Computational Fluid Dynamics Visualization for Unmanned Aerial Systems in Bridge Inspections

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Abstract  Bridge inspections are an expensive and time-consuming process, varying significantly with a bridge’s style, height, width, and length. Inspections create interruptions that interfere with bridge use, as the examination requires partial or total closure, causing traffic delays. Unmanned aerial system (UAS) use has increased significantly over the past decade, including assistance and coordination during bridge inspections. However, the impact on a UAS from high winds and turbulent airflows induced by a bridge’s structure can decrease flight safety during inspections. Visualization of these hazards is difficult for UAS operators; therefore, a process to estimate the velocity and locations of these hazardous flows was created. The process begins by generating a simplified 3D model using the structural elements of a concrete and steel girder bridge based on the parameters and characteristics of the bridge. The model is then processed by a computational fluid dynamics application that estimates the locations and velocities of the wind flows around the structure. Finally, the results are converted into a standard computer model file type that is either an augmented reality or computer application to display so to assist the UAS operator.

Keywords  computational fluid dynamics, unmanned aerial systems, bridge inspections, augmented reality
INTRODUCTION

The unmanned aerial system (UAS) market has grown significantly over the past decade. The increase in drone use has expanded from hobbyist-seeking entertainment to a multibillion industry with a wide range of applications, such as medical and package deliveries, law enforcement, safety inspections, and surveying (Kapustina et al., 2021; Mohamed et al., 2020). These new applications have reduced processes historically considered labor-intensive and improved the safety of employees in several professions. Because a significant amount of capital has been invested in the UAS industry, the capabilities of UAS devices have improved, enhancing the quality, safety, efficiency, and accuracy of inspections. However, inspecting large and complex structures such as bridges presents unique challenges to UAS operators regarding visibility, wireless strength, and overall safety. Therefore, efforts to enhance the functionality of UAS vehicles have accelerated. Bridges are unique in their positioning, as their structures are generally located in areas where wind flows typically generate significant turbulence and wind shear around the internal bridge structure (Patro et al., 2013). UASs can withstand considerable wind gusts and velocity; however, the bridge structures may decrease the UAS vehicle’s capabilities by obscuring the positioning information from the GPS navigation (Floréen et al., 2010). Any deterioration of GPS positioning information, changing wind velocity, and wind shear locations presents unique navigation challenges in maintaining an accurate and stable UAS location.

The challenges of bridge inspections can be mitigated by using experienced UAS operators. However, the availability of pilots capable of conducting confined flights inside and around the bridge structures is limited. Training additional pilots to become skilled and comfortable with challenging conditions, such as bridge inspections, will take significant practice time (Carstens et al., 2019). Therefore, the UAS operators may not exhibit the confidence required for some time due to the limited practice and training time. Converting current civil engineering bridge inspectors to a UAS pilot/inspector has been the current trend of government departments of transportation and private inspectors. Providing the UAS pilots with advanced external tools to identify hidden hazards, such as wind turbulence and velocity, could mitigate inspection risks.

The unique combination of difficult flight environments with inexperienced pilots challenges the UAS operators to understand the complexities. This essay aims to describe a process capable of supplying UAS operators with 3D models detailing the bridge structure and computational fluid dynamics (CFD) wind flow. The operator can use the generated model to identify multiple types of wind hazards, such as shear lines, turbulence, and velocity increases. The proposed process can generate a
visual model for the UAS pilot to avoid dangerous locations that present hazards to the flight vehicle or image quality. Using existing bridge data and the environmental conditions from the bridge location, the operator can request and receive a wind flow model within 10 minutes of location arrival.

LITERATURE REVIEW

Bridge inspections follow complex procedures and require teams with specialized skills to be dedicated to conducting them. The inspection teams perform various tasks ranging from measuring and evaluating the bridge structure by structural engineers to traffic management studies of pedestrians and vehicles. Bridge inspections typically require closing the structure to most or all forms of traffic, creating interruptions and delays on the bridge and in the areas below and near the bridge, thereby increasing the risk of traffic incidents and injuries to the inspection workers (Ishak et al., 2012). Therefore, limiting the period a bridge is restricted is critical to safety. The closure duration depends on the bridge's location, type, and age. Most bridge inspections require a combination of skilled crews, some of whom physically climb the concrete and metal pillars and others who operate telescopic trucks with bucket lifts to physically inspect the portions of the bridge above and below the deck. The inspection procedures require documentation of a visual inspection on all surfaces of a structural member, including internal edges and faces. The inspection procedures are similar to those for large structures, such as cellular towers and elevated water tanks, requiring crews to scale the structures. However, these other structures are typically located in remote areas where managing traffic flows and bystanders is less necessary (PrecisionHawk, 2021).

The visual capabilities of UASs have increased significantly as camera technology has improved the resolution capacity of imaging sensors. The improved quality of cameras has led to increased use of photogrammetry methods that create accurate high-resolution models from photos. Photogrammetry creates models with accuracy comparable to LIDAR-based sensors and visual inspections (Zhang et al., 2022). Creating photogrammetry models requires precise control of camera parameters such as the focus, the white balance, and the aperture. In addition to cameras, multiple advanced sensor types, such as infrared thermal imaging, LIDAR, and multispectral, are now available on UAS platforms. The benefit of additional sensor types is their capability to reveal subsurface cracks by comparing the thermals of the concrete and steel members in the search process (Szymanik & Psuj, 2016).

A certification is required to operate a UAS in the U.S. National Airspace System, and the ability to perform inspections is subject to Federal Aviation Administration
regulations (Part 107). Federal Aviation Administration regulations outline the procedures for UAS operations around buildings, people, and airspace. The operation of UAS vehicles can be intimidating and complex, and for individuals with limited flight experience, the complexity of the operation can be daunting without the supervision of an experienced UAS pilot (Scott et al., 2015; Watkins et al., 2020). UAS operators typically practice and train using UASs in open scenarios; transitioning to UAS operations at or near large structures increases the complexity and risks. The additional perils include the vehicle’s proximity to the structure, the activities above and below the individuals or vehicles, and the external factors affecting the performance of the UAS. The pressure and stress around inspections can be mitigated by increased training, supplemental flight tools, and simulated operations in a controlled environment (Sakib et al., 2021). Using mock structures and setup procedures as part of training and certification can establish enhanced guidelines and capabilities for UAS operators (Campbell, 2019; Salinas, 2020).

UAS operations near and around large civil structures may be affected significantly by challenges such as GPS denial of service, wind shear, and ground effect. Experienced pilots are familiar with such hazardous elements and can navigate to avoid them more effectively than inexperienced pilots. The large concrete and steel structures commonly found in bridges, water towers, and cellular towers can cause interruptions in the GPS navigation signal (Floréen et al., 2010). A lost GPS signal can cause issues in the navigation systems due to the reliance on GPS as the primary navigation method. Typical UAS flight systems are capable of mitigating brief, temporary GPS outages. However, an extended period of obstructed GPS signals will cause location accuracy to decline. A typical backup guidance system for GPS signals is an inertial measurement unit; however, the degree of electromagnetic interference and vibration on a UAS can create anomalies in the vehicle that accumulate into significant position shifts. Operations inside and around bridge structures will exacerbate the probability and length of GPS denial. These periods further deteriorate the capability of the UAS to maintain precise locations due to the forces created by the wind, turbulence, and the ceiling effect. Wind compensation capabilities of UAS platforms vary depending on the physical characteristics of the vehicle and the compensation algorithm. Multiple UAS platforms can withstand substantial wind velocities, often up to 20 knots. Wind compensation quality depends on the steady state and intensity of the wind gusts. When the vehicle relies solely on the inertial measurement unit during periods of obstructed GPS signals, the wind correction capabilities decrease.

Wind flowing through the bridge structures can accelerate and produce shear and turbulence. Wind shear and turbulent areas are a significant concern due to the differences in wind velocity and unpredictability (Green, 2021). Multirotor UAS vehicles
have unique characteristics when operating near flat surfaces. The high-speed rotors create a vacuum around the blade tips and directly above the propeller, causing a strong suction force toward the structure. This phenomenon, known as the ground effect, causes a low-pressure area, limiting the distance the vehicle can operate from flat bridge surfaces (Conyers, 2018; Sanchez-Cuevas et al., 2017). Therefore, operations inside bridge structures with multiple flat surfaces can cause issues, forcing the UAS to operate safely away from the structure. Current mitigation procedures focus on mechanical solutions such as cages to prevent rotor damage. Newer flight vehicles, such as the DJI Mavic 3 and the Skydio X2, contain onboard sensors that prevent the vehicle from creating the ground effect (DJI, 2021).

CFD has become a valuable tool in predicting the heading, velocities, and pressure of fluids inside and around structures. Computer technology’s continued advance has increased CFD’s potential applications by allowing calculations to be performed on personal computers. Simulations on large bluff bodies, such as bridge structures, generate significant turbulence that will shed vortices or cause shear lines (Campitelli et al., 2013). The turbulence generated by the bridge can be modeled using unsteady turbulent flow simulations. Three typical methods that are discussed for large structure simulations are Reynolds-averaged Navier-Stokes (RANS), direct numerical solution (DNS), and large eddy simulation (LES) (Y. Liu et al., 2022; Mannini et al., 2016). Each method contains unique benefits; however, RANS has commonly been applied for large structures due to the reduced calculation costs. The unsteady RANS (URANS) and LES methods use an additional time component to simulate the changing turbulence conditions during the simulation.

The application of CFD toward UAS flight modeling has increased in recent years as urban air mobility has continued development. Previous studies have focused on predicting the effects of constant and turbulent wind flows on UASs while operating in a dense urban environment to reflect the potential operation area of urban air mobility. The effects of the wind flow on UASs are amplified compared to traditional manned aircraft due to their light weight, low flight speed, and small size (Wang et al., 2019). Studies further analyzed the effect of wind on the UAS by conducting an empirical analysis of UASs by measuring the capabilities in a wind tunnel and a controlled laboratory environment (Gupta et al., 2022). In addition to the UAS operation, the vehicle’s environment will further affect the flight characteristics. The simulation of flow around large-scale buildings has created unique environments for UAS operations (Adkins, 2019). Many factors in the building’s shape, design, and layout affected the UAS operations. The effect of sudden heading shifts and shear lines caused by buildings was documented by Nathanael et al. (2023) during a UAS flight path.
METHODOLOGY

CFD models allow the user to mathematically process fluid flow through an area around objects. Applying the same concept to airflow around civil structures can allow the CFD model to predict wind flows (Liu et al., 2018). For example, a UAS operator can interpret the CFD model results to establish safe operating areas during a bridge inspection. Creation of the CFD model relies on generating the structure of the bridge and then converting the CFD model into a usable file format (Figure 1).

Computer-Aided Design Model Creation

The CFD software process begins with a computer-generated model of the bridge structure. Multiple file types and models are supported for CFD processing; however, increasing the model's complexity increases the processing requirements. Therefore, 3D models suitable for CFD simulations may not be readily available for existing bridge structures. Bridges are complex structures with thousands of parts, and the number and complexity of the parts will vary based on the bridge's dimensions, age, and style. The use of 3D models, which contain every element and detail of the bridge, will dramatically increase the processing time for the CFD software. Simplifying the model to include only the primary components that affect the UAS will decrease the computing constraints while maintaining a reasonable 3D file size. The simplified model can provide adequate wind characteristics for UAS operations without requiring every bridge component.

The bridge model generation process begins with selecting a procedure determined by bridge type. Seven unique methods are required to represent the different bridge classifications in the United States. The process is managed through a Python script containing the steps and variables necessary to generate the model. The user inputs variables for various bridge parameters into the program through a comma-separated variable form. The Python script then interacts with FreeCAD, an open-source computer-aided design (CAD) program, to re-create the bridge (Machado et al., 2019).
The bridge selected for analysis is a concrete and steel beam walking bridge crossing the Wabash River in Lafayette, Indiana. The bridge is located between two automotive bridges to the north and south. Both were excluded from the CFD calculation to reduce model complexity and limit the focus to the walking bridge. Bridge dimensions were collected using publicly available data and were measured as necessary. The script developed has a system of checks to ensure that the dimensions do not fail to generate a bridge. These include reasonableness checks, such as preventing overlapping geometry from a beam width greater than the road deck width. The order of parameters was derived from initially creating the CAD file and setting the dimensions to parametric. The parameters and values used to replicate the walking bridge are shown in Table 1. The generated CAD model from the beam bridge Python script using the user-entered variables is shown in Figure 2.
CFD Setup and Configuration

The CFD software selected is the Open-Source Field Operation and Manipulation (OpenFOAM) numerical solver. OpenFoam contains multiple utilities and solvers designed to initialize and complete a CFD model calculation. The computational domain is a hexahedral mesh generated using the OpenFOAM utilities blockMesh and snappyHexMesh. The utilities were selected for their parameter-controlled properties, ease of modification, speed, and efficiency during mesh generation. The density of mesh vertices and the number of vertices affect simulation performance and calculation time. Closer points yield more accurate results; however, closer spacing increases computing time. The spacing between the vertices is controlled by mesh generation and refinement parameters within blockMesh and snappyHexMesh. The vertex spacing was selected where the UAS would cover at least two vertices in each dimension (Al-Room et al., 2021). The UAS selected was based on vehicle usage and purchases from bridge inspectors, where the DJI Mavic 2 Pro and Skydio 2+ were the most common vehicle platforms. Both vehicles share a similar frame size, with a measured width of 36 centimeters (14 inches) and 28 centimeters (11 inches). A spacing of 50 centimeters was selected for the mesh-generation process. The computational mesh is initialized as an empty 3D hexahedral grid by the blockMesh utility. The bridge object generated by the Python script is merged with the blank grid mesh using snappyHexMesh. The mesh is refined around the bridge surfaces until the 50-centimeter spacing value has been reached; the snappyHexMesh process is illustrated in Figure 3. The completed mesh resulted in 185,237 cells sharing 218,801 unique vertices.

The final step for the mesh is to define the boundary planes required for the transitions between the internal and external computational domains. The wind origin, exit, and transfer planes are established using symmetry, ground, inlet, and outlet planes. The model uses two types of transfer planes: symmetry and ground planes. Symmetry planes represent free-flowing wind in the environment outside the computational domain, while ground planes represent the boundary layer created by terrain. Three symmetry planes are used in the model to control the ceiling, left, and right mesh limits. The river flow was defined as a nonmoving ground plane to

Figure 3. Mesh Refinement Process during Mesh Generation
reduce the simulation complexity of running water. The ground plane was set to four feet above the lowest points of the pillars, as the water level will typically vary from two to eight feet during the year. The inlet and outlet planes represent the origin and departure of wind flow from the internal mesh. Figure 4 shows an overview of the mesh, including the various boundary planes. The inlet establishes the 10 meters per second wind conditions perpendicular to the bridge span, and the outlet maintains the pressure created by the inlet flow.

The completed mesh can be solved through multiple turbulent or steady-state flow models, each with various benefits and drawbacks. Three models commonly used in practice to solve simulations with a high Reynolds number are RANS, URANS, and LES (Blocken, 2015; Segui et al., 2022). The RANS method averages the turbulent flow to create an incompressible steady-state simulation. Once the values have converged, there is little change in the velocity and pressures of flow. Compared to the URANS and LES methods that can determine turbulent flows at specific time steps, however, due to the long duration of the flight and the wide variety of locations, an area is assumed to be constantly subjected to turbulence. Since the goal is to determine the locations of turbulence rather than the velocity, the RANS averaging process was assumed to be valid for the CFD solver. Therefore, the RANS method was selected as the solver for the CFD process. While the instantaneous and time-dependent velocities are lost due to the averaging process, the decrease in computational performance is a valid tradeoff for this use case.

The process used for solving the RANS equations is the simpleFoam solver native to OpenFoam (SimpleFoam is a guess-and-correct process for the RANS method of estimating wind velocities across large structures containing turbulent airflow) (Caretto et al., 1973; Jones et al., 2012). The turbulence model selected for the RANS solver is the Shear Stress Transport k-ω due to the advantages in boundary layers, the
transmission of turbulent stress, and fluid separation. For incompressible Newtonian flow, the velocity and pressure equations of the RANS momentum equations are shown in Equation (1),

\[
\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{\partial p}{\partial x_i} + \nu \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_j} \right) + \frac{\partial}{\partial x_i} \rho = 0 \tag{1}
\]

where \( u_i \) or \( u_j \) is the velocity component in the \( x, y, \) or \( z \) direction; \( \rho \) is the density of the fluid, and \( \nu \) is the kinematic coefficient of the viscosity. The RANS equations are solved using the sum and current state mean, with \( \bar{u} \) representing the velocity and \( p \) as pressure, as shown in Equation (2):

\[
u(x,t) = \bar{u}(x) + u'(x,t), \quad p(x,t) = \bar{p}(x) + p'(x,t) \tag{2}
\]

Substitution of the RANS equation in Equation (2) with the incompressible Newtonian flow equations from Equation (1) yields the RANS equations as shown in Equation (3), where \( \partial S_{ij} \) represents the mean rate of the strain tensor:

\[
\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial}{\partial x_j}(\bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \nu \bar{u}_i + \frac{\partial S_{ij}}{\partial x_i}, \quad \frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{3}
\]

A drawback to RANS is the potential of the calculation to reach an unstable state. However, the instability can be eliminated by using relaxation factors. The high RANS number solution’s relaxation factors were \( 0.3 \) for pressure, \( 0.7 \) for velocity, and \( 1 \times 10^{-4} \) residual convergence (He et al., 2019). Four hundred iterations were calculated, with the final time step result exported to the UAS operator. The average computation time for the CFD calculations and model generation for five runs was six minutes.

Model Visualization

The results from the CFD computation are converted into an Autodesk Kaydara FilmBox Digital Content file (FBX). FBX is a standard format for interoperability between digital content creation software for a 3D design capable of being viewed on multiple software packages. A Python script generates the file and parses the results database, converting the cell location and velocity information into an FBX model. While the file can be viewed in any format that supports it, a custom application is required to manage the multiple objects correctly. The application was developed with the Unity Game Engine, which contains development utilities and tools capable of deploying the same software package to multiple platforms, such as Android, iOS, and Windows.
The FBX file consists of the generated bridge model and multiple wind layers. Each wind velocity layer is displayed as a 2D layer plane around the 3D bridge model. Every layer is spaced equidistantly at 50 centimeters to maintain adequate vertex coverage for the flight vehicle. The layers are generated by inserting a plane in the computational mesh at the location of the selected velocity layer. The intersection of the plane and the cell faces results in a line. The midpoints of all the intersections are then added to the velocity layer, with nearby points combined into triangle faces. Every vertex retains pressure and velocity information from the original cell, and the vertices display the velocity as a color grade. All layers are independent within the FBX format, allowing for manipulation of the subobjects within the file, color data, and platform interoperability. A screenshot of the model with the 1-meter layer slice visible and the bridge model overlaid is shown in Figure 5.

The interoperability of the file format allows use on any computer or smartphone application. Two software versions—personal computers and smartphones—were created to assess operator use of the application. The software version for the laptop uses a traditional navigation window similar to those associated with CAD packages and similar design packages. The smartphone application will rely on augmented reality for viewing and navigation, enabling the UAS operator to physically navigate the model in three dimensions (Goetten et al., 2019). In addition, the interactions with augmented reality increase the UAS operators’ awareness of hazards and safe locations to fly the UAS (Pullan et al., 2019). The phone application uses Google’s ARCore and Apple’s ARKit to provide the framework for deployment on any mobile phone. The UAS operator can navigate the applications by buttons on the top right of...
the screen. The application cycles through the CFD results at 1-meter intervals, with the colors representing the predicted wind velocities. A velocity legend was added to help assist the predicted velocity. The colors use the Jet scheme, which indicates red as the higher velocities and blue as the lower velocities. A screenshot of the augmented reality application on a Samsung S9, which represents what a UAS operator will view when using the app, is shown in Figure 6. For the sample bridge model, the CFD results contained 120 velocity layer objects (60 vertically and 60 horizontally), for a total size of 15.4MB.

CFD Discussion

The UAS pilot can select the wind velocity layer closest to the current altitude or position of the UAS to view the corresponding wind information. The colors represent the velocity of the wind flow using the Jet color scheme (red is high velocity, and blue is low velocity). The velocity is the total magnitude relative to the initial condition of 10 meters per second perpendicular to the bridge span. The results of the CFD simulation resulted in a wind velocity increase and decrease to 17.4 meters per second and 0.4 meters per second, respectively. UAS operators can then identify hazardous locations created by the wind shear and high-speed airflow.

Wind shear is a hazard to UAS operators, as the asymmetric thrust applied to the vehicle increases the difficulty of maintaining position and producing a stable image. An example of wind shear from the CFD model is displayed in the white box in Figure 7. The severity of the shear line decreases as the flow moves leeward from...
the pillar. All the figures express the wind velocity in terms of total U magnitude, the three-axis vectors combined.

Another concern during UAS operations is the generation of high-velocity wind around bridge components. The stronger-velocity wind flows cause the vehicle to increase the current draw on the battery, decreasing the UAS performance (Liu et al., 2022). Therefore, minimizing the duration the vehicle spends in the high-velocity wind flows will improve the efficiency of the flight. Dark red–colored regions identify the high-velocity wind flows in the figures. The increased velocity above the bridge reduces the correction capabilities of the UAS location during GPS conditions. Figure 8 shows the high-velocity area between the bridge pillars, where the velocity increases to 14 meters per second from the starting 10 meters per second. The venturi effect of the pillars and beams causes an increase in velocity.
Multiple viewing perspectives of the velocity slices improve the operator’s awareness of wind hazards. The side view shown in Figure 9 displays additional wind shear and high-velocity areas that were not apparent in the top view. Similar to the wind shear around the pillar, the severity increases as the UAS moves windward until past the bridge. The profile of the steel beams creates multiple low-velocity pockets across the length of the span.

CONCLUSION

The process presented in this essay is the process for a software tool used by UAS pilots that can aid in wind hazard identification. Managing the wind conditions is critical for the UAS operator in maintaining inspection quality, safety, and efficiency. Successful inspections require the UAS to traverse wind shear lines and maintain position in high-velocity flows. Therefore, preparing the UAS operator for wind hazards can mitigate the risks during bridge inspection. The process includes constructing bridge models using open-source software and parametric scripting models, which are solved by a CFD simulation, allowing individuals to generate results.

Future iterations of the software process will focus on CFD fidelity, the number of available bridge models, improving the visualization, and integration with autonomous UAS utilities. The CFD fidelity can be improved by increasing the number
of vertices in the mesh or adopting a higher-accuracy CFD solver. Such modeling enhancements will require additional processing power to offset the increase in computational time for a complex model, which will be improved as the capabilities of computers continue to increase. The proof of concept shown in this essay focused on a single bridge type. However, a plethora of types can be found throughout the world. Increasing the options and validating the CFD process for additional bridges will improve the flexibility of the process. Improving the augmented reality visualization by overlaying the safe areas onto the bridge can further assist the UAS operator in understanding the hazardous locations. Integration with autonomous flight planning software may reduce the workload on the UAS operator by creating automated flight paths or further assisting the operator’s awareness of hazardous areas.

Applying wind prediction to a large building such as a bridge showed similar results to the predicted values from previous studies. Although the previous studies focused on the effect of the wind in dense urban environments, the cross-application to bridges showed similar results. The CFD results presented provide an initial base for the processing. However, additional work on the CFD validation is needed, which will require using a UAS with an anemometer to collect real-world information and compare it to the results generated by the software workflow.

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