Design of a Control Law for an Autonomous Approach and Landing Spacing System

Lance Sherry,[1] Oleksandra Snisarevska,[2] and John Shortle.[3]
Center for Air Transportation Systems Research at George Mason University, Fairfax, Va., 22030, U.S.A.

One of the flow bottlenecks in the National Airspace System is the landing runway. Flights are at their lowest speed for the approach and landing phase, and must be sequenced in close proximity to maximize use of the runway but with enough separation to avoid a wake vortex encounter. Self-separation, Required-Time-of-Arrival and other technologies have reduced the excess separation between flights that contributes to decreased runway throughput. A critical parameter in these technologies is the excess spacing buffer, over and above the required wake vortex separation distance, that is required to account for stochastic phenomena that affect separation in the approach such as atmospheric conditions, ATC instruction execution delays, and aircraft performance. This paper describes a closed-loop control law to autonomously calculate and adapt the excess spacing buffer in real-time to achieve the desired level of safety while maintaining maximum throughput.

I. Nomenclature

AALS	=	Autonomous Approach and Landing System
ALS	=	Actual Level of Safety
FAF	=	Final Approach Fix
MSSD	=	Minimum Safe Separation Distance (e.g. wake vortex separation distance)
OM	=	Outer Marker
p_actual	=	actual probability in left tail of inter-arrival distance distribution
p_error	=	difference between p_actual and p_target
p_target	=	target probability of left tail of inter-arrival distance distribution
SBD	=	Spacing Buffer Distance
TLS	=	Target Level of Safety
TSD	=	Target Separation Distance

II. 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 for the follow aircraft to avoid an encounter with the wake vortex of the lead aircraft (Figure 1). The separation must also ensure that the lead aircraft has vacated the runway before the follow aircraft crosses the runway threshold. In this way, flights are spaced at the Final Approach Fix (FAF) for the final approach segment. They then fly "open-loop," without intervention, down the final approach segment such that they cross the runway threshold with sufficient inter-arrival spacing. Since the final approach segment is conducted in a highly stochastic environment due to factors such as atmospheric conditions, aircraft performance, ATC and pilot technique, and delays in ATC-flight communication, Air Traffic Control (ATC) adds a "buffer distance" to the required wake vortex separation distance [1], [2]. The buffer distance is a conservative measure to make sure that the follow flight does not encroach on the lead flight and violate the required wake vortex separation. A buffer distance that is too large results in reduced runway throughput. A buffer

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[1] Director, Center for Air Transportation Systems Research at George Mason University, AIAA Member.
[2] Ph.D. Student, Center for Air Transportation Systems Research at George Mason University, AIAA Student Member.
[3] Professor and Dept. Chair, Systems Engineering and Operations Research at George Mason University.

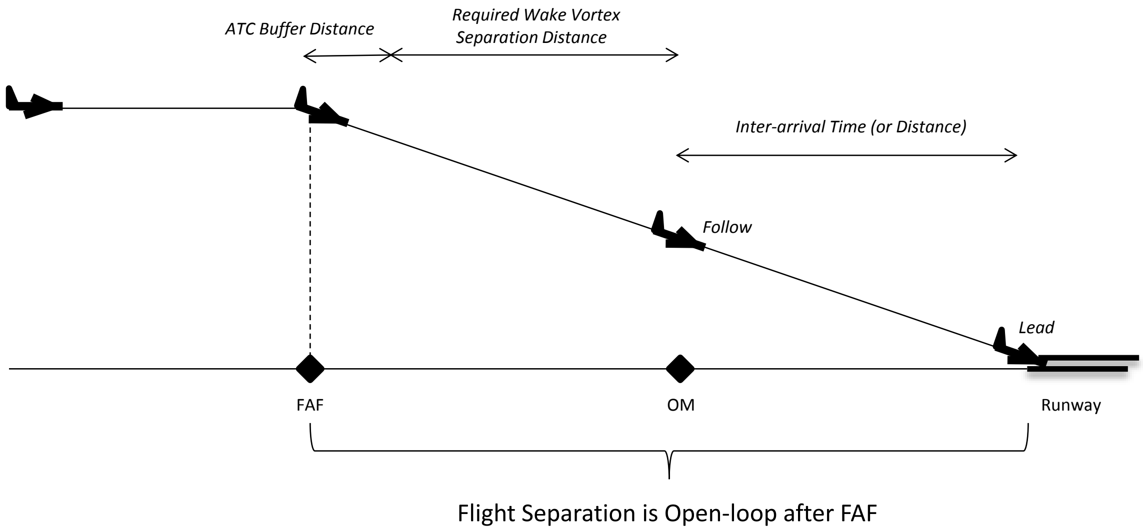

Fig. 1 Final Approach Segment

distance that is too short leads to separation violations.

The efficiency of the approach and landing process is represented by the inter-arrival distance at the runway threshold. Maximum efficiency is achieved when the inter-arrival distance for all the flights is exactly the required wake vortex separation distance. Since the approach and landing process is inherently stochastic, the inter-arrival distance results in a distribution in (Figure 2). This distribution is normalized to the required separation distance between sequential flights such that a pair flights at the exact separation distance is at zero. The magnitude of the left-tail of the distribution determines safety margins of the approach process. The probability associated with the left tail (p_actual) is the Actual level of Safety (ALS). The magnitude of the right tail of the distribution represents gaps in the flow and inefficiency in runway throughput.

The Minimum Safe Separation Distance (MSSD) is the required wake vortex separation distance (Figure 2). The Target Separation Distance (TSD) is the sum of the MSSD and a Spacing Buffer Distance (SBD). The SBD is additional spacing buffer inserted to account for stochasticity on the final approach segment.

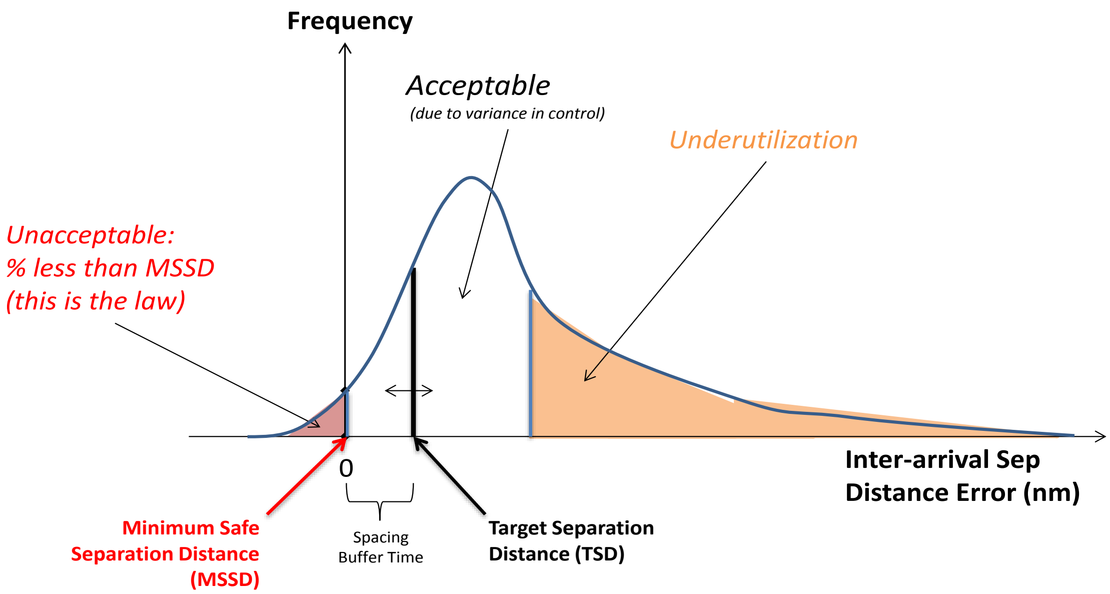

Figure 2: Distance distribution for inter-arrival time at Runway Threshold. Magnitude of the left-tail represents the Target Level of Safety

The Actual Level of Safety (ALS) is the area in the left tail. This represents the probability of a flight violating the MSSD. The SBD must be continuously adjusted to ensure that the ALS is at the Target Level of Safety (TLS). A typical TLS might be 0.05.

This inter-arrival distance distribution is not available to Air Traffic Controllers managing the approach process. The Actual Level of Safety (i.e. the probability of the left-tail) is also not provided to the controller. Instead, the controller, must accumulate experience to determine and adjust the SBD to maximize safety as the same time as minimizing excess spacing.

Further, new concepts of operations and automation have been proposed to space flights at the final approach fix: time-based separation (e.g. [3]), self-separation (e.g. [4], [5]), and paired approach (e.g. [6]). As in the case of manual separation, the automated processes must calculate the SBD based on current conditions in order to set the TSD to meet the TLS. The TSD will naturally vary with atmospheric conditions, wind, aircraft performance, fleet mix, and traffic flow and must be assessed and updated continuously.

This paper describes an autonomous, closed-loop control law to calculate the SBD and set the TSD to meet the TLS. Section III describes the concept-of-operations. Section IV describes the design of the closed-loop control law. Section V demonstrates the control with simulation results. Section VI provides conclusions.

III. Proposed Concept-of-Operations for Autonomous Approach and Landing Spacing

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 3). 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.

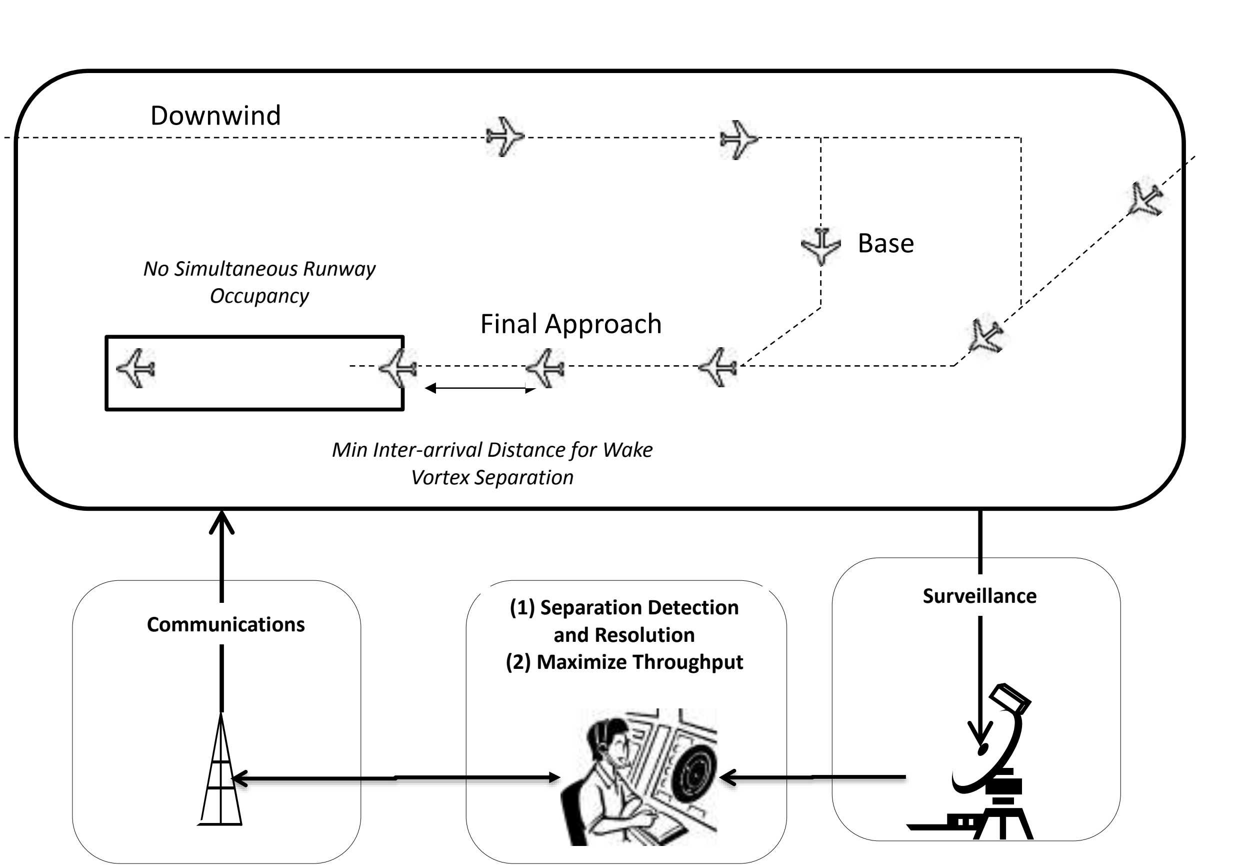

Figure 3: Air traffic controller monitors flights on surveillance "radar" and issues instructions to flights to maintain required safe separation distance.

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. The real-time distance distribution is not provided to the controller, nor is the ALS.

An Autonomous Approach and Landing Spacing (AALS) System [7] replaces the manual closed-loop spacing system with an automated system (Figure 4). 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.

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.

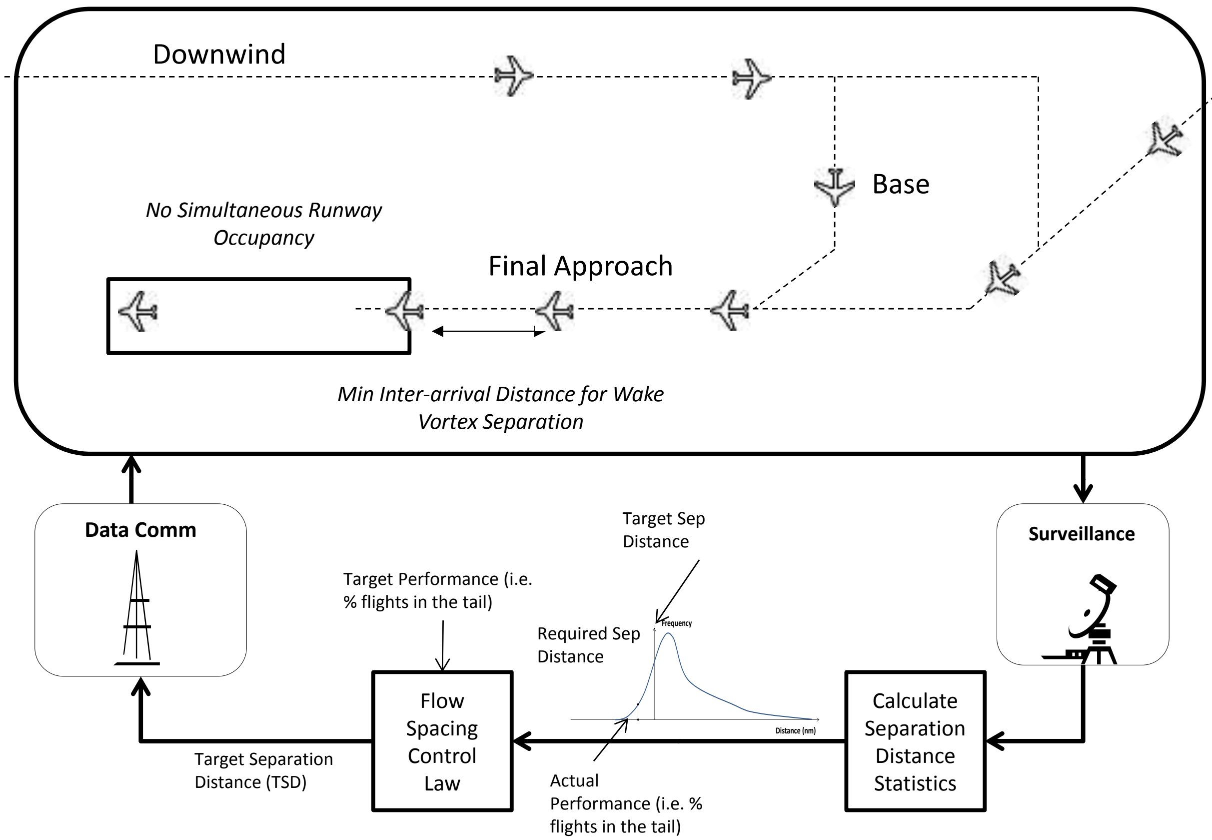

Figure 4: Autonomous system generates inter-arrival time distribution from surveillance “radar” and issues instructions to flights to maintain the required safe separation distance based on the flow spacing control law.

The probability associated with the left tail is used as feedback for a closed-loop control law (Figure 5). 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 5). The dashed-line shows the distribution with the AALS.

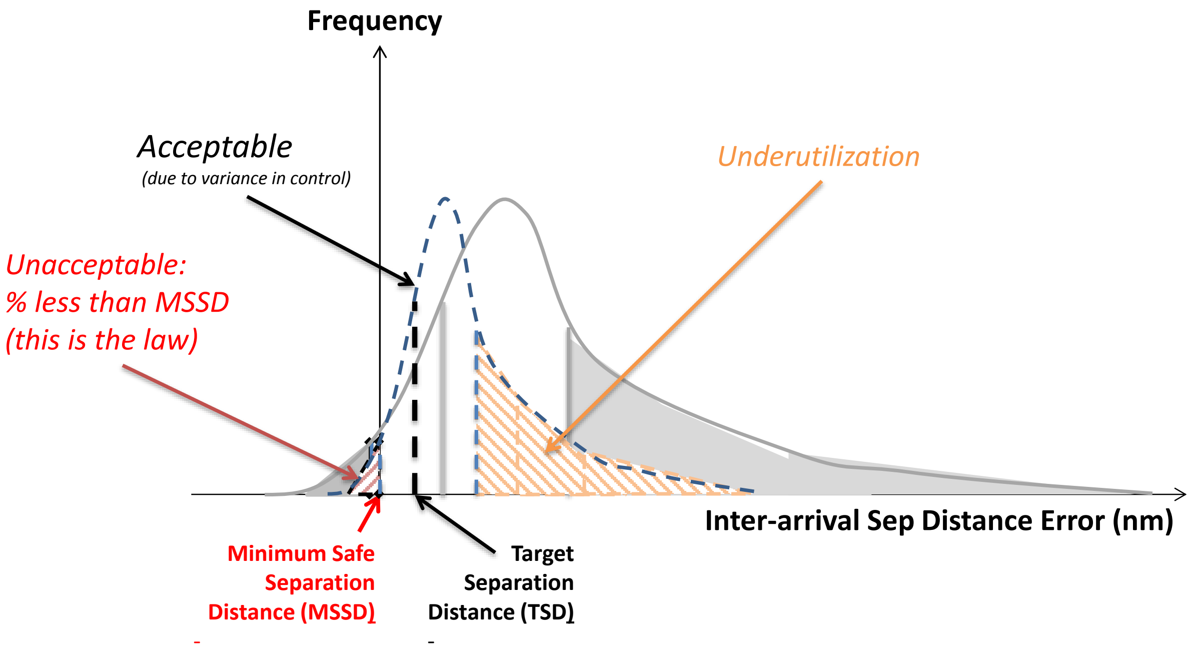

Figure 5: Flow spacing control law maintains the Target Level of Safety as conditions change

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.

IV. Control Law for Autonomous Approach & Landing System

A closed-loop control law for autonomous calculation of the TSD is illustrated in Figure 6. The TSD Is sum of the MSSD and the SBD (i.e. TSD = MSSD + SBD). Since the MSSD is fixed, the control adjusts the SBD.

First, the control law calculates the inter-arrival distance distribution at the runway threshold based on a growing sample of sequential flights. Based on the distribution, the control law determines the actual probability of flights in the left-tail (p_actual). This value is compared with the p_target (i.e. the Target Level of Safety) to generate a p_error. This p_error is submitted to the control law algorithm to calculate the SBD to achieve the TSD that ensures the ALS is equivalent to the TLS.

The Actual Probability of flights below the MSSD for a given TSD is calculated only once the sample size exceeds a threshold defined by a confidence interval of 95% with a 2% margin of error:

$n = z^2 \, p \, (1-p) / M^2$,

where:

n = sample size, z = 1.96 for 95% confidence interval
p = sample proportion
M = margin of error

When the sample size criteria are set, the Actual Probability is calculated and compared to an Upper and Lower Threshold for a Target Probability of 95% Confidence Interval. This Confidence Interval is adjusted for sample size. As the sample size increases, the thresholds approach the Target Probability. Upper and Lower Threshold are calculated as follows:

Upper / Lower Threshold = Target Probability +/- ($t_{1-\alpha}$ * (1/SQRT(#flights)))

The TSD is calculated as according to the following rules:

- The TSD remains unchanged when the Actual Probability is less than the Upper Threshold and greater than the Lower Threshold.
- The TSD is incremented when the Actual Probability transitions above the Upper Threshold.
- The TSD is decremented when the Actual Probability transitions below the Lower Threshold
- The TSD is incremented when the Actual Probability remains above the Threshold for a sample size of flights (e.g., 30). This is the condition where the Actual Probability remains above the Upper Threshold for an extended period.
- The TSD is decremented when the Actual Probability remains below the Lower Threshold for a sample size of flights (e.g., 30). This is the condition where the Actual Probability remains below the Lower Threshold for an extended period.

The flow chart for the algorithm is provided in Figure 7.

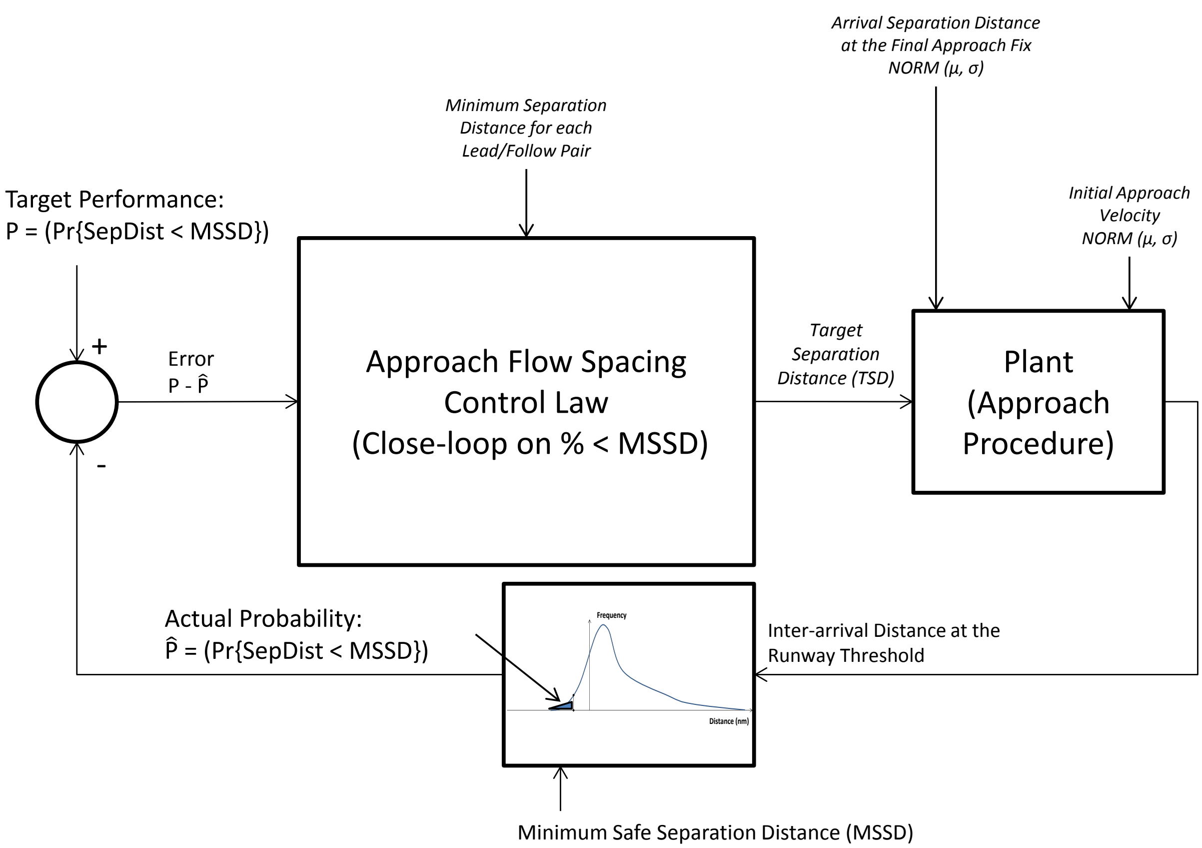

Figure 6: Closed-loop Control Law for Autonomous Spacing for Approach & Landing

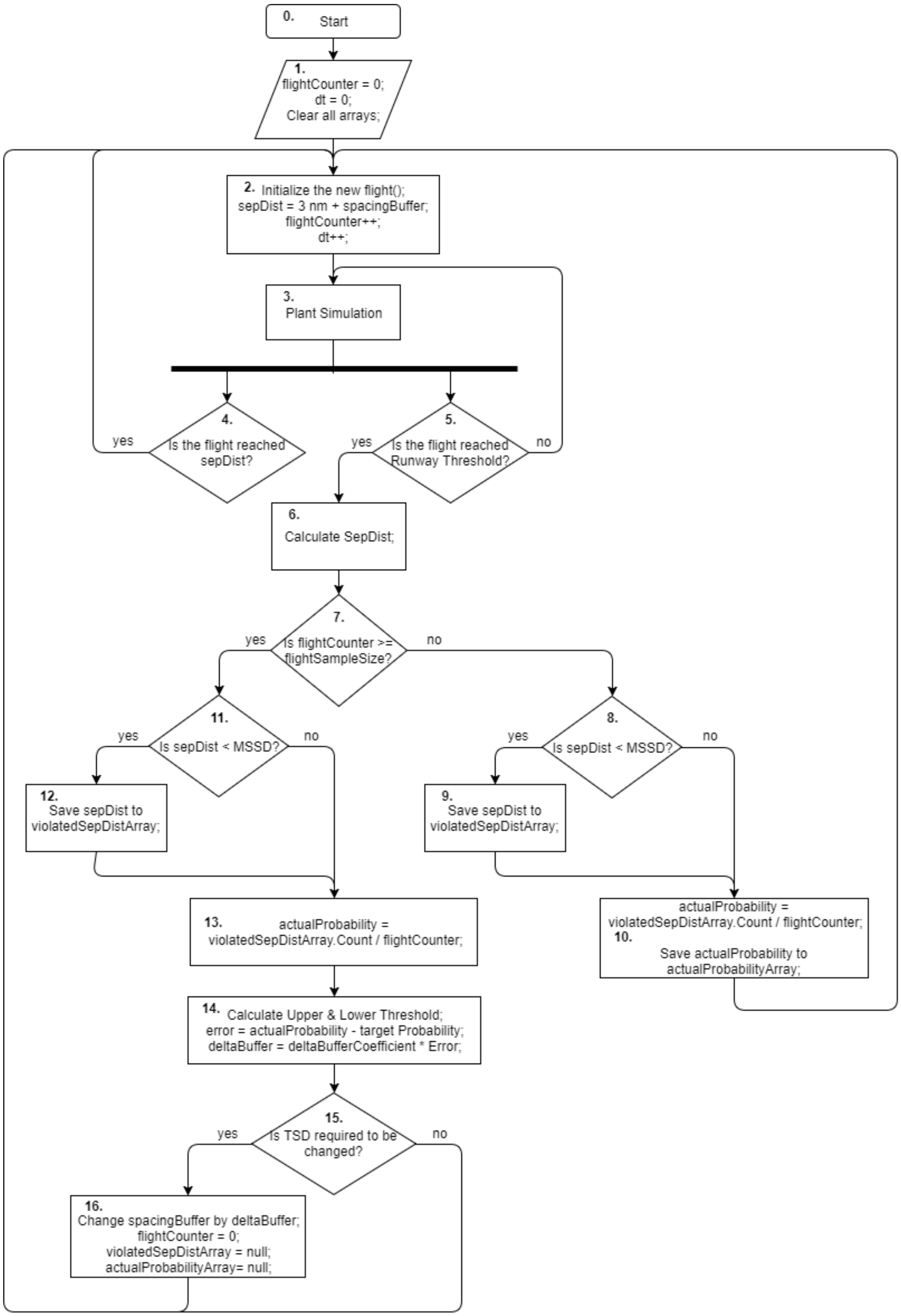

Figure 7: Flow chart for algorithm for the closed-loop control law

V. Simulation Results

The closed-loop control law was developed and demonstrated via simulation. The simulation is described in detail in [8]. The simulation was run for 1000 homogenous flights on approach with the Autonomous Approach and Landing System active. The target velocity for reference landing speed was set to 120 knots with a standard deviation of 5 knots for the first 500 flights. The standard deviation for the landing velocity was increased to 10 knots for the last 500 flights to simulate a change in stochasticity on the final approach segment (e.g. transition from VFR to IFR or presence of crosswinds). The Spacing Buffer was initialized to 10 seconds with a standard deviation of 2.5 seconds. The target percentage of flights in violation of MSSD is set to 5%. The minimum sample size threshold was set to 30 flights.

The results of the simulation are summarized in Figure 8. The horizontal axis is the sequence of flights from 1 to 1000. The Spacing Buffer (orange) is shown in the upper chart with vertical axis time in seconds. The Actual Probability (blue) is shown in the lower chart with vertical axis shown as a percentage. The lower chart also shows the upper/lower thresholds that account for low sample size (red). The Upper and Lower Thresholds change according to the current flight counter (i.e. sample size). The flight counter is set to zero every time the Spacing Buffer is modified. As the flight counter increases, the threshold for Actual Probability (p_actual) converges towards the Target Probability (p_target). The Target Probability is shown as a red-dashed line. The difference between the p_actual and p_target is an input to the closed-loop control law that generates a new TSD. The spacing buffer time is modified whenever the actual probability (blue line) transitions from inside to outside the probability thresholds (red lines).

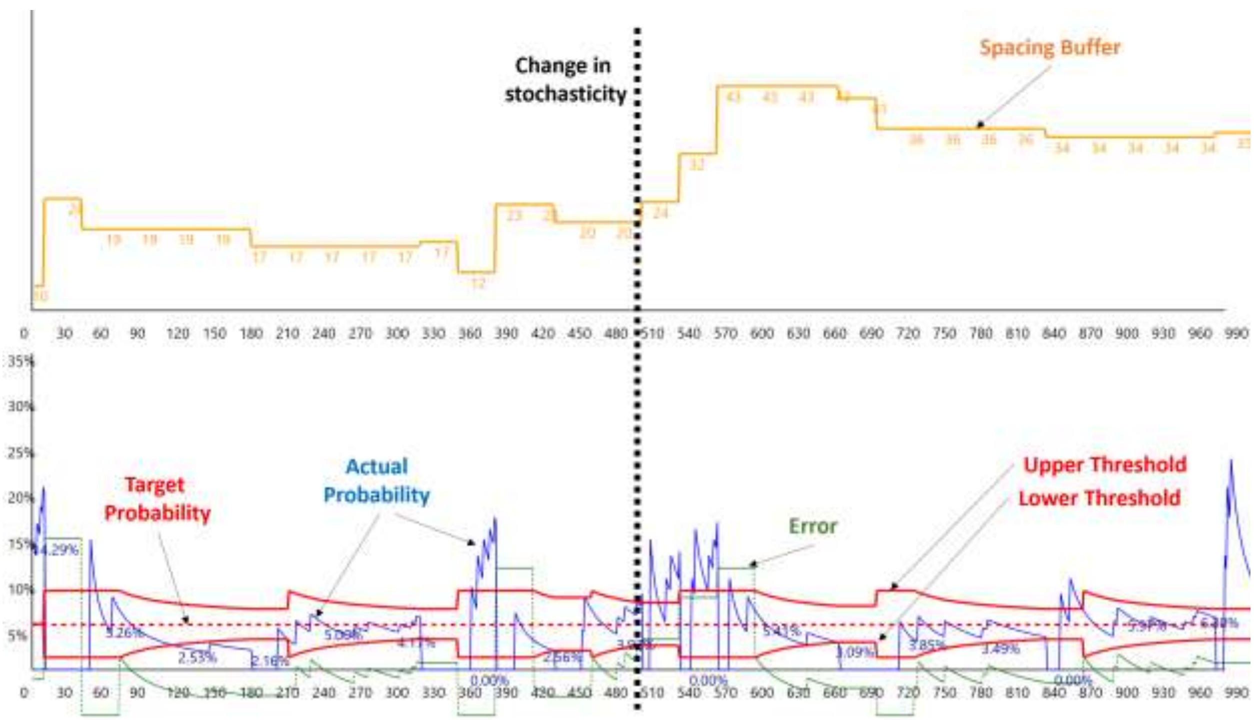

FIGURE 8: Closed-loop control of Spacing Buffer in the presence of stochastic factors in the final approach.

In this example, a change in stochasticity in the approach process occurs at 500 flights when the Initial Velocity's standard deviation is increased from 5 to 10 knots (black-dashed line across the charts). For the first 500 flights, with Initial Velocity standard deviation set to 5, the Spacing Buffer fluctuates between 10 (initial settings) and 24 seconds settling on an average steady-state of 18 seconds. After 500 flights, with the standard deviation for Initial Velocity now set to 10, the Spacing Buffer Time autonomously adjusts initially to 24 seconds and then an average and steady-state value is 35 seconds.

VI. Conclusions

This paper describes the design of closed-loop control law for autonomous calculation of the optimum spacing of flights on the final approach segment. The control law is capable of real-time adjustment for stochastic factors such as transition between IFR and VFR, atmospheric conditions (e.g. crosswinds, headwinds), fleet mix changes, and pilot techniques, to maintain the desired level of safety.

The control law can be used by air traffic controllers for manual control of the spacing of approach traffic. The control law can also be used for an automated approach and landing system in conjunction with self-separation, time-based spacing and required time of arrival. For the automated system, the control law provides and updates the critical target spacing required by each of these technologies that are focused on the individual aircraft, not the flow.

A. Sensitivity and Closed-loop Control Law Parameters

As in the design of any closed-loop control law there is a necessary tradeoff between responsiveness (i.e. rise time) and nuisance changes (i.e. settling time). Since the AALS is adjusting to relatively slow moving stochastic changes in the final approach, the adjustment of the spacing buffer time should only respond to repeatable trends in the inter-arrival distribution. This is consistent with using a larger sample size. However to maximize throughput in peak operations the spacing buffer should be adjusted more frequently. Parameters that affect this performance are the flight sample size, the limits on the upper/lower thresholds, and the size of the incremental buffer adjustment. Design heuristics for setting these parameters in the control law is the subject of future work.

B. Setting the Target Level of Safety

A critical design parameter for the Approach and Landing Spacing System, whether it is used in an automated manual setting, is the value used for the TLS. When flights are released at the FAF at the separation standard, the process is an inherently “mean-reverting” process. That is, by design there is no chance of a run-away 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. Humans cannot perform this task as the cognitive processor does not have the ability to generate distributions. Some type of automated decision support process is required.

C. 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 (e.g. [9]), active runway surveillance (e.g. [10]), runway assignments and flight sequencing (e.g. [11], [12]) and taxiway guidance (e.g. [13]).

D. 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.

E. 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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