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Computer-Aided Design and Applications

Modeling of the Bridge Spaces in the Bridge Maintenance Information Model for Displaying Inspection Results in Virtual Reality

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Abstract. ICT technologies such as VR are being used to improve the efficiency of bridge maintenance and management. However, due to the characteristics of VR displays of bridges, it is difficult to understand which part of the bridge is being inspected, and it takes time to evaluate defects in specific locations. To solve the above issue, we focused on the fact that workers recognize inspection ranges by span numbers and proposed to define the space as a VR work area for each span and incorporate it into the information model. Based on the proposed model, we construct a system that supports moving viewpoints and capturing viewpoint positions.

Keywords: Bridge Inspection, Industry Foundation Classes (IFC), Virtual Reality (VR), Bridge, Bridge spaces
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1 INTRODUCTION

In recent years, maintenance and management of social infrastructure such as bridges and tunnels have become an issue. There are approximately 730,000 bridges in Japan. In 2032, 59% of bridges in Japan are 50 years old [11]. In addition, inspection work is conducted once every five years according to national standards. Creating an inspection report that evaluates defects in the structural elements of each bridge span is time-consuming. Since the work must be carried out with limited personnel, improving the efficiency of inspection and maintenance work for aging bridges is necessary. In recent years, there has been a growing trend toward using Information and Communication Technology (ICT) to maintain and manage civil engineering structures such as buildings and bridges to improve work efficiency. Much research has been performed on bridge maintenance as part of this trend. In one such research, we proposed a bridge maintenance management information model [14] by extending Industry Foundation Classes (IFC) [8], an international standard for Building Information Modeling (BIM). IFC is a 3D building information model for information management throughout the building lifecycle. It was developed by buildingSMART International to realize BIM (Building Information Modeling) and is widely used as an international standard for BIM, including infrastructure. IFC is an open standard and independent of software vendors. It can handle a wide range of data from design to construction and operation and is therefore supported by many BIM software applications. IFC is also suitable for managing bridge data that must be archived for decades and accessible as needed because of its upward compatibility.

Virtual Reality (VR) is one of these ICT technologies; however, when displaying bridges in VR, it was difficult to understand which elements were being inspected due to the characteristics of VR. Additionally, because bridges are enormous compared to people, it takes time to move to specific locations and check for defects. In this study, since workers can recognize the inspection range by the span number, We propose defining the space above and below the bridge as a VR work area for each span and incorporating it into the information model. Furthermore, when creating an Unmanned Aerial Vehicle (UAV) inspection plan, it is necessary to represent the surrounding area fully [1, 7], so we propose modeling the bridge's upper and lower space and its site information and incorporating them into the information model. Although this information has been discussed concerning Geographic Information Systems (GIS) [6], there is not enough discussion regarding the detailed structure. In addition, based on the proposed information model, we construct a system that supports viewpoint movement and obtaining viewpoint position in a VR environment.

2 RELATED RESEARCH

Some research has been made to apply Building Information Modeling (BIM) to infrastructure maintenance, including bridges. For example, innovative solutions such as the SeeBridge system, which utilizes Industry Foundation Classes (IFC) for rapid and intelligent inspection and evaluation, have been proposed for bridge maintenance, repair, and renovation [13]. BIM-based Bridge Management Systems (BMS) have also been developed to include detailed information on safety diagnostics and maintenance, enhancing the sustainability of bridge maintenance practices [15]. It has also been proven that creating a well-defined extension of IFC is possible [4]. A bridge maintenance information model that includes defect information based on extending IFC was also proposed [14]. While there has been significant focus on the structural elements of bridges, there is a lack of representation for non-structural elements, such as space.

The use of ICT has become essential for efficiency. Many studies are being conducted to utilize an extended reality (XR), a type of ICT technology, for bridge inspections, and it is possible to conduct bridge inspections remotely in an environment similar to that on-site. As part of this effort, BIM-based mixed reality (MR) applications were being developed to enhance and facilitate remotely managing bridge inspection and repair work from the office [12]. A new visual inspection method that uses an xR device (headset) to detect and quantify structural defects interactively [2] was also proposed. Additionally, a new approach using digital models and XR technologies for immersive meetings was proposed, which can be utilized not only during the operational phase but also in other lifecycle phases of the structure [9]. Many studies used XR to conduct field assessments remotely while providing a collaborative work environment for engineers, inspectors, and other third parties [5]. Although many studies using XR have been published, one of the unsolved problems in XR is the difficulty of position recognition for inspecting enormous structures such as bridges.

Much research was also being conducted into using UAVs for bridge inspections, which was expected to reduce costs and improve work efficiency compared to surveys performed by engineers. A UAV-based methodology for bridge inspection and assessment of defects has been proposed that utilizes aerial data acquired by remotely operated multi-rotor UAVs equipped with high-resolution cameras [10]. In addition, an integrated implementation of bridge information modeling (BrIM) and unmanned aerial vehicle (UAS) technology was proposed as a framework to solve problems associated with bridge inspection and management [16]. Autonomous navigation for infrastructure inspection by a fleet of UAVs was also proposed, providing solutions to problems such as defining reference trajectories and designing positioning devices [3]. However, modeling of information around bridges was necessary to create UAV navigation routes in advance to avoid trees and other obstacles; some researchers have attempted to obtain geographic information by integrating GIS [6], but GIS alone was insufficient as a model for surrounding areas or spatial information.

3 IMMERSIVE VR DISPLAY AND CHALLENGES OF STUDY

In this research, workers collect the information necessary for inspection by automatically measuring bridges using UAVs. Then, the 3D model is generated automatically by Structure from Motion (SfM) software such as Agisoft metashape and RealityCapture. The workers use the 3D model to evaluate defects by observing bridges in an immersive VR environment. The immersive VR display allows the viewpoint to change as the user's head moves, making it easy to check the situation around the defects and to freely check the defects in a situation closer to the site. On the other hand, as shown in Figure 1, there are the following problems regarding movement and recognition of the viewpoint position;

- It takes time to move the VR viewpoint significantly between different spans to check for any defects;
- Communicating the viewpoint and UAV position to VR workers and other engineers in VR space is difficult.

As shown in the current immersive VR image in Figure 1, to check for bridge defects in a VR environment, it is necessary to concentrate on viewing from a close position to the bridge. At this time, it becomes difficult to identify which span you are inspecting. Additionally, when inspecting across spans, you need to move several hundred meters, and the time spent moving the viewpoint results in a time loss.

The bridge is enormous compared to the workers, so moving the viewpoint and understanding the position becomes serious problems. They are common issues for XR devices such as HMDs, MR, and large projection systems. In order to solve the above problems, this paper proposes the following items:

- Defining the bridge space, which is the place where the VR viewpoint and UAV exist in the bridge structure;
- Implementing the function to move the viewpoint position to the specified bridge space and the function to display the bridge space where the viewpoint exists.

The advantage of representing the bridge space is that it allows workers to specify viewpoints easily, making it easier to inspect each span and communicate inspection areas. Bridge space provides helpful information when planning UAV flight plans. In this study, the bridge site and space are referred to as the surrounding area of the bridge. However, detailed modeling of the bridge site is a topic for future research.

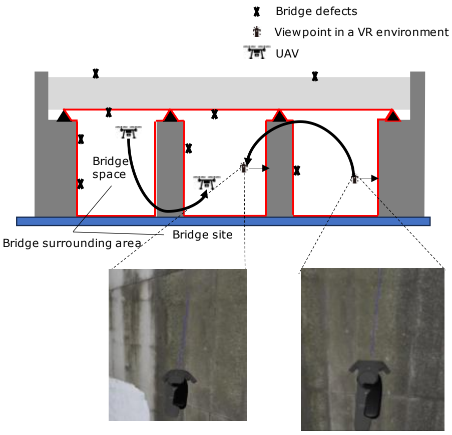

Figure 1: Immersive VR display problems.

4 DDEFINITION AND REPRESENTATION OF THE BRIDGE SPACE

4.1 Definition of Bridge Space and Information Requirements

In this paper, bridge space is defined as the spatial area occupied by the bridge other than the physical elements of the bridge. The bridge space consists of the following regions: the regions obtained by sweeping the superstructure contained in each span in the Z-axis direction of the bridge coordinate system to the maximum Z-value of the upper structure (such as the height of poles) and the regions obtained by sweeping that superstructure to the ground in minus Z-axis. Figure 2 shows a schematic diagram of the bridge space. The bridge space has an upper and lower area corresponding to the superstructure and substructure of the bridge, respectively. The bridge space is divided into regions corresponding to span numbers. The information requirements for applying bridge space to VR are as follows:

- It is necessary to represent it as part of the bridge structure since the bridge space is a bridge component;
- It is necessary to represent information regarding its relationship with the connected bridge structure (such as the relationship between lower space 2 and Pier 1 and 2);
- It is necessary to represent the shape (boundary surface) to determine where the viewpoint is in the VR environment's bridge space and implement the viewpoint's movement specifying the space.

We propose using IfcSpace, defined in IFC as a bridge space, to meet the above requirements. In this study, the bridge space is used for VR displays, but future applications include representation of the operable area when using UMV.

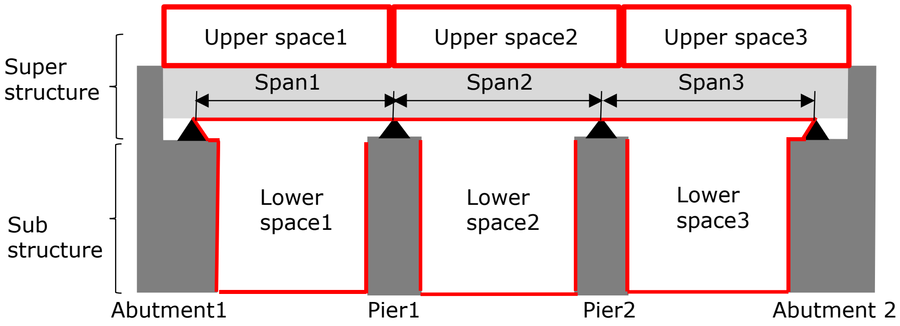

Figure 2: Schematic diagram of the bridge space.

4.2 Spatial Structure Representation of Bridge Space Using IFC

The IfcSpace is an entity that represents the space itself in a building in IFC. Figure 3 shows a spatial structure in IFC that can represent the bridge space. In this representation, the whole-part relationship (IfcRelAggregates) represents the bridge space as a part of the structure. The space boundary element relationship (IfcRelSpaceBoundary) is also used to represent the relationship information with the connected bridge structure. For example, the IfcSpace, which represents the upper space1, is represented as a part of the superstructure by the whole-part relationship. The spatial boundary element relationship of that IfcSpace represents the relationship with IfcBridgePart, which is the superstructure contained in span 1. This structure can apply to all types of bridges. It is possible to automate the creation of spatial structures.

The IfcSite is a defined area of land on which the construction is to be completed. The IfcSite is on the top of the spatial structure. The detailed model structure of the IfcSite is under development.

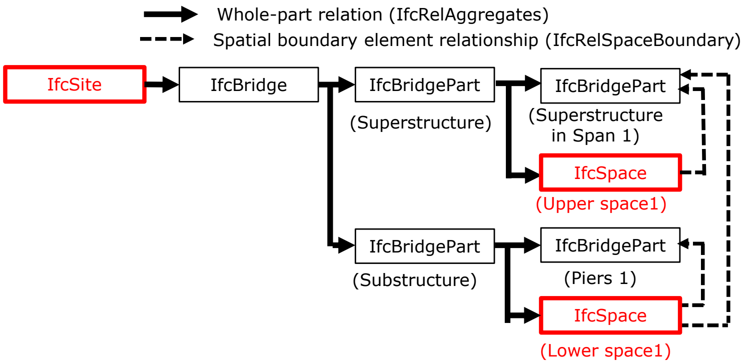

Figure 3: Spatial structure representation of the bridge space using IFC.

4.3 Physical Structure Representation of Bridge Space Using IFC

Next, we explain the physical elements of the space element (IfcSpace). Figure 4 shows a physical structure representation of the bridge space using IFC. This Figure is described using the EXPRESS-G diagram, a graphical notation of EXPRESS. Square boxes represent entities. The thin lines extending from the entity indicate the entity's attributes and the thick lines indicate the inheritance relationship between supertypes and subtypes.

IfcProduct, representing the physical structure, and IfcSpace, representing the bridge space, are linked by IfcRelContainedInSpatialStructure. The IfcProduct is an abstract representation of any object related to a geometric or spatial context. IfcProduct has a subtype, IfcElement, which is a generalization of all components that make up a facility. IfcVirtualElement, IfcFeatureElement, and IfcGeographicElement are subtypes of IfcElement. IfcVirtualElement represents an element that provides imaginary, placeholder, or provisional areas, volumes, and boundaries. Typically, a physical element of IfcSpace corresponds to this entity. This structure can apply to all types of bridges. It is possible to automate the creation of physical structures.

IfcFeatureElement represents a generalization of all existence-dependent elements that modify the shape and appearance of the associated master element. This entity represents the physical elements of an IfcSpace using a bridge element associated with the IfcSpace. IfcGeographicElement is a generalization of all elements within a geographical landscape. This entity can be used to represent the physical elements of the surrounding area, IfcSite.

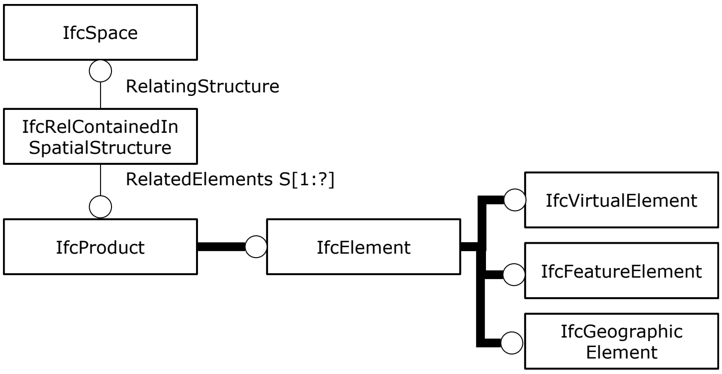

Figure 4: Physical structure representation of the bridge space using IFC.

4.4 Shape Representation of Bridge Space

It is necessary to represent the shape of the bridge space to satisfy the information requirements. If the bridge is a simple structure, the space of the bridge can be represented using a rectangular box parallel to the axes. In the IFC, such a box (axis-aligned bounding box) can be represented using IfcBoundingBox.

The shape of the bridge space is created from a detailed and precise bridge model. Figure 5 shows the derivation method of the space of the bridge. The maximum and minimum values of X and Y coordinates are extracted from the vertex coordinates of the superstructure included in each interval to create a rectangle surrounding the superstructure. The rectangle is then extended to the Z minimum of the substructure in the minus Z-axis direction, and a rectangular shape is created as the spatial shape of the bridge.

In this paper, the target of the bridge is a concrete girder bridge with a simple and limited geometry. Complex bridge shapes such as curved bridges are one of the future works.

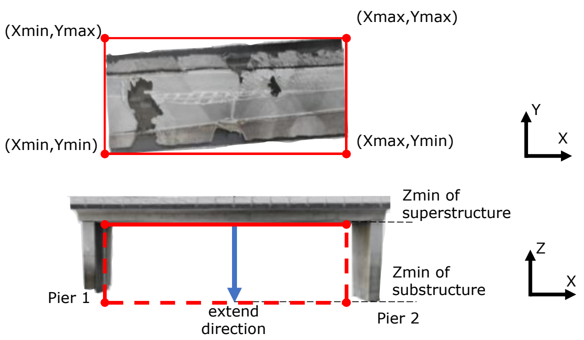

Figure 5: Derivation of bridge space.

5 VR SYSTEMS USING THE BRIDGE SPACE

5.1 Overview of the VR system

The structure of a proposed VR system is shown in Figure 6. The bridge maintenance information model is created from an as-is bridge model obtained from measuring technologies such as the Structure From Motion (SFM) and measured data such as photo images of the defects. The as-is model is segmented into bridge components. For simple bridge structures, the surrounding area, especially the bridge space, is automatically created based on the algorithm defined in the previous section.

The VR display results of the bridge SfM data with a texture photographic image can be obtained from the web server using webXR technology and a VR device. The function for moving the viewpoint by specifying the bridge space is also implemented in this system. In this function, the viewpoint moves to the center of gravity of the spatial shape as a representative point where the entire bridge structure surrounding the bridge space is visible.

The function that shows the viewpoint position by text is also implemented. This function displays the name of the bridge space where the current viewpoint exists by calculating from the viewpoint and geometric representation of bridge spaces.

5.2 Functions of operating the viewpoint in VR display system using bridge space

In this study, the essential functions, moving the viewpoint and displaying the position of the viewpoint, were implemented in the VR display system.

First, the viewpoint movement function is explained. Figure 7 shows the flowchart used to move the viewpoint to the specified bridge space. The program sets up a selection menu in response to the number of spans contained in the bridge. Pressing the trigger button moves the viewpoint to the center of gravity of the space while the beam from Controller 1 is in contact with the menu representing the space to be moved. In this case, the center of gravity can be derived from the shape representation of the IfcSpace. The program can move to the viewpoint in the initial position at any time by pressing the trigger button on Controller 2.

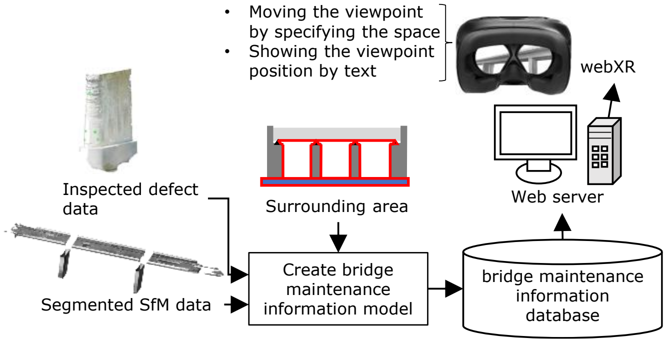

Figure 6: Structure of a developed VR system.

Second, a function for displaying the position is implemented. Using shape representation of the IfcSpace, this function evaluates which IfcSpace the current viewpoint is in and displays the name of the IfcSpace containing the viewpoint.

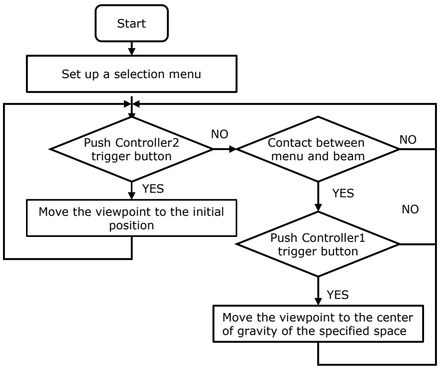

Figure 7: Flowchart for moving the viewpoint function.

5.3 The Implemental Result of the System

Figure 8 shows a full view of the sample bridge and spaces of the bridge used in the VR environment. The bridge has three spans, each modeled to have three upper spaces and three lower spaces. Table 1 shows the minimum and maximum spatial coordinates and center coordinates of each space of the created bridge model with bridge spaces. Based on the created model, functions such as moving the VR viewpoint between different spans and displaying the current position in the VR environment are executed. Figure 9 shows the function of moving the VR viewpoint between different spans. Figure 9 (a) shows the space selection screen. By selecting any bridge space the worker wishes to move to on this menu screen, the VR viewpoint moves to the center of gravity point of the selected bridge space. Figure 9 (b) shows the moving result of selecting the Lowerspace 1, and Figure 9 (c) shows the moving result of selecting the Lowerspace 2. Figure 9 (a) also shows that the bridge and spaces are modeled accurately, as the structure of the bridge spaces for the example bridge matches the list of spaces in the image.

Figure 10 shows the current position displaying function. Current VR viewpoint coordinates are added to the caption of Figure 10 (a) and (b). When the trigger button of the controller is pushed, the name of the space that the VR viewpoint is in is shown. The above implementation examples show that the immersive VR challenges described in Section 3 have been addressed. The usefulness of the proposed model is also shown.

In previous studies and frameworks, the bridge space is not modeled as a component of the bridge model, so extra computation time is required to realize the functions mentioned above. In this study, the proposed space model introduced into the bridge model allows the functions mentioned above to be performed in real time. As a result, it assists workers in performing their work in the VR environment.

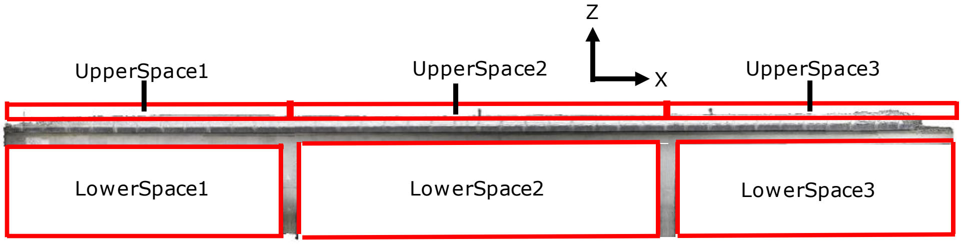

Figure 8: Full view of the sample bridge and spaces of the bridge.

Date	*Xmin*	*Xmax*	*Ymin*	*Ymax*	*Zmin*	*Zmax*	*Center of space*
Upperspace1	-64310	-25705	-10257	9446	1021	6100	(-45008,-406,3561)
Upperspace1	-23415	16294	-6497	9521	1894	6312	(-3651,1512,4103)
Upperspace1	18598	63413	-5721	10260	1993	6029	(41006,2270,4011)
Lowerspace1	-64310	-25705	-10257	9446	-8819	1021	(-45008,-406,-3899)
Lowerspace2	-23415	16294	-6497	9521	-10349	1894	(-3561,1512,-4228)
Lowerspace3	18598	63413	-5721	10260	-10349	1993	(41006,2270,-4178)

Table 1: Minimum and maximum spatial coordinates and center coordinates of each space.

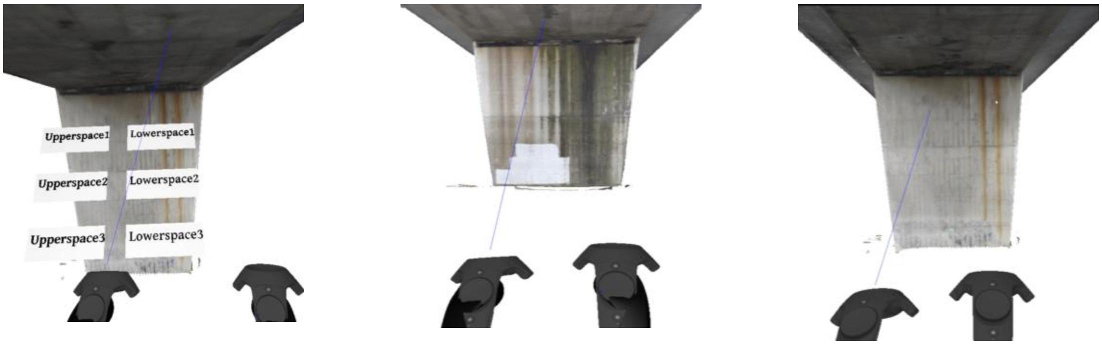

Figure 9: Function of moving the VR viewpoint: (a) Space selection screen, (b) After selecting Lowerspace1, and (c) After selecting Lowerspace2.

Figure 10: Current position displaying function: (a) Position in Lowerspace1(-26000,0,-4000), (b) Position in Lowerspace2(16000,0,-4000)

6 CONCLUSIONS

In this paper, a bridge maintenance and management information model that can represent the space of a bridge was proposed to solve the problem of immersive VR display for bridge inspection and maintenance, reflecting that workers recognize the inspection area by span number. In this paper, the IfcSpace, which is an entity that represents the space inside a building in IFC, was utilized to represent the bridge space. The spatial structure, physical structure, and shape expression of the bridge space were also clarified. Structural parts related to space, such as physical and spatial structures, can be automatically derived from the existing bridge model. If the geometry is simple, the derivation of the geometry can be automated. A shape representation and automatic modeling algorithm were proposed when the bridge shape was simple. Since such simple geometries represent many bridges, applying the proposed model to many cases is possible.

In addition, we implemented a function to move the viewpoint using the bridge space and a function to display the viewpoint by the bridge space name. We confirmed that it is effective for the problem of immersive VR display for bridge inspection and maintenance.

The contribution of this research is that it modeled spatial information that can apply to all bridges and demonstrated its usefulness, whereas, in the past, no research has focused on space, which is a part other than the structures of bridges.

Future challenges include more accurately representing the shape of the bridge space and modeling the surrounding area of the bridge to represent the operable area of the UAV.

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