A STUDY ON AIRCRAFT TAXI PERFORMANCE USING NONLINEAR FEEDBACK CONTROL

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Abstract

Whenever traffic density becomes so critically high that it begins to jeopardize efficiency and safety, the answer lies in the ability to improve traffic coordination and movement precision. This study considers the surface-traffic problem at major airports, and establishes the possibility of high-precision taxi operations by applying state-of-the-art automatic control technologies. Due to the high-speed environment, high-precision taxi is most difficult on or across the runway, where such ability is also potentially most beneficial. In this study, a nonlinear guidance and control system is synthesized and its potential performance in high-precision taxi control is verified, including the ability to taxi continuously immediately after landing to cross an adjacent runway with the tightest of time margin.

I. INTRODUCTION

The anticipated increase in air travel demands a more efficient air transportation system. NASA and FAA have several programs that address this problem: Center/TRACON Automation System (CTAS) [1][2], Terminal Area Productivity (TAP) program [3]–[5], Surface Movement Advisor (SMA) [6], and most recently the Advanced Air Transportation Technologies (AATT) program. Current experience with CTAS, a set of tools and technologies to aid Center and TRACON controllers in handling arrival air traffic, has been extremely successful in fulfilling its objectives of enhancing traffic efficiency through time-based metering. As it improves the efficiency in arrival traffic, it also reveals that airport surface traffic will become a weak link in the air-traffic equation if it is not accorded the attention commensurate with other air traffic automation tools.

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There are two basic approaches to address the problem of increased surface traffic, and both may be required in a two-prong approach to the problem. The first involves increasing usable airport real estate in terms of runways, taxiways, ramp, and terminal areas. The second is to increase efficiency by reducing separation, hence increasing density, of vehicles in traffic.

Under the first approach, increasing the number of runways and taxiways to handle more traffic also increases the complexity of the airport configuration. The tower controllers have more aircraft to control, and more taxiway intersections and runway crossings to worry about. Under most airport configurations, adding runways results in some runways blocking the traffic between the terminal and other runways farther away from the terminal. This necessitates runway crossing or construction of taxiways around the inside runways.

Under the second approach for handling more air traffic by reducing aircraft separation to increase efficiency, the increase in utilization of the outside runways will lead to an increase in the need for runway crossings. Furthermore, the reduced separation associated with the increase in utilization of the inside runways means that the time windows available for crossing of these runways are reduced.

This study focuses on the scenario of runway crossing to establish the potential improvement from high-precision taxi as part of a complete and coherent solution for surface traffic control. The reason for choosing this scenario is that surface traffic on the runway is more time-critical than traffic on the taxiways, and runway crossing can impact runway operations and hence runway utilization efficiency immensely.

In order to accomplish safe operation when the traffic demands more occurrences of runway crossing with smaller time windows, it is imperative that aircraft taxi operations be enhanced to enable runway crossing through really narrow time windows. Minimization of runway-crossing time implies maximum taxi speed, which can benefit from a maximum permissible initial speed. As illustrated in Section II, a major portion of the benefits associated with advanced technologies to improve runway-crossing efficiency is attributable to the ability to taxi across the runway when permitted without having to stop at the hold line. Moreover, not having to stop can further benefit surface traffic efficiency by reducing taxi traffic backup. An additional benefit is the improvement in fuel efficiency due to the reduction in braking and acceleration associated with stop and go, and the reduction in engine idle time.

To taxi continuously and cross runways safely without requiring a large safety margin in the time window will require a high precision in aircraft taxi control in arriving at the runway accurately at the time when the window opens. The guidance and control designs in Section III explore the use of automation in precise and fast runway crossing. The analyses in Section IV demonstrate the potential performance of such an automated system through digital simulations and Monte-Carlo analysis. The findings will be useful in two areas. Firstly, the automation concept can be expanded to the full-scale development of cockpit automation for taxi operations. The vehicle performance data under different operating conditions are applicable to all taxi phases, including runway crossing as well as traffic sequencing and scheduling at merging taxiways. Such data will be useful in the design of a ground ATC automation system for coordinating surface traffic over the entire airport.

II. RUNWAY-CROSSING TIME ANALYSIS

The analyses in this paper use an aircraft dynamic simulation model adapted from the NASA Transport System Research Vehicle (TSRV), which was a B-737 flight research aircraft. The 12^{th}-order state vector includes three inertial position components, three velocity components, three body Euler angles to represent body attitude, and three angular velocity components. Seven control inputs are included in the TSRV model implementation: aileron, elevator, rudder, tiller, throttle, and left and right brakes.

The two key factors affecting runway-crossing efficiency are: (i) runway-crossing time (i.e. width of time window required), and (ii) accuracy of arrival time at the runway-crossing hold line for aircraft in motion. This section examines the runway-crossing time factor. Prior to crossing, the aircraft is either stationary holding short of the runway or in continuous motion ready to cross the runway without stopping. The dimensions used in the analyses herein are based on the DFW airport layout. With the DFW runways ranging between 150ft and 200ft in width, and the length of the TSRV in the order of 100ft, the analysis assumes that the aircraft needs to travel 100m (i.e. over 300ft) for crossing the runway.

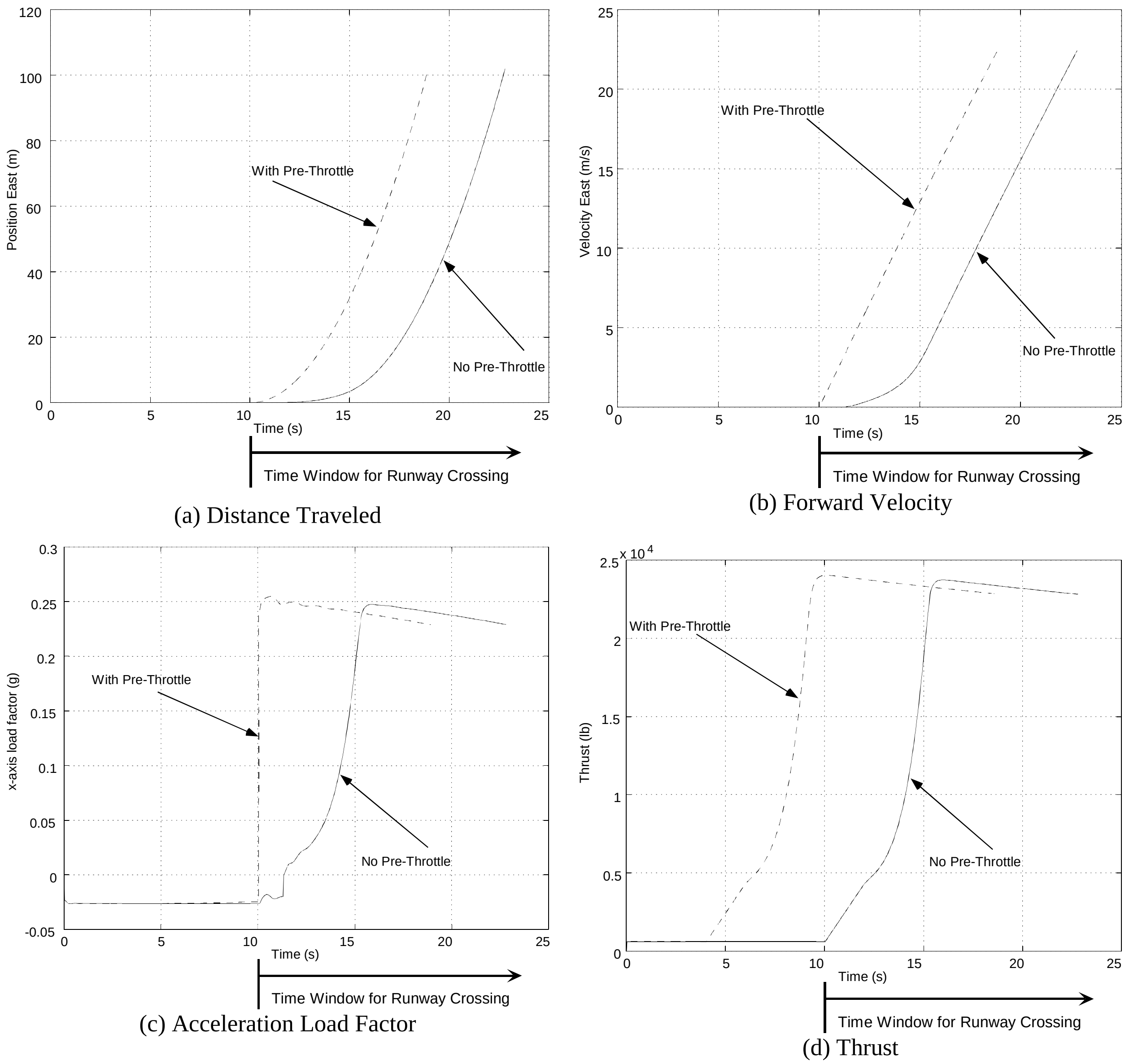
For the situation where the aircraft is stationary prior to crossing, two cases are compared. They assume that the window for crossing would open at the 10s point of the simulation. In both cases the aircraft has 100% brakes applied until the 10s point. In the first case, the throttle remains at idle (i.e. 0%) until the 10s point, at which time it is allowed to increase to 100%. In the second case, the throttle is allowed to be set to deliver acceptable thrust prior to the 10s point.

From previous experience including TSRV flight tests, the maximum acceleration for take off and maximum deceleration after landing are both around 0.25g. Hence it is reasonable to assume that the maximum acceleration acceptable for passenger comfort is about 0.25g, and the throttle for the analyses would be reduced when the load factor reaches 0.25g. For the first case where there is no pre-throttle, the throttle is cut back to 75% shortly after 15s. For the second case where there is pre-throttle, the throttle value is set to 75% at 4s, i.e. 6s ahead of the runway-crossing window, so that the acceleration load factor can jump instantaneously to 0.25g when the window opens. It is assumed that no continuous adjustment of the throttle is allowed to maintain the acceleration at 0.25g as the vehicle picks up speed. The results are depicted in Figure 1, with the final time data tabulated in Table 1. Although in both cases the final throttle value is set to 75%, the load factor for the pre-throttle case initially goes above 0.25g briefly, because the thrust of the engine is typically higher at lower in-take speed.

Table 1. Runway Crossing Results with Acceleration Load-Factor Limit of 0.25g

	Runway Crossing Time (s)	Final Speed (m/s)	Average Speed (m/s)
No Pre-Throttle	12.7	22.2	7.9
With Pre-Throttle	8.7	22.4	11.2
Constant Speed 30kn	6.5	15.4	15.4

Table 1 shows a 31.5%reduction in runway-crossing time due to pre-throttle. Table 1 also includes the runway-crossing time for an aircraft in motion at 30kn without stopping prior to crossing. Even though 30kn is substantially below the final speed reached by the earlier cases, the runway-crossing time is a mere 6.5s. This shows the additional benefit if the aircraft is allowed to taxi without stopping when crossing the runway.



(a) Distance Traveled

(b) Forward Velocity

(c) Acceleration Load Factor

(d) Thrust

Figure 1. Comparison of Throttle Timing for Runway Crossing from Rest with Acceleration Load-Factor Limit of 0.25g

III. GUIDANCE AND CONTROL DEVELOPMENT

This section explores the use of automation in the form of guidance and control to enable high-precision taxi for arriving at a runway for crossing at the instant when a cleared window opens. If the runway-crossing time window has to be padded with a substantial margin to account for imprecision of aircraft taxi, then much of the savings in crossing time would be lost, although the benefits of reduced traffic backup and improved fuel efficiency will still be valuable.

III.1 Overall Guidance and Control Concept

The objective of the automation system is to control the TSRV in accordance with the taxi clearance. The concept includes a guidance subsystem and a control subsystem as depicted in Figure 2. The guidance function in the outer loop of Figure 2 is to generate the vehicle trajectory time history for achieving the taxi clearance. The taxi clearance for a landing aircraft may include the assigned exit and a time window for crossing an adjacent runway. The trajectory may include position and velocity as functions of time. The control function in the inner loop of Figure 2 is to

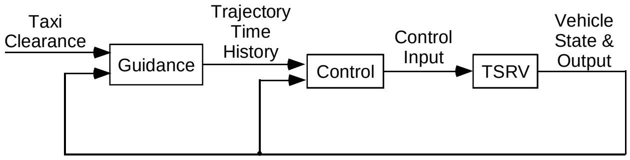


Figure 2. Overall Guidance and Control Structure

produce the control-input commands necessary to make the vehicle state track the reference trajectory provided by the guidance function. The control and guidance functions are discussed in Section III.2 and III.3, respectively.

III.2 Nonlinear Controller based on Feedback Linearization

III.2.1 Control Loop Structure

This study applies a form of feedback linearization [7]–[9] to design the control function in the inner loop of Figure 2. Figure 3 illustrates the design concept. The design treats the TSRV as a point-mass model, with its state x consisting of the position vector r and velocity v. The acceleration a is assumed to be some nonlinear function f of the control input u and state x, where u contains the seven control commands described above.

The control function has two components: a feedback-linearization controller and a linear controller. The feedback-linearization controller $\tilde{f}$ is designed so that, given x, the composite function $f(x, \tilde{f}(x, a_c))$ is linear in the commanded acceleration a_c. In fact, it is desirable to have

$$f(x, \tilde{f}(x, a_c)) = a_c$$

This means that when given x, $\tilde{f}$ behaves like the inverse of f, $f(x, \tilde{f}(x, \cdot))$ behaves like an identity feed-through, a would track a_c precisely, and the system in Figure 3 with the feedback-linearization controller would behave like a simple double integrator. Under this condition, any conventional linear design technique [10] can be used to synthesize a linear controller to complete the closed-loop system of Figure 3 to provide desirable performance for trajectory tracking.

The effort to determine the function f for representing the TSRV is described in Section III.2.2, followed by the descriptions of the feedback-linearization controller $\tilde{f}$ and the linear controller in Sections III.2.3 and III.2.4, respectively.

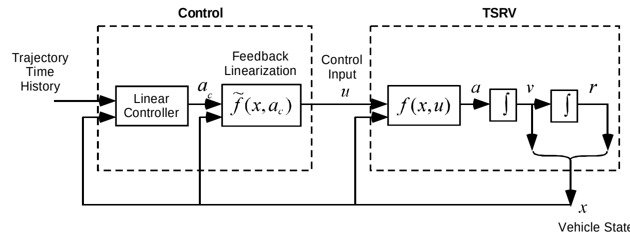


Figure 3. Simplified Illustration of Controller Design with Feedback Linearization

III.2.2 TSRV Design Model

The controls for taxi operation are throttle and brakes for speed control, and tiller (superceding rudder pedals) and differential brakes for turns. The scenario assumes that the taxi speed is sufficiently low that the aerodynamic effects can be ignored. The performance data required for controller synthesis for forward motion include the effect of throttle on propulsion thrust and the effect of brakes on friction for deceleration. The propulsion performance is known to depend on air speed at the intake. To generate the data, the TSRV simulation is hard-coded to run at different speeds, and the steady-state effects on thrust due to different values of throttle are recorded. Figure 4 depicts the effect of throttle settings on the achieved thrust at various taxi speeds.

To obtain the performance data for the effect of brakes on friction, the TSRV simulation is hard-coded to run at different speeds, and the steady-state effects on friction due to different values of parallel braking are recorded. The resulting data in Figure 5 shows that the braking effect is independent of vehicle speed.

The throttle and parallel braking controls for forward acceleration/deceleration have opposing effects and hence should be commanded in a

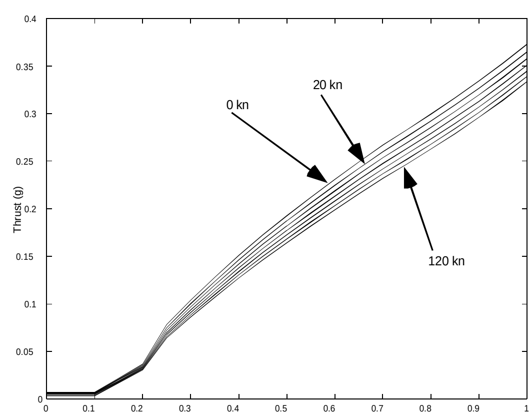


Figure 4. Effect on Thrust due to Throttle at Various Speeds

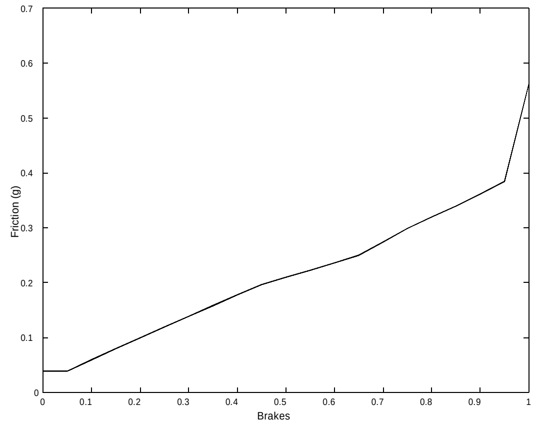


Figure 5. Effect on Friction due to Parallel Braking

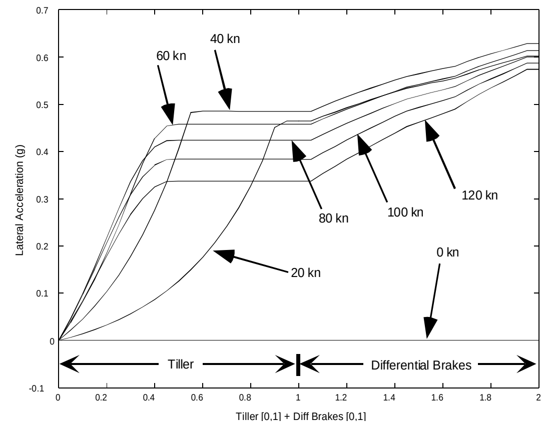


Figure 6. Effect on Lateral Acceleration due to Tiller and Differential Braking

mutually exclusive manner. If necessary, any desired negative values of braking would translate into positive values of throttle, and vice versa. This throttle-brake conversion is important when differential braking is applied to accomplish turns that cannot be achieved with the tiller alone, resulting in some level of braking that has to be compensated for with the throttle.

Small turns are accomplished through rudder pedals, while the tiller extends the control beyond the rudder's limit. If tighter turns are needed, differential braking can be applied. Analysis results show that if lateral load factor is limited to 0.15g, then the tiller should have enough control authority. Differential braking is included in the controller design for the sake of completeness [11].

To compile the performance data of lateral acceleration due to these control inputs, a special TSRV simulation is implemented with a feedback system designed to adjust the engine thrust to maintain speed while turning, so that steady-state lateral acceleration can be determined as a function of these controls. Figure 6 depicts the resulting steady-state effects of the tiller and differential braking on lateral acceleration. The first 100% of the control is due to rudder and tiller. Since differential braking should be used only after the tiller has reached its limit, the second 100% of the control represents differential braking in addition to maximum tiller.

III.2.3 Feedback Linearization Algorithm

The performance data are used in the design of the Feedback Linearization controller, which maps the commanded acceleration to the desired control input. Let the acceleration a_c commanded by the linear controller be represented by the longitudinal a_{xc} and lateral a_{yc} components. The desired a_{xc} dictates the necessary amount of engine thrust or brake friction from Figure 4 and Figure 5. Similarly, the desired a_{yc} dictates the amount of tiller and differential braking from Figure 6. The only possible complication may arise when the superposition of differential braking on parallel braking causes one of the two brakes to be out of range. An algorithm to implement differential braking has been developed as part of the controller [11].

III.2.4 Linear Controller

With the feedback linearization designed to mitigate the nonlinearities of the TSRV model, a linear controller for shaping the feedback system to deliver the desired performance can be designed to complete the control function. This study uses conventional proportional-plus-derivative (PD) control for designing the linear controller. The controller gains are selected to prescribe a desirable natural frequency and damping ratio for the closed-loop system.

III.3 Guidance Trajectory for Taxi

The guidance function for airport taxi is designed for piecewise-linear routes. Transition between linear segments is accomplished through turning along a circular arc, modeled according to constant speed and centripetal acceleration.

Figure 7 shows a scenario at DFW where airplanes landing on Runway 18C would turn off at exits E3, E5 or E6 to cross Runway 18L. The path between the point of landing and the runway-crossing hold line is made up of three segments as in Figure 8. The trajectory profile includes a deceleration leg immediately following nose-gear touch down. The exit involves a shallow turn-off from the landing runway, transitioning to a second turn ending on a taxiway normal to the two runways.

To generate the trajectory given the taxi time to the hold line, a final taxi speed is selected for the guidance function. With this speed the trajectory profile can be generated backwards through the two turns to the landing runway. The deceleration can be uniquely determined based on the landing speed and the final taxi speed to complete the total trajectory profile to achieve the cleared taxi time.

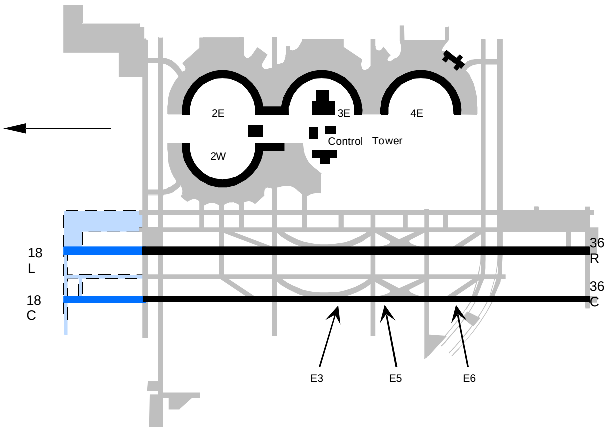


Figure 7. Example of Landing, Turn Off and Runway Crossing at DFW

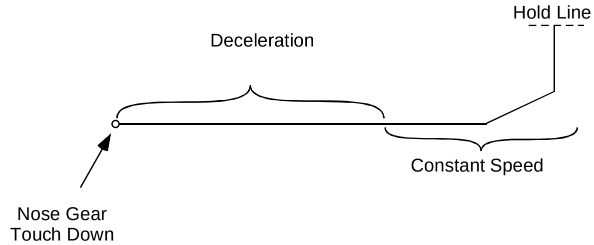


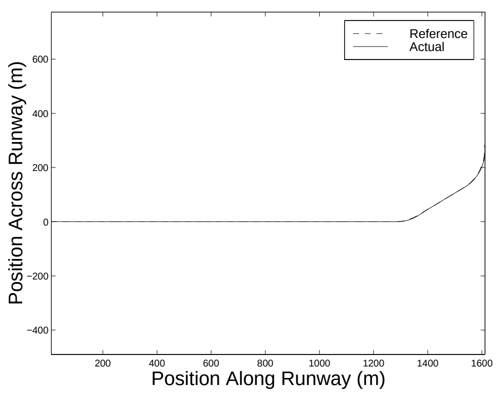
Figure 8. Generic Taxi Path for Landing, Exit and Runway Crossing

IV. GUIDANCE AND CONTROL EVALUATION

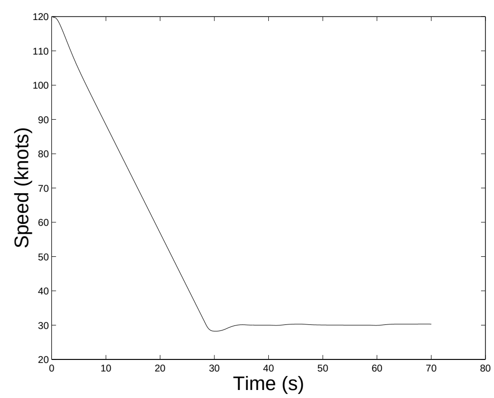
The evaluations are based on the condition that the TSRV is 3000ft past the threshold of Runway 18C when the nose gear touches down, at a speed of 120 knots. To minimize actuation delay, the implementation uses the nose-gear position instead of the CG as the reference for trajectory tracking.

IV.1 Initial Evaluation

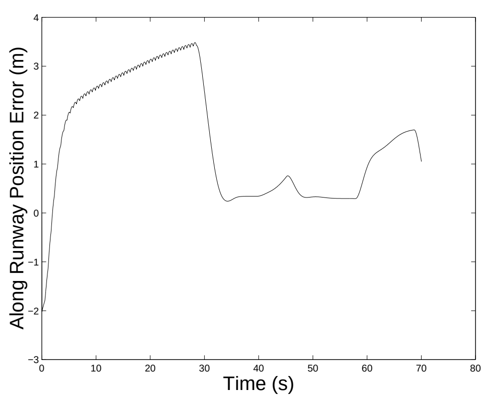
The initial test is based on a 30kn turn off at Exit 5. The lateral acceleration used for computing the turn arcs is 0.15g. Figure 9 contains the



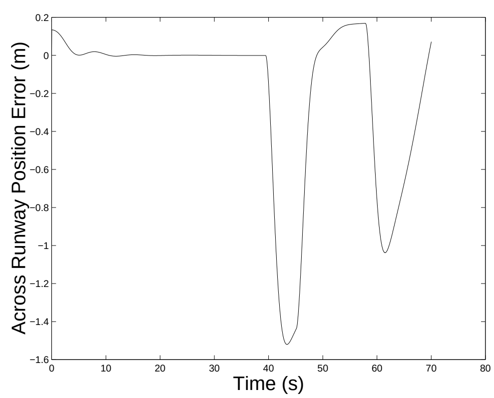
(a) Actual and Reference Trajectories



(b) Speed

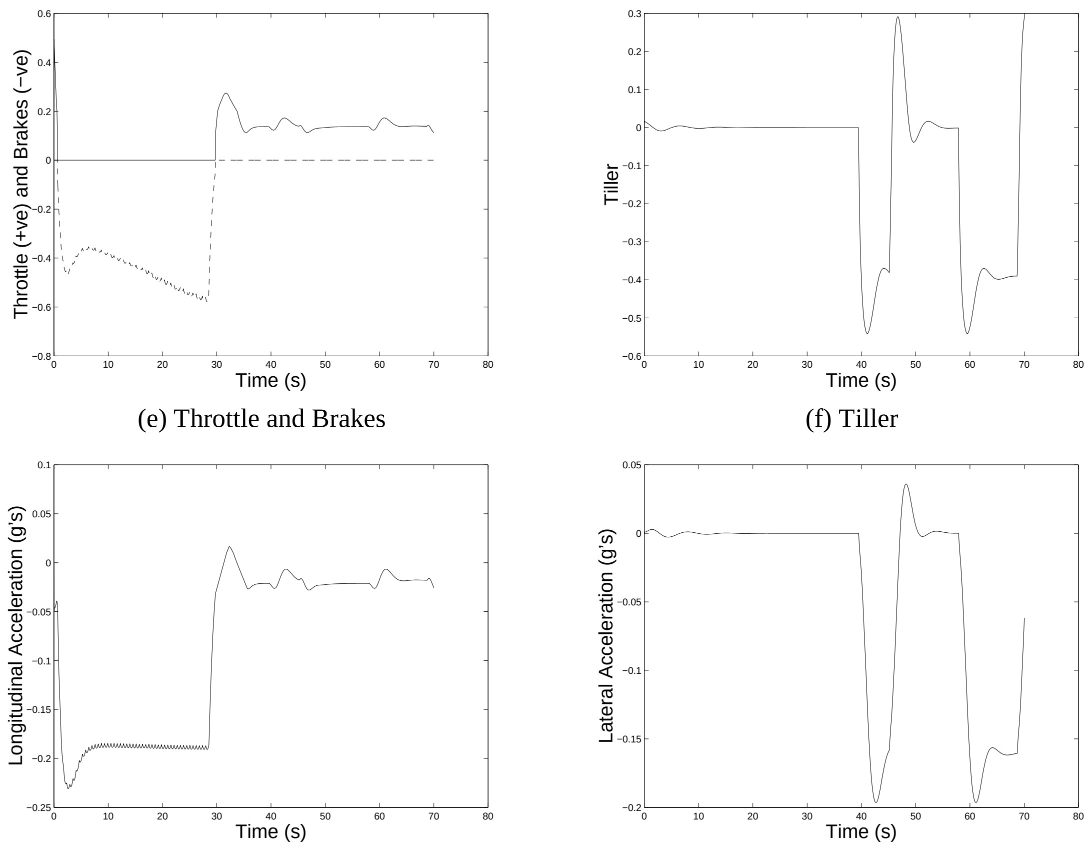


(c) Position Error in Direction of Runway



(d) Pos Error Normal to Runway Direction

Figure 9. Simulation Results for 30kn exit to E5



(e) Throttle and Brakes (f) Tiller

(g) Longitudinal Acceleration (h) Lateral Acceleration

Figure 9. Simulation Results for 30kn exit to E5

simulation results. The runway-crossing time error is –0.004s, with a cross-track error of 1.07m. The position error in the direction of the runway in Figure 9(c) shows that the along-track error was largest during the initial deceleration phase. Since the error is along the direction of the runway and the aircraft executed two turns to go normal to the runway, only the initial portion of the error corresponds to along-track error. The errors shown in parts (c) and (d) of Figure 9 indicate that the aircraft is lagging slightly behind the reference trajectory.

IV.2 Guidance Taxi Time Range

Before further evaluation of the guidance and control design, the range of possible taxi times for arriving at the adjacent runway is determined. Figure 9(h) shows that the lateral acceleration can experience an overshoot exceeding 0.15g, even though the centripetal acceleration used for computing the turning arcs is set to 0.15g. Consequently, the centripetal acceleration used for defining the turning arcs is reduced to 0.1g for taxi speeds up to 25kn. For the 30kn case, if the centripetal acceleration is set at 0.1g, the turn radius would be too large for TSRV to complete the second turn before crossing the hold line at Runway 18L. For this reason, the centripetal acceleration is set at 0.15g for the 30kn case. The range of taxi times for Exits 3, 5, and 6 is depicted in Figure 10.

IV.3 Performance over Different Exits with Different Distances

The effects of performing runway-crossing taxi through different exits based on the same taxi speed are studied next. In this case, a taxi speed of 20kn is selected. Since the three exits would require the TSRV to taxi for different distances, the taxi time would increase accordingly. Table 2 tabulates the results of the simulations. It is immediately obvious that the runway-crossing time error and cross-track error are negligible in all cases.

IV.4 Effect of Taxi Speed

The effect of different taxi speeds is evaluated for an Exit 5 turn-off. Three taxi speeds are used: 10kn, 20kn, and 30kn. The different taxi speeds call for different taxi times. The results are tabulated in Table 3. Again, the runway-crossing time errors and cross-track errors were all negligible.

Table 2. Comparison of Taxi Performance through Three Different Exits: Taxi Speed of 20kn

Exit	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
3	75	74.97	-0.03	0.26
5	90	89.97	-0.03	0.20
6	105	104.97	-0.03	0.23

Table 3. Comparison of Taxi Performance with Three Different Taxi Speed through Exit 5

Taxi Speed (kn)	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
10	150	149.92	-0.08	-0.002
20	90	89.97	-0.03	0.20
30	70	69.996	-0.004	1.07

The reason behind the larger final cross-track error for the 30kn case is that the TSRV at this higher speed is just transitioning out of the second turn at the moment of runway crossing. The transient response at this moment contributes to the cross-track error. This error can be reduced if there is more room to straighten out after the turn. The error is nonetheless smaller than expected navigation error.

IV.5 Effect of Initial Delay in Automation Engagement

Initial delay can be caused by misjudgment in landing time or landing position, or it can be caused by communication delay. For this part of the study, the guidance trajectory is assumed to have been pre-computed to anticipate landing at 3000ft beyond the runway threshold. To simulate the delay, the TSRV would taxi without braking for a pre-specified delay time before the automatic guidance and control engage. The scenario is based on the 20kn taxi through Exit 5, with 90s taxi time. The delays considered are 1s, 5s, and 10s.

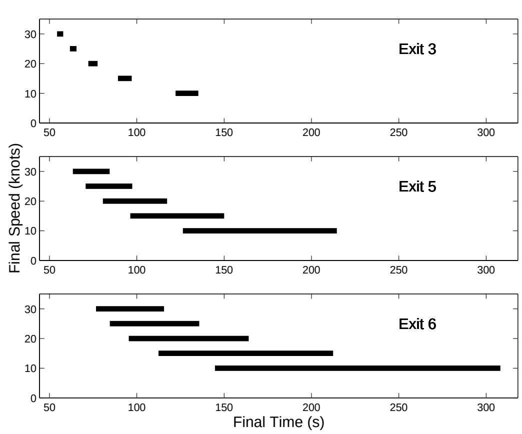


Figure 10. Range of Taxi Times from Landing to Runway Crossing through Exits 3, 5 and 6

Once the guidance and control engage, the automatic system would try to make up for the time lost by exercising heavy braking. As it catches up with the predetermined trajectory, the final runway-crossing time error of –0.03s and cross-track error of 0.2m are achieved in all cases. The throttle-and-brakes profiles are compared in Figure 11.

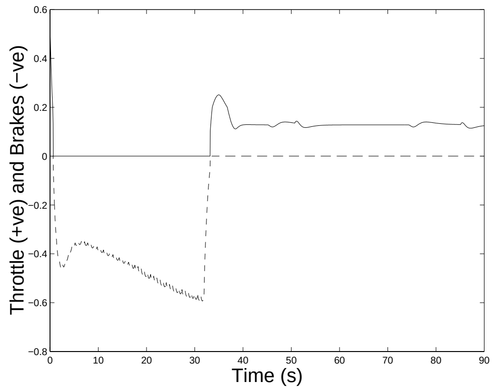
As the delay increases, maximum braking is required to slow the vehicle down to the predetermined trajectory. In the 10s-delay case, the heavy braking induces an overshoot, which in turn triggers the throttle to engage for a few seconds.

The heavy initial braking also causes the deceleration to exceed the 0.25g limit for the 5s and 10s cases. Figure 12 shows the longitudinal acceleration for the 5s case. One way to overcome this reaction is to continuously re-compute the reference trajectory prior to touch down, so as to eliminate any trajectory mismatch. Another way is to limit the braking to a level that satisfies the deceleration limit. As long as the delay is not so large as to render deceleration to taxi speed impossible, the control law will ultimately be able to mitigate the initial errors.

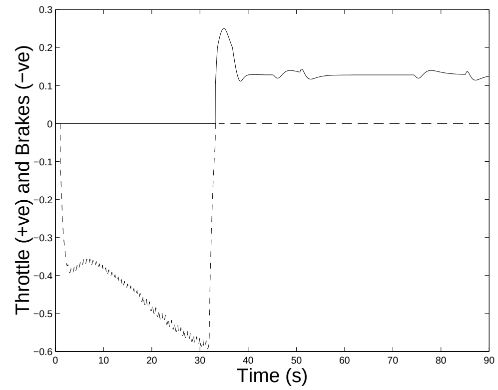
IV.6 Human Performance Factors

If the control commands generated by the automatic guidance and control functions are used as advisories to the pilot in a form analogous to a flight director, the pilot’s reaction has to be taken into consideration, as it affects the conformance to the advisories [12]. This effect is initially studied by approximating the pilot’s reaction delay with a first-order lag, whereas the phase-advance factor of the pilot is already adequately modeled by the PD controller described above. For the 20kn scenario off Exit 5 with 90s taxi time, four time constants are considered: 0.1s, 0.2s, 0.5s, and 1s. The effects of the pilot reaction lag on the final results are tabulated in Table 4. Throttle-and-brakes profiles for the 0.5s and 1s cases are shown in Figure 13, whereas that with a zero time constant is given in Figure 11(a). Observe that a time constant of 1s corresponds to a rise time of 4s to 5s, which represents really sluggish reaction by the pilot.

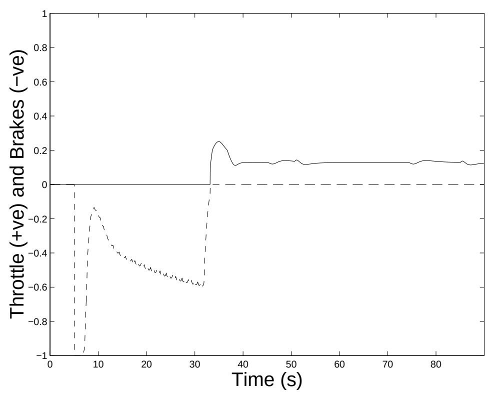
An interesting observation from Figure 13 is that with a first-order lag of 1s time constant, the throttle and brake controls become rather oscillatory. However, the results tabulated in Table 4 still



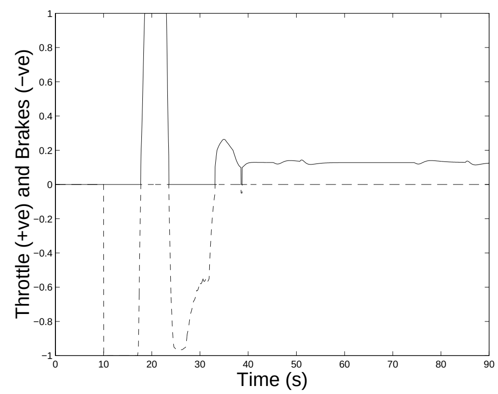
(a) No Delay



(b) 1s Delay



(c) 5s Delay



(d) 10s Delay

Figure 11. Comparison of Throttle and Brakes due to Initial Delay: Exit 5, Taxi Speed 20kn, Runway-Crossing Clearance Time 90s

indicate that the runway-crossing time and cross-track errors have not increased.

Table 4. Effect of First-Order Lag in Approximating Pilot Reaction

Time Constant (s)	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
0	90	89.97	-0.03	0.20
0.1	90	89.97	-0.03	0.20
0.2	90	89.97	-0.03	0.19
0.5	90	89.97	-0.03	0.17
1	90	89.96	-0.04	0.13

To add realism to the problem, an input disturbance is added to the input of the first-order lag to model inaccurate advisory conformance by the pilot. The disturbance is modeled with zero-mean Gaussian white noise. Standard deviations of 0.01 and 0.05 are used for the analysis. Since the analysis is based on digital simulation, it effectively approximates the Markov process model of the disturbance by a Markov sequence [13, p.342]. To account for this approximation, the standard deviation has to be scaled up in the digital simulation by a factor of $1/\sqrt{\Delta T}$, where ΔT with a value of 1/30 sec is the integration step size of the simulation.

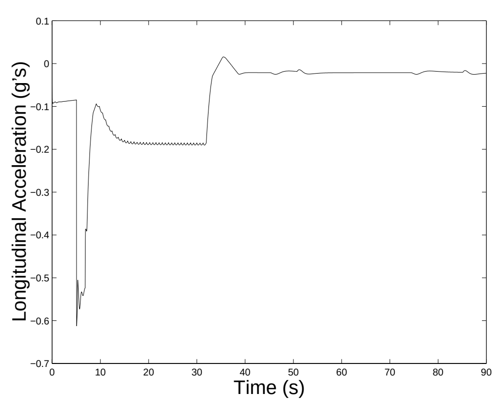
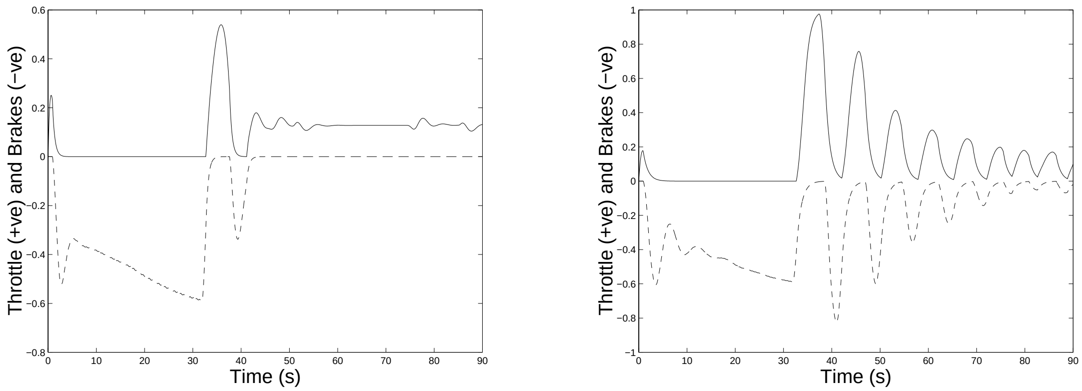


Figure 12. Longitudinal Acceleration due to Initial Delay of 5s



(a) 0.5s Time Constant (b) 1s Time Constant

Figure 13. Throttle-and-Brakes Profiles with Pilot Reaction Lag

Table 5. Effect of 0.5s First-Order Lag with Disturbance for Modeling Pilot Reaction

Standard Deviation	Cleared Taxi Time (s)	Actual Taxi Time (s)	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
0	90	89.97	-0.03	0.20
0.01	90	89.97	-0.03	0.18
0.05	90	89.98	-0.02	0.21

The results for the 20kn case off Exit 5 and 90s taxi time are tabulated in Table 5 and compared to the case with no disturbance, i.e. standard deviation = 0. The throttle-and-brakes profiles for the cases with 0.01 and 0.05 standard deviations are given in Figure 14. Although the control signals appear noisy, the final errors in Table 5 are similar to the previous results, as the noise is basically outside the bandwidth of the vehicle dynamics.

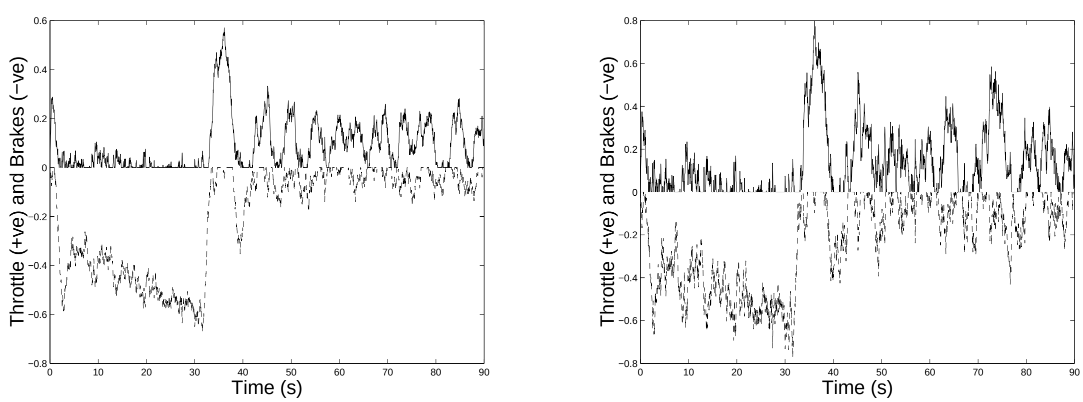
To more appropriately assess the effect of the random disturbance, a Monte-Carlo analysis is performed. The ensemble results with 30 runs for the case with 0.05 standard deviation are given in Table 6, which indicates the errors are consistent with the deterministic values observed before. Ensemble position error statistics in direction of runway is plotted in Figure 15, showing the mean position error bounded by the associated standard deviation. The performance of the guidance and control in meeting a cleared taxi time is extremely high, even in the presence of disturbance.

Table 6. Statistics from Monte-Carlo Analysis

	Runway-Crossing Time Error (s)	Runway-Crossing Cross-Track Error (m)
Mean	-0.0312	0.1591
Standard Deviation	0.0167	0.0369

V. CONCLUDING REMARKS

Whenever traffic density is so high as to jeopardize efficiency and safety, improvements are needed in traffic coordination and movement



(a) 0.01 Standard Deviation (b) 0.05 Standard Deviation

Figure 14. Throttle-and-Brakes Profiles with Pilot Reaction Lag of 0.5s Time Constant and Disturbance with Standard Deviations of 0.01 and 0.05

precision. This study has considered the surface-traffic problem at major airports, and has proven that state-of-the-art automatic control technologies are capable of performing high-precision taxi operations.

Due to the high-speed environment, high-precision taxi is most difficult on or across the runway, where such ability is also potentially most beneficial. By focusing on the runway-crossing problem, this study has established ways to minimize the runway-crossing time. More importantly, the study has verified the potential performance of a nonlinear guidance and control system that can achieve high-precision taxi control for surface movement, including taxiing continuously immediately after landing to cross an adjacent runway with the tightest of time margin.

One obvious possible future effort is a full-scale development of the guidance and control system as an extension to the flight management system. However, full realization of the benefits from this technology will require an effective ground control system to coordinate the traffic. Truly optimal traffic flow will require tight coordination of the traffic, which will require more efficient ATC-cockpit communication. Under tight coordination and high-precision vehicle control, the safety and efficiency of airport surface traffic can be enhanced.

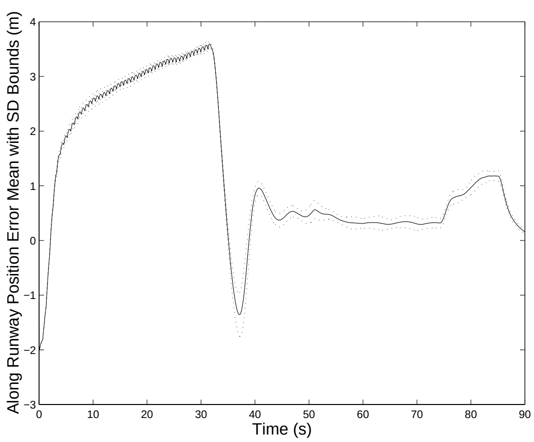


Figure 15. Monte-Carlo Result of Position Error in Direction of Runway: Mean ± Standard Deviation

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