# A Survey and Analysis of Mobility Models for Airborne Networks

Junfei Xie, *Student Member, IEEE,* Yan Wan, *Member, IEEE,* Jae H. Kim, *Senior Member, IEEE,* Shengli Fu, *Senior Member, IEEE,* and Kamesh Namuduri, *Senior Member, IEEE.*

***Abstract*—Mobility models serve as the foundation for evaluating and designing airborne networks (ANs). Due to the significant impact of mobility models on the networking performance, the mobility models must realistically capture the attributes of ANs. In this paper, we present a comprehensive survey and comparative analysis of mobility models that are either adapted to or developed for AN evaluation purposes. We evaluate these mobility models based on the following metrics: adaptability, networking performance, and ability to realistically capture the mobility attributes of ANs (including high mobility, mechanical and aerodynamic constraint, and safety requirements). To provide a deeper understanding and facilitate the selection and configuration of these mobility models, we also evaluate them based on randomness levels and associated applications.**

***Index Terms*—Airborne networks, random mobility models, randomness.**

## I. INTRODUCTION

WITH more manned and unmanned vehicles in the airspace, communication among these aerial vehicles is envisioned to be critical for safe maneuvering, real-time information sharing, and coordination for mission success. Airborne networking with dynamic topology and high mobility is significantly more challenging compared to ground sensor networking with static topology or slow mobility. The major difficulties reside in the unique attributes of airborne networks (ANs), including high node mobility, frequent network topology changes, mechanical and aerodynamic constraint, strict safety requirements, and harsh communication in the disconnected, intermittent, limited bandwidth (DIL) environments [17], [74]. Because of these properties, networking protocols that are built for traditional ground-based networks will not work well for airborne networks. Most of the current research efforts including the newly developed ones that used field tests [19], [20] and simulation environments (e.g., EMANE/CORE [4], [5], NS-3 [1] and OPNET [2], [21], [22], [42], [54], [56]), are focused on evaluating the performance of networking protocols.

While previous investigations provided invaluable insights into airborne networking, they also point out one critical need in the current AN research: *realistic mobility models*. By realistic, we mean that the models are able to capture the *unique mobility attributes* of ANs as mentioned above, such as high mobility, mechanical and aerodynamic constraint, and safety requirement (e.g., a safe separation distance). The need to use mobility models to evaluate networking performance is driven by the fact that field tests are very costly and restricted to specifically designed settings which make it hard to generalize performance evaluation results. As such, simulations using random mobility models that cover a large number of scenarios are considered to be a low-cost, systematic and robust alternative [18]. However, the mobility models that serve as the basis for most simulation environments are designed for traditional Mobile Ad hoc Networks (MANETs) [3], [9], [18]. As the mobility of ground vehicles is very different from that of aerial vehicles due to aerodynamic constraint, MANET models may not truthfully emulate ANs. Because of the significant impact of mobility models on the performance of networking protocols [18], [37], [56], using MANET models for performance evaluation may mislead the results. This limitation suggests an urgent need to comprehensively investigate AN mobility models, so as to permit the development of simulation environment and subsequent design and evaluation of airborne networks. Very recently, there were some studies on understanding the unique features of aerial mobility and capturing them in realistic mobility models. The purpose of this survey paper is to provide a comprehensive summary of the current advances in AN mobility modeling, and to discuss research gaps, challenges, and future directions in this emerging field. Specific contributions of this paper include:

1) *A thorough survey of existing AN mobility models*. Mobility models that are used for AN evaluation can be mainly classified into two categories: i) traditional MANET models directly used or adapted for ANs, and ii) very limited number of *new* models developed *specifically* for ANs. Besides describing these models and their statistical properties, we also discuss these models based upon three evaluation metrics: i) adaptability of these models for ANs if they are not directly designed for ANs, ii) AN networking performance, and iii) whether the particular mobility patterns are realistic in capturing AN mobility attributes in terms of high mobility, mechanical and aerodynamic constraint, and safety.
2) *A comprehensive comparison of AN mobility models*. In order to obtain meaningful performance evaluation

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J. Xie, Y. Wan, S. Fu, and K. Namuduri are with the Department of Electrical Engineering, University of North Texas, Denton, TX, 76203. Correspondent Author: Yan Wan (e-mail: yan.wan@unt.edu).

J. H. Kim is with Boeing Research & Technology (BR&T), Seattle, WA, 98124-2207.

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results, we need to select the most suitable mobility model and realistically set up parameter values in the model. This requires a comprehensive understanding of the differences among these AN mobility models. Besides the above three evaluation metrics, we also compare the models using two additional metrics: i) degree of randomness, and ii) associated AN applications. To our best knowledge, this survey study represents the first attempt to provide comprehensive guidelines for selecting and configuring AN mobility models. This study also helps with the understanding and proper use of general mobility models.

3) *Research gaps and directions for future development*. Although mobility modeling serves as the foundation for airborne networking, many research questions remain in this nascent field. We discuss several critical research needs, including i) model validation using real trace data, ii) balancing between realistic modeling and analysis capability, and iii) mobility-driven performance analysis and networking protocol design. We will further discuss some additional mobility models that have the potential to be adapted to ANs.

It is worthy to note that AN mobility modeling is related to several other topics, including but not limited to aerial target tracking [29], [39], [47], [65], and the control and coordination of UAVs [15], [16], [66], [79]. These fields are also partially concerned with the modeling of aerial vehicle trajectories. In particular, the goal of aerial target tracking is to estimate the trajectory of a moving target from observation data. The estimation is based upon dynamic models that describe the target's physical movement. Similarly, the control of UAVs for formation and collision avoidance tasks is also model-based, and concerned with designing controllers to shape the trajectories of UAVs to meet certain desired performance and safety requirement. As these studies investigate the physical behavior of aerial vehicles in detail, they provide the theoretical foundations and insights to develop AN mobility models. However, we note that these models are typically more complicated than needed for AN mobility modeling, because of their emphasis on the precise prediction and control of *individual* trajectories, rather than on the abstraction of *group* patterns for the purpose of effectively designing and evaluating communications and networks. Our interest is to develop the realistic mobility models that reflect the unique features of aerial vehicles and are *simple* enough to facilitate tractable connectivity analysis and systematic routing design.

The remainder of the paper is organized as follows. In Section II, we provide a brief overview of the mobility modeling research for MANETs. In Section III, we discuss some of the MANET mobility models adapted to ANs. In Section IV, we describe five representative mobility models recently developed specifically for ANs. Section V contains a comparative study of existing AN mobility models to facilitate model selection. In Section VI, we discuss several critical research needs in this nascent field. Finally in Section VII, we provide a brief conclusion of this paper.

## II. Overview of Mobility Modeling Research

Before we describe mobility models suitable for ANs, we start with a brief background review of the research on general mobility models. Readers interested in more details on general mobility models can refer to the reference papers, e.g., [8], [9], [18], [46], [57].

### A. Significance of Mobility Modeling Research

Mobility models have been used as the kernel to evaluate MANET routing protocols over two decades. They specify the movement patterns of mobile agents, which lead to the statistical analysis of a variety of performance measures, such as packet delivery ratio, end-to-end delay, throughput, and overhead. It should be noted that the so-called synthetic random mobility models [9] have received more attention than traces recorded from real movement, due to the rich information they can provide. These models are not designed to precisely capture the movement behavior of each specific mobile agent; instead, they typically *abstract* the key statistical features of Mobile Ad hoc Networks (MANETs), from which rich mobility ensembles can be generated to comprehensively test the performance of routing protocols.

### B. Focuses in Mobility Modeling Research

Despite the advantage of synthetic random mobility models in providing rich trajectory ensembles, the abstraction in model design frequently leads to the question of whether these models capture the specific mobility patterns observed in traces. Designing realistic and accurate synthetic mobility models is important, as it has been shown that mobility models have a determining effect on the performance of routing protocols [9], [18]. Driven by this need, significant recent research has been focused on designing *application-specific* random mobility models that capture the mobility patterns observed in a particular setting (see references [8], [9], [18], [46], [57]).

Besides constructing mobility models, major research efforts have also been directed towards understanding the statistical properties of these mobility models, including node distribution, average number of neighbors, link duration, path duration, etc. (see references [12], [13], [49]). These statistical analyses not only permit a better understanding of these models, but also suggest the connection between model parameters and model properties, as a step toward 1) the selection of model parameters, 2) tractable performance analysis of routing protocols, and 3) automatic network design and evaluation. The importance of statistical analyses also suggests that in designing mobility models, tractability is an important issue. Simple models that reasonably capture the reality are preferable. Complicated models better reflect reality but at a cost of analysis capability. There is a tradeoff between complexity and analysis capability.

### C. Classification of General MANET Mobility Models

Mobility models for traditional MANETs in the literature range from the simple Random Walk (RW) and Random Waypoint (RWP) models to complex models that capture the details of traces in specific MANET settings. Typical mobility models can be classified into the following five categories according to the reference papers [8], [9] (see Figure 1). A more thorough classification can be found in [57].

The first category includes the pure *random* models which do not consider any additional constraints. Examples include the Random Walk, Random Waypoint, and Random Direction (RD) mobility models, which we will discuss in more details in Section III-A. The second category includes models with *temporal dependence*. In particular, mobility patterns at different time slots are correlated. A widely applied example is the Gauss-Markov (GM) model that we will thoroughly analyze in Section III-B. Also well-known is the Smooth mobility model [11], in which the correlation of mobility for the Stop-Turn-and-Go behavior of ground vehicles is modeled. The third category includes models with *spatial dependence*. In particular, the mobility of an agent is affected by other *spatially* distributed agents and thus these models capture the cooperative behavior of nearby nodes. One example is the Reference Point Group Mobility (RPGM) model, in which all nodes in a group follow the mobility of a group leader [30]. A set of other spatially correlated mobility models such as Column mobility model, Pursue mobility model and Nomadic Community mobility model are also discussed in [30]. The fourth category includes models with trajectories restricted by *geographic constraints*. Examples include the Pathway mobility model that restricts node movement to pathways defined by a map or a graph [67], and the Obstacle mobility model that describes the movement of nodes to avoid obstacles in the way [33]. The fifth category includes *hybrid* models that have at least two characteristics of the above categories. For instance, in the Freeway mobility model [26], mobility of a road vehicle is temporally dependent (Category 2), influenced by neighboring vehicles (Category 3), and also restricted to lanes on freeways (Category 4). Another example is the Disaster-area model [7], in which heterogeneous node movements are involved.

We note that despite all of these advances on traditional MANETs, only little effort has been spent on AN-specific mobility models until very recently. In the next two sections, we will focus on discussing mobility models for airborne networks. When we introduce these AN mobility models, we will refer to the above five-category classification of mobility models.

## III. MANET Mobility Models Adapted for ANs

In this section, we review some traditional MANET mobility models that have been adapted for the evaluation of AN networking performance. As these models have been extensively studied in the literature (refer to the references [8], [9], [18], [46], [57]), we will briefly describe the fundamentals of these models and evaluate mainly based on the following three metrics: 1) adaptability of these models for AN mobility modeling, 2) AN networking performance based on simulation studies using these models, 3) ability to realistically capture the mobility attributes of ANs including high mobility, mechanical and aerodynamic constraint, and safety requirements. We survey AN networking performance for the completeness of the study, instead of as a criterion to judge which model is more useful. In particular, AN networking performance is unjustified unless the correctness of these mobility models in capturing aerial mobility is proved.

### A. MANET Random Mobility Models

The most fundamental mobility models such as the RW, RD, and RWP have been widely used to evaluate the performance of MANETs. Very recently, they have also been adapted to evaluate the performance of ANs, through choosing appropriate model parameters (e.g., speed, node density) reflective of typical ANs [50], [59], [60].

*1) Basic Model Description:* The three basic models and their statistical properties are summarized below.

*a) Random Walk Model:* In the Random Walk model, an agent randomly chooses a heading direction and speed and travels for a fixed duration, before it chooses a new set of direction and speed [18]. At boundaries, the agent can either reflect back from the boundary, or wrap around from the other side of the region [48].The concept of Random Walk was first raised by Pearson [53] in 1905. The model was then widely adopted to describe random moving processes in a variety of fields, such as the diffusion of molecules/particles in physics and biology [10], the swarming of animals in ecology [23], and the movement of mobile agents in communication [18]. As shown in Figure 2(a), RW trajectories typically show sharp directional changes. At the time of direction change, a newly selected heading direction is uncorrelated with the current direction.

*b) Random Waypoint Model:* The Random Waypoint model assumes that an agent travels to a destination selected randomly in a region and moves toward the destination with a randomly selected speed. After it reaches the destination, it pauses for a while before moving to a newly selected destination. The RWP model was first introduced in [34] in 1996 to mimic the random movement of mobile users, and then soon became the standard simulation model to evaluate MANET routing protocols. As shown in Figure 2(b), RWP trajectories are similar to RW trajectories in terms of sharp directional changes. The major difference (which can be observed from the comparison between Figures 2(a) and 2(b)) is that nodes in the RWP model tend to appear more frequently toward the center of the region.

Significant research has been focused on understanding the statistical properties of the RWP model, such as node distribution [13], [14], [32], transition length [13], and link and path durations [49]. As closed-form expressions typically do not exist for this model, approximations have been pursued. A notable fact about the RWP model is that the stationary node distribution is non-uniform, even if the model assumes a uniform initial distribution. In particular, the distribution is bell-shaped, with top in the middle but close to zero at boundaries [9]. This phenomenon is caused by the restriction of region boundaries, biasing node locations toward the center of the region.

*c) Random Direction Model:* The Random Direction model was constructed to address the lack of analyzability caused by the non-uniform node distribution of RWP [58]. In the basic RD model, an agent randomly chooses a direction

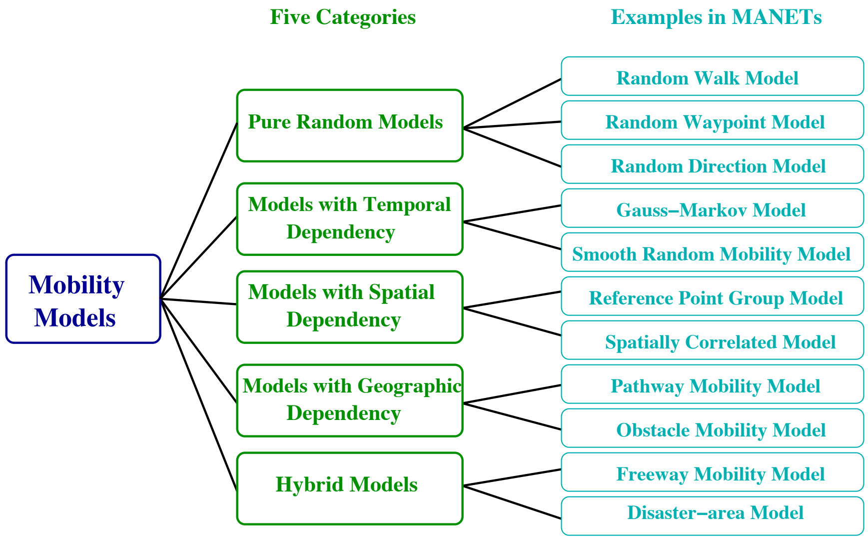



Fig. 1. Categories of mobility models in MANETs

and speed, moves to the boundary, pauses for a while, and then randomly chooses another direction to move. Unlike the basic RD model which is restricted to change directions at boundaries, the modified RD model (or simply referred to as RD model in this paper) generalizes by allowing an agent to randomly select the duration to travel [58]. As shown in Figure 2(c), RD trajectories also show sharp direction changes. The trajectories of RD and RW models are similar, with the only difference in whether the traveling duration is constant or random; however, this difference is hard to be observed directly from the trajectories. In fact, the modified RD model is also referred as one kind of RW models in a reference paper [18]. It was proved that the stationary node distribution of the RD model is uniform, regardless of the initial node distribution [48]. The uniformity of node locations can also be observed in Figure 2(c).

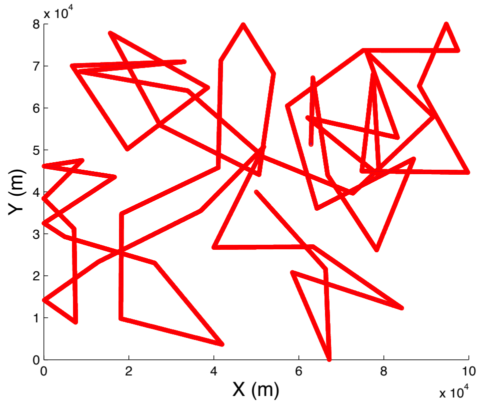
*2) Adaptability for ANs:* These MANET random mobility models only capture very basic features of random mobility, and ignore many details in realistic environment, such as gradual mobility changes, correlations between new and current directions, and interactions among agents in a mobile network. Because of the elimination of many details, these models are simple to model and implement, and have been widely used for AN studies. The most common way to adapt these models for ANs is to configure parameters such as the range of random speed, and the size and shape of simulation area, all based upon real AN settings.

Of note, a Restricted RW (RRW) model was used to describe the movement of UAVs in a highly restricted area [64]. The model considers the interaction among spatially distributed aerial nodes. In particular, the lead aerial node follows the RW mobility model; each follower maintains the same speed with the leader and has a restricted set of directions to select. It was shown that if the node distribution is uniform initially, the network remains uniformly distributed.

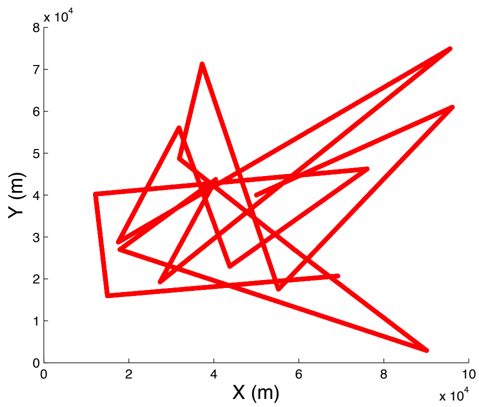
*3) AN Networking Performance:* These basic MANET mobility models (and their small variants) have been used to obtain insights of AN networking performance.

In [49], the RWP model was used to understand the impact of transmission range, node velocity, number of hops and node density on the average path duration of ANs. It was shown that the average path duration increases almost linearly with the increase of transmission range, drops exponentially with the increase of speed, and gains little with the increase of node density. In [59], the RWP model in the OPNET simulator was used to simulate and understand the impact of Doppler effect, Rician fading, and mobility speed on the performance of Dynamic Source Routing (DSR) protocols for ANs. It was shown that the bit error rate for Rician fading channels increases with the increase of speed. Further studies from the same group [60] investigated the use of Delay Tolerant Networking (DTN) routing protocol to improve the networking performance. It was suggested that traditional routing protocols such as DSR, Optimized Link State Routing (OLSR), and Ad hoc On Demand Distance Vector (AODV) do not work well because of the highly random network structure. Along the lines, [54], [55] and the references therein used a slightly modified RWP model with zero-pause time (using the NS-3 simulator) to demonstrate the improved performance of the Aeronautical Routing Protocol (AeroRP) over traditional MANET protocols.

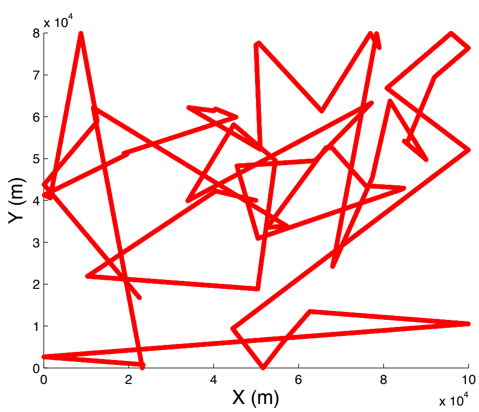
*4) Ability to Capture Mobility Attributes of ANs:* High mobility can be easily captured, by configuring the speed variable in these models. The major disadvantage is that at the time of heading change, the new heading is uncorrelated from the current heading. Such ignorance of the correlation of movement across temporal and spatial dimensions does not reflect mechanical and aerodynamic constraint to aerial mobility, and thus results in sharp directional changes. These models are typically referred to be memoryless because of the independence of mobility across different randomly-selected time slots. These models may be too abstract and unrealistic for ANs as reflected in the non-smooth trajectories. Moreover, maneuvering safety requirements are not considered.




(a) RW




(b) RWP




(c) RD

Fig. 2. Sample trajectories of a) RW, b) RWP, and c) RD models, using Matlab. All three trajectories show sharp directional changes. RW and the modified RD models show uniformly distributed node locations, whereas node locations of the RWP model tend to accumulate toward the center of the simulation area. The minor difference between the RW and RD models is that the travel duration of the RW model is constant and that of the RD model is random.

### *B. Gauss-Markov Random Mobility Model*

Gauss-Markov mobility models belong to the category of temporally correlated mobility models. This temporal correlation avoids sharp motion changes. The introduction of Gauss-Markov models can be traced back to [65] in 1970, when this model was first constructed to track the trajectories of maneuvering targets. A series of further enhancements and analyses can be found in [29], [47]. The survey paper [39] contains a thorough summary of this model in the field of aerial target tracking. A simple variant of this model was then introduced to track mobile movement in Personal Communication Service (PCS) networks [40]. Because of its attractive temporal dependency, this model has received significant attention over the years for communication and networking applications, and has been widely used as a mobility model to evaluate networking performance [31], [69]. Here, let us first describe the Gauss-Markov mobility model for MANETs. We start the description with the continuous-time dynamics, which provides rich insights into the properties of the model and also naturally leads to the suitability analysis of this model for ANs. Different from other typical surveys of Gauss-Markov mobility models, we emphasize on a complete understanding of Gauss-Markov mobility models, especially on the derivation of underneath physical concepts.

*1) Basic Model Description:* The continuous-time dynamics of the most widely used Gauss-Markov mobility model is represented by:

$$\dot{x}(t) = -\beta x(t) + \beta \bar{x} + \sqrt{2\beta}\sigma n(t), \tag{1}$$

where $x(t)$ is the state variable of interest, $\sigma$ is a constant, $n(t)$ is the Gaussian white noise with mean 0 and variance 1, $\beta$ captures the correlation of $x(t)$ across time, and $\bar{x}$ is the average of $x(t)$ at steady state (when the system will maintain current state). Fundamentally, Equation 1 describes the dynamics when Gaussian white noise passes through a linear system. In a 2D simulation environment, the state variable vector $x(t)$ could either represent velocities in $x$ and $y$ directions $v_x(t)$ and $v_y(t)$ [9], [40], or heading speed $v(t)$ and heading direction $\phi(t)$ [18], [69].

Now let us derive the autocorrelation of model states from the continuous-time dynamics, so as to demonstrate the key property of the GM model: memory of motion to avoid sharp motion changes. Define $\widetilde{x}(t) = x(t) - \bar{x}$, and $\widetilde{n}(t) = \sqrt{2\beta}\sigma n(t)$. As the autocorrelation of the Gaussian process $R_{\widetilde{n}\widetilde{n}}(\tau) = E(\widetilde{n}(t+\tau)\widetilde{n}^*(t)) = 2\beta\sigma^2\delta(\tau)$, the power spectrum $S_{\widetilde{x}\widetilde{x}}(w)$ can be calculated from $S_{\widetilde{n}\widetilde{n}}(w) = 2\beta\sigma^2$ as

$$\begin{aligned} S_{\widetilde{x}\widetilde{x}}(w) &= S_{\widetilde{n}\widetilde{n}}(w)H(w)H^*(w) \\ &= 2\beta\sigma^2 \frac{1}{jw-\beta}\frac{1}{-jw-\beta} = \frac{2\beta\sigma^2}{w^2+\beta^2}, \end{aligned} \tag{2}$$

and hence the autocorrelation of $x(t)$ at steady state is the Fourier inverse [52]

$$R_{xx}(\tau) = \sigma^2 e^{-\beta|\tau|} + \bar{x}^2. \tag{3}$$

Equation 3 suggests that the correlation of $x(t)$ decays exponentially with the increase of time interval $\tau$. When $\tau$ is tiny, the states are highly correlated, avoiding sharp uncorrelated motion changes.

The discrete-time version (or called the computerized model) of Equation 1 can be obtained according to [52], where $\Delta t$ is the sampling time:

$$x[k+1] = \alpha x[k] + (1-\alpha)\bar{x} + \sqrt{2\beta}\sigma \int_{k\Delta t}^{(k+1)\Delta t} e^{-\beta\Delta t} n(t)dt \tag{4}$$

When $k \rightarrow \infty$, $\sqrt{2\beta}\sigma \int_{k\Delta t}^{(k+1)\Delta t} e^{-\beta\Delta t} n(t)dt$ is an independent Gaussian process with mean 0 and variance $(1 - e^{-2\beta\Delta t})\sigma^2$. As such, we can write

$$x[k+1] = \alpha x[k] + (1-\alpha)\bar{x} + \sqrt{1-\alpha^2}\sigma g[k] \quad (5)$$

where $\alpha = e^{-\beta\Delta t} \approx 1 - \beta\Delta t$, and $g[k]$ is an independent Gaussian process with mean 0 and variance 1.

Equation 5 represents the form of Gauss-Markov model widely used as simulation models for routing protocol evaluation [9], [18]. The Gauss-Markov model has four parameters: independence level $\alpha$, average $\bar{x}$, variance of the Gauss Random noise $\sigma$, and the simulation time step $\Delta t$. In particular, increasing $\alpha$ enlarges the correlation of motion between consecutive time steps. At the extreme, $\alpha$ being 0 represents the complete loss of memory, and $\alpha$ being 1 represents that the process is deterministic and the motion (captured by the state variable $x[k]$) does not change over time. Several Gauss-Markov Parameter Estimators (GMPE) have been developed, including GMPE_ACR [40], [41] using an Autocorrelation (ACR) technique, GMPE_RLSE [27] using a Recursive Least Square Estimation (RLSE) technique, and GMPE_MLH [43] using a Maximum Likelihood (MLH) technique. According to [43], GMPE_MLH outperforms the other two estimators with reduced message transmission overhead, and GMPE_ACR is the simplest to implement in practice.

The agents near boundaries can either follow the reflection boundary model similar to that of the RD [45], [48], or be forced back when they move into the buffer zone (within certain distance from the boundary [69]) by reversing the average heading. Simulation in [45] shows that the node distribution is similar to that of the RW model, using the reflection boundary model.

*2) Adaptability for ANs:* The above 2D Gauss-Markov model has been extended to model 3D ANs [6], [17]. Specifically, two formations were discussed in [17]. In the first one, speeds along three dimensions $x$, $y$, and $z$ are modeled as independent Gauss-Markov processes. As the independence of $x$ and $y$ coordinates does not reflect the movement of aerial vehicles [17], an improved version uses an alternative coordinate: heading speed $s_n(t)$, heading direction $d_n(t)$, and pitch $p_n(t)$ are modeled as independent Gauss-Markov processes. In order to avoid sharp direction changes at boundaries, the concept of 2D buffer zone is extended to 3D [6]. In particular, if a node enters one of the 26 sectors at the boundary of a 3D simulation box, the mean direction is added by $\pi$ to push the node to the center of the 3D box.

*3) AN Networking Performance:* A series of further studies have used the 3D Gauss-Markov mobility model to evaluate the performance of AN routing protocols [22], [25], [42], [51], [56]. Specifically, [56] compares the performance of AeroRP with OLSR and Destination-Sequenced Distance Vector (DSDV) using three mobility models: 3D Gauss-Markov, constant position and RWP, all in NS-3. It was found that AeroRP outperforms OLSR and DSDV in terms of packet delivery ratio (PDR), using the Gauss-Markov model. Of particular note, among the three mobility models, the Gauss-Markov leads to the worst PDR performance. On the other hand, the Gauss-Markov results in less overhead, as nodal headings in the Gauss-Markov model are dominated by the constant average headings. A complete comparison of AeroRP and four traditional routing protocols including OLSR, DSDV, DSR, and AODV is discussed in [22], demonstrating the advantage of AeroRP. In addition, a movement prediction-based geographic routing algorithm was proposed based on the Gauss-Markov movement [42], in line with the original use of Gauss-Markov model for target tracking.

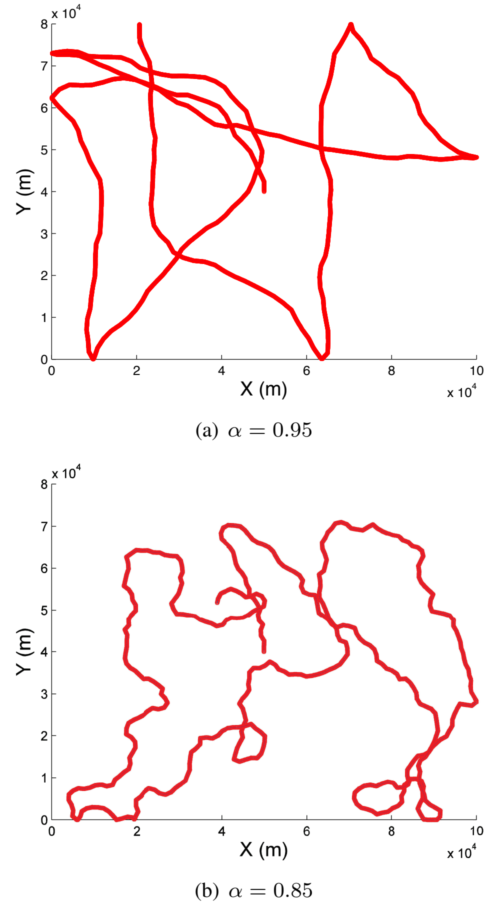



Fig. 3. Sample trajectories of the Gauss-Markov model with two values of the correlation parameter $\alpha$. Distinct from those of the RW, RWP, and RD mobility models, both trajectories are smooth, dominated by the average heading direction. A higher $\alpha$ produces straighter trajectories with less noise-induced variations.

*4) Ability to Capture Mobility Attributes of ANs:* High mobility is again easily captured by configuring the average speed. Safety requirement is not considered. Compared with the traditional MANET mobility models, the *memory-based* Gauss-Markov mobility models are believed to be more realistic for ANs in capturing aerodynamic constraint. In particular, as the heading variable in the Gauss-Markov model is correlated across time, we do not observe abrupt direction changes (see Figure 3 with two different values of the correlation parameter $\alpha$, and also [17]). Its trajectory typically appears to be zig zag, with noise coupled to the heading dominated by the average heading direction. A higher $\alpha$ indicates tighter correlation of mobility across time, and produces straighter trajectories with less variation.

Here, let us investigate whether the Gauss-Markov model can capture the specific memory inherent to the aerial mobility due to mechanical and aerodynamic constraint. We note aerial vehicles favor straight trajectories and slight turns. During a typical turn, the heading speed and turn rate are close to constants [39], resulting in a special correlation of headings, instead of a constant heading corrupted by random noise. To understand this mathematically, let us further analyze the 2D Gauss-Markov model with the heading speed $v(t)$ and heading direction $\phi(t)$ modeled as independent Gauss-Markov processes. Also denote the turn rate (or angular velocity) as $w_n(t)$, which is the derivative of $\phi(t)$. The dynamics of $w_n(t)$ can be written as

$$\dot{w}_n(t) = -\beta w_n(t) + \sqrt{2\beta}\sigma\dot{n}(t), \quad (6)$$

by taking the derivative of Equation 1. As the derivative of white noise $n(t)$ is large, the above equation fundamentally suggests that $w_n(t)$ has huge variations across time, very different from being a constant during typical turns. Furthermore, as the centripetal acceleration $a_n(t)$ can be represented by $a_n(t) = v(t)\dot{\phi}(t)$, $a_n(t)$ also changes dramatically across time even with a constant $v(t)$. The above analysis suggests that Gauss-Markov models have limitations in capturing *typical aerial turns*.

In order to capture aerial turns using the Gauss-Markov-type models, it may be more appropriate to model turn rate (instead of heading) as the state variable. In the aerial target tracking field, Gauss-Markov models for turn rate have been used to describe aerial turns [29], [39].

As turn behavior is typical to aerial movement, and is crucial to the performance of airborne networking (especially when directional antennas are used [19], [20]), tractable mobility models that can capture aerial turns are of critical need. In the next section, we will discuss AN mobility models that address this need.

### C. Summary

The major contribution of Section III is the evaluation of these MANET models' capability for ANs from the following aspects: model description, adaptability to ANs, AN networking performance, and ability to capture mobility attributes of ANs in terms of high mobility, mechanical constraint, and safety requirement. Please see Table III in Section V for a complete comparison from the above aspects. The comparison shows the incapability of these models to capture the correlation of aerial mobility for smooth typical turns. Here we also provide the random variables and parameters in these models and the categories that they belong to (see Table I).

## IV. Existing AN-Specific Mobility Models

In this section, we present several mobility models recently developed specifically for ANs. These models distinguish from the MANET models presented in Section III in that they capture *smooth aerial turns caused by mechanical and aerodynamic constraint* [75]. As these AN-specific models are not discussed in any existing mobility survey papers (per the knowledge of the authors), we thoroughly describe their fundamentals, and evaluate them based upon 1) the basic model description, 2) AN networking performance if there is any, and 3) ability to capture high mobility, mechanical and aerodynamic constraint, and safety requirement. The purpose of reviewing AN networking performance is to complete the review on studies using these AN mobility models, but not to determine which model is more useful. Usefulness of these models is fundamentally determined by their capabilities to capture features of realistic aerial mobility.

### A. Semi-Random Circular Movement Mobility Model

The Semi-Random Circular Movement (SRCM) mobility model restricts UAVs to circle around a *fixed* center with variable radii [73]. This model is developed for scenarios where a potential target location is known, and UAVs are dispatched to collect information in nearby area. A typical application is search and rescue, in which the last known location of the lost victim can naturally serve as the circling center.

*1) Model Description:* In the SRCM model, each aerial node is assumed to move independently on a 2D disk with a fixed center and a radius $R$. Initially, a node starts from a point on the disk with a polar location $(r, \theta)$, where $0 \leq \theta < 2\pi$, and $r \in \frac{i}{M}R$, $i \in \{1, 2, \ldots, M\}$. Along the circle defined by $r$, the node then selects a speed $v$ uniformly distributed in $[v_{min}, v_{max}]$ and a destination with traveling angle $\varphi$ uniformly distributed in $[\varphi_{min}, \varphi_{max}]$. Once the node reaches the destination, it randomly selects another speed $v$ and destination with traveling angle $\varphi$ along the same circle, and moves toward it. This process continues until the node completes a round. Upon the completion, it randomly chooses another radius $r \in \frac{i}{M}R$, transits to this new circle, and repeats the above process. As shown in Figure 4(a), a major feature of the trajectory is the smooth circular movement around a fixed center. Transitions among circles with different radii are sharp along straight lines.

*2) Networking Performance:* Fixing the circling center simplifies the performance analysis, and also brings in tractable properties in terms of node distribution, coverage, and network connectivity. In particular, it was shown in [73] that the node distribution is approximately uniform, through both mathematical analysis and numerical simulation. Besides this, compared to the RWP model, the SRCM model has faster coverage speed and larger steady-state coverage percentage. Furthermore, the SRCM model demonstrates less fluctuation in connectivity probability, indicating a more stable communication network.

*3) Ability to Capture Mobility Attributes of ANs:* The SRCM model guarantees smooth turning trajectories constrained by mechanical and aerodynamic constraint, except during the transitioning from one circle to another. The model assumes that the transition time is much less than the circling time, as such the non-smooth movement during transitioning is neglected. However, fixed circling center places a constraint on mobility variability. High speed is easily ensured, similar to all other mobility models. Safety requirement can potentially be addressed, if a mechanism is added to restrict multiple vehicles from selecting the same circle.

### B. Three-Way Random and Pheromone Repel Mobility Models

Two models were developed in [35], [37], [38] for group reconnaissance applications: 1) a Markov chain based Three-

TABLE I
RANDOM VARIABLES, PARAMETERS, AND MODEL CATEGORY OF THE MANET MOBILITY MODELS

| Model | RW | RWP | RD | Gauss-Markov |
|---|---|---|---|---|
| Random variables | Speed, heading | Speed, destination | Speed, heading angle/ destination, duration | Gaussian noise |
| Fixed parameters | Simulation time step | Simulation time step | Mean of the duration variable if exponentially distributed | Independence level, average heading and speed, variance of Gaussian noise, simulation time step |
| Model Category | Pure random | Pure random | Pure random | With temporal dependence |

Way Random mobility model, and 2) a spatially-dependent mobility model, named the Pheromone Repel mobility model. The latter model is developed based upon the Three-Way Random mobility model; in addition, it permits each aerial node to adjust its direction to enhance scan coverage, through avoiding areas which have recently been visited.

*1) Model Description:* Let us first describe the basic Three-Way Random mobility model, and then the modifications that lead to the Pheromone Repel model. In the Three-Way Random mobility model, the heading speed and turn radius are assumed to be constants at all times. The mobility pattern is defined on a Markov chain, the states of which represent three mobility modes: going straight (denoted as state $s_1$), turning left ($s_2$), and turning right ($s_3$). The selection of mobility mode at the next time step $k+1$ is dependent on the current mode at time step $k$, with the conditional probability defined in the probability transition matrix $P(s[k+1] \mid s[k]) \in R^{3\times 3}$, where $s[k] = \begin{bmatrix} s_1[k] \\ s_2[k] \\ s_3[k] \end{bmatrix}$, and the $(i,j)$-th entry in $P(s[k+1] \mid s[k])$ represents the probability to transfer from state $s_i$ to state $s_j$. The numerical transition matrix used in [38] is $P(s[k+1] \mid s[k]) = \begin{bmatrix} 0.8 & 0.1 & 0.1 \\ 0.3 & 0.7 & 0 \\ 0.3 & 0 & 0.7 \end{bmatrix}$ based on data. For instance, the probability to turn left is 0.1 if the current mode is going straight. Larger diagonal entries indicate that the vehicle is more likely to maintain its current mode; keeping straight movement or making a typical smooth turn.

Movement close to boundaries is similar to that of the Gauss-Markov model; if a vehicle is within certain distance to the boundary, it chooses a turning direction away from the boundary, until the heading direction is pointing toward the inner of the region, e.g., the angle between the heading direction and the normal line to the boundary reaches a value randomly selected between $\pm\frac{\pi}{4}$ [36].

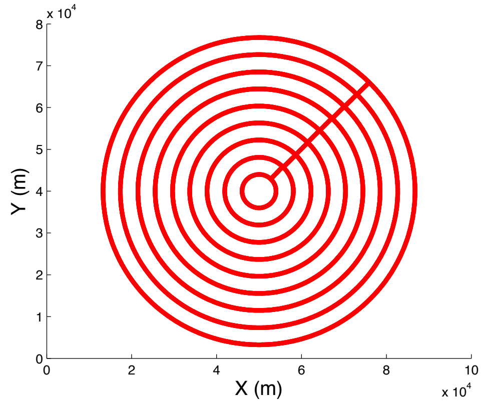
As shown in Figure 4(b), the trajectory is smooth with random turns. Different from the SRCM model, turn centers are no longer fixed. Distinct from the GM models, an average heading does not exist; furthermore, turns have constant turn rates. We note that fixing all turns with a constant radius is a strong abstraction.

In the distributed Pheromone Repel model, the probability to select mobility modes is also guided by pheromone maps. In particular, the field is partitioned into small grids. Each aerial node tracks a pheromone map of the field, marking the time instances $k_i$ when the node visits grid $i$ within a time span $\bar{k}$. Neighboring vehicles within the transmission range can merge their pheromone maps through regular broadcasting. The local merged pheromone map produces a measure called pheromone smell, capturing the local view of how recently each grid is visited. Mathematically, the pheromone smell of grid $i$ at time $k$ is expressed as $ps_i[k] = I(k_i - (k - \bar{k}))$, giving more weight to a more recent visit. Here the function $I(x)$ equals $x$ when $x > 0$ and 0 when $x \leq 0$. Each vehicle then determines its mobility mode according to the aggregated pheromone smells. In particular, the probability to choose the mobility mode $s_j$ at time $k$ is defined as $\frac{\sum_{i\in circles1,2\&3} ps_i[k] - \sum_{i\in circlej} ps_i[k]}{2\sum_{i\in circles1,2\&3} ps_i[k]}$, where circle $j$ includes all grids in a defined circle ahead of the scan area at time $k$: with $j = 1$ denoting the circle straight ahead, $j = 2$ denoting the circle to the left, and $j = 3$ denoting the circle to the right. In the case that the aggregated pheromone smells in all three circles are 0, the basic Three-Way Random mobility model is used to determine the probability of mode selection.

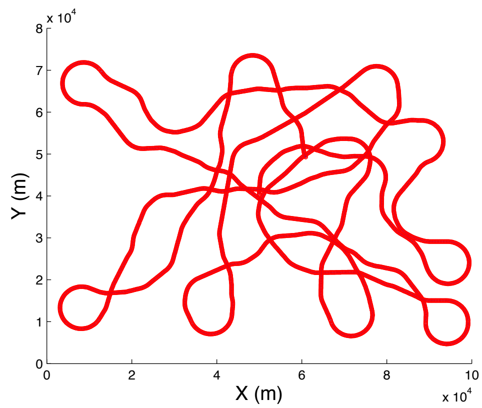
The boundary model used in this model is also defined based on pheromone maps. According to [35], when a node moves close to the boundaries, it is guided toward the inside of the simulation area by assigning pheromone smells outside the simulation areas very high values. In the case that a node is guided toward corners due to the low pheromone smells in the circle straight ahead, the node is forced to turn right. In our simulation, the pheromone smell of a circle is assigned infinity if its center is outside the simulation area. A node is guided to turn left or right if all three circles have infinite smells. If left and right circles both have infinite smells while the circle straight ahead has a finite smell, the node is forced to turn right.

Figure 4(c) shows the simulated trajectories of 30 aerial nodes following the Pheromone Repel mobility model. One of the trajectories is marked in red. Distinct from all the other mobility models discussed in this paper, this model belongs to the category of mobility models with spatial dependency. Pheromone smells contain collective information about how recently the simulation area is visited by aerial nodes, and thus guide aircraft to avoid recently visited regions.

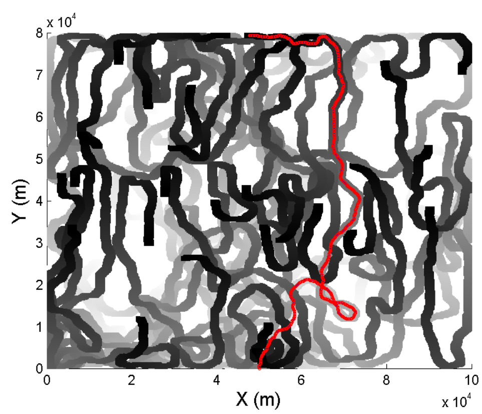
*2) Networking Performance:* The Pheromone Repel model has improved coverage properties compared to the Three-Way Random model [35]. The simulations suggest that the Pheromone Repel model can reach the steady-state coverage (i.e., the state when the coverage ratio remains close to a constant) faster with slightly larger steady-state value; in addition, the intervals between consecutive scans are more




(a) SRCM




(b) Three-Way Random mobility model




(c) Pheromone Repel mobility model

Fig. 4. Sample trajectories of a) SRCM, b) Three-Way Random mobility model, c) Pheromone Repel mobility model. The red curve in c) is the trajectory of one of 30 simulated aerial nodes. Intensities of pheromone smells are indicated by grey-scale values. Darker curves represent more recently visited areas. The trajectories of the SRCM model is circular around a fixed center. The Three-Way Random mobility model is different in the sense that the center is no longer fixed; however the turn radius is fixed for all turns. The Pheromone Repel mobility model guides aerial nodes to less recently visited areas.

uniformly distributed, avoiding rescanning an area very recently visited. The price paid is network connectivity: the Pheromone Repel model tends to have a larger number of disconnected clusters compared to the Three-Way Random mobility models in transient time. Because of the lack of connectivity, traditional MANET routing protocols may not work well. The same group proposed the geographic routing protocol (named Location Aware Routing Opportunistic Delay-tolerant networks (LAROD)) and a location service (named the Location Dissemination Service (LoDiS)) for such type of Intermittently-Connected Mobile Ad hoc Networks (IC-MANETs) [36], [37]. Simulations suggest that LAROD-LoDiS has better networking performance than the spray and wait protocol, in terms of delivery ratio and overhead. In addition, a comparison between the Pheromone Repel and RWP models using the LAROD-LoDiS protocol supports the statement that mobility models play significant roles in the performance of routing strategies, and thus the mobility research for ANs is important.

*3) Ability to Capture Mobility Attributes of ANs:* Both the Three-Way Random and Pheromone Repel models allow aircraft to perform typical turns with constant turn rates, reflective of mechanical and aerodynamic constraint. Unlike the SRCM model, these two models do not require the turn center to be fixed; however, the turn radius is fixed, constraining the mobility variability. Safety requirement is not addressed.

### *C. Smooth Turn Mobility Model*

The Smooth Turn (ST) mobility model was developed to capture the tendency of freely-moving airborne vehicles toward making smooth trajectories (e.g., straight trajectories or typical turns with large radius) [71], [72], [76]. This is made possible by directly modeling the centripetal and tangential accelerations, following the physical laws of aerial turning objects. Such mobility patterns are typical in applications such as patrolling. We first introduce the Smooth Turn concept using the basic 2D formulation, and then discuss the enhanced general model. Finally, we evaluate the model based on networking performance and ability to capture AN mobility attributes, and also discuss its connection with the Three-Way Random mobility model discussed in Section IV-B, and the RD model discussed in Section III-A.

*1) Basic Model Description and Statistical Properties:* We first introduce the basic 2D ST mobility model, and then briefly discuss the two extended 3D ST mobility models.

*a) Basic 2D ST mobility model:* In the basic 2D ST mobility model, an aerial vehicle selects a point on the 2D plane along the line perpendicular to its heading direction and circles around it for an exponentially elapsed duration with mean $\frac{1}{\lambda}$, where $\lambda \neq 0$ is a finite number. The perpendicularity ensures smooth turning trajectories. The circling dynamics is mathematically captured by

$$\begin{aligned} \dot{\Phi}(t) &= -w(t) = -\frac{V}{r} \\ \dot{l}_x(t) &= v_x(t) = V cos(\Phi(t)) \\ \dot{l}_y(t) &= v_y(t) = V sin(\Phi(t)) \end{aligned} \quad (7)$$

where $l_x(t)$, $l_y(t)$, $v_x(t)$, $v_y(t)$, $w(t)$, and $\Phi(t)$ represent $X$ coordinate, $Y$ coordinate, velocity in $X$ direction, velocity in $Y$ direction, angular velocity, and heading angle of an aerial node at time $t$. The forward speed $V$ is assumed to be a constant in the basic model. The inverse of $r$ is normally distributed with zero mean and variance $\sigma^2$, so as to capture the preference toward straight trajectories and slight turns. Once the exponentially elapsed duration is completed, the vehicle chooses another $r$, determines the new turn center, and repeats the above process.

The three parameters $V$, $\lambda$, and $\sigma^2$ in the model can be selected to capture a wide range of aerial moving patterns. In particular, a smaller $\lambda$ indicates that the vehicle tends to continue its current turn center instead of choosing a new one. Moreover, a larger $\sigma^2$ indicates more chances for turns with small radii.

The behavior of vehicles at boundaries can be modeled as reflecting back to the region, or wrapping around and appearing at the other side of the region. In addition, the vehicles can follow a more realistic boundary model similar to that of the Three-Way mobility model. Specifically, if a vehicle is within a distance of $2R$ to the boundary, it follows a smooth circle with radius $R$ to move back to the inner region [76], where $R$ is the minimum turn radius.

Using the reflection boundary model, the simulation model for the ST model can be represented in the following. Here we assume that $\Delta t$ is the simulation time interval. The turning angle at each time step $k\Delta t$ is then represented by $\theta = \frac{V}{r[K_i]}\Delta t$, where $K_i \le k \le K_{i+1}$, $k$, $K_i \in Z^+$, and $K_i\Delta t$ and $K_{i+1}\Delta t$ are the two consecutive time instances to change turn radius

$$
\begin{aligned}
c_x[K_i] &= l_x[K_i] + r[K_i]sin(\Phi[K_i]) \qquad (8)\\
c_y[K_i] &= l_y[K_i] - r[K_i]cos(\Phi[K_i])\\
\Phi[k+1] &= \Phi[k] - \theta - 2\pi\left\lfloor \frac{\Phi[k]-\theta}{2\pi} \right\rfloor\\
l_x[k+1] &= \Big| c_x[K_i] - r[K_i]sin(\Phi[k+1])\\
&\quad -2W\left\lfloor \frac{c_x[K_i] - r[K_i]sin(\Phi[k+1])}{2W} + 0.5 \right\rfloor \Big|\\
l_y[k+1] &= \Big| c_y[K_i] + r[K_i]cos(\Phi[k+1])\\
&\quad -2L\left\lfloor \frac{c_y[K_i] + r[K_i]cos(\Phi[k+1])}{2L} + 0.5 \right\rfloor \Big|
\end{aligned}
$$

where $c_x[K_i]$ and $c_y[K_i]$ represent the location of the turn center at time $K_i\Delta t$, and $W$ and $L$ represent the width and length of the simulation region. The floor functions realize the reflection boundary model (see [71] for the detailed discussion). A sample trajectory using this simulation model is shown in Figure 5. The trajectory is smooth and the turns are with constant turn rates, reflective of the mobility of aerial vehicles. Distinct from the SRCM and the Three-Way Random mobility models, both turn centers and turn radii are random.

*b) 3D ST mobility models:* The above basic 2D ST mobility model has been extended to 3D. Two 3D ST mobility models have been developed: $z$-dependent and $z$-independent ST mobility models [76].

In the $z$-dependent ST mobility model, maneuver planes are introduced (which may not be the $x$, $y$ plane) to capture the correlation of movements along the $z$ dimension and in the $x$, $y$ plane. The movement on the maneuver plane is same as that in the 2D ST mobility model. The difference is that at the time of turn center change, the vehicle randomly chooses a new

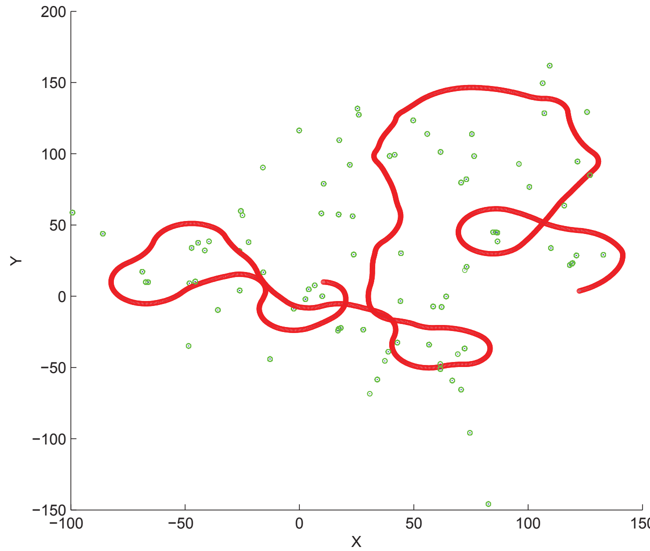



Fig. 5. Sample trajectory of the 2D ST model [71]. The green spots are the randomly selected turn centers. The trajectory is smooth with typical turns of constant turn rates. Both turn centers and turn radii are random.

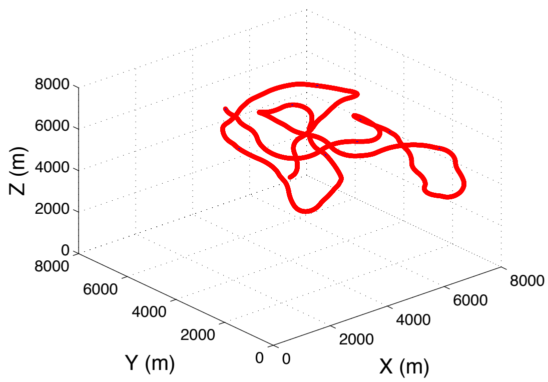
maneuver plane and a new turn center on the plane. The new maneuver plane intersects the current maneuver plane with a line aligned with the current heading direction. As the sample trajectory shows in Figure 6(a), correlations can be observed among all three dimensions.

In the $z$-independent ST mobility model, the movement along the $z$ coordinate is independent from that in the $x$, $y$ plane. The movement in the $x$, $y$ plane follows the 2D ST mobility model. The movement along the $z$ dimension can be modeled separately to reflect real flight data. As shown in Figure 6(b), the trajectory does not demonstrate the dependence of $z$-directional movement on the movement in the $x$, $y$ plane.

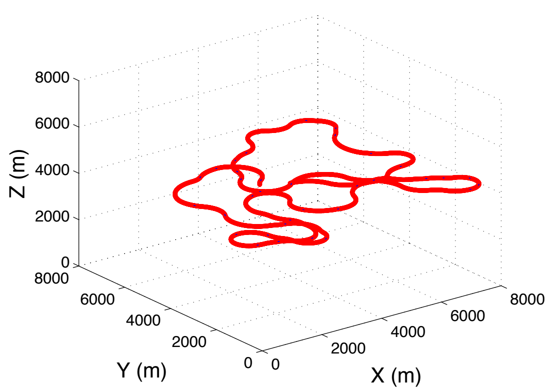
*2) Networking Performance:* The tractability permitted by the simple dynamics makes possible further statistical analyses such as the node distribution and the number of neighbors. It was proved in [71] that the basic 2D model has uniform distribution, which adds to the value of this model, as rich statistical results can be achieved from the uniformity.

For instance, the expected node degree for a given node is $E(D) = \frac{\pi N d^2}{A}$, where $N$ is the number of nodes, and $A$ is the area of the region, and $d$ is the transmission range [12]. Furthermore, when $N$ is large and also $d$ is small relative to $A$, the probability of the number of neighbors for any given node is approximately $P(D=m) = \frac{e^{-E(D)}E(D)^m}{m!}$ [12]. Therefore, the probability for a node to be isolated can be easily derived as $P(D=0) = e^{-\frac{\pi N d^2}{A}}$ [12].

The probability for a network to be connected, denoted as $P(connected)$, is less than or equal to the probability for the network to have no isolated nodes, calculated as $P(No\ isolated\ node) = (1 - P(D=0))^N$ [12]. It was also shown that $P(No\ isolated\ node)$ is a tight bound for $P(connected)$, especially when $P(No\ isolated\ node) \to 1$. For the wrap-around boundary model with large $N$ and small $d$, this bound is approximately $e^{-Ne^{-\frac{\pi N d^2}{A}}}$ [12]. Some other studies also investigated network-level connectivity for




(a) 3D $z$-dependent ST




(b) 3D $z$-independent ST

Fig. 6. Trajectories of a) the 3D $z$-dependent ST mobility model, and b) the 3D $z$-independent ST mobility model [76]. The difference between the two models resides in the existence of correlation between the movement along the $z$ dimension and that in the $x$, $y$ plane.

networks with uniform distribution [28], [78]. For instance, for a circular region with boundary (e.g., the reflection model), if the transmission range $r = \sqrt{\frac{\log N + c(N)}{N\pi}}$, then $P(connected) \to 1$ as $N \to 1$, if and only if the constant $c(N) \to 1$.

$k$-connectivity is often of interest to establish a network robust to agent failures. Similar to the development for 1-connectivity, the probability for the network to have no node with degree less than or equal to $k - 1$ is a higher bound for $P(k - connected)$. In particular, $P(k - connected) \leq (1 - P(D \leq k - 1))^N$. It was also shown that the upper bound is tight, especially when $P(D \leq k - 1) \to 1$ [12].

*3) Ability to Capture Mobility Attributes of ANs:* The ST models capture smooth turns with flexible radii. As it is constructed using aerial kinetics, the model naturally captures the spatiotemporal correlation of accelerations reflective of aerodynamics. Second, the model has very simple dynamics. It also captures high mobility and frequent network topology changes. Aerial nodes in this model are free to travel inside the simulation area with variable turn centers and turn radii. Besides the smooth trajectory constraint and possible safe requirement, no other constraints limit the movement of aerial nodes.

Here, we connect the basic ST model with the RD model and the basic Three-Way Random model. Similar to the basic RD model, an aerial node randomly chooses a direction for an exponentially elapsed duration. The only difference is that the RD model chooses a random straight direction, whereas the ST model chooses a random turn radius. The Three-Way Random model can be considered as a variant of the ST model. As opposed to the fixed duration between the changes of directions in the Three-Way Random model, the duration in basic ST mobility model is random. Moreover, the turn radius in the ST mobility model can take continuous values in a large range, but in the Three-Way Random model, three values are considered: $+r$, $-r$, and $\infty$, representing left turn with radius $r$, right turn with radius $r$, and the straight trajectory. Furthermore, the probability of direction selection in the Three-Way Random model is state-dependent; but in the basic ST model is based on the exponentially elapsed duration distribution and the radius distribution.

### *D. Flight-Plan based Mobility Model*

Pre-defined trajectory plans may be directly used as mobility models [68]. Such pre-defined plans may not exist for completely autonomous ANs; however, they are typically available for ANs that involve commercial flights, cargo planes, and pre-defined AN backbones [62], [68].

*1) Model Description and the Use in Mobility-Aware Routing:* In [68], pre-defined flight plans together with the Mobility-Aware Routing and Mobility Dissemination Protocol (MARP/MDP) are used to effectively maintain the networking of AN backbone nodes. In particular, initial flight plans are recorded in a global mobility file, which contains the location and gesture information of each aircraft, tagged with time. The global mobility file is then used to generate a Time-Dependent Network Topology (TDNT) map and then the routing table for each time. Uncertainties in the environment (such as weather) might cause deviations from the flight plan. A hello-and-acknowledge mechanism is used to check if the TDNT is up-to-date. If not, the TDNT map is updated and then a new routing table is generated.

*2) Networking Performance:* To understand the performance of the model and the associated routing protocols, the authors constructed a small-scale network with four nodes in circular movement and a medium-scale network with 18 nodes in circular and race-track movement. The MARP/MDP protocol is shown to outperform the AODV and OLSR protocols in terms of throughput, latency, and package delivery ratio. The overhead of this routing protocol is slightly worse than that of AODV and OLSR. This study also suggests the importance of mobility, and its use in developing high-performance routing protocols for ANs.

*3) Ability to Capture Mobility Attributes of ANs:* Because of the current safety concerns in flying autonomous aerial vehicles, flight plans are typically available. The model captures high mobility, safe constraint, and aerodynamics, as they are all reflected by flight plans.

### *E. Multi-Tier Mobility Models*

The airspace is highly heterogeneous with aerial vehicles of different types and operating for different missions [61]. As it is impossible to use a common mobility model for all these vehicles, networking in such heterogeneous networks requires mobility models that incorporate multiple mobility patterns.

*1) Model Description:* To meet this need, Multi-Tier mobility models (belonging to the category of hybrid models) are introduced (see [17], [62], [63], [68]). In particular, the Multi-Tier mobility models in [17] contains aircraft of different types flying at different altitudes. Aerial networks may also be connected to fixed control stations or ground vehicle teams to form multi-domain communication networks [17], [61], [68].

ANs with backbone structures can also be modeled using Multi-Tier mobility models [44], [62], [63], [68]. As robust networking is very difficult to establish for highly random autonomous ANs, imposing designable deterministic backbone structures can significantly enhance the reliability and scalability of ANs. In particular, backbone nodes have planned trajectories [62], [68] and serve as the base stations (or fusion centers) [62], [70] for information exchange among themselves, and with other vehicles. In [62], the UAV backbone nodes are moving deterministically in circles, but with designable velocities, locations, radii and transmission ranges. Algorithms were developed to design these parameters for two goals: 1) maintaining connection among the backbone nodes, and 2) achieving wide coverage.

*2) Networking Performance:* Due to the complexity of these heterogenous Multi-Tier mobility models, not many studies have been on their networking performance, per knowledge of the authors. Some studies are on the performance evaluation of simple settings involving fixed ground stations and several aircraft following pre-planned orbits [19], [68]. Of particular interest, flight tests are implemented in [19] to evaluate link availability, data rate, link latency, link up/down jitter, and route availaiblity in a simple setting. More details on the results of [68] can be found in Section IV.D. A more complicated field demonstration that involves ground stations, UAVs, and ground vehicles is discussed in [24].

*3) Ability to Capture Mobility Attributes of ANs:* Multi-Tier models can capture the heterogeneous property of airspace environment, and we envision that they will be used frequently for AN studies in the future. Its capability to capture mobility attributes of ANs is determined by the capability of individual mobility models.

### *F. Summary*

Section IV surveys and compares the mobility models designed specifically for ANs, with a complete comparison summarized in Table III in Section V. In particular, these models are evaluated from the following aspects: model description, AN networking performance, and the suitability for ANs, in terms of high mobility, aerodynamic constraint, and safety. All of these models can produce smooth trajectories. The most notable difference is the additional constraints placed on the mobility: the Flight-Plan (FP) based model constrains the whole trajectory, the SRCM model constrains the turn center, and the Three-Way Random and Pheromone Repel models constrain the turn radius. The ST models are considered as the AN mobility models with the least unnecessary constraints.

To obtain a more straightforward understanding of how to configure these models, we also provide the random variables and parameters in these models, and the categories that they belong to (see Table II).

## V. Comparison of the Mobility Models for ANs

As mobility models have determining effect on routing performance, choosing the suitable mobility model is critical for the evaluation of networking performance. In this section, we further compare the above AN mobility models from two aspects: 1) randomness level, and 2) associated application. We then provide a comprehensive comparison of these mobility models in Section V-C that also summarizes the key contributions of this paper. The discussion presented here represents the first step toward a systematic procedure to select and configure mobility models for different scenarios of interest.

### *A. Randomness*

The degree of randomness is a natural metric to characterize and differentiate mobility models [71], [72]. Because of the difficulties facing a robust networking of autonomous ANs, deterministic pre-defined flight plans are typically adopted nowadays in small-scale field tests. However, with the rapid growth of this field, we envision that less controllable flight trajectories and more random AN topologies will appear in the future.

In [71], an *entropy-rate-based* measure was introduced to quantify the degree of randomness for mobility models. The entropy rate is defined on a Markov-chain representation of the mobility. In the Markov chain, each state captures the mobility status of an aerial node, such as location, heading direction, speed, and so on, depending upon the specific scenario. The entropy-rate-based randomness measure is then defined as: $H = -\int_i \int_j p_i Q_{ij} \ln Q_{ij}$, where $p_i$ represents the probability to stay at status $i$, $Q_{ij}$ represents the probability to jump from status $i$ to status $j$ in a unit time $\Delta t$.

In [71], the randomness of four mobility models including RD, ST, SRCM, and FP are quantified using this randomness measure. Through configuring the models with a similar set of parameters such as forwarding speed ($V = 40m/s$), and waiting time distribution (exponential with $\lambda = 2/s$), we find the randomness of RD, ST, SRCM, and FP in a decreasing order: RD around $0.018$, ST typically below this, SRCM at the order of $10^{-6}$, and FP almost negative.

We here further quantify the randomness of the Three-Way Random mobility model. Using the transition matrix presented in Section IV-B as the example, we first note that the probability to move forward, left, or right at steady state is $p_1 = 0.6$, $p_2 = 0.2$ or $p_3 = 0.2$, respectively. Assume $\Delta t = 0.001s$ to be consistent with that in [71]. As the vehicle only changes the mode at the end of every $2s$ [37], we find the entropy rate as

$$\begin{aligned} H &= -\int_i \int_j p_i Q_{ij} \ln Q_{ij} = -\sum\nolimits_i p_i \sum\nolimits_j Q_{ij} \ln Q_{ij} \quad (9) \\ &= -\frac{0.6\Delta t}{2}(0.8\ln(0.8) + 0.2\ln(0.1)) \\ &\quad -\frac{0.4\Delta t}{2}(0.7\ln(0.7) + 0.3\ln(0.3)) = 3.3 \times 10^{-4} \end{aligned}$$

TABLE II
RANDOM VARIABLES, PARAMETERS, AND MODEL CATEGORIES OF EXISTING AN-SPECIFIC MOBILITY MODELS

| **Model** | **SRCM** | **Three-Way Random** | **Pheromone Repel** | **Basic ST** | **FP** | **Multi-Tier** |
|---|---|---|---|---|---|---|
| **Random variables** | Turn radius, speed, way-point on the same circle | Mobility mode | Mobility mode | Turn radius, duration | Noise | Dependent on individual models |
| **Fixed parameters** | Range of turn radius, turn center | Speed, transition probability, radius | Speed, transition probability, radius, pheromone intensity | Mean of duration, speed, inverse variance of turn radius | Whole trajectory | Dependent on individual models |
| **Model Category in terms of heading** | Temporal dependency | Temporal dependency | Temporal dependency, spatial dependency, hybrid | Temporal dependency | Geographic constraint | Hybrid |

Comparing to the other mobility models (see results in [71]), we see that its randomness level is higher compared to the SRCM model, but less than all the other models. To permit a fair comparison with the ST model, we may also assume that the waiting time to change mobility mode has the same exponential distribution with $\lambda = 2/s$. As within $\Delta t$, the vehicle has a probability of $\lambda\Delta t$ to change mode and $1 - \lambda\Delta t$ to keep its current mode, we find its randomness as

$$\begin{aligned} H &= -\sum_i p_i \sum_j Q_{ij} \ln Q_{ij} \quad (10) \\ &= -0.6((1-\lambda\Delta t)\ln(1-\lambda\Delta t) + 0.8\lambda\Delta t \ln(0.8\lambda\Delta t) \\ &\quad +0.2\lambda\Delta t \ln(0.1\lambda\Delta t)) - 0.4((1-\lambda\Delta t)\ln(1-\lambda\Delta t) \\ &\quad +0.7\lambda\Delta t \ln(0.7\lambda\Delta t) + 0.3\lambda\Delta t \ln(0.3\lambda\Delta t)) \\ &\quad = 0.0157 \end{aligned}$$

which is comparable to that of the ST mobility model.

## *B. Application*

Another more straightforward criterion to compare and select mobility model is application-type. Airborne networks are envisioned to have a wide range of applications. In different applications, ANs are typically associated with different mobility patterns; and therefore should be described using different mobility models or mobility models with different configurations. We compare in this section the AN mobility models from the angle of application-type.

The Flight Plan model has pre-defined deterministic trajectories, and therefore is good for cargo and transportation scenarios where flight destinations are known beforehand. The SRCM model has a pre-defined turn center and therefore its random trajectory is highly restricted. This model may be suitable for search applications in which the potential location of a search target is known. The ST mobility models and the Three-Way Random mobility model capture more flexible trajectories and therefore are suitable for patrolling and reconnaissance applications without much pre-planned information. The Three-Way Random mobility model is less flexible in restricting the turn radius to be a pre-defined value. The ST models are currently the most flexible models and can be configured to capture a wide range of mobility patterns. The 3D $z$-independent ST mobility model is sufficient for typical civilian and commercial applications with less correlation of mobility between the $z$ and $x$, $y$ dimensions. The 3D $z$-dependent ST mobility model can capture complicated 3D mobility with large variation along the $z$-dimension correlated with that in the $x$, $y$ plane, and therefore is more suitable to military applications and air show-type applications. Furthermore, we also note that the Pheromone Repel mobility model is suitable for group reconnaissance applications that require faster coverage through the information sharing among aerial nodes.

## *C. Summary on the Comparison of Mobility Models for ANs*

The focus of this paper is on surveying the existing mobility models for ANs, and understanding whether they are suitable for ANs. To summarize, the differences among mobility models that we have discussed in this paper (except the Multi-Tier model which is a combination of other models) are listed in Table III.

*1) Model description:* As summarized in the table, all mobility models are random models with different constraints and flexibility.

*2) Adaptability for ANs:* The SRCM, Three-Way Random, Pheromone Repel, ST, and FP models are designed for ANs. Simple extensions have been made to adapt RD, RWP, RW, and Gauss-Markov models for ANs; however all these adaptations do not reflect the feature unique to typical aerial turns.

*3) Networking performance:* The purpose of surveying networking performance studies using these models is only to summarize studies that have been made in this respect, instead of as a criterion to judge the capabilities of these mobility models.

*4) High node mobility and frequent topology change (first feature of aerial mobility):* All models can be configured to have high mobility. The SRCM, Three-Way Random, and the Flight Plan models have further constraints on turn center, turn radius, and trajectory, respectively.

TABLE III
COMPARISON AMONG MOBILITY MODELS FOR ANS.

| Model | RD, RWP, RW | Gauss-Markov | SRCM | Three-Way Random & Pheromone Repel | 2D and 3D Smooth Turn | Flight Plan |
|---|---|---|---|---|---|---|
| **Description** | Randomly select direction or destination | Memory-based movement corrupted with noise | Circle around a fixed center with variable radii | Randomly choose a fixed turn radius or straight trajectory based on a Markov chain | Randomly choose a turn radius to favor large turns and straight trajectory | Pre-defined trajectory updated to account for variations |
| **Adaptabality for ANs** | High speed values, RRW | 2D to 3D | N/A | N/A | N/A | N/A |
| **High Node Mobility and frequent topology change** | Yes | Yes | Partial, constrained with fixed turn center | Partial, constained with fixed turn radius | Yes, variable radius permitted | Partial, constrained with flight plans |
| **Mechanical and Aerodynamic Constraint** | No, sharp movement | No, temporally dependent | Partial, smooth trajectory on the same circle | Yes, flexible smooth turns | Yes, flexible smooth turns | Yes, deterministic trajectory |
| **Safety constraint** | No | No | No | Partial | Partial | Partial |
| **Applications** | MANETs | MANETs | Search and rescue | Reconnaissance | Patrolling, reconnaissance, etc. | Cargo, commercial and AN backbone |
| **Randomness** | Highest | N/A | Low | High/Medium dependent on parameters | High/Medium dependent on parameters | Lowest |

*5) Mechanical and aerodynamic constraint (second feature of aerial mobility):* This constraint leads to the smoothness of aerial trajectories. The MANET models including the RD, RWP, RW and the current form of Gauss-Markov do not capture this constraint. The SRCM model satisfies this constraint except during the transitioning among circles. The Three-Way Random, Pheromone Repel, Smooth Turn, and Flight Plan models all capture this constraint.

*6) Safety requirement (third feature of aerial mobility):* In the FP model, safety is to some extend coded in the pre-defined flight plans. No mobility models have comprehensively considered safety requirement such as collision avoidance. The SRCM, Three-Way Random, and the Smooth Turn mobility models can be easily configured to guarantee the minimum turn radius requirement.

*7) Applications:* Different models and model configurations should be selected for different applications. Please refer to the discussions in Section V-B.

*8) Randomness:* The randomness degrees of these models (except the GM model which is modeled using a different form) have been quantified according to the entropy-rate measure. These mobility models can be ordered according to an increasing degree of randomness: FP, SRCM, Three-Way Random, Smooth Turn, and RD.

## VI. DISCUSSIONS OF CRITICAL RESEARCH NEEDS

AN mobility models build the foundation for the research on robust AN networking; however, many questions remain open. In this section, we summarize several critical research needs that we envision in this emerging field.

### A. Model Validation and Parameterization

Model validation and parameterization from traces are critical for AN mobility research. Because of the difficulty and high cost associated with field tests, very limited trace data are currently available for ANs. Most of the models are not yet validated by real trace data. Analyzing these data will also bring forth rich insights into enhancing the existing mobility models. As the first attempt to model validation, the Smooth Turn mobility model (in particular, the 3D $z$-independent mobility model) was estimated and validated using real flight test data [77]. The good match between the estimated trajectories and the real trajectories suggests the suitability of this Smooth Turn model for ANs.

Furthermore, each of the mobility models has some design parameters that can significantly impact mobility patterns. For most of the simulation studies, these parameters are chosen without real data support or justification. Parameterization of these models from data is of critical need to establish realistic AN evaluation environment.

### B. Selection of Model Granularity

Finding the trade-off between precision and analyzability in mobility model design is also a critical issue. Mobility models do not need to be at a very fine level. The best abstraction level is the one that both reflects the reality for the need of AN networking studies, and is simple enough for tractable analysis.

The best granularity level needed for AN networking studies is not yet understood. A critical note is that the best granularity is also dependent on other factors such as vehicle type, speed, transmission range, etc. The role of vehicle types can be drawn from the fact that jets cannot stop in the air, but helicopters can. Furthermore, the different combination of speeds (associated with different aerial vehicles) and transmission strengths is also an important factor. To conceptually illustrate this, if the transmission range is very large compared to the speed, the fine details of smooth maneuvering can be neglected, and thus traditional MANET models may still be valid.

In order to better understand the granularity level needed for AN networking studies, a critical task is to compare the networking performance obtained from real flight field tests with that using random mobility models. Such comparison will better suggest the impact of model granularity on networking performance and help determine the best granularity level. However, such comparison study is impossible currently due to the lack of real AN field test data. As airborne networking is a very nascent area, most of AN studies are based on simulations, and there do not yet exist performance studies for real autonomous ANs that use multi-hop communication per knowledge of the authors. The closest pioneering study was conducted by MIT Lincoln Lab ( [19]), where the networking performance was evaluated for real flight tests. However, as in [19], flights follow pre-planned race-track orbits and the network is composed of only two aircraft and a ground station, more AN field tests are badly needed to enable this networking performance comparison study.

### C. Other Potential Models

Other MANET models may also be adapted for ANs, such as the Smooth Mobility Model [11], and the coordinated-turn models in the tracking literature [39]. Let us also briefly discuss these models, focusing on their potential use for ANs.

*1) Smooth Mobility Model:* The Smooth mobility model assumes that a ground agent travels along a straight line with a randomly selected target speed, and reaches that target speed incrementally [11]. When it changes direction, the duration to finish the directional change (curve time) $\Delta t_c$ and the direction difference $\Delta\Phi$, are selected randomly. The agent then determines the turn radius $r_c = \frac{v\Delta t_c}{\Delta\Phi}$, and finishes the turn following this radius.

The trajectory of this mobility model is almost same as that of the RD, but with smooth curves during directional changes. Further enhancements include the correlation of directional change and speed change in the three processes associated with a ground vehicle turn: slow-down, turn, and speed-up. For aerial vehicles following majorly straight trajectories, this model may be adapted to render the details at directional changes. Because this model does not change the coarse-level trajectory of RD models, the node distribution is uniform for both the wrap-around and the reflection boundary models.

*2) Coordinated-Turn Models from the Tracking Literature:* A number of 2D and 3D coordinated turn models are reviewed in [39]. These models may directly be used for highly-random airborne networks at a fine granularity level, provided that the parameters are chosen properly.

### D. Model Analysis and Mobility-aware Routing

Quantified understanding of the relationship between mobility and communication quality is also of critical need. Currently, most of the studies assume that the communication can be established when aerial vehicles are within a fixed transmission range, and otherwise is lost. However, this is not true in reality. Beaming direction, body blockage and uncertain environment, also affect the quality of communication. Tractable analysis on how mobility affects networking performance can significantly facilitate the automatic design of mobility-aware networking protocols.

## VII. Summary and Conclusion

This paper represents the first attempt to a comprehensive survey and comparative analysis of the mobility models of airborne networks. In particular, we analyze and compare the existing mobility models for airborne networks. Other than MANET mobility models such as RD, RWP and RW that are adapted for ANs, there is limited existing research on mobility models specific for ANs, including the Smooth Turn, Pheromone Repel, Semi-Random Circular Movement, Flight Plan, and Multi-Tier mobility models. Besides investigating the specifics of each mobility model, we evaluate these models based on i) the adaptability of these models for ANs if they are not directly designed for ANs, ii) AN networking performance, and iii) whether the particular mobility patterns are realistic to capture AN mobility attributes, in terms of high mobility, mechanical and aerodynamic constraint, and safety requirement. These models are further compared in terms of i) the degree of randomness and ii) the associated AN applications, to facilitate model selection. Please refer to Section V for a detailed summary on such comparison. The major results of this paper include: i) the identification of a key property for aerial mobility: the smoothness of trajectories due to constant turn rates for typical turns, ii) the analysis that MANET mobility models (including the Gauss-Markov model) cannot capture the key property of aerial mobility, iii) the conclusion that mobility models designed for ANs can all basically capture the key property, iv) the quantification of randomness for the Three-Way Random and the SRCM mobility models and v) the comprehensive comparison of all mobility models that have been used for AN studies. In the end, we discuss critical research needs, including model validation, identification of the best model granularity, and the mobility-driven framework for AN performance evaluation and networking design. The most critical need is AN field test data and the use of them to validate and parameterize mobility models and to determine the best model granularity.

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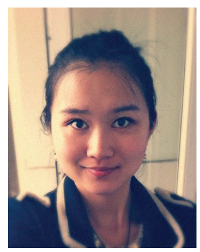
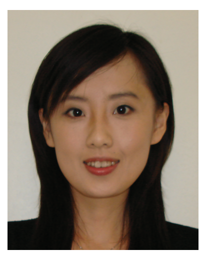


**Junfei Xie** (S'13) received the B.S. degree from University of Electronic Science and Technology of China, Chengdu, China in 2012, and the M.S. degree from University of North Texas, Denton, Texas in 2013. She is now working toward the Ph.D. degree in the department of Computer Science and Engineering in University of North Texas. Her research interests include airborne networks, complex information systems, and air traffic flow management, etc.

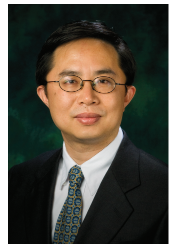


**Yan Wan** (S'08-M'09) received the B.S. degree from Nanjing University of Aeronautics and Astronautics, Nanjing, China in 2001, the M.S. degree from The University of Alabama, Tuscaloosa, AL in 2004, and the Ph.D. degree from Washington State University, Pullman, WA in 2009. She is currently an Assistant Professor with the Department of Electrical Engineering, University of North Texas, Denton. Before that, she worked as a postdoctoral scholar in the Control Systems program at the University of California at Santa Barbara. Her research interest lies in decision-making tasks in large-scale networks, with applications to air traffic management, airborne networks, sensor networking, biological systems, etc. She was the recipient of the prestigious William E. Jackson Award (Excellence in aviation electronics and communication) in 2009, presented by Radio Technical Commission for Aeronautics (RTCA).

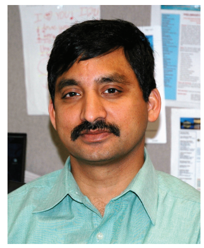
**Jae H.Kim** is an Executive / Senior Technical Fellow of Boeing Research & Technology in the area of Communications and Network Systems. He has been a Principal Investigator and Program Manager for a number of U.S. Department of Defense (DoD) contract programs from DARPA, Army CERDEC, Air Force AFRL, Navy ONR and NASA. Dr. Kim has been serving as an Affiliate Professor and Graduate Faculty of Electrical and Computer Engineering Department, University of Washington, Seattle, WA since 2000. He has also served as an IEEE Associate Editor for a monthly Technical Journal of Communications Letters for a decade since 2001. Prior to joining Boeing in 1991, Dr. Kim has been a Member of Technical Staff, then Task Manager as Senior Research Scientist at the California Institute of Technology, NASA Jet Propulsion Laboratory since 1987.

His research area of interests is wireless communications and mobile networking, with specific interests in adaptive MANET, UAV-based airborne internetworking, resilient NetOps with auto-configuration and distributed information services, and spectrum and jamming-aware MANET under extreme environments.

Dr. Kim received his Ph.D. degree from University of Florida, Gainesville, M.S. and B.S. degrees from Seoul National University all with Electrical and Computer Engineering. He is an author/co-author of 100 publications, receives 6 U.S. Patents, 10 NASA Technical Innovation Awards and 25+ Boeing Technology Awards for outstanding technical performance recognition. Dr. Kim edited a book, Green IT: Technologies and Applications published by Springer-Verlag (August 2011), that has been listed as a top 25 most downloaded eBooks in the relevant Springer eBook Collection in 2012.



**Shengli Fu** (S'03-M'05-SM'08) received his B.S. and M.S. degrees in telecommunication engineering from Beijing University of Posts and Telecommunications, Beijing, China, in 1994 and 1997, respectively, the M.S. degree in computer engineering from the Wright State University, Dayton, OH, in 2002, and the Ph.D. degree in electrical engineering from the University of Delaware, Newark, DE, in 2005. He is currently an associate professor in the Department of Electrical Engineering, University of North Texas. His research interests include coding and information theory, wireless communications and sensor networks, and mobile ad-hoc networks.



**Kamesh Namuduri** (SM'97)received his B.S. degree in Electronics and Communication Engineering from Osmania University, India, in 1984, M.S. degree in computer science from University of Hyderabad in 1986, and Ph.D. degree in computer science and engineering from University of South Florida in 1992. He worked in C-DoT, a Telecommunication firm in India from 1984 to 1986, where he participated in the development of the first indigenous digital exchange in India. He also worked in GTE Telecommunication Services Inc., USA, (now Verizon) from 1993-1997, where he participated in the development of a mobile telephone fraud detection system. From 1998 to 2002, he worked as a Research Scientist in the Center for Theoretical Studies of Physical Systems at Clark Atlanta University in Atlanta. From 2002 to 2008, he was a faculty member in the Department of Electrical Engineering and Computer Science at Wichita State University. Currently, he is with the Electrical Engineering Department at University of North Texas as an Associate Professor. His areas of research interest include information security, image/video processing and communications, and ad hoc sensor networks.