BALANCING THROUGHPUT AND SAFETY: AN AUTONOMOUS APPROACH AND LANDING SYSTEM (AALS)

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Abstract

One of the bottlenecks in air traffic flow is the final approach segment and the runway. Flights must be sequenced and spaced before the Final Approach Fix (FAF) to meet the safety separation requirements on the final approach segment. The final approach segment is conducted in a highly stochastic environment due to factors such as atmospheric conditions, aircraft performance, fleet mix, and flight crew technique. The stochasticity is evident in the inter-arrival time distribution at the runway threshold. The magnitude of the left-tail of this distribution determines the Actual Level of Safety (ALS) of the process.

When spacing methods such as Required Time of Arrivals (RTA) and self-separation are applied to the approach to eliminate gaps in the traffic flow, they result in a shift of the inter-arrival distribution to the left, and an increase in the magnitude of the left-tail resulting in a degradation in the ALS.

A proposed Autonomous Approach & Landing Spacing (AALS) System is designed to continuously balance the throughput gains of RTA and self-separation with the safety for the approach and landing process. The AALS monitors the stochasticity of the approach process (via the runway threshold inter-arrival time distribution), and adjusts the spacing buffer-time to ensure the Target Level of Safety (TLS) is maintained even as the stochasticity in the approach changes. This paper describes the analysis of runway throughput and safety in the presence of stochastic approach performance with the AALS. The implications and limitations of this technology are discussed.

Introduction

One of the bottlenecks in air traffic flow is the final approach segment and the runway. Flights are at their lowest speed for the approach and landing phase, and must be sequenced in a flow in close proximity to each other to maximize use of the runway.

To maintain safety, flights are separated longitudinally by sufficient distance to avoid wake vortex encounters and to avoid landing on the runway while the preceding flight is still on the runway. In this way, flights are spaced at the Final Approach Fix (FAF) for the final approach segment. They then fly "open-loop" without much range for intervention down the final approach segment such that they cross the runway threshold with sufficient spacing.

Since the final approach segment is conducted in a highly stochastic environment [13] due to factors such as atmospheric conditions, aircraft performance, ATC and pilot technique, and delays in ATC-flight communication, the inter-arrival time at the runway threshold exhibits a distribution (Figure 1). The magnitude of the left-tail of the distribution determines safety margins of the approach process [14]. The magnitude of the right tail of the distribution represents gaps in the flow and reduced runway throughput.
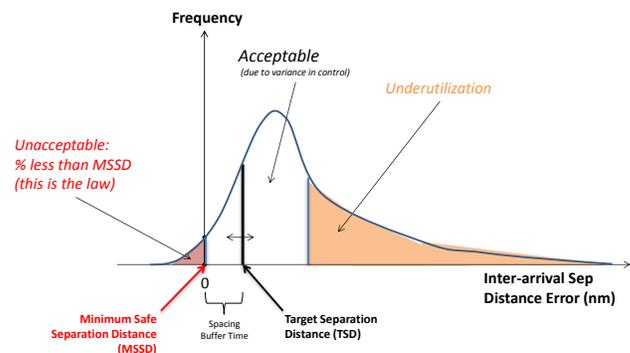
Figure 1: Time distribution for inter-arrival time at Runway Threshold. Magnitude of the left-tail represents the Target Level of Safety

Proposed concepts-of-operations to improve throughput of runways, by eliminating gaps in the approach traffic flow by increasing the accuracy of spacing arriving flights at the Final Approach Fix (FAF), reduce the magnitude of the right tail of the distribution. Required Time of Arrivals (RTA) [1][2][3] places flights at the FAF according to a pre-defined time schedule. Self-separation [4][5] "pulls" sequential flights with a specified time (or distance) separation.

Although these methods reduce the right-tail of the inter-arrival time distribution at the runway threshold, without explicitly accounting for the stochasticity of the approach process, they tend to inadvertently reduce safety margins by *increasing the magnitude of the left-tail* of the distribution.

Sherry, Shortle, Snisarevska, Donohue (2017) proposed an Autonomous Approach & Landing Spacing (AALS) System [6] to actively balance the throughput and safety. The AALS monitors the inter-arrival times at the runway threshold and sets the buffer-time in excess of the wake vortex separation time to meet a Target Level of Safety (TLS). The AALS, working in conjunction with RTA and/or self-separation, continuously adjusts to stochastic factors in an independent manner, requiring no external intervention.

This paper describes the analysis of runway throughput and safety in the presence of the AALS. Section 2 provides an overview of the approach and landing process and defines throughput and safety. Section 3 describes the AALS. Section 4 describes the results of simulation analysis of runway throughput and safety with and without AALS. Section 5 discusses the implications of this technology.

The Approach and Landing Process

The approach and landing process is managed by "Approach Control." An Air Traffic Controller (ATCo) monitors the traffic flow on "radar" screen showing surveillance data (Figure 2). Instructions and adjustments to flight trajectories are relayed to the flight crew via push-to-talk VHF radio.

The flight crew in aircraft on the approach, monitor traffic in their flight path, and follow the controller instructions by adjusting thrust, rate of descent, flaps/landing gears and/or heading. While

maintain separation, the flight crew must simultaneously configure the aircraft to meet stable approach criteria and land the aircraft.
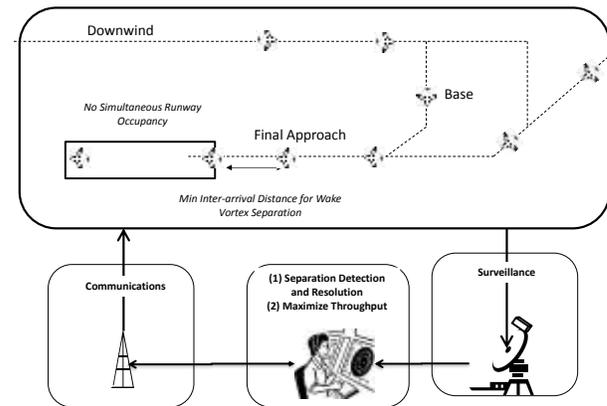
Figure 2: Air traffic controller monitors flights on surveillance "radar" and issues instructions to flights to maintain required safe separation distance.

From the perspective of the ATCo, the final approach segment is conducted in a highly stochastic environment. Not only are controller instructions to adjust the aircraft trajectory subject to delays due to the time for the flight crew to execute the instruction and the subsequent aircraft performance, but also each aircraft will have a different approach speed (e.g. different landing weights), and changing wind conditions (e.g. headwind). In addition, to account for the case when the lead aircraft is slower than the follow aircraft, extra spacing must be inserted for the "compression" in separation distance.

As a consequence, the Air Traffic Controllers must insert an additional "buffer time" between the wake vortex separation distance of the lead aircraft and the follow aircraft prior to the final approach segment.

By inserting the buffer, the air traffic controller also ensures that the probability of the inter-arrival time distribution in excess of the separation standard is below the defined probability threshold determined by a Target Level of Safety (TLS). If the buffer time is too short, safety margins are reduced. If the buffer time is too long, throughput is reduced. Further buffer-time is highly variable depending on the factors and must be adjusted continuously throughout the day.

It should be noted that real-rime information on buffer time is not currently provided to the air traffic controller. This can result in a conservative spacing based on worst-case conditions that contributes to reduced throughput.

Inter-Arrival Spacing and Buffer Time

The inter-arrival spacing at the Runway Threshold for lead-follow pairs on the approach can be represented by the time distributions shown in Figure 1. The horizontal axis is the difference in the actual separation relative to the required Minimum Safe Separation Distance (MSSD) for wake vortex between a lead and follow aircraft.

When the actual separation is less than the MSSD, the follow aircraft is closer than it should be. In this way, the left tail of the distribution is considered "unacceptable" and must be limited to maintain the desired target level of safety. The right-tail of the distribution represents excess spacing resulting in under-utilization and reduced throughput of the runway.

Due to the inherent variability in the spacing process, the "unacceptable" left-tail of the distribution is controlled by spacing the sequence of flights according to MSSD plus a spacing buffer distance labelled the Target Separation Distance (TSD).

TSD = MSSD + Spacing Buffer

The TSD is typically not specified in air traffic controller procedures (e.g. FAA J.O. 7110.65) and is determined by experience working the specific approach and landing process for each runway. The TSD will naturally vary with atmospheric conditions, wind, aircraft performance, fleet mix, and traffic flow.

In this way, the TSD is the control variable used by the controller to space the sequential flights and takes into account the variance at any time in the process (Figure 2). Depending on the process behavior, a TSD too close to the MSSD can result in excessive violations of the MSSD and reduced safety margins. A TSD that is too distant from the MSSD can result in reduced runway throughput and utilization of the runway.

Establishing the Target Level of Safety

The Target Level of Safety (TLS) represents the probability of a wake vortex encounter. The TLS is based on the characteristics of the spacing distribution, in particular the standard deviation of this distribution. The TLS is determined by the probability of the left tail of the separation distribution below a specified threshold. For example, assuming an approach has been operated with a TSD of 4 nm for an MSSD of 3 nm (i.e. spacing buffer of 1nm) and yields a separation distribution that is normal with a mean of 4 nm separation and standard deviation of 0.5 nm. This would yield a 2.3% of flights below the MSSD and TLS of 3.2 * 10-5 for a 95% probability of wake vortex encounter at 2 nm separation.

Runway Throughput

Runway throughput is a measure of the number of flights landed per unit time (e.g. flights per hour). The throughput is directly determined by the inter-arrival time between flights. The shorter the inter-arrival time, the more flights can be processed. For example, for a homogeneous fleet mix of flights with a 90 second wake vortex separation and 120 knots approach speed, the runway would have a theoretical throughput of 40 flights per hour. In reality, the excess spacing between flights as a consequence of the ATC Buffer would reduce the throughput to between 36 and 32 flights per hour.

Autonomous Approach and Landing Spacing (AALS) System

An Autonomous Approach and Landing Spacing (AALS) System has been proposed by Sherry, et. al. [6]. This system spaces the sequence of flights for the approach according to the required Minimum Safe Separation Distance (MSSD) such that the probability associated with the actual tail of the inter-arrival distribution meets the desired target to achieve the TLS. The system is constantly adjusting the TSD to maximize throughput while maintaining the safety margin.

This concept replaces the manual closed-loop spacing system with an automated system (Figure 3). The AALS processes the surveillance data to calculate the inter-arrival distribution at the runway threshold. The system calculates the spacing buffer

to achieve the TLS, and issues a digital data communication instruction to the avionics and the flight crew directly.
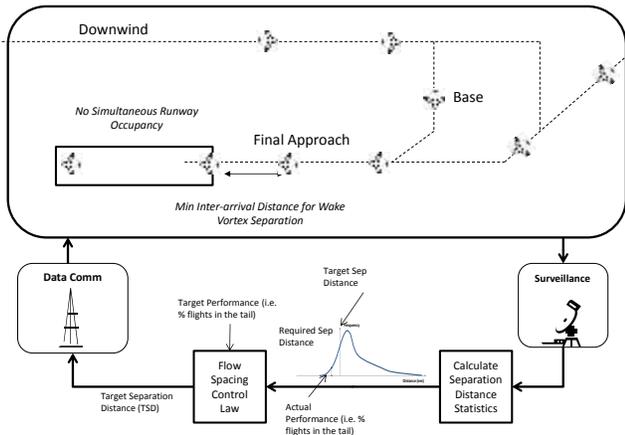
Figure 3: Autonomous system generates inter-arrival time distribution from surveillance "radar" and issues instructions to flights to maintain the required safe separation distance based on the flow spacing control law.

The probability associated with the negative tail is used as feedback for a closed-loop control law (Figure 4). The control law continuously adjusts the spacing buffer based on the stochastic performance of the system (including vehicle performance and environmental factors) to maximize throughput and maintain the TLS. As a consequence, the variance in the Inter-arrival spacing is reduced eliminating the excess separation while simultaneously maintaining the TLS (Figure 4).
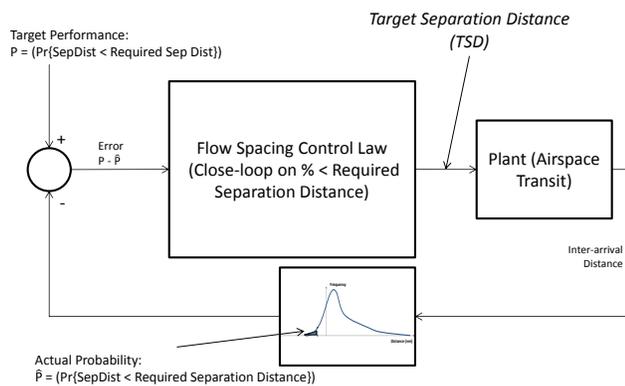
Figure 4: Closed-loop stochastic control of the approach and landing process.

The result of the AALS is an inter-arrival time distribution that continuously balances the trade-off between throughput and safety to actively maintain the TLS.
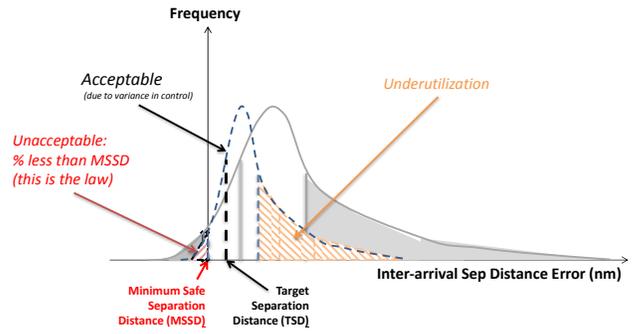

Figure 5: Autonomous system optimizes inter-arrival time distribution to simultaneously maintain safety margins while reducing underutilization.

Analysis of Runway Throughput

The objective of the analysis is to determine the trade-off between increased throughput through more precise spacing to the FAF and the probability of violating the MSSD. That is, reduce the right-tail of the inter-arrival time distribution at the runway threshold without increasing the magnitude of the left-tail.

The analysis was conducted using an approach and landing simulation developed by Snisarevska et. al. [12] (see Figure 6 and 7).

The simulation defines the approach distance (6nm) and altitude of the Final Approach Fix (2000'AGL). The simulation also configures the distribution of the approach velocity for flights at the Final Approach Fix to account for variations in landing speeds. The target % of flights in violation of MSSD is set (e.g. 5%). The simulation GUI is illustrated in Figure 6.
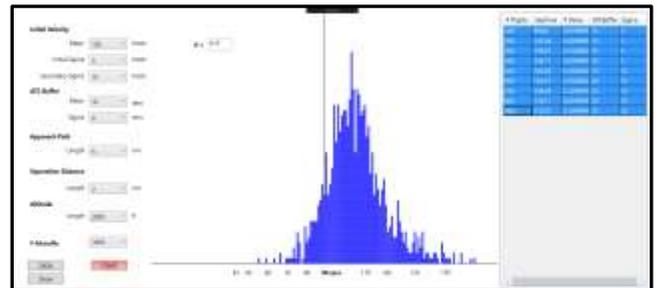
Figure 6: Approach and Landing simulation GUI

The output of the simulation is illustrated in Figure 7. The chart shows the desired level of safety as the probability of left-tail adjusted for sample by a confidence interval (red), actual left-tail probability (blue) and the ATC Buffer Time. (orange). The ATC Buffer time is increased when the actual probability is above the desired probability Confidence Interval. The ATC Buffer time is decreased when the actual probability is below the desired probability Confidence Interval. In this example, the average ATC Buffer time is 14.7 seconds.
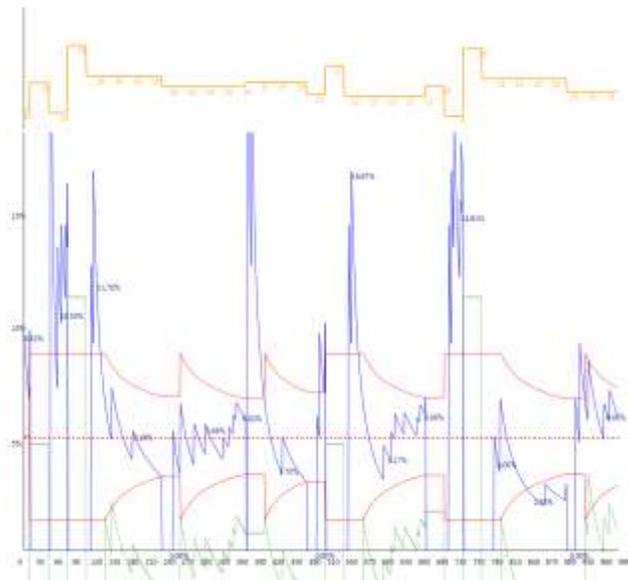

Figure 7: Approach and Landing simulation output shows adjustments to ATC Buffer Time based on stochastic performance of the approach

Design of Experiment

The experiment was run to compare the Runway Throughput performance and safety margins (i.e. probability of violating the MSDD)

For the purpose of the analysis, the Initial Velocity was set to 120 knots. The standard deviation for Initial Velocity was varied from 5 seconds to 10 seconds.

The ATC Spacing was established by the Spacing Buffer for the open-loop control scenarios, and by the AALS for the closed-loop scenarios. The ATC Spacing Buffer standard deviation was set to 0, 2.5, and 5 seconds.

The design of experiment is summarized in Table 1.

Results

The simulation was run for 10,000 flights on approach, with and without, the Autonomous Approach and Landing System active. The desired probability of violating the MSSD was set to 5%. The results are summarized in Table 1.

Manual FAF Spacing (without AALS)

The first half of the table has Initial Velocity of 120 knots with a standard deviation of 10 seconds representing manual spacing of flights arriving at the FAF.

For treatments 1, 2, and 3, the approach was run in open-loop with ATC buffer time set to 10 seconds and drawn from a normal distribution with standard deviation set to 0, 2.5 and 5 seconds. For these cases, the separation distance was too small resulting in ~30% of the flights in violation of the MSSD restriction.

For treatments 4, 5, and 6, the approach was run in open-loop with ATC buffer time set to 40 seconds and drawn from a normal distribution with standard deviation set to 0, 2.5 and 5 seconds. For these cases, the separation distance was large enough to have only 3.41% to 4.4% of the flights in violation of the MSSD restriction. With this reasonable safety margin, the Throughput was 28 flights per hour.

Manual FAF Spacing with AALS

Treatment 7, closed-loop control of ATC Spacing Buffer with AALS only, the average spacing buffer was 38.9 seconds with a standard deviation of 4.71 seconds. The probability of violating the MSSD restriction was 4.81% (~5% target). The throughput was 28 flights per hour.

Automated FAF Spacing without AALS

The second half of the table has Initial Velocity of 120 knots with a standard deviation of 10 seconds. This reflects more accurate spacing of flights at the FAF using RTA or self-separation.

For treatments 8, 9, and 10, the approach was run in open-loop with ATC buffer time set to 10 seconds and drawn from a normal distribution with standard deviation set to 0, 2.5 and 5 seconds. For these cases, the separation distance was too small

Table 1: Results of Simulation Experiment

No.	Configuration	Input				Output					
		Initial Velocity, knots		Spacing Buffer, secs		Average Inter-Arrival Time, secs		Average Spacing Buffer, secs		P (Left-tail)	Throughput (flights per hour)
		μ	σ	μ	σ	μ	σ	μ	σ		
1	FAF Man Sep	120	10	10	0	101.72	22.32	10	0	30.50%	36
2	FAF Man Sep	120	10	10	2.5	101.84	22.22	10	0	29.93%	36
3	FAF Man Sep	120	10	10	5	101.7	22.68	10	0	30.54%	36
4	FAF Man Sep	120	10	40	0	130.12	22.57	40	0	3.41%	28
5	FAF Man Sep	120	10	40	2.5	130.09	22.88	40	0	3.76%	28
6	FAF Man Sep	120	10	40	5	130.09	23.41	40	0	4.40%	28
7	FAF Self Sep With AALS	120	10	NA	NA	129.05	23.55	38.93	4.71	4.81%	29
8	FAF RTA/Self-Sep	120	5	10	0	100.01	11.12	10	0	17.35	36
9	FAF RTA/Self-Sep	120	5	10	2.5	99.99	11.52	10	0	17.66%	36
10	FAF RTA/Self-Sep	120	5	10	5	99.98	12.24	10	0	19.25%	36
11	FAF RTA/Self-Sep	120	5	20	0	110	11.11	20	0	3.21%	33
12	FAF RTA/Self-Sep	120	5	20	2.5	109.97	11.43	20	0	3.72%	33
13	FAF RTA/Self-Sep	120	5	20	5	110.04	12.24	20	0	4.96%	33
14	FAF RTA/Self Sep with AALS	120	5	NA	NA	110.74	12.73	20.74	3.6	4.76%	33

and 17% to 19% of the flights violated the MSSD restriction.

For treatments 11, 12, and 15, the approach was run in open-loop with ATC buffer time set to 20 seconds and drawn from a normal distribution with standard deviation set to 0, 2.5 and 5 seconds. For these cases, the separation distance was large enough to have only 3% to 5% of the flights violated the MSSD restriction. With this reasonable safety margin, the throughput was 33 flights per hour.

Automated FAF Spacing with AALS

Treatment 14, closed-loop control of ATC Spacing Buffer with AALS, the average spacing buffer was 20.74 seconds with a standard deviation of 3.6 seconds. The probability of violating the MSSD restriction was 4.76% (~5% target). The throughput was 33 flights per hour.

Discussion

Manual spacing to the FAF, treatments 4, 5, & 6, can achieve a throughput of 28 flights per hour with the required spacing buffer to achieve the 5% probability of MSSD tail at ~40 seconds.

By introducing RTA/Self-separation only, treatments 8, 9, 10, throughput is improved from 28 to 36 flights per hour. However, the inter-arrival time distribution now has a large magnitude tail where between 17.35% and 19.25% of the flights violate the MSSD.

By introducing RTA/Self Separation with AALS, treatment 14, the MSSD probability is reduced to the target 5% with a spacing buffer now be adjusted to ~21 seconds. The resulting throughput is now 33 flights per hour.

Conclusions

This analysis demonstrates the ability of the AALS to adjust the Target Separation Distance (TSD) (e.g. MSSD + Spacing Buffer) to adjust for stochastic factors that affect throughput and safety margins on the final approach segment. The AALS successfully reached the optimum TSD for each stochastic process.

By coupling AALS with RTA or Self-Separation the benefits of eliminating gaps in the arrival flow to the FAF can be balanced with maintaining the desired Target Level of Safety.

Further the AALS continuously adjusts as the stochastic approach factors change over time.

Increasing Throughput and Managing Safety

The AALS specifically manages the left-tail of the inter-arrival time distribution. This ensures that the TLS is maintained even in the presence of the changes in stochastic performance of the approach process.

RTA to the Final Approach Fix or self-separation, manage the right-tail ("under-utilization") by closing any gaps in the flow.

When RTA/self-separation are coupled with AALS, the system can actively balance safety *and* throughput.

Setting the Target Level of Safety

A critical design parameter for the Approach and Landing Spacing System, whether it is automated or not, is the setting of the TLS [13]. When flights are released at the separation standards the process is an inherently "mean-reverting" process. That is, by design there is no chance of a runaway process whereby the inter-arrival time would continuously decrease. The system always reverts back to the standard separation plus the buffer time. The challenge is to set the desired probability in the left-tail balance the runway throughput with required safety requirements.

Automating the Whole Approach Process

The AALS analyzed in this paper, is one of several functions that would be required to fully automate the complete approach process. A complete autonomous approach and landing system at airports would include at least the following functions: automated weather reporting, automated traffic collision [7], active runway surveillance (e.g. [8]), runway assignments and flight sequencing (e.g. [9], [10]) and taxiway guidance ([11]).

Interaction with RTA and Self-Separation

The approach and landing process is designed to have the aircraft configured and stable at the Final Approach Fix (FAF) for the start of the final approach segment such that the stable approach criteria can be met at 1000' and 500' AGL. All spacing, whether it is achieved by an Air Traffic Controller, RTA, or Self-separation must be completed prior to the FAF. In this way the AALS provides the human or automated system with critical information about the stochastic performance of the approach that can be incorporated into the separation instructions.

Future Work

The simulation currently runs only a homogeneous fleet mix (e.g. all Large aircraft). Future work includes enhancing the simulation to include a non-homogeneous fleet mix.

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Acknowledgements

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