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Update on Including Turbulent Winds in Simulated Environments for Unmanned Aircraft Systems

by Cheryl Klipp, Kelly Kirk, Carl Lederman, and Brent Kraczek

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14. ABSTRACT The objective of this effort is to develop a more realistic understanding of turbulence effects in urban environments, with the goal of designing more realistic simulation environments for unmanned aircraft systems (UASs). With the future Army in mind, US Army Combat Capabilities Development Command Army Research Laboratory's Battlefield Environment Division is constructing a flexible development platform for the simulation of quadcopters in urban environments. The planned methodologies will enable realistic, site- and weather-specific simulations to enhance training, mission planning, and, potentially equipment configuration, by leveraging DEVCOM Army Research Laboratory developments in physics, meteorology, and controls. This platform is implemented such that the functionality can be exported to Army immersive environments when they become available. Within this environment, we are able to simulate simple mean wind fields and their effects on UAS control. A simplified turbulent static wind field constructed from time series field data is now available to start modeling the impact of environmental turbulence on UAS control.						
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1. Introduction

The objective of this effort is to develop a more realistic understanding of turbulence effects in urban environments, with the goal of designing more realistic simulation environments for unmanned aircraft systems (UASs). The US Army Combat Capabilities Development Command Army Research Laboratory's Battlefield Environment (BE) Division is developing methodologies to enable the use of Army-owned, mission-specific data to be used within synthetic environments currently under development for the Army. The planned methodologies will leverage DEVCOM Army Research Laboratory developments in physics, meteorology, and controls to enable realistic, site- and weather-specific simulations to enhance training, mission planning, and, potentially, equipment configuration.

2. Vision and Motivation

The advancement of synthetic environments (SEs), enabled by virtual reality (VR) and augmented reality (AR), is a hot topic in the technology space. Current advances in SEs, VR, and AR depend on the concurrent, rapid improvement and adoption of graphics processing units and artificial intelligence (AI). The anticipated universe of virtual worlds is currently called the "metaverse" or the "Omniverse". (The latter name is used by Nvidia, the graphics chip market leader.) Brian Santo, editor-in-chief of EETimes, has recently discussed how the market for the metaverse may ultimately eclipse the smartphone market (Santo 2021). Similarly, multiple Forbes contributors have recently projected that Nvidia's market value may eclipse that of Apple's within the next 5 years. These projections are based on the strength of Nvidia's position in developing hardware and software tools for the metaverse, as well as for the importance of their hardware and software in AI applications (Hackl 2020; Kindig 2021).

The US Army has similarly recognized the importance of VR and AR, as represented by the creation of the Synthetic Training Environment (STE) cross-functional team. In 2019 and 2021, the Army awarded contracts for three related software development projects totaling between $300 and $400 million: STE, the Common Synthetic Environment (CSE) and One World Terrain (OWT), with first deliverables expected in the coming months (NSTXL 2019; Rozman 2020; AP News/Light Professional IT Services 2021). Collectively, these tools are being developed to assist in training and mission planning. For example, OWT will be a high-fidelity mapping tool, similar to the commercial product, Google Earth. OWT will generate realistic models of the terrain and buildings so that Soldiers can become familiar with the physical environment prior to performing a mission.

Assuming that the metaverse, VR, and/or AR become widely adopted, all militaries will need to consider carefully how to use it to enhance operations and training. As with any technology, these will level the competition in some respects, but will also open new opportunities for overmatch. One potential area for overmatch will be physical realism, which is only as good as the underlying simulation technology. In some use cases, such as collision detection and rag-doll physics, gaming physics engines are well developed and reasonably accurate. But in many cases, the physics themselves are not yet fully understood.

Atmospheric effects, both mean wind and turbulence, are one aspect of the outdoor environment currently overlooked by simulation environments. Environmental turbulence is ubiquitous in the atmospheric surface layer, roughly the first 50–200 m above the earth's surface, and is stronger near the ground and near obstacles such as buildings and trees. The atmosphere near the earth's surface is always in motion to some degree with variation in speed and direction at all spatial and temporal scales from kilometers to millimeters, hours to fractions of a second, as well as daily, synoptic (weather systems), and annual variation (Stull 1997). The variation on scales relevant to small UASs is the focus of this report. UAS relevant scales range from the length of its mission to the size of the aircraft to the size of the rotors and control surfaces.

It is important to include turbulence, in addition to mean winds, in flight simulation environments, especially when lighter weight aircraft are included in the simulation. The wind-related forces affecting flight are proportional to the lift and drag surface areas of the craft, while the mass of the craft is proportional to the volume. This means that, as functions of UAS size, UAS mass becomes smaller at a faster rate than the area-related forces, resulting in greater sensitivity to turbulent forces in the environment (Klipp and Measure 2011). Ultralight, flapping wing, bird-mimicking UASs will be especially vulnerable to environmental turbulence when they become operational.

3. Progress to Date

Previous BE efforts have established a flexible development platform for the simulation of quadcopters in urban environments, with an emphasis on the intersection of drone and environmental physics along with the control algorithms employed (Lederman et al. 2021). The simulation utilizes Unreal Engine, version 4 (UE4), which enables seamless interaction with arbitrary physics and control algorithms coded by BE, in addition to state-of-the-art visualization and user interface tools. Further, we have leveraged existing software, such as AirSim, PX4 and ROS2, which are already compatible with UE4 and employed software that compromise real-world drones. The software toolchains developed in BE employ widely used and supported open source software libraries. These toolchains have been carefully implemented to enable transition from Unreal Engine to STE/CSE/OWT when those tools are released to the broader Army Science and Technology/Research and Development community.

Work to date has focused on static-in-time wind fields in a portion of Chicago. For our current implementation, we generated city landscapes from OpenStreetMap data. BE's Y Wang computed dynamic wind fields on this landscape using ABLE-LBM, a lattice Boltzmann fluid flow model of the atmospheric boundary layer (Wang et al. 2020a, 2020b). A mean wind field over an hour period was then used to generate winds in the UE4-based UAS simulation. Although static in time, these mean winds vary in space and can pose a challenge in themselves to high-quality quadcopter navigation. However, more realistic and real-world relevant modeling additionally requires modeling and controlling for small-scale in time environmental effects on the drone trajectory. A sample of the graphical output from the current state of this simulator is given in Fig. 1.

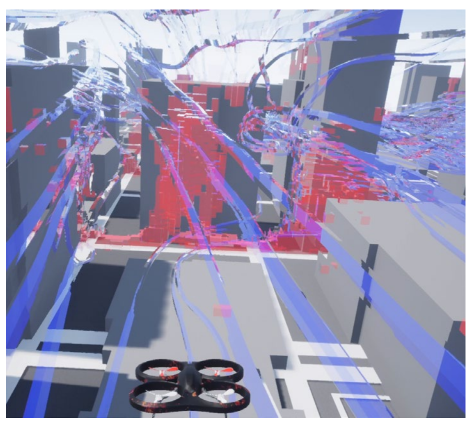

Fig. 1 Graphics from DEVCOM ARL, UAS simulation of Chicago. Glassy, blue stream tubes show averaged streamlines of wind. Red foggy regions show areas of likely high turbulence, as determined by the magnitude of wind vector components in the vertical direction. Winds were simulated by Y Wang. The current wind field used varies in space but not time, taken from the mean winds over a 1-h period.

3.1 Control, Physics, and Wind Simulation Components

The physics-controls-wind simulation is completed using UE4 (https://www.unrealengine.com/), with a controller plug-in and external applications for serving wind data and drone navigation. The controller determines the dynamics of the UAS within the environment. At present, we have three separate such controls in varying stages of development, based individually on AirSim (https://microsoft.github.io/AirSim/), PX4 (https://px4.io/), or ROS2 (https://docs.ros.org/en/foxy/). The Drone Navigation Path controller and the Wind Server connect to the UE4-controller plug-in system using Remote Procedure Calls (RPCs). For this, we have used the MessagePack-RPC (https://github.com/msgpack-rpc/) binary serialization method. In some implementations, we have also explored the use of Real-Time Publish Scribe (RTPS) data transfer, employing FastDDS (https://github.com/eProsima/Fast-DDS), for manual control in the PX4 and ROS control schemes. The likely final product will employ both the RPC and RTPS systems.

The main function of the wind server is to manage the wind field data, which may be on the order of 10 GB or more of data in a 4-D space-time format over the domain sizes currently modeled by ABLE-LBM. The data are stored in the Network Common Data Form file format (NetCDF, https://www.unidata.ucar.edu/software/netcdf/) using the Climate and Forecast (https://cfconventions.org/) metadata conventions. The data are managed in a distributed manner within the wind server using xarray, (xarray.pydata.org/en/stable/) for the efficient handling of large data sets (Fig. 2).

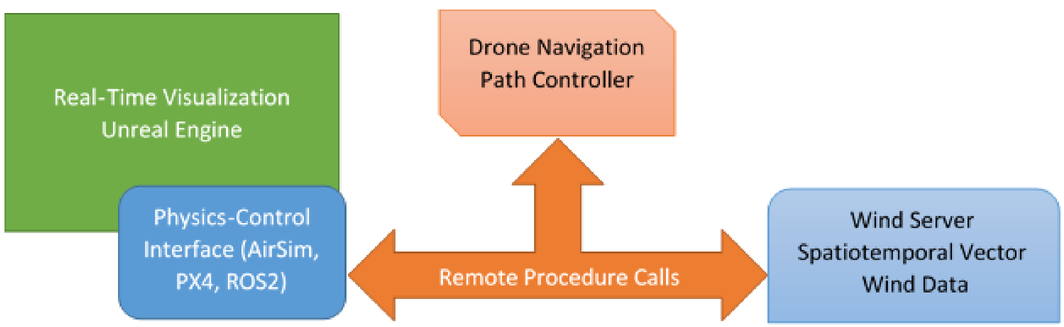

Fig. 2 Brief schematic of component connections in the physics-wind-control simulations

3.2 The Turbulent Wind Field

So far, the wind field used in the simulated environment is a static mean wind field provided by ABLE-LBM. A typical approach to adding turbulence to a static wind field would be to create random stochastic variations generated with a Gaussian random number generator. Stochastic models of turbulence replicate some of the statistics of turbulence but do not capture the intermittent nature of turbulence. Compared to measured velocity differences both in laboratories and the atmosphere, stochastically modeled turbulence lacks an appropriate number of instances of large and small velocity differences at short time scales (Appendix A). Turbulent velocity differences over time and spatial scales comparable to UAS scales have significant impact (Klipp and Measure 2011). Data measured from physical fluid flows will capture these important impacts more realistically than modeled turbulence.

3.2.1 Data Source

The turbulence data used here are taken from a street canyon and intersection in the central business district of Oklahoma City, Oklahoma. The data were collected as part of Joint Urban 2003 (JU2003), a field campaign funded by the Defense Threat Reduction Agency and the Department of Homeland Security (Allwine and Flaherty 2006). The data are time series of the three components of the wind vector measured at a rate of 10 times per second by sonic anemometers deployed in the middle of the one block of Park Avenue and in the intersection with North Robinson Avenue, at the western end of that block. Samples of the data are plotted in Fig. 3. Subsets of the data reflecting an overview of different inflow wind speeds and directions will be used. One use of the field data will be to simulate a UAS attempting to hold its position using the time series data from a sonic anemometer at that position.

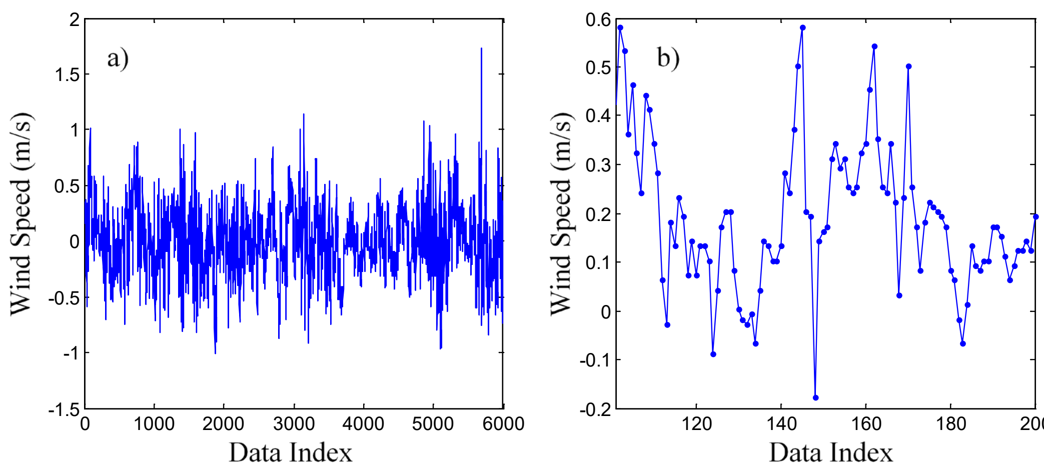

Fig. 3 a) Ten minutes of vertical component data, 1800–1810 Universal Time Coordinated (UTC) (near noon local time) of day 190, and b) 10 s of the same data

Although mean winds and large scale turbulent variations are primarily a function of the boundary conditions of the flow such as the presence of the earth's surface and buildings, the small-scale turbulent variations, where intermittency is observed, are universal in nature (Tennekes and Lumley 1972). The energy contained in turbulence is dissipated at small scales as heat via viscosity. To maintain turbulent fluctuations, energy is constantly being added at larger scales via processes such as stirring, differences in fluid speed (shear), surface heating (buoyancy generated), and/or vortex shedding off of obstacles. The input energy cascades through a continuum of successively smaller scales until dissipated at viscous scales. The large energy input scales are specific to the flow conditions, while the viscous scales are primarily a property of the fluid. Turbulent motions at scales not directly affected by the environment or fluid viscosity are called the inertial subrange of turbulence. Turbulence properties in the inertial subrange are observed to be fairly universal over most flow conditions and a variety of fluids. Intermittency is observed at the smaller scales of the inertial subrange. This allows us to use intermittent-scale data from one city and apply it in any other city.

3.2.2 Creating a Spatial Wind Field from Time Series Data

One shortcoming of using field data is that anemometers record data at single points and from a finite number of locations, not throughout the entire volume of interest for the simulation environment. This can be partially overcome by using the frozen turbulence hypothesis to convert the time series data into spatial data (Appendix B). Instead of a time series of turbulence data at a single point, there is spatial data strung along a line passing through the sonic anemometer location. Time series from several sonic anemometers result in several spatial lines of data, but still do not fill in the full volume of interest. Most of the turbulence data from JU2003 are from inside the urban canyons or just above the building roofs. For this initial proof of concept using turbulent winds, the simulated flights will be restricted to below the building tops.

Since turbulence varies in both space and time, volumetric wind data that fills the simulation domain and updates for each time step of the simulation is a large amount of data. This is one reason the first wind field is based on mean winds constant in time. The next step in complexity will be to create a constant in time turbulent field for the simulated flyer to traverse, substituting motion through a spatially varying field for a field that varies in time. In setting up this new static spatial field, it is important to ensure that the aircraft is encountering the data in the same time order, or reverse time order, as the original time series data. This is necessary to preserve the intermittency contained in the field data. Sampling the data in random order will result in the same effect as a stochastic simulation of turbulence. Sampling every other data point, or every third, will not seriously degrade the fidelity of the simulation, but as the skipped interval increases, the intermittency effects are lost (Frisch 1996).

The turbulent static wind field constructed from the time series data can be visualized as a series of slabs inside the building canyons, as shown in Fig 4. If there were data from only one sonic anemometer, each slab would span the width and height of the canyon. The along-canyon thickness of each slab, assumed to be along the primary flight direction, corresponds to the data rate of 0.1 s converted to a length using the mean wind speed, so if the mean wind is about 5 m/s the slab thickness will be about 0.5 m. Within one slab, the static field will have the three wind vector components of one data point from a sonic anemometer. In the next slab, the static field will have the three wind vector components of the next data point in the time series and so on for the entire length of the canyon. In theory, as the spatial position of the simulated flyer progresses along the urban canyon, the wind server will provide turbulent wind data in roughly the same time order and at roughly the same spatial scales as the field data.

The geometry of the slabs in the intersections is less straightforward. In order to preserve intermittency effects, the geometry in the intersections should be such that the flight path will most likely cross several slabs rather than inadvertently staying in just one or two. Ideally this will be true whether the simulated path continues across the intersection or turns down the cross street. The turbulence intensity in the intersections is considerably larger than at mid canyon reflecting the complex interaction of flow channeled through orthogonal canyons (Nelson et al. 2007). As the data-based simulated turbulent wind field transitions from using mid-canyon data to using intersection data, continuity issues will need to be addressed since the mid-canyon mean flow characteristics do not represent the mean flow characteristics near the end of the canyon near the intersections (Nelson et al. 2007).

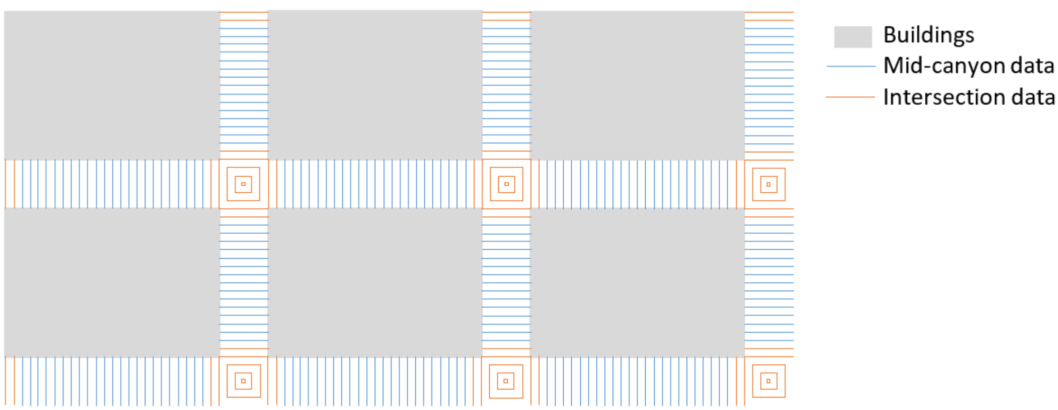

Fig. 4 One possible arrangement for spatial data slabs. Within one canyon, the 3-D winds for each adjacent slab would be from adjacent data points from the canyon sonic data. Adjacent data points from the intersection sonic anemometer would be used in the slabs in the intersections.

This simulated turbulent wind field will be constructed from field data, and is the next logical step toward better environmental physics in simulated environments. It will enable better understanding of the environment faced by UAS, and will help develop tools needed for UAS–wind interaction simulations. However, this wind field will be too simplified to truly capture turbulence impacts in urban areas and will need to be improved for the following reasons: First, it will be static in time. Second, it will not reflect variations in turbulence intensity at different positions within the canyon, from the minima very close to hard surfaces to the expected maxima at street intersections. Third, it will not capture secondary mean flows inside street canyons, such as large-scale rolls. Moving forward, we will develop models based on data in parallel with UAS and wind simulation models, including the use of ABLE-LBM, to generate coordinated models that capture spatial and temporal variations. This should lead to better understanding and simulation of UAS-wind interactions.

4. Conclusions

With the future Army in mind, a flexible development platform for the simulation of quadcopters in urban environments has been developed as a stand in for anticipated Army-specific simulation environments. Within this environment, we have been able to simulate simple mean wind fields and their effects on UAS control. A simplified turbulent static wind field constructed from the time series data is now available to start modeling the impact of environmental turbulence on UAS control. As new functionality is developed, it will be implemented such that the functionality can be exported to the Army immersive environments when they become available.

One limitation of simulating turbulence, no matter how faithfully, is that no simulation of turbulence will be able to predict with absolute certainty if, when, or where damaging levels of turbulence will happen. Although the field of fluid dynamics cannot create deterministic models of fluid turbulence, we can construct statistical models that will be able to determine the likelihood of damaging or dangerous conditions at various places and times.

5. Future Work

This project is an ongoing effort. Moving forward, realistic turbulence needs to be added to every grid point throughout the simulation volume. Since field data is limited to point sensors, finding ways to leverage computer-modeled winds is the ideal solution. Commonly used Large Eddy Simulation models only resolve turbulent eddy sizes down to spatial scales on the order of four grid spacings. The remaining effects of turbulence are parameterized statistically. Although this approach can explicitly model the secondary urban canyon flows in addition to mean wind speed and direction, it does not provide intermittency effects at the scales needed to challenge UAS control. Lattice Boltzmann methods (LBMs) for fluid flow modeling take a different approach. Instead of just a mean flow vector at each grid point, LBM models have a distribution of many discrete micro-velocities at each grid point. The vector sum of all these micro-velocities is the mean flow at that point (Sukop and Thorne 2006).

There is turbulence information in the LBM micro-velocities, but it is not known if that information can be used to simulate intermittency. LBM micro-velocities will need to be compared to field data to determine if they can be used to simulate turbulence in the way we need. Since the micro-velocities are not meant to be exact models of small-scale turbulent motion, comparison with measured turbulence will not be straightforward.

If the LBM micro-velocities do not yield useful intermittency information, then methods will need to be developed to append turbulence behavior to the mean winds obtained from computer models. An advantage of this approach is that it can use mean winds from any fluid flow model, not just LBM models. A drawback is that turbulence behavior in locations without field data will need to be inferred. Turbulence intensity varies significantly throughout the urban environment, potentially making this approach a time-consuming exercise in implementing special cases.

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Appendix A. Turbulence Intermittency

The order of turbulence data matters even though it appears to be random at first glance. Although the distribution of measured wind variation is nearly Gaussian, the distribution of the difference between adjacent wind speeds, the wind increment, reflects an exponential distribution (Fig. A-1). This effect only occurs for short time scale wind increments. As the time scale of the increments increases, taking the difference between every other data point or every tenth data point, the distribution of wind increments becomes more like a Gaussian distribution.[1]

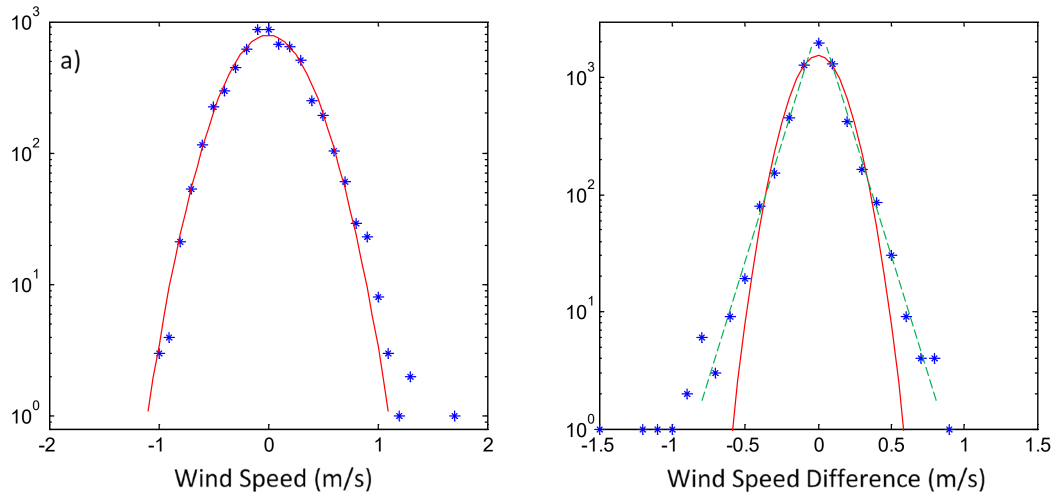

Fig. A-1 a) Probability density function (PDF) of 10 min of vertical component data from CASES99, day 190, 1800–1810 UTC, and b) PDF of differences between adjacent data points. The red lines are Gaussians with same mean and standard deviation as data. The green dashed lines are exponentials.

The exponential distribution of short time scale wind increments results in more wind increments with extreme values (fat tails) and near zero values than expected from a Gaussian distribution. This combination of extremes and near zeros is an example of one type of intermittency. Although this was discovered at least as early as 1949, it is still an open research area as to whether or not it is caused by small-scale coherent structures such as vortex filaments.[1]

[1] Frisch U. Turbulence. Cambridge University Press; 1996. p. 312. ISBN: 0 521 45713 0.

Appendix B. Taylor’s Frozen Turbulence Hypothesis

In 1938, GI Taylor[1] hypothesized that for cases where turbulent eddies change on time scales longer than the time it takes those eddies to advect past a sensor, turbulence might be considered to be frozen. This condition is almost always true for small-scale eddies and never true for the largest scales of motion. In current practice, Taylor's hypothesis is considered to be applicable if the standard deviation of the wind speed is less than about half of the mean wind speed.[2]

To use field data from only a few locations to fill in space, Taylor's frozen turbulence hypothesis can be used to convert the time series data into a spatial representation. In the ideal case, a turbulent variable A is frozen in time when the total derivative dA/dt = 0. The total derivative can be expanded into partial derivatives yielding

$$\frac{dA}{dt} = \frac{\partial A}{\partial t} + \bar{U}\frac{\partial A}{\partial x} + \bar{V}\frac{\partial A}{\partial y} + \bar{W}\frac{\partial A}{\partial z} = 0$$

where an overbar indicates the mean value. If $\bar{V}$ and $\bar{W}$, the horizontal and vertical cross-stream mean winds, are negligible with respect to $\bar{U}$, the streamwise mean wind, then the time increment of the time series can be converted to a spatial increment with $\Delta x = \bar{U}\Delta t$.

In cases where the data are from an open location with a long distance of similar terrain upwind of the sensor, something like a snapshot of turbulence structure is built up. It will capture a frozen picture of the small-scale turbulence characteristics very well. Large-scale eddy structures will not be captured since the large eddies will change on time scales required to resolve them. Since changes in terrain and the presence of obstacles such as buildings are a source of turbulence generation, the turbulence characteristics are different near these obstacles than they are farther downwind from these obstacles. In these cases, applying Taylor's frozen turbulence hypothesis does not produce a snapshot since the turbulence is evolving spatially as well as temporally.

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[2] Stull RB. An introduction to boundary layer meteorology. Kluwer Academic Press; 1997. p. 684. ISBN: 90 277 2769 4.

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
4-D	four-dimensional
AI	artificial intelligence
AR	augmented reality
ARL	Army Research Laboratory
BE	Battlefield Environment
CFT	cross-functional team
DEVCOM	US Army Combat Capabilities Development Command
JU2003	Joint Urban 2003
LBM	Lattice Boltzmann method
LES	Large Eddy Simulation
OWT	One World Terrain
PDF	probability density function
RPC	Remote Procedure Call
RTPS	Real-Time Publish Scribe
SE	synthetic environment
STE	Synthetic Training Environment
UAS	unmanned aircraft systems
UE4	Unreal Engine, version 4
UTC	Universal Time Coordinated
VR	virtual reality

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