DroneSAR: Extending Physical Spaces in Spatial Augmented Reality using Projection on a Drone

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Rajkumar Darbar, Joan Sol Roo, Thibault Lainé, Martin Hachet
Inria Bordeaux, France
{rajkumar.darbar,joan-sol.roo,thibault.laine,martin.hachet}@inria.fr

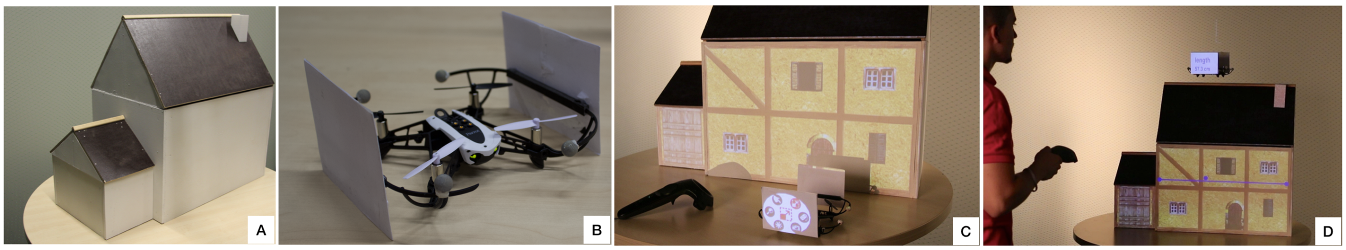

Figure 1: An example scenario of DroneSAR. (A) A physical house mock-up. (B) A drone is mounted with two white paper panels. (C) The house is augmented using projection, and the main menu composed of a set of virtual tools projected on the drone panel. (D) A user selected the 'measuring tool' application using a controller. Then, the user positions the drone at the desired location in the 3D space (i.e., on top of the house) and draws a line shown in blue color on the augmented house to measure its width. Finally, the measured length is displayed on the drone panel.

ABSTRACT

Spatial Augmented Reality (SAR) transforms real-world objects into interactive displays by projecting digital content using video projectors. SAR enables co-located collaboration immediately between multiple viewers without the need to wear any special glasses. Unfortunately, one major limitation of SAR is that visual content can only be projected onto its physical supports. As a result, displaying User Interfaces (UI) widgets such as menus and pop-up windows in SAR is very challenging. We are trying to address this limitation by extending SAR space in mid-air. In this paper, we propose *DroneSAR*, which extends the physical space of SAR by projecting digital information dynamically on the tracked panels mounted on a drone. DroneSAR is a proof of concept of novel SAR User Interface (UI), which provides support for 2D widgets (i.e., label, menu, interactive tools, etc.) to enrich SAR interactive experience. We also describe the implementation details of our proposed approach.

CCS CONCEPTS

• **Human-centered computing → Interaction paradigms**; **Mixed / augmented reality**; **Collaborative interaction**;

KEYWORDS

Spatial Augmented Reality; Flying User Interface; Drones; Projections; Mid-air Display; 3D Interaction.

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1 INTRODUCTION

Spatial Augmented Reality (SAR) [3] transforms physical surfaces into augmented surfaces by projecting digital content directly onto them. Compared to see-through augmented reality techniques, SAR allows multiple users to observe 3D augmented objects with natural depth clues, and without the need of being instrumented. This opens many opportunities in architecture [31], education [32], and so on.

Unfortunately, one of the main limitations of the SAR environment is that, contrary to see-through AR technologies, visual content can only be displayed onto physical supports. As a consequence, displaying User Interfaces (UI) widgets such as menus and pop-up windows in SAR becomes challenging. These widgets need to be positioned onto the augmented physical objects, which results in a visual clutter that affects the overall user experience. The geometry and material of the physical scene even sometimes make it impossible to display legible UI widgets. We are trying to address these limitations by extending SAR space in mid-air. In the traditional SAR, it is not possible to display mid-air information unless using dedicated optical systems such as [5, 21] or head-tracked anamorphic illusions [16]. In this paper, we are using a flying display within the SAR environment to display mid-air content.

We propose DroneSAR, a tracked drone mounted with two rectangular white panels on which it is possible to display digital information on the fly (see Figure 1). Drones have the advantage to be flexible, as they can be positioned quickly with an acceptable accuracy around any augmented space. This allows us to extend the augmentation space and creates opportunities for new applications. In particular, DroneSAR makes it possible to embed 2D interactive widgets within the SAR experience.

The concept of extending the SAR space around the physical objects can be achieved with alternative approaches such as holding mobile devices surrounding the physical objects or adding extra projection screens around the real objects. However, our proposed solution has several benefits from its counterparts. For example, in the case of mobile devices, the users need to divide their attention between the augmented objects and the phone display. With drones, the augmentation takes place in the relevant 3D physical space, which can be at a distance from the observer. Regarding the use of extra projection screens around the objects, this makes the physical environment static, whereas the projection on a drone is more dynamic by bringing the screen where we need it. Using a robotic-arm carrying a display could be an option too, but it requires a complex motion planning setup, whereas the drones are much more flexible in terms of navigating inside a space.

In our implementation, we chose to use projection rather than equipping drones with an LCD screen. This allows us to use smaller drones, which are cheaper, safer, and less noisy. Furthermore, it does not require to send synchronized video streams to the individual displays, and the rendering of the visual content remains uniform over the all augmented scene.

In summary, our contributions in this paper are (i) the exploration of the DroneSAR framework and its related interaction techniques, and (ii) a concrete implementation and description of the technical details of this approach.

2 RELATED WORK

2.1 Interaction in Spatial Augmented Reality

An emblematic example of SAR is Shader Lamps [3], where Raskar et al. utilized digital projectors to augment physical objects with computer-generated images to simulate different materials. Bandyopadhyay et al. [4] extended the concept of shader lamps with dynamic tracking to allow the users to paint onto physical objects using a tracked brush. MirageTable [33] enables the user to perform freehand interaction with virtual 3D objects in a tabletop SAR scenario. In [2], Marner et al. proposed the concept of Physical-Virtual Tool (PVT) in SAR by projecting application-specific GUIs on a physical tool that is carried by the user in the projection area. This allows to overload a single tool with several functions to interact with SAR. Park et al. [18] integrated mobile devices in projection-based AR to afford user interfaces to design interiors effectively. In our approach, the drone panel is augmented with the widget elements, and it allows the users to interact with the SAR scene from a certain distance.

Displaying labels in SAR is a challenging task. It is common to observe the legibility degradation in labels because of the non-planar and textured projection surfaces. In the past, researchers developed a novel label layout method to geometrically correct the deformation of the projected labels [14]. HySAR [34] combined an optical see-through head-mounted display (OST-HMD) with a projector to improve material rendering in the SAR system. Another approach is to project labels on a surface next to a working place [19]. DroneSAR uses the flying window to display labels which are independent of the projection surface.

As it is not possible to project mid-air information, Karnik et al. [20] and Plasencia et al. [21] introduced novel AR systems combining glass cases to merge the space in front and behind them. The main limitation of their systems is that the users need to observe the scene through a glass, which introduces a distance and make direct touch interaction impossible. In [5, 6], the authors developed optical imaging systems and techniques for anchoring real objects with mid-air contents and allow the users to manipulate mid-air information by simply moving the physical objects. Moreover, other possible ways for displaying mid-air information are anamorphic illusions [16] or stereo projection with 3D shutter glasses [17] that require the observer to be head-tracked. In our technique, the drone window simply provides physical support to display mid-air contents without the need to equip the user.

Due to the rigid mapping between physical and virtual parts in SAR, the virtual scene cannot be explored in different scales and points of view. To overcome this issue, previous works fused multiple mixed reality modalities (like VR-HMD, handheld see-through display) [7, 8] and also combined shape-changing interface with SAR to alter the object appearance [22–24]. In our research, instead of deforming the physical geometry of the objects, we are extending its geometric space dynamically integrating a 2D surface.

2.2 Drone as a mid-air display

Researchers have studied drones as a self-levitating floating display to share information between multiple people. Scheible et al. presented DisplayDrone [25], a projector-augmented drone that can project information onto a fixed surface. In [28], Knierim et al. displayed context-aware navigation instructions directly in the real world from a quadcopter-mounted projector for pedestrian navigation. Similarly, Hoggenmueller et al. [36] described a conceptual drone-based in-situ projection application to support people crossing a busy road that lacks dedicated pedestrian crossings. FlyMap [27] investigated mid-air gestural interaction with geographic maps projected on the ground from a drone. LightAir [29] and drone.io [30] introduced body-centric user interface to facilitate natural interaction with drone projected information.

Schneegass et al. proposed Midair Display [10], where a drone is equipped with an off-the-shelf iPad to create temporary navigation signs to control crowd movements in emergency situations. Flying Display [11], a movable public display, consists of two synchronized drones - one is carrying a projector, and another one is mounted with a screen. In Gushed Light Field [12], a drone is equipped with a spraying device and a small projector to render aerial images by aerosol-based fog screens. iSphere [26], a flying spherical high-resolution display, is created by covering a drone with arcuate LED tapes. In ARial Texture [1], the authors used the drone propellers as a display screen. Zhang et al. [35] proposed a hologrammatic telepresence system by projecting a remote user's head on the drone-mounted retro-reflective cylindrical surface. Tobita et al. [37] developed a blimp type drone-based telepresence system.

Intel used 300 drones synchronously to form the US flag [13]. However, such a complex system does not allow direct user interaction at a room-scale. In BitDrones [9], the authors considered each nano-quadcopter as a voxel, and by combing multiple of them, it would be possible to create high-resolution 3D tangible displays in the future. They also used the drones to carry widgets elements.

In summary, many authors explored the drones as a promising approach to display mid-air information. We also continue to pursue this exploration. On the other hand, none of these work investigated the drone as an extension of the augmented physical scene in SAR environments, as we do.

3 DRONESAR

The overall motivation behind DroneSAR is to extend and enhance the projection space around the augmented physical scene, as illustrated in Figure 2. To do so, we mounted a small projection screen on a drone whose position can be controlled in real-time either by the system or by the user. This drone panel acts as a 2D planar surface along the display continuum [15]. It adds physical space to the scene when needed without modifying the actual geometry of the physical objects. It allows displaying virtual content that would be difficult to display in the SAR scene otherwise.

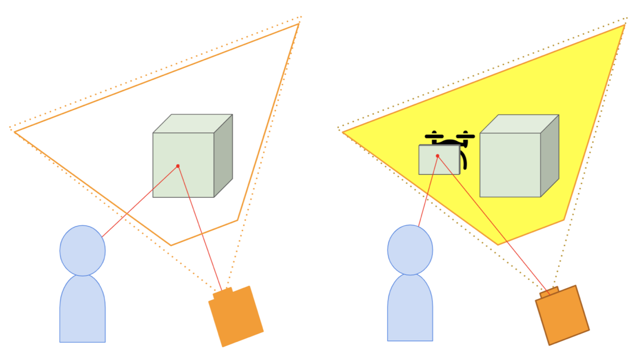

Figure 2: (Left) In SAR, the projection space is limited by the size of the physical object. (Right) DroneSAR extends this projection space (shown in yellow color) with a flying panel that can be positioned in the surround of the physical scene.

Embedding widgets within an SAR environment is challenging, as mentioned in the introduction section. Prior works proposed to provide widget elements in SAR either on the surface of a table [4], on a tracked panel [2], or via an external tablet carried by the user [18]. These approaches solve the problem partially. However, they incline to disconnect the UI elements from the observed augmented scene.

In our approach, we can display visual content on a flat-screen almost anywhere around the physical objects. This approach has several advantages. First, compared to the direct projection on an object, the projection quality does not depend on the geometry and material of the physical scene, which ensures good visualization of the widgets. Second, the user can concentrate on the region of interest without dividing their attention with a second area of interaction (i.e., mobile phone, tablet, etc.). Third, they can position the widgets at specific 3D locations, which can be at a distance. The proposed technique allows them to see the widgets in their 3D spatial contexts. The users will have the impression that projected content on the drone is always semantically linked to the augmented physical surfaces. Finally, several users are able to perceive the same information at the same time; this favors collaborative work.

This paper describes three possible ways to provide support for 2D widgets in the SAR context to enhance the interactive experience. However, many other functionalities could be imagined, where DroneSAR brings the standard desktop applications within the realm of SAR environments.

3.1 Displaying Annotations in Mid-air

In mobile or head-mounted AR applications, view management is an important part of designing intuitive user interfaces. This is about the spatial layout of 2D virtual annotations (i.e., text, image, video) in the view plane for real-world objects to show in-situ information to users.

In a similar way, adding annotations in SAR will enrich the user experience, but the placement of labels associated with the augmented physical world is not trivial because of its non-planar and textured projection surface. To address this problem, DroneSAR allows projecting virtual annotations on the drone, independently of the projection surface. While displaying the label in mid-air, the users can position the drone next to the physical object using a handheld controller to create a link between the annotation and the region of interest (ROI) in the physical space. They also have the flexibility to position the drone automatically defined by the application. Moreover, our system enables the users to interact with those projected labels with the controller input buttons. If it is a text or an image, they can use controller trackpad to modify its orientation. In the case of video, they can play or pause it with the trigger button. To display labels, we implemented a label widget. As described in Figure 3(a), when the label '*chimney*' needs to be displayed, the drone automatically (i.e., in a system defined way) comes close to the house chimney and hovers there. In the same way, to point at a specific location in mid-air, we projected a cursor image on the drone panel and using the trackpad, the users change its orientation (see Figure 3(b)). Last but not the least, DroneSAR also displays 2D video within the scene as shown in Figure 3(c).

3.2 Providing Interactive Tools

In SAR, the users act as passive viewers most of the times. It would be interesting to provide interactive tools to them to play with the virtual augmentation on physical objects dynamically. Inspired by 'dynamic shader lamps' [4], we augmented the drone panel with several virtual tools. The users can select a tool by pointing at it using a controller. Once selected, the controller becomes the proxy of that tool and enables to perform tool specific operation on the augmented content. For example, a user can select a measuring tool from the drone panel main menu. As illustrated in Figure 1(d), the participants draw a line on the augmented house using the controller trigger button, and the measured length is displayed on the drone panel. It can be easily extended to a painting application where the drone panel will be augmented with different tools like color palette, brush stroke, etc.

Furthermore, instead of providing a GUI of virtual tools, the drone itself can act as a proxy of a particular tool too. By moving the drone with a controller, the users accomplish that tool function.

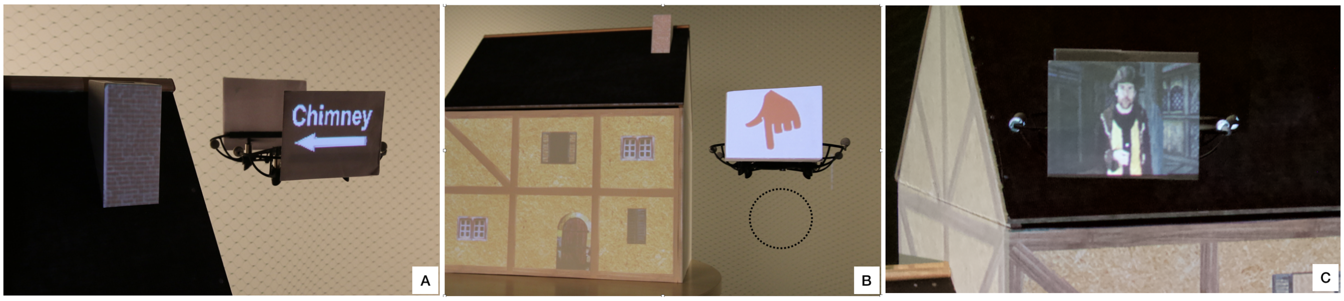

Figure 3: (A) The drone is hovering next to the chimney to display its corresponding label. (B) A flying cursor allows participants to point at a specific location in the scene. The dotted circle in the image represents the particular location in mid-air. (C) A video explaining about the history is displayed near the medieval house.

To exemplify this, we provide a light source tool. In this case, the drone acts as a proxy of the virtual light source. The users can interactively modify the position of the light using a grab gesture, which would be difficult to perform without the feedback of the mid-air position that the drone provides. The appearance of the house is modified accordingly when they move the light from the right to the left (see Figure 4(a & b)). This provides a tangible visualization of a non-physical object which is inspired by 'Urp' project [38].

3.3 Supporting Different Viewpoints

Another interesting feature of DroneSAR is to display an interactive 3D view of the observed augmented object close to the area of interest. Indeed, even if SAR environments have various interesting advantages, their physicality implies also strong limitations compared to purely virtual environments. It is not feasible to see the augmented physical objects from the top or back view, and the scale of the objects always remains fixed. Inspired by the concept of *One Reality* [8] that combines SAR and VR for adding flexibility in physical worlds, we propose an approach where DroneSAR is used as a contextual 3D interactive viewer. The participants can see the house from various angles and at different scales by using the controller trackpad and trigger button while keeping anchored in the physical environment. Hence, they can easily link the real-augmented object and its virtual counterpart (see Figure 4(c)).

4 IMPLEMENTATION

Our system is comprised of a projector, a small lightweight drone, a controller, and a motion tracking system; the technical components are accompanied by a physical mock-up for demonstration purposes. In the following sections, we describe the details of the individual components and how they are interconnected to implement the overall system (see Figure 5).

4.1 DroneSAR System

All components of our system are controlled from an application created using Unity3D 2018.3, running on a Windows 10 workstation with an Intel i7- 6700 processor, 32 GB of RAM, and an NVIDIA GeForce GTX 1080. Each of the physical elements of the scene was digitized manually using OnShape[1]. This application handles the SAR augmentation, the drone navigation and the user interaction.

4.2 Tracking System

The tracking is performed in a secondary Windows PC, running Motive 1.9 software[2] over the Ethernet. It samples with 120 Hz at a sub-millimeter accuracy. The setup is comprised of 6 Flex-13 cameras placed above the interaction volume, covering an interaction space of 3 m x 3 m x 3 m, and tracking all dynamic elements including the drone. The drone can then hover anywhere inside this interaction volume.

In order to support a comfortable interaction with the projected contents, we used HTC VIVE controller, which are tracked by two VIVE lighthouses. The calibration between OptiTrack space and VIVE space was computed using a gradient descent algorithm and has error under 0.8cm. To avoid infrared interference, we also synchronized the OptiTrack cameras with the HTC lighthouses[3].

4.3 Projector Calibration

We used an LG PF80G projector to augment our physical world with virtual information. To maximize the accuracy over the projection volume, the projector was manually calibrated by measuring its intrinsic parameters under controlled conditions. This was achieved by placing the projector perpendicular to a flat vertical surface, and then measuring the distance from the lens to the surface, the dimensions of the projected image, and the vertical offset between the center of the lens and the center of the projected image. The extrinsic information was obtained via external tracking (OptiTrack).

4.4 Drone Hardware

We chose a commercially available Parrot mambo quadcopter[4] as it is less noisy than bigger drones, and safe enough to fly in an indoor environment close to people. It is powered by a 660 mAh LiPo battery, providing approximately 8 min of flight time without any attached accessories. To increase its payload capacity, we removed its camera but kept the propeller guards attached for safety reasons.

[1] https://www.onshape.com/
[2] https://optitrack.com/products/motive/
[3] https://v20.wiki.optitrack.com/index.php?title=Sync_Configuration_with_an_HTC_Vive_System
[4] https://www.parrot.com/global/drones/parrot-mambo-fpv

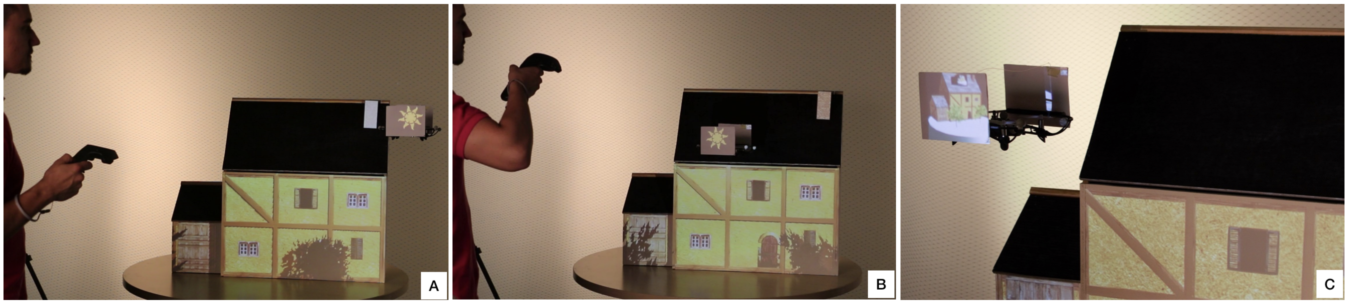

Figure 4: (A - B) The light source of our scene is at the drone hovering position. By moving the light source, the user is casting shadows on the scene. (C) An interactive 3D model of the mock-up displayed next to the physical one allows the user to observe the scene from another viewpoint.

For projection on the drone, we attached two white panels (size: 12cm x 10cm) made out of paper on both sides, and the maximum weight of these two panels was 13 grams. We also put five retro-reflective markers on the drone for tracking. The total drone weight was around 80 grams, with a flight time between 4 mins to 5 mins. It was connected to our Unity3D application via Bluetooth low energy (BLE) by a middle-ware running on a Raspberry Pi.

4.5 Drone Navigation

The drone navigation was controlled using a discrete PID controller to follow trajectories obtained via A* pathfinding algorithm over a volumetric grid segmentation of the interaction space (see Figure 6). The following subsections detail this process.

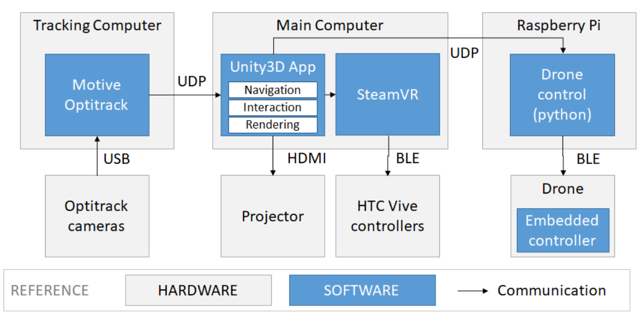

Figure 5: Overall architecture of DroneSAR system.

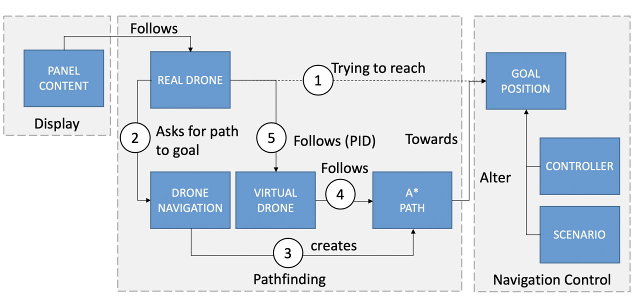

Figure 6: Drone flight control to reach the goal position.

4.5.1 Space Discretization. To define navigation paths over the physical scene, we first discretize the space on a regular grid (cell diameter = 10cm). Based on the physical object's position, each cell of the grid is flagged as either solid or empty (see Figure 7(b)). Once a cell is detected as a solid cell with static content, it does not update anymore, while the rest of the cells are updated in real time. To prevent the drone from flying under physical objects (e.g., under the table), all cells under a solid one are marked as solid too. We found that the drone airflow interacts differently with the available surfaces, causing more or less turbulence depending on their geometry. This creates a required minimum empty volume of 10 cm in diameter to consider a cell safe (see Figure 7(c)). Then, we categorize the complete space into 'safe' and 'unsafe' cells.

4.5.2 Path Finding and Following. With a discretization of space, it is then possible to use navigation algorithm. Here, we utilized a simple volumetric A* algorithm prioritizing vertical movements, in order to obtain the navigation way-points (see Figure 7(d)). Given that the drone is controlled via yaw, pitch, roll commands, we implemented a positional PID corrector (proportional, integral, derivative) in order to control it with 3D positions. With this corrector, we continuously reduce the distance error between the drone position and waypoint, and at the same time, we convert the command into yaw, pitch, roll movements. In order to avoid oscillations, we established a *dead zone* threshold of 10cm (i.e., the drone is considered *"at the target location"* if the distance is under 10cm).

4.6 User Interaction

In our system, users experience the augmented scene at a certain distance. As soon as they are not close to the physical mock-up, direct touch interaction is not possible. For that reason, we consider all interactions using a handheld controller. The users are either carrying a VIVE controller, or they can share it among themselves.

4.6.1 Drone positioning. With the controller, they can position the drone anywhere they want inside the safe area of the tracked volume. They can also directly interact with the visual content projected on the physical scene or the drone panels. In the following, we describe these two interaction modes in details.

When a display screen is required at a given location (e.g., to display a label), then the drone reaches this location following the pathfinding approach. In this situation, target position of the drone

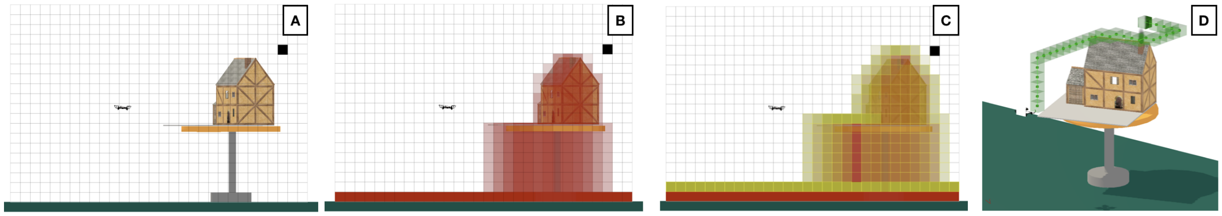

Figure 7: The referenced scene (A) is decomposed into solid cells (in red) (B), then 'safe' cells (in yellow) (C). Example of waypoint cells (in light green) (D).

is system defined, and the users act as passive viewers. We called it as *automatic* mode.

Moreover, our system also allows manual drone displacement by pressing the grab button of the controller, under a *guided* mode. While *grabbed*, the drone movements are mapped one-to-one to the controller movements. To avoid collisions, the displacement is performed via the path-finding module: if the users try to position the drone beyond its safety boundary, our system warns them via vibration from the controller, while clipping the displacement to the nearest safe position. In our current implementation, the X/Y/Z movements of the controller are mapped to the drone movement without any rotation, as the drone must face the user position.

4.6.2 Interacting with the augmented contents. The users can point and select virtual content projected on the physical objects (i.e., house) using ray-casting from the controller, which is a popular 3D interaction technique. We borrow that concept to perform pointing in SAR. The same approach could be used to interact with the content projected on the drone panels. However, these panels being small and the stability of the drone being limited, we found it more comfortable to interact with these UI elements through a 2D cursor associated to the controller 2D trackpad.

5 LIMITATIONS & FUTURE WORK

We have shown that combing SAR with a drone opens new opportunities to extend the interaction space. Even when promising, our approach is not without limitations.

The drone can hover almost perfectly in mid-air (with ±8cm positional error) when there are no physical objects nearby. This amount of positional error is acceptable as the virtual augmentation on the drone always follows its real position (tracked drone), not the target location. On the other hand, bringing the drone close to the physical objects (e.g., sides or exactly on top of the house) is difficult due to its downwards air-flow. However, we noticed sufficiently stable hovering when the drone is at least 30cm away from the physical surface.

The size of the panel attached to the drone is quite small (12cm x 10cm) as we restricted ourselves to use a lightweight drone for the users' safety. The small size of the drone panels restricts us to project only limited content on it. In this context, it would be interesting to explore spatial menu concepts like virtual shelves [41] and m+pSpaces [42]. Another area of exploration would be the exploration of lightweight non-planar mediums (e.g., cloth, circular surfaces), better suited for non-flat content. In order to extend the display surface, it could be possible to combine multiple of these drones to create a bigger surface dynamically. We also envision that there will be improvements in the drone payload capacity and battery life with less noise in the coming years. Blimps might also be an alternative option in this direction, trading speed for projection surface and stability.

The drone does not consider the user's presence while computes a path to reach the goal. In the future, our navigation module should take into account the human position.

Moreover, as we use a front projector, shadows of the user and the drone are inevitable. This could be overcome by using multiple projectors set up [40].

Beyond these limitations, it would be interesting to explore additional features. For example, in this work, user interaction is performed by a handheld controller. We can think about hands-free interaction where the users will directly grab the drone to position it [39][9]. They can also perform direct touch interaction on the drone panels as well as on the augmented physical surfaces for manipulating virtual contents.

6 CONCLUSION

SAR is strongly linked to the related physical scenes. This makes the user experience with SAR unique, and it provides numerous advantages compared to see-through AR approaches. On the other hand, the physical nature of SAR also induces limitations. We have introduced DroneSAR to overcome some of these limitations. By extending the space on which digital content can be displayed, we have proposed a way to extract the augmentation from the physical constraints. The mid-air drone augmentation is always contextually connected to the physical 3D augmented scene. In our approach, we have explored a set of interactions where the users keep immersed in the augmented scene, and they can benefit from additional displays functionalities. This is a proof of concept of how to extend the physical space of SAR using drone augmentation. Once the technology is stable enough, we will conduct a set of user studies to assess the potential and limits of such an extended SAR environment compared to traditional smartphone or tablet-based augmented reality system.

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