks between January 27 2016 and February 17 2016, with 69,137,191 minute-by-minute updated locations. Our main contributions can be summarised as follows:

- Highlighting the importance of tracking requirements for aviation safety and security of individual aircraft, in addition to collision-avoidance between two aircraft;
- Estimating the amount of satellite bandwidth required for communicating the locations by collecting time-series data from flight radars;
- Predicting the precise location on the next interval based on either previous locations on same trajectory or previous trajectories;
- Using locality-sensitive hashing technique to verify the predicted trajectory against anomalies with less bandwidth by accuracy rather than by precision; and
- Assessing the reduction of satellite bandwidth to address the scalability requirement.

For safety, all systems are verified to detect anomalies to the projected trajectory; for security, locality-sensitive hashing instead of crypto-hashing is used for continuous phenomena in physical domain; and for accuracy, the boundary check decision is no longer based on unnecessarily high precision, in order to accommodate high demand on sampling frequency (i.e., liveness) and scalability.

The remainder of the paper is organised as follows. Section 2 explains why the state-of-the-art satellite telecommunications have not been deployed for tracking aircraft in motion; Section 3 presents the definitions of five live blackbox requirements to enable time-series analysis for predicting trajectories and detecting anomalies for a large scale of aircraft responsibly. Section 4 reports our pilot experiments to evaluate the feasibility of using flight radar data and locality-sensitive hashing, to achieve the proposed live blackbox requirements. It also discusses threats to validity in those experiments. Section 5 presents related work from monitoring problems, security requirements, to existing air traffic control-specific requirements. Finally, Section 6 concludes the study with a few directions for further research.

### II. Tracking Aircraft in Motion: Data in Communications

To track aircraft in motion, the basic requirement is to get sufficiently high quality flight data. Now there are two fundamental ways in collecting flight data, via satellites and radars. Similar to how mobile phones locate themselves, GPS locations are obtained on the aircraft by aligning with Global Position Systems satellites. Locating GPS is anonymous and does not require additional satellite communication bandwidths. On top of the GPS location data (i.e., longitude, latitude, altitude), modern aircraft broadcast their identities and the identities of the associated air-traffic control radar zone, flight speed, vertical speed using the automatic dependent surveillance-broadcast (ADS-B) radar technology. Companies such as FlightRadar provide low cost wireless ADS-B receivers for clients to gather radar signals of the aircraft in range. Owners of such systems upload the received data to FlightRadar servers, through crowd-sourcing, which leads to a live updated status of global aircraft. When ADS-B signals are not available, FlightRadar uses the Multi-lateralation (MLAT) technique to aggregate multiple observations into aircraft GPS locations.

In this work, we acquire flight tracking data using the FlightRadar API. The data obtained are minute-by-minute, and they cover populated area in the globe, except for scarcely populated areas such as forests, deserts and oceans. For each of the data point, we get longitude, latitude, altitude, speed, vertical speed, as well as flight number, origin airport, destination airport, radar zone, and last update time.

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^ahttps://www.flightradar24.com/
An aircraft is chosen for the most data points amongst the 21,616 aircraft over three weeks. Each aircraft has variable numbers of data-points during the three weeks period, on average there are 3,198 data points per aircraft. The aircraft with the most data points is identified by “06A0BC”, which has 25,714 data points. Its latitude, longitude, and altitude changes are shown in Figure 1.

From the flight id of aircraft 06A0BC\(^b\), it is clear that the aircraft is operated by Qatar Airlines on multiple (origin, destination) pairs of journeys. The Boeing 787 flew from Doha, Qatar to Edinburgh, London in the UK, Stockholm in Sweden, Zurich in Switzerland, Kuala Lumpur in Malaysia, etc., and back forth. That is why there are segments on the curves with different latitude/longitude end-points. Observable from the curves of longitude/latitude is the fluctuations at the phase of landing, where the flights often hover around the airport to wait for an opportunity to touch down on the runway. Worth noting are the sudden changes of altitude during these flights. From the non-zero speed and altitude data, it is also observable that the flight data obtained are mostly in-flight, which is when the ADS-B broadcasts are turned on. In fact, the altitude in cruise mode are fluctuating, ranging between 36,000 and 44,000 feet.

III. Requirements for Live Blackboxes

With the data collected from Flight Radars, it is possible to articulate the requirements for live blackboxes more precisely, which would help with understanding the pilot experiments we report next. Informally, Figure 2 illustrates these requirements in the context of one flight journey of an aircraft. The tracking requirement shall record the flight data and communicate to the radar or satellite; the prediction requirement shall tell the motion of the aircraft based on the previous data points in the trajectory; the verification requirement shall be able to determine whether the flight is on track; the liveness requirement shall report any anomalies within a time interval; and scalability requirement shall guarantee the bandwidth of satellite communications is enough for the above requirements.

These requirements are defined by the data points collected, which lead to the overall requirement for live blackboxes. The first requirement is to track airports in motion.

**Requirement 1 Tracking.** An aircraft is tracked on an interval of \(\tau\) if from every time stamp \(t\) during its aviation journey, there is at least one data point(s) between \((t, t + \tau)\). The data point needs to contain

\(^b\)Can be monitored live at https://planefinder.net/flight/z.NO-06A0BC
Our radar dataset satisfies this requirement to the level of $\tau=1$ minute. U.N. aviation agency has approved for International Civil Aviation Organisation (ICAO) to propose a new standard that aircraft on oceans shall update their locations every 15 minutes,\(^{10}\) rather than every 1 hour before the MH370 incident. In other words, $\tau=15$ minutes. Generally speaking, the smaller the interval is, the better it would help track the aircraft.

**Requirement 2 Prediction.** Given the location data of an aircraft up to time $t$, the location at the next interval $t+\tau$ could be predicted as $L'(t+\tau)$. Compared to the location in reality at $t+\tau$, the error of prediction $e$ can be judged by a threshold of physical distance: when $\|L'(t+\tau) - L(t+\tau)\| < e$, the prediction is accurate, otherwise it is faulty. Given the threshold $e$, the overall prediction requirement aims to find a model to lower the chance of faulty predictions.

There are many ways to implement this prediction requirement, such as regression models and decomposition analysis, given the datasets collected.

It is our hypothesis that when the tracking interval $\tau$ is smaller, the prediction model is more likely to be correct with respect to a given threshold $e$. Part of our experiments will be to check this hypothesis by intentionally ignoring some data points of smaller interval to see whether the accuracy of prediction of the trajectory could be affected.

However, when intervals get smaller, the number of data points on a given trajectory will increase, hence the scale of telecommunications to transmit the location data to analyse. Once the data arrives at the ground, it is considered acceptable to use cloud computing to deal with the computational scalability issues. Hence, the main technical concern is how efficient can telecommunication be scaled up to include all the hundreds of thousands of aircraft.

**Requirement 3 Scalability.** Given the average duration of a flight $D$, the amount of bandwidth required for communicating location data of $n$ aircraft in motion at an interval of $\tau$ is estimated to be at the scale of $n \times D/\tau \times B$, where $B$ is the number of bytes for representing the location data.

For the experiments we will use at least 3 independent flight data variables (longitude, latitude, altitude), and consider each variable in double precision require $B = 7 + 7 + 5 = 19$ bytes. Using the 3 weeks data we collected from flight radars, at $\tau=1$ minute interval, there are at least $69,137,191 \times 19$ bytes = $1,313,606,629$ bytes of communication spanning across 3 weeks of 30,240 minutes. The entire radar datasets, including aircraft ID, speed and timestamps, would otherwise costs more than 10GB after compression. On average, it is 43,439 bytes per minute.

Broadcasting at $\tau=15$ minutes, it satisfies the ICAO satellite communication requirement, and the bandwidth requirement is reduced to 3,048 Bpm, or 24,387 bps (one byte is 8 bits). Having been reviewed in the ICAO, apparently, this rate is acceptable for the current satellite communication technology and the cost can be shared by airlines. However, if we would decrease the $\tau$ interval below that of the current radar datasets, while still maintaining the capability in predicting the location of aircraft in motion, it requires some innovative solution.

One could use hashing function to reduce the bandwidth requirement because any change of the input value will almost certainly lead to a different hashing value. However, verifying objects in the physical domain cannot be that simple, because a perturbation of the input caused by small wind, for example, should not be considered as catastrophe or meaningful for the aircraft motions to be considered as abnormal. Instead, a locality-sensitive hashing may provide a way to achieve the compression of inputs without losing the capability in verifying the locations. Inspired by the concepts of locality-sensitive hashing (LSH),\(^{11}\) the definition of the verification requirement is presented below:

**Requirement 4 Verification.** To tell whether an aircraft in motion is in a location far away from the predicted trajectory, the locality-sensitive verification is to tell, with $c \geq 1$ that (1) the probability for the aircraft to be within the distance $d$ as predicted is no smaller than $P_1$, and (2) the probability for the aircraft to be outside the distance $cd$ is at most $P_2$, where $P_1 > P_2$.

The two probability parameters $P_1$ and $1 - P_2$ could tell us respectively how confident one could be when the hashed location is known. If we choose $c = 1$ it will be crisp (i.e., binary) in verifying the location either matches or not matches with the predicted trajectory.
Again, a family of LSH functions could satisfy the verification requirement above by definition. However, we aim to find a function that requires smaller number of bytes for communication, without missing the opportunity in detecting abnormal motions. Once an LSH function is chosen, both on-board aircraft and the ground tracking system need to use the same function consistently in this protocol.

From the aircraft to satellite and to the receiving ground stations, telecommunication imposes delays. According to the vision of 5G standard, the next generation of telecommunication would introduce an adaptive layer to allow for the interpolation of data points in-between two consecutively transmitted points. Otherwise, the speed limit of light imposes a 50 ms limit for the receiver to get the data packets from the sender. In other words, if the interval \( \tau \) is larger than 50 ms, it is still possible to fill it up with projected values in the predicted trajectory. The aim of such interpolations is to achieve the liveness requirement.

**Requirement 5 Liveness.** Given the data points collected from the past, the live prediction is to tell, with as short delay \( \tau_{\text{min}} \) as possible, the location of aircraft in motion.

When \( \tau_{\text{min}} < 50 \text{ms} \), it is required to apply interpolations. Although the current satellite communication may not yet support this level of transmissions, we are speculating that in the future it is indeed feasible. In order to estimate whether the liveness through interpolation could sacrifice predictability and verifiability requirements mentioned earlier, we also conducted some experiments using flight radar data, on larger pairs of \( \tau_{\text{min}} \)=1 minute and \( \tau = 15 \) minutes, just to see whether it is feasible to foresee such effect.

## IV. Pilot Experiments

In the interest of understanding the proposed requirements, results of a pilot experiment are reported.

### A. Predicting aircraft trajectory in time-series

In the first experiment we evaluate whether statistical methods are effective in predicting trajectories of aircraft in motion. To this end, we construct prediction models using collected flying data and cast the models as a regression problem and a seasonal decomposition problem, respectively.

Linear regression is one of the most commonly used predictive analysis. Regression estimates are used to describe data and to explain the relationship between one dependent variable and at least one independent variable. Given a time-series data set \( \{(y, x_1, \ldots, x_p)|i = 1, \ldots, t\} \) of \( t \) samples, a linear regression model assumes that the relationship between the dependent variable \( y \) and the \( p \)-vector of independent variables \( x \) is linear. This relationship is modelled through the following equation.

\[
y(t) = \beta_0 + \beta_1 x_1(t) + \beta_2 x_2(t) + \cdots + \beta_p x_p(t) + \epsilon \tag{1}
\]

where \( \beta_0, \ldots, \beta_p \) are the regression coefficients, \( \epsilon \) is the error term that captures all other factors which influence the dependent variable \( y \) other than the independent variables \( x \).

In the trajectory prediction scenario, we want to predict the longitude (or latitude/altitude) of an aircraft at time \( t+\tau \) when there is no collected data. Taking longitude for example, the factors that influence longitude can include previous longitude, latitude, altitude, and the horizontal and vertical speeds of the aircraft which were collected at time \( t = \tau \). Therefore, we have the dependent variable \( y \) denoted by \( \text{longitude}_{t+\tau} \) and the vector \( x \) includes \( p = 5 \) independent variables: the previous longitude, latitude, altitude, horizontal speed and vertical speed. That is, \( x = \{\text{longitude}_t, \text{latitude}_t, \text{altitude}_t, \text{speed}_t, \text{vspeed}_t\} \). To predict location at each time stamp \( t+\tau \) where \( t = i\tau \) and \( i \in \mathbb{Z}^+, i \geq 1 \), we take the following data set as training set\(^c\), whose size incrementally increases as \( i \) increases:

\[
\{\text{longitude}_t, \text{longitude}_{t-\tau}, \text{latitude}_{t-\tau}, \text{altitude}_{t-\tau}, \text{speed}_{t-\tau}, \text{vspeed}_{t-\tau}\}_{t=1}^{t=2\tau} \tag{2}
\]

Because the training set changes at each time stamp, the obtained regression coefficients and error terms are different at different timestamps, that is \( \beta_0(t), \ldots, \beta_p(t) \) and \( \epsilon(t) \). We have applied the regression approach to the data of aircraft 06A0BC and predicted one of its trajectories flying from Doha to Edinburgh airport on 27th January 2016.

To see how the tracking requirement \( \tau \) affects the accuracy of prediction, we manually removed some data points to vary the interval of data collection. Figure 3 shows the performance of the regression approach.

\(^c\)There is no previous data that can be trained at time \( t = \tau \) where \( i = 1 \).
when the data collection interval $\tau$ is at every one and five minutes. The prediction for longitude and latitude is always good. However, altitude prediction is not accurate at a sudden increase or drop in the data, especially when the data collection interval $\tau$ is five minutes. The fine-grained data (i.e., collected at every one minute) improves the prediction because there are more data in the training data set.

We showed the prediction error when $\tau$ is five minutes in Figure 4 by computing the difference between the actual and predicted values. The error of predicting longitude and latitude decreases as time increases because the regression model has more data to learn the correct coefficients. However, the error for altitude is almost zero at the beginning until there is a sudden increase in altitude. This is because altitude does not change for a long time at the beginning and this can be quickly captured by the regression model.

An alternative to the regression approach is the seasonal decomposition of time series, which is widely used for forecasting time series when time series of previous periods are available.
The decomposition approach divides a time series into notional components, including seasonal, trend, cyclic and random (containing anything else in the time series). Assuming an additive model, a time series \( y_t \) can be written as follows:

\[
y_t = S_t + T_t + C_t + R_t
\]

where \( y_t \) is the time-series data at time \( t \) and \( S_t \) (resp. \( T_t, C_t \) and \( R_t \)) is the seasonal (resp. trend, cyclic and random) component at time \( t \).

In the prediction scenario, we used the historical trajectories of a same air route of an aircraft as the time-series training data and predicted future trajectories using the decomposition approach. More specifically, we learned the components from two historical journeys of the air route between Doha and London Heathrow airport of aircraft 06A0BC where the data is collected at an interval of every five minutes. As expected, the prediction performs better than the regression approach for longitude and latitude. For altitude, it performs less well only at the beginning of the trajectory.

**B. Analysing anomalies with respect to prediction**

Once the trajectories are predicted, anomalies can be analysed where the measured metrics are far away from the predicted ones. For example, when the distance between the predicted and the measured locations are larger than a threshold, it could trigger further investigations. Sudden changes of the altitude, e.g., could be “normal” operations of the pilots during a flight, however, when combining with sudden changes of longitude/latitude from the predicted trajectory, it can mark them as alarming.

To analyse anomalies would typically require full data records of locations for every interval. Depending on the update frequency, however, it may exceed the bandwidth of existing satellite communication technology. Therefore, we experiment some candidate LSH function to see whether losing precision does not necessarily lead to the loss of accuracy.

**C. Rounding hash for verification**

A general approach to satisfy the defined location-sensitive verification requirement is to “hash” both actual and predicted aircraft locations in such a way that close locations are more likely to be hashed to the same value than far-away locations are. Specifically in the aircraft motion scenario, we are interested in detecting abnormal motions in longitude, latitude and altitude so that by comparing to a threshold \( d_{lon} \) (resp. \( d_{lat}, d_{alt} \)) we can determine whether an actual longitude (resp. latitude, altitude) is indeed astray from a predicted value. Hence an actual longitude value over \( d_{lon} \) distance away from the predicted value is defined as abnormal motion assuming the predicted locations are accurate and reflect the normal motion as shown in Section A. Using a hashing function, we consider any pair of the actual and predicted locations at single timestamps that are hashed to the same value an identified normal motion pair, otherwise an identified abnormal motion pair. The hope is that most of the identified abnormal motion pairs are truly far-away locations (i.e., the actual abnormal motion), and only a small fraction of close locations could be misidentified as abnormal.

We use the rounding approach to create the hashes of the actual and predicted longitude, latitude and altitude respectively with different levels of rounding accuracy. More specifically, if we focus on the altitude, \( |h(Altitude_t) - Altitude_t'| \leq d_{alt} \) indicates that the actual value \( Altitude_t \) and the predicted value \( Altitude_t' \) are close. Then a rounding function \( h() \) with certain accuracy (e.g., 100, 1000) rounds of \( Altitude_t \) and \( Altitude_t' \) to certain values \( h(Altitude_t) \) and \( h(Altitude_t') \). The chosen accuracy of rounding determines the probabilities \( P_1 \) and \( P_2 \) as follows:

- if \( |Altitude_t - Altitude_t'| \leq d_{alt} \), then \( h(Altitude_t) = h(Altitude_t') \) with probability at least \( P_1 = \frac{\#\ of\ correctly\ identified\ normal\ pairs}{\#\ of\ actual\ normal\ pairs} \);
- if \( |Altitude_t - Altitude_t'| \geq cd_{alt} \) where \( c = 1 \), then \( h(Altitude_t) = h(Altitude_t') \) with the probability at most \( P_2 = \frac{\#\ of\ mistakenly\ identified\ normal\ pairs}{\#\ of\ identified\ normal\ pairs} \),

where \( P_1 > P_2 \).

We used the trajectory data of aircraft ‘06A0BC’ from Doha to Edinburgh airport to evaluate the performance of the rounding approach. We set the threshold \( d_{lon}, d_{lat} \) and \( d_{alt} \) as 0.1, 0.1 and 400 respectively, and rounded of each pair with different levels of rounding accuracy, (1, 5, 10) for longitude and latitude and
(400, 600, 800, 1000, 1200, 1400, 1600) for altitude. The changes of LSH probabilities \( P_1 \) and \( P_2 \) are shown in Figure 5, indicating that the LSH condition \( P_1 > P_2 \) always holds for any rounding (accuracy) parameter. For longitude and latitude, the \( P_1 \) is always 0.99 or one and \( P_2 \) is always zero. Therefore, the rounding parameter should be set as 10 to obtain minimum communication cost.

To choose the rounding parameter of the best performance in identifying abnormal motion pairs, we look at the recall and precision scores when different levels of rounding accuracy are implemented. As shown in Figure 6a, the recall score for identifying abnormal motion in altitude increases as the rounding parameter changing from 400 to 1,000. Considering precision and recall together with a preference for recall, the rounding approach has the best overall performance when the accuracy is 500, where the recall score is 1 and precision score is 0.8.

![Figure 5: LSH probabilities](image1)

Figure 5: LSH probabilities

![Figure 6: Effect of applying an LSH encoding](image2)

Figure 6: Effect of applying an LSH encoding

**D. Update the scalability and liveness requirements**

Using the proposed LSH scheme to replace the original full representation of locations, one can get reasonably good precision/recall performance. Now the question is, how much can it enhance the scalability and liveness requirements. Since there are room to improve accuracy by choosing different levels of intervals on the tracking requirement, here we aim to have a rough estimation rather than a precise estimation. Based on the size of flight radar data, earlier we have estimated that it costs at least 514,784 Kbps to transmit the locations of all 21K aircraft in operation through satellites, if the interval is every 15 minutes. Now, if one reduces the monitoring interval to every 1 minutes, it would increase the bandwidth requirement to 7,540 Mbps. Further, to live update at 50 ms (before interpolation), the bandwidth requirement could be increased further to 150,800 Mbps. This had not yet include the other data from Flight Data Recorders, such as cockpit
voices, passenger voices, etc. On the other hand, the use of Rounding function, the bandwidth requirements can be cut by at least half, while computing the Rounding function has the time/spatial complexity of $O(1)$.

With the compression of LSH, it is estimated a saving from 19B per data point (i.e., longitude and latitude contribute 7B respectively, and altitude contributes 5B according to the collected data) to 4B, thus a 4.75x saving of the bandwidth in these scenarios. Table 6b details the bandwidth saving while varying the rounding accuracy parameter. To achieve a recall score of 100%, we selected 10 (and 500) as the rounding parameters for longitude/latitude (and respectively for altitude). Therefore, the compressed bandwidth per data point is reduced to 4 bytes.

E. Threats to Validity

Construct validity Amongst the 21K aircraft, some were only recorded for one journey during the last three weeks. For such flights, even though decomposition analysis is believed to be more effective to reduce errors by periodical data, the alternative approach to prediction by the previous location would be more applicable. Despite that, the accuracy shown in the prediction of both methods can tolerate coarser granularities introduced by rounding hashes. Although both regression and decomposition of time series methods are widely used in the prediction of trajectories for forecasting, we are aware of other approaches, such as online learning, which may have better accuracy in the prediction. However, the aim here is only to show that statistical methods can be applied to improve on the prediction and verification.

Our internal tests show that the precision score is very low had we implemented the LSH function by converting location to binary data and comparing the Hamming distance between the converted actual and predicted locations. The very fact that rounding function of our intuitive choice is better than Hamming distance function suggests that choosing an LSH function could lead to further improvement. The experimental results presented here do not compare the effectiveness of all the commonly used LSH functions, which is left as our future work.

External validity The dataset was obtained by FlightRadar directly from globally distributed network of ADS-B receivers monitoring the flying-by aircraft. Relying solely on radar data source could be a risk to the validity of our findings, nonetheless the availability of data on densely populated lands is constantly improving. Due to data sensitivity, we cannot release the entire datasets as is without permission. After careful anonymisation through adaptive sharing and cloud-based privacy protection, we will be able to provide the fully captured tracks of aircraft of the period of the past three weeks to peer researchers.

V. Related work

For global civilian aircraft in motion, we propose to monitor the phenomena at the boundary of cyber- and physical-spaces into data accurate enough for diagnosing the departures from predicted trajectories. It applies the approach to monitoring and diagnosing software requirements generally to systems in physical domains and to problems at global scale.

Aviation safety and security requirements Nuseibeh et al. proposed that requirements techniques such as trust assumptions and structured argumentation can be combined to enhance the safety and security of air traffic control (ATC) systems. It emphasised that “one reason that an analyst may fail to construct a convincing argument is that there is not enough information available to justify some claim.” Indeed, without sufficiently rich and verified air traffic data, it is hard to instantiate decisions made to implement security requirements. Furthermore, Lockerbie et al. and Maiden et al. combined the i* method with satisfaction argumentation to analyse dependable ATC systems such as Departure Management (DMAN), from the ground, what could go wrong in the design processes. Following an ontology on security requirements to analyse and support lifelong evolving critical systems such as Arrival management (AMAN) and DMAN, Bergmann et al. used event-condition-action rule-based change management tools; Yu et al. proposed an automated approach to incorporating risk assessment into security requirements analysis. Recently, Gramatica et al. proposed to extend the strategic dependency analysis to analyse the economic drives for airline stakeholders to enhance aviation security.

Before the incident of MH370, most commonly studied aviation safety requirement for ATC is about collision avoidance or prevention, which focuses mostly on the separation of aircraft at a safe distance, either in flight or on runways for AMAN and DMAN. They apply to a few aircraft physically close to each other.
In this work, however, we focus on the new challenge in tracking and verifying all aircraft in motion using live blackboxes, which could greatly improve the predictability of the global civilian aviation industry and thus could become one of economic concerns for airline stakeholders.

**AEROSPACE SOFTWARE VERIFICATION AND VALIDATION REQUIREMENTS** For validating the design of unmanned aircraft systems, it is important to characterise message latency, and existing work has focused on constructing a distributed simulation environment. When the aircraft are manned, simulation cannot replace real-time monitoring of aircraft at the global scale.

Formal statistical model checking has been applied in verifying the correctness of aerospace software systems from behaviour aspects such as scheduling in a stochastic environment. Our proposed verification requirements are currently limited to verifying the recorded flight data against their prediction, without looking into the implementation of aviation software systems.

**UNCERTAINTY AND ACCURACY REQUIREMENTS** The combination of security requirements and their satisfaction argumentation arises from the perspective of insider stakeholders, i.e., designer of the ATC systems. The uncertainty of aviation security manifested by MH370, however, may not be fully satisfied resorting to existing technology due to uncertainty.

The tracking requirements listed here are of high level initially, however, used at large scale with limited bandwidth in satellite communications, a trade-off between information accuracy and precision is needed to deal with uncertainties. Letier et al suggested that information accuracy is what matters to decision making for software architectures. Likewise, it is considered more important in judging whether the aircraft is on track or not, instead of the exact location with absolutely high precision. For scalability and liveness, if possible, one could and perhaps should sacrifice some unnecessary precision if the judgement is still accurate, while saving the required bandwidth.

**VERIFICATION OF LARGE-SCALE TRANSACTIONAL DATA** Verifying large quantities of transactions can be achieved for crypto-currencies, where the correctness of every transaction can be verified by using the associated hashing values of the “proof of work”. Counter-intuitively, verifying digital values using crypto-hashing functions such as SHA-256 may not be ideal for the continuous data values collected from cyber-physical phenomena, because a slight perturbation of input could cause different decisions. Here, we proposed a slightly different verification requirement based on the locality-sensitive hashing concepts. The current location of an aircraft is regarded abnormal only when its distance to the location predicted by the trajectory is larger than a threshold, with a higher probability than otherwise. In this way, large amount of locations of all aircraft in motion could be efficiently communicated by limited satellite bandwidth because they are mathematically equivalent to verify whether the locations of aircraft are highly likely to be abnormal by comparing the LSH values.

**VI. Conclusion and future work**

In this paper, we have proposed a handful of requirements for tracking and verifying the locations of aircraft in motion, using ADS-B and other radar tracking signals at an interval of 1 minute. By varying the sampled intervals, we have also used the FlightRadar24 data to assess the feasibility of enhancing the scalability of satellite communication requirements for aircraft over remote oceans at an interval below the ICAO recommended 15 minutes. The results have shown that locality-sensitive hashing technique is effective in compressing the communication bandwidth without losing the capability to verify the predicted live trajectory at runtime.

We further suggest that the LSH scheme could be extended to non-location data recorded by the flights, e.g., voice recordings in cockpits, for which we aim to look for suitable LSH functions that can also verify other type of multi-dimensional data, as applied in the database domain. Although the simple rounding function we introduced satisfies the verification requirements, it might be possible to choose more efficient bandwidth compression techniques, to further improve the granularity of verification.

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