Achieving Equilibrium for Dense (1000s), Integrated, Heterogeneous Vehicle Navigation

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Drone usage has proliferated in recent years with many applications that have market-changing potential. Applications ranging from parcel delivery to wildlife protection, from precision farming to law enforcement, and from industrial inspection to digital fireworks. We use drones to mean both UAV (Unmanned Aerial Vehicle) and sUAS (small Unmanned Aircraft System) vehicles. Flight infrastructure can currently only support a few thousands aircraft flying over the United States National Airspace System (NAS) at any given time. A delay at one airport sends ripple effects through the system, causing more delays and missed connections. Once regulations and safety policies are put in place to allow for the widespread use of unmanned drones, the number of aircraft in the NAS is expected to skyrocket to millions, potentially congesting the airspace resulting in possible separation violations. In air traffic control, separation is the concept of keeping an "ownship" aircraft outside a minimum distance from "intruder" aircraft to reduce the risk of the aircraft colliding, as well as preventing accidents due to secondary factors, such as wake turbulence. Maintaining proper separation is safety critical for drones in the airspace. This paper addresses separation in time and in distance for high volume corridors (en-route) and lanes (on ground). The requirements and necessary conditions for maintaining proper separation and reaching maximum throughput for a given corridor/lane are addressed assuming unidirectional corridors/lanes where an aircraft arrives from one side and departs from the opposite side. The problem is first considered in two dimensions (forward and lateral) before scaling it to three dimensions (vertical). A formally verified solution is proposed that guarantees a set of drones to reach the equilibrium state, which is defined as a state when a set of *n* aircraft moving at a relatively constant speed and uniform spacing from each other in a congested system. A congested system is defined as a state when the aircraft cannot move at its maximum speed. Unlike existing centralized and pre-planned approaches, the proposed solution is fully distributed and the aircraft autonomously decide to adjust their speed and distance with respect to the preceding aircraft, dynamically. An analysis is performed on the proposed solution to determine its characteristics, stability, and predict the time it takes to reach the equilibrium state. Simulation results are presented that assess the feasibility of the approach using a large number of drones and evaluate the scalability of the proposed solution. Details of a formal verification effort are discussed.

Nomenclature

UAV = Unmanned Aerial Vehicle
sUAS = Small Unmanned Aircraft System
NAS = National Airspace System
PVS = Prototype Verification System
NASA = National Aeronautics and Space Administration

I. Introduction

Drone usage has proliferated in recent years with many applications that have market-changing potential. Applications ranging from parcel delivery to wildlife protection, from precision farming to law enforcement, and from industrial inspection to digital fireworks. We use drones to mean both UAV (Unmanned Aerial Vehicle) and sUAS (small Unmanned Aircraft System) vehicles. Flight infrastructure can currently only support a few thousands aircraft flying over the United States National Airspace System (NAS) at any given time.

II. Background

A. What is Meant by Separation?

In air traffic control, separation is the concept of keeping an "ownship" aircraft outside a minimum distance from "intruder" aircraft to reduce the risk of the aircraft colliding, as well as preventing accidents due to secondary factors, such as wake turbulence. Maintaining proper separation is safety critical for drones in the airspace.

Describe what is meant by safety critical system.

B. Separation in Time

Define and describe current approaches

C. Separation in Distance

Define and describe current approaches

D. Separation en-route vs. lanes

Describe pros and cons of centralized, pre-planned vs. dynamic, distributed approaches

III. Proposed Solution

Describe system parameters.

Describe steady state vs. equilibrium state, how do they differ, etc.

Describe proposed solutions for the separation problem as it addresses both time and distance dimensions at the same time.

Provide a high-level argument about its feasibility.

Provide minimum system requirements to reach steady state.

Provide analytical results/measures for reaching steady state.

Provide minimum system requirements to reach equilibrium state.

Provide analytical results/measures for reaching equilibrium state.

Demonstrate effectiveness of the proposed solution via simulations.

Provide formal proof of the proposed idea.

A. Simulations

Provide simulation results for various number of drones, from a handful to 1000 of drones.

Plots of time it takes to reach the equilibrium state.

B. Analysis – Pen and Paper

Provide pen and paper analysis, showing why the proposed solution guarantees a solution for a given system.

C. Formal Verification

The formal proof of the algorithm is completed in the Prototype Verification System (PVS) theorem prover. This paper illustrates that theorem provers are more capable than model checkers and simulation when verifying an algorithm with potentially infinitely many input values using a concise algorithm for a general problem that produces a solution. PVS allows a user to input a proof of a mathematical statement, which it checks for logical correctness. Thus, the verification of this algorithm in PVS illustrates that, in more complicated problems when the correctness property is essential, such as a safety-related condition, there is an advantage to using an interactive theorem prover rather than simulating, testing, or model checking. If the system itself has a large number of parameter or an infinite number of input values, it is typically impossible to guarantee that, for a given algorithm, a particular property, and for safety critical systems, a safety property, holds by using simulating, testing or model checking, but it is possible when using an interactive theorem prover.

Provide details of formal proof and PVS model of the proposed solution, including lemmas and theorems.

IV. Conclusion

A proposed solution is presented for separation of drones in the NAS. Pen-and-paper analysis, simulations results, and formal verification of a proposed solution are provided.

References

[1] Shankar, N., Owre, S., Rushby, J.M., Stringer-Calvert, D.W.J.: PVS System Guide, PVS Language Reference, PVS Prover Guide, PVS Prelude Library, Abstract Datatypes in PVS, and Theory Interpretations in PVS, Computer Science Laboratory, SRI International, Menlo Park, CA (1999).

[2] *Shankar, N., Owre, S., Rushby, J.M., Stringer-Calvert, D.W.J.: PVS System Guide, PVS Language Reference, PVS Prover Guide, PVS Prelude Library, Abstract Datatypes in PVS, and Theory Interpretations in PVS, Computer Science Laboratory, SRI International, Menlo Park, CA (1999)*.

[3] Owre, S.; Shankar, N: A Brief Overview of PVS, Theorem Proving in Higher Order Logics (TPHOLS) 2008, in Lecture Notes in Computer Science (LNCS), Volume 5170, pp 22-27, August 2008.