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From God's Eye to Ground Level: Aerial LiDAR as an Avenue to a Volumetric Understanding of Urban Spaces

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Abstract

Recent advances in high resolution, aerial LiDAR data collection can facilitate a more thorough understanding of three dimensional (3D) urban space across a range of viewpoints from the God's eye view to the ground level. Using an extremely high resolution aerial LiDAR dataset collected over a $1.5km^2$ area of central Dublin, Ireland as a case study, this work pursues new vertical and volumetric understandings of the controversial Spire of Dublin. Viewing this structure in a fully elaborated, 3D environment with the capacity to experience the space from a range of perspectives enables a clearer understanding of the monument's relative proportion to the space of the built environment both in terms of verticality and volume. Arguably, this in turn provides insight into relationships of power, modernity, tradition, and enclosure that inform a richer understanding of the arguments of both supporters and detractors of this piece of modern, public sculpture. This essay concludes with a suggestion of potential future work in high-resolution, aerial LiDAR collection to aid in developing resources in urban studies more broadly.

Introduction

As populations grow, cities are expanding vertically. This increased three-dimensionality means that traditional, flat representations of space such as maps and plans are increasingly limited in their ability to represent urban environments for both those designing such environments and those working and living in them. As such, researchers and practitioners are becoming more interested in comprehending the three-dimensionality of urban spaces through a variety of new paradigms. The most prominent threads in such research are those of verticality and volumetric space, both of which are severely hampered when only traditional two-dimensional (2D) God's eye views of space are employed. While urban research works towards enhanced understandings of three-dimensional (3D) space, novel 3D representation is also increasingly available across consumer technologies including virtual reality (VR), augmented reality (AR), hyper-realistic video game environments, and highly democratizing tools like Google Street View. Applications span from real estate and virtual tourism to life-quality indexing and personal navigation. In all of these areas, remote sensing data has the potential to revolutionize the way 3D space is recorded, viewed, understood, and ultimately modified. In this paper, high-resolution laser scanning [also known as Light Detection and Ranging (LiDAR)] is presented as a common form of remote sensing extremely well suited when deployed from the air, to generate uniquely detailed and inherently 3D means to better understand and conceptualize urban space. This is demonstrated herein through a case study exploring the spatial, social, and aesthetic implications of The Spire of Dublin, a millennial sculpture built in the heart of Dublin, Ireland as part of an effort to revitalize O'Connell Street, Dublin's main thoroughfare north of the River Liffey.

Verticality and Volumetric Space

The maturation of urban research in verticality and volumetric space exploration is paralleled by improvements in LiDAR data collection, but these two lines of research have yet to achieve significant interaction or overlap. Despite increasingly high resolution and ever more ubiquitous access to low-cost or no cost LiDAR (e.g. Environment Agency; OpenTopography Facility; Laefer et al.), urban researchers and practitioners seem not to have embraced LiDAR, which provides a geo-referenced point cloud that can be viewed and explored using open-source software. LiDAR data allows users to view and analyze urban space in 3D, accounting for differences in structural footprints at different elevations and providing a basis for fully immersive analysis through AR or VR. However, due to a combination of lack of training in the use of LiDAR point clouds, an absence of a seamless way to integrate LiDAR data into existing workflows, and the market dominance of GIS and other 2D systems in both government agencies and corporate consulting firms, most urbanists have remained wedded to geographic information systems (GISs), mental mappings, representational drawings, and traditional cartography (Ahmed and Sekar; Yang et al.; Belanger; Dodge). While these representational systems are well embedded in current curricular based training, deeply seeded in the workplace, and provide an adequate basis for baseline spatial analysis, they fall short in representing the fully 3D nature of urban environments and are especially limited in truly volumetric representations of space. This section provides a brief overview of verticality and volumetric space studies in the urban context before a discussion of LiDAR and its relevance to these 3D concepts and understandings of urban space is presented.

Building on Weizman's seminal work on the politics of verticality and the philosophy of spheres employed by Klauser (326-340) and Sloterdijk, Graham and Hewitt have prominently advocated for vertical conceptions of urban spaces (e.g. Graham and Hewitt 72-92; Hewitt and Graham 923-937; Graham 618-645; Graham). Specifically, they argue for the development of research into a "fully volumetric urbanism…which addresses the ways in which horizontal and vertical extensions, imaginaries, materialities, and lived practices intersect and mutually construct each other" (Graham and Hewitt 74). Through this lens, the verticalization of urban space is presented as a form of perpendicular splinterings, thereby raising questions not only of the physical separation of elites from street-level life but also the divergence of conceptualizations of the city from the elevation of a God's eye view versus that of the street level experience (Graham and Hewitt 79). Graham and Hewitt (72-92) also suggest verticality as a framework for exploring the politics of both airborne surveillance and control, along with the subterranean burrowing that emerges in response to God's eye surveillance techniques.

In their own work, Graham and Hewitt largely employ this volumetric conception to consider the politics of housing developments, whereby the wealthy and the privileged live above the ground level sprawl of the lower classes after the negative optics of high rise affordable housing projects have given way to the "luxification" of the skies (Graham 618-645; Graham and Hewitt 72-92; Hewitt and Graham 923-937). This line of enquiry is also pursued by O'Neill and Fogarty-Valenzuela (378-389), who explore urban segregation not only through the traditional horizontal divisions of walls and gates but also through the vertical segregation seen in the high rises of Guatemala City where newly built high rises are the exclusive province of the elite, while less prosperous citizens are relegated to the street level or the lower elevations of the sunken barranco areas.

In contrast, Harris (601-620) advocates a more inclusive mode of verticality in which the vertical is not only seen as the locus of physical and social violence but as a space of highly complex understandings and imaginaries of height and all that it symbolizes. Referencing the skywalks of Mumbai, which remove hawkers from the street and delineate the street-level as a space for the vehicles of the elite, Harris (606) argues that power is not strictly top-down, and

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that the over application of this verbal metaphor to physical space has limited vertical urbanisms and reduced the power to understand the full range of urban realities across the physically and culturally varied globe.

From an urban planning perspective, volumetric and vertical understandings of urban space can also play a more practical role. Specifically, Ahmed and Sekar (393-408) advocate for the use of volumetric studies at all levels and granularities of urban planning to relieve planners from their reliance on "mental maps" used to determine intensity (Ahmed and Sekar 396). In contrast to 2D understandings enhanced by mental maps of intensity, "a volumetric study is a quantitative study," which "establishes the 'volumetric-ness' of an urban space, i.e. a study of the built environment density, the volume and intensity of activities it generates, and its influence over an urban space" (Ibid.).

However, Ahmed and Sekar's case study of water supply networks in Chennai, achieved though enabling a more detailed, volumetric understanding of the needs of a vertically intensive built environment, is nonetheless based on extruded outlines derived from Google Maps and paired with a time-consuming primary survey of the built-up verticality of the space. Despite providing first steps in developing volumetric methods to address urban problems, this methodology suffers from the same inherent roughness and inaccuracies seen in other two-and-a-half dimensional (2.5D) models where verticality is seen as a strictly perpendicular element represented exclusively by elevation values. In contrast to these 2.5D models, Virilio's early work on verticality (e.g. Virilio and Lotringer) sees the world not as horizontal and vertical but as variously inclined planes. Virilio and Lotringer (34) note that "there is practically nothing flat on the surface of the earth. Nothing. There are many more inclined planes." This emphasis on inclined planes and the variety of angles at which surfaces are realized is incompatible when using 2.5D extruded footprint models that are highly limited to depicting perpendicular relationships between flat horizontal and flat vertical surfaces. Ahmed and Sekar also highlight the limitations of current 3D models for analysis including "inadequate support for analysis, planning and decision-making" (398), as well as the static nature of the models (399).

Visibility analysis is another approach that has turned towards volumetric consideration of urban space. Building upon the 2D isovist approaches of Benedikt (47-65) and Tandy, which defined visibility as a 2D plane of points visible from a given vantage point, Batty (123-150) added the need to understand not only how much and how far one can see, but also how much space is enclosed in that view. This later expanded into 2.5D viewshed analyses using raster data in a GIS, but to date urban planners and related researchers have struggled to apply fully 3D analyses to real urban environments (Yang et al. 973). To foster this, Yang et al. (975) proposed a volumetric model for understanding visibility and spatial analysis but were unable to address fully 3D forms such as bridges or cantilever structures, because of their use of raster data in a GIS (as opposed to vector data in a fully 3D viewer). So, while computational tools in the engineering community continue to expand in their development and deployment, a strong reliance on 2.5D models in urban planning persists, which hampers a truly 3D conception of volumetric questions in the urban environment. A related effort to go beyond the map view is the employment of "from the side" schematic views (Belanger 5-7), but as yet there has been surprisingly limited urban research conducted on truly 3D representations of the city-scale urban environment given the increasing availability of such data both through reconstructions obtained from imagery and that achieved directly from LiDAR.

LiDAR

Originally developed in the 1960s, LiDAR has been applied to a range of applications including measuring clouds (Whiteman et al. 3068-3082), determining wind speed for wind turbine optimization (Schlipf et al.), and imaging a range of physical forms from the surface of the moon (e.g. Smith et al. 1591-1611), the sea floor (Tulldahl et al.), and the Amazon rainforest (e.g. Oliveira et al. 479-491). A common way that LiDAR captures the 3D geometry of a scene is by recording the time between when a laser pulse is emitted and when that same pulse is returned after reflecting off an element in the environment. This time of flight information is then used with a pre-calibrated global positioning system to derive a set of 3D coordinates for each point. When an area is scanned, the result is a series of points (each with an x, y, and z coordinate and an intensity value), which is representative of a combination of atmospheric, scanner, and material considerations. Together these points form a point cloud, which provides a 3D representation of all visible points in the scene, as the technology is based on line-of-sight data collection.

LiDAR is usually collected through one of three primary modalities: terrestrial, mobile, or aerial. Terrestrial scanners are commonly employed for scanning single buildings or construction sites where a scanner can be placed in a limited number of locations to scan the entire area of interest. Though this method can provide very high density, high resolution data, it is limited in scope and requires significant man hours to collect and co-register larger extents. Mobile LiDAR is typically collected from scanners mounted on motor vehicles but is increasingly able to be collected from backpack scanners (Tompkinson) or even hand-held scanners (Maxwell) that can be carried around the area of interest by a person on foot or bicycle. Though this form of LiDAR can more quickly capture larger extents, it is still limited by a position at the ground level, and is only able to move into areas with sufficient clearance for the vehicle or person carrying the scanner. Nonetheless, as increasingly many autonomous vehicles are put on the roads, the mobile LiDAR scanners on these vehicles have the potential to populate extensive models of anywhere accessible by road from a ground-level perspective.

The most common method for collecting LiDAR data for modeling purposes, however, is from aircraft whether unmanned aerial vehicles, helicopters, or fixed-wing aircraft. This aerial data capture is an inherently God's eye technology, as the scanner views the world exclusively from above and collects data by looking down from the skies. While these data may at first glance seem to differ little from traditional 2D maps or aerial photography, when the points are color coded by intensity as seen in Figure 1, the 3D component begins to become clearer. The intensity serves as a proxy for elevation and provides a sense of the relative heights of the built environment. In some surveys, however, especially those used for floodplain modeling, the God's eye perspective is reinforced by the delivery of a "bare earth" model that has been stripped of all non-topographical information. From above and at an initial glance this form of LiDAR is in many ways similar to a traditional topographical map, or a GIS map with building footprint extrusions, but a point cloud can be much more powerful than that.

A comparison of representations of central Dublin. Fig. 1 a. (top left) Google maps "Map"; Fig. 1 b. (top right) Google Maps satellite imagery; Fig. 1 c. (bottom left) 3D LiDAR data in grayscale. Fig. 1 d. (bottom right) 3D LiDAR data seen from a God's eye view with intensity values mapped to a viridis color scale. Digital renderings by Brittney O'Neill and Debra Laefer, 2017; Map imagery extracted from Google Maps, 2017.

Flying lower and slower enables capture of not just building footprints and elevations as seen in large scale surveys but also detailed roof features, façade data, vegetation information, and even street furniture (Hinks et al.). This form of data can furnish the basis for a unique volumetric understanding of urban space not only showing the rough contours of the urban canyon but also providing a detailed comprehension of how both horizontal and vertical surfaces create the 3D urban environment and the physical and political relationships that are enacted within it. Where Weizman argues that understanding of politics of verticality "requires an Escher-like representation of space, a territorial hologram in which political acts of manipulation and multiplication of the territory transform a two-dimensional surfaces into three-dimensional volume" (Weizman 2) a perhaps more comprehensible and manageable alternative could be use of the inherently 3D LiDAR data to underpin a fully 3D spatial data system into which political acts can be inscribed and described in reference to their full spatial reality beyond the limitations of horizontal planes and linear political boundaries. This is opposed to "onto which" for traditional 2D mapping, which may vastly change the conceptualization of such acts (Figure 1).

At the cutting edge of this form of data collection, Hinks et al. have developed novel flight planning and data collection techniques that enable reaching centimeter level resolutions with point densities in excess of 300 pts/m^2 with traditional commercial LiDAR equipment for which 50 pts/m^2 has been considered the high end of achievable point density. Initially collected over 1.5km^2 of the city centre of Dublin, Ireland, this dataset provides an opportunity to explore and understand urban spaces in a uniquely volumetric and verticality sensitive manner (Figure 2). No longer is the view only from above, or from above with an elevation value, but instead is in fully elaborated 3D with which the researcher can navigate from an infinite number of elevation or perspective views, thereby fostering the maximal understanding for their particular research purposes. In addition to this visual and experiential aspect, the inherent three-dimensionality and georeferencing of LiDAR data provides opportunities to begin to overcome the analytical limitations of 3D models based on extruded polygons (Ahmed & Sekar 398), by allowing multi-modal data to be geo-referenced and linked to 3D spatial extents as small as a single point, or as large as an entire city (see Aljumaily et al. for early progress in this area). Thus, the range of data types used in planning analyses can be powerfully expressed as components of spatial reality and analyzed accordingly (Figure 2).

Fig. 2. Dublin LiDAR data seen in 3D looking northward from Westmoreland street, across the Liffey River and up O'Connell street. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

The Spire of Dublin: A God's Eye View with Nowhere to Stand

As the first example of this extremely high-resolution data was collected over central Dublin, it allows exploration of a unique case study in urban art and the design of public spaces. In 2003, the Spire of Dublin, a project in honor of the millennium, was completed but not without very mixed responses from the local and wider communities. The Spire, an extremely slender cone 3m at its base and 120m in height (Figure 3), rises out of historic O'Connell Street. This street forms a critical site in the Irish national narrative for independent statehood, especially in the context of the 1916 Rising, which has just seen its centenary. The 1916 Rising or Easter Rising was a pivotal event in the Irish Nationalism movement with fierce street fighting and gun battles across Dublin for 6 days. The Rising's leaders were headquartered in the General Post Office (Figure 4), and as a result of the Rising, three quarters of the buildings along O'Connell Street were destroyed. Though the Rising was quelled by the British army it was the first armed rising of the Irish revolutionary period and played a pivotal role in the Irish independence movement, which ultimately succeeded a mere six years later (Figure 4).

Fig. 3. The Spire of Dublin (By User:Vmenkov - Self-photographed, CC BY-SA 3.0. https://commons.wikimedia.org/w/index.php?curid=3035872)

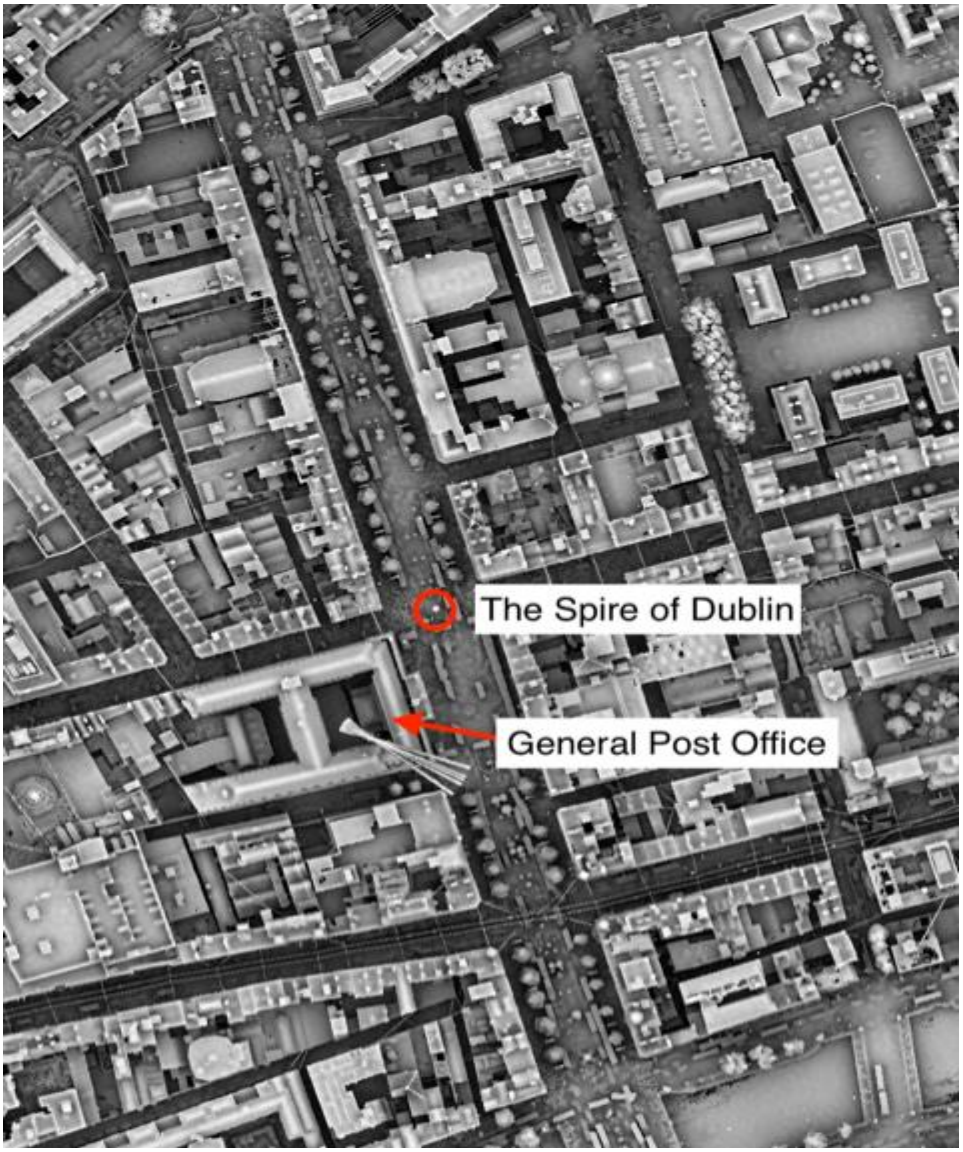

Fig. 4. God's eye view of LiDAR data for O'Connell Street. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

In addition to this historical legacy, which drove some of the original trees to be retained despite plans to replace them in recent urban renewal campaigns, as they were deemed to be the last living witnesses of the Rising (O'Brien), O'Connell Street hosts monuments to six famous Irish figures—five of which were prominent nationalist heroes. The street was also the site of the 1966 bombing of Nelson's Pillar, which signaled the beginning of a period of decline. Though revitalized after the 1916 Rising, after 1966, O'Connell Street became associated with cheap arcades, fast food shops, and vacant lots. It was deemed dangerous and run down and was often seen a "no go" area (Corcoran 69-86). Nonetheless, despite this decline over the latter half of the 20th century, O'Connell Street holds an important place in the Irish national imagination and is also the most prominent artery northward from the Liffey River which divides the city into North and South sides.

On a 2D representation of the city, The Spire with its 3m diameter is a barely noticeable speck (Figure 4) with a very small footprint (Figure 5), but when that view becomes 3D (Figure 6), the 120m tall Spire quickly dominates the skyline with its height, despite its slenderness.

Fig. 5. LiDAR data looking straight down from the point of The Spire showing the relatively small footprint of the monument. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

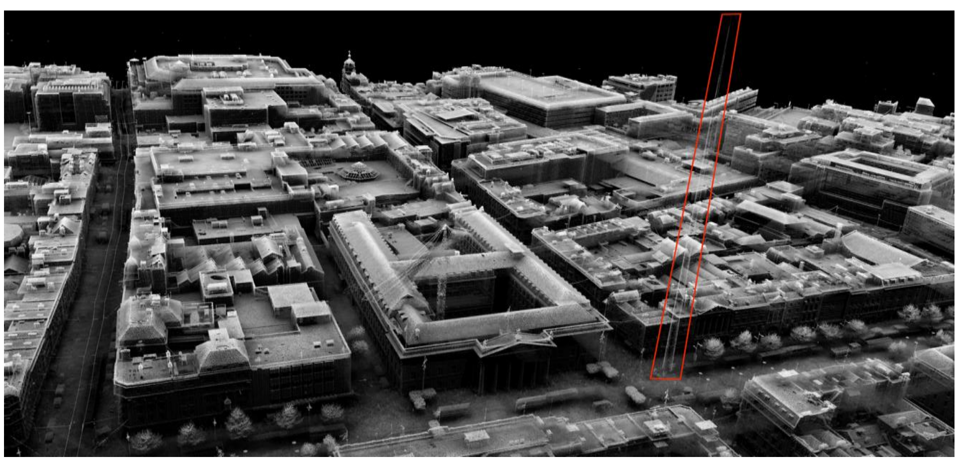

Fig. 6. LiDAR data showing the vertical relationship between The Spire (outlined in red) and the General Post Office (left of the spire) looking west. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

Hence, it must be considered within a volumetric and vertical framework lest its most prominent aspect be neglected. As seen in Figure 2 and Figures 6-8, aerial LiDAR data is uniquely helpful in this conceptualization. Through the 3D representation, the fact that the Spire is nearly five times the height of the adjacent buildings becomes apparent, as does its relative isolation in the middle of the wide expanse of O'Connell Street.

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Fig. 7. LiDAR data depicting the height and positioning of The Spire of Dublin (outlined in red) within the enclosed area of O'Connell Street looking south. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

Fig. 8. LiDAR data showing the Spire in the larger context of central Dublin looking south. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

The Spire is not only physically isolated but conceptually isolated as the only vertically oriented, modernist, steel structure on the street. Such verticality has been identified as representing power and dominance in disputed territory. For example, Elden states that "height plays an important role in the power relations of this fractured and contested space" (Elden 38) in reference to the Israeli-Palestinian conflict; the role of height as an indicator of power in contested space is also prominent in the case of The Spire. Arguably this is done by empowering the modern global identity of Dublin by elevating it over the contested space of O'Connell Street with its history of nationalism and violence, including the destruction of the previous structure on the site: Nelson's Pillar, a 4m wide by 40.8m high monument depicting the British hero Admiral Nelson. The bombing and destruction of that monument in 1966, was a historically significant event in the ongoing Irish struggle to reclaim their identity from what many Irish would consider the British oppressors, who had studded the country with elevated statues of important British figures. Admiral Nelson was not the only British hero to be knocked from his elevated position by the Irish republicans (Fallon 22 Dec. 2016), but he was the only one to be replaced by an even taller monument to a bright, peaceful, and productive modern Ireland.

The height of the pillar serves not only as a nod to a modern global identity but as a way of separating this new conception of O'Connell Street from the less desirable street-level reality of poverty, drug use, and crime. Though The Spire is not a residential complex, its height mirrors that of the elite spaces discussed by Graham and Hewitt (72-92) at the tops of skyscrapers where only individuals possessing both wealth and status can rise above the less desirable aspects of the city. This contrast between the existing low historic architecture and the striking modern verticality of The Spire was whimsically and pointedly criticized by Mícheál Ó Núalláin, the brother of Irish novelist and satirist, Flann O'Brien, as likely to reduce the rest of O'Connell Street to "an absurd Lilliputian dimension" (Fallon 12 Mar. 2016). This criticism finds support in the comparison depicted in the previously seen Figure 6, where the massive height of The Spire dwarfs the historically important General Post Office.

However, to quote Bondi, "A single example may be ambiguous: in its combination of slenderness and verticality Toronto's CN tower combines masculine and feminine connotations" (Bondi 159). Similarly, the height of the Spire can be seen not only as hegemonic and divisive but also as "brave and symbolic" (Dunne), with its disproportionate height necessary to impart an impactful change upon the previously decrepit street. Even as it has been said to be "a metaphor for Celtic Tiger Ireland – confident, flashy, overweening" (Kenny), the monument also memorializes a time of unprecedented optimism and growth in Ireland. "Building up has been a consistent feature of what defines urban life" (Harris 604) and so in a relatively low city, like Dublin, height is an assertion of urbanity, of development, and of growth on an international scale. This notion is further emphasized by the designers' description of the monument as having been erected in "celebration of Ireland's confident future in the third millennium" (Ian Ritchie Architects).

The conflict of opinion between those who see the erection of the spire as mismatched in the more historic and traditional space and those who celebrate its bold modernist design (e.g. Corcoran 69-86; Elkin; Fallon 12 Mar. 2016) is also reflected in discussions of modernist or Cubist space versus volumetric space. Condon (1-14) discusses how the work of Le Corbusier including his *The Radiant City* (Jeanneret-Gris), which has informed many modern cityscapes, ascribed to a conception of space wherein buildings are placed into space, in contrast to more traditional urban forms wherein buildings create space by containing it. Condon (1-14) calls these modes of understanding space "cubist" and "volumetric," respectively. To borrow these concepts in reference to O'Connell Street as seen in 3D, the street largely fits within a volumetric ideology of urban space. The relatively uniform height of the buildings on either side of the street provide walls, which contain a public space for leisure, commerce, and civil action. Though it is a wide boulevard, the overall impression is one of an enclosed corridor with facades of equal height and depth. Like traditional plazas, some of the buildings are porticoed providing the human comfort of both prospect and refuge, as described by Appleton.

However, in the midst of this otherwise enclosed space, The Spire represents a very modern, Cubist idea. It has very clearly been placed *within* space rather than to *contain* space. Reflecting the shining steel image of Le Corbusier's planned (but never realized) *Radiant City* composed of dramatic freestanding skyscrapers arranged in orderly linear forms across ample green space (Jeanneret-Gris), The Spire replicates the visual impact of a freestanding skyscraper, drawing the eyes skyward and impressing upon the viewer the sheer majesty of its height in an otherwise low environment. This reference to the skyscrapers of modern cities like New York and London points to an ambition for Dublin to be realized as a modern, global city, with the economic and political power associated with glistening skyscrapers and steel, rather than the traditional low rise brick and stone that dominate the city.

Though clearly speaking to an aesthetic of modernity and power, The Spire represents a rift in the contained volumetric space of the street. It disrupts the impression of enclosure as it spears up into the sky breaking the roofline and, thus, breaking the perceived ceiling of the space. This relationship between The Spire and the surrounding spaces becomes clear in the previously seen Figure 8 where the 3D representation viewed from above the rooftops is split by the height of The Spire dwarfing the enclosed space of the street below.

In addition to The Spire's surroundings, its precise location necessarily positions it relative to the previous occupant of the location: Nelson's Pillar. The pillar was the tallest Doric column in Europe and featured a viewing platform, which offered a God's eye vista over the city. By contrast, The Spire, though spiking up 120m above the city, much taller than the original pillar, offers no viewing platform. The Spire is deeply suggestive of the power of the God's eye view as it stretches to the heavens, but unlike Nelson's Pillar, there is nowhere to stand.

Mary Kenny also contrasts the two monuments in terms of their narratives. This invocation of the human need for story parallels Appleton's emphasis on evolutionarily driven preferences for prospect and refuge. Where Admiral Nelson, despite not being Irish had a vibrant and widely known story, the Spire does not.

> The problem with the Spire is the problem with most abstract art and sculpture – there is no accessible story. Abstract art and sculpture may have their own beauty of shape and sensation, but they lack a narrative element, and the need for story and narrative will always be stronger than the sometimes more high-brow values of pure design. (Kenny par. 6-7))

In a country like Ireland where narrative and story is highly valued, this is a nearly damning indictment.

Arguably, the lack of a viewing platform, combined with the lack of narrative or explanation, has also contributed to its mixed reviews from locals and tourists alike, many of whom seem to fail to see the "point" of The Spire (e.g. The Irish Times; Elkin; Fallon 12 Mar. 2016). In Figure 9 and 10 using the LiDAR data, the viewer can see the God's eye vantage point at the point of The Spire. But even if there were a viewing platform, in the relatively low city of Dublin, the Spire proves still too high to see the history and detail of the street that it surmounts; instead it provides a broad image of a European city with little to differentiate it. Hence, the Spire provides no local frame of reference or accessible narrative, standing alone as a shining steel monolith to a vision of Dublin that is bold, masculine, technologically advanced, and economically powerful, but perhaps out of scale with the history and the people that live there. Using LiDAR data, this unique structure can be more fully understood not only in terms of its own verticality, but also in terms of its interactions with and impact upon the volumetric space that surrounds it.

Fig. 9. LiDAR data depicting the view northwards from the point of The Spire. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

Fig. 10. LiDAR depicting view southwards from the point of The Spire. Digital rendering by Brittney O'Neill and Debra Laefer, 2017.

City Scale LiDAR as a New Way to See the City

As illustrated by the images and discussion of Dublin's O'Connell Street, LiDAR opens up a whole new way to conceptualize urban spaces in a richly elaborated and accurate 3D model without which critical vertical and volumetric aspects may be insufficiently considered, as demonstrated in the case of the Spire. At a city scale, this technology has the potential to revolutionize urban studies by allowing planners a more accurate conception of the urban space, free from the limitations of mental maps, to facilitate a fully city-scale building information model wherein data of a range of types and modalities can be linked to truly 3D spatial entities in the form of LiDAR point clouds. Early work on such truly 3D spatial databases has shown great promise for integration of varied data types and sources within the unified 3D space (Aljumaily et al.). Furthermore, the increasing availability of VR systems (Zion Market Research) promises a future in which these 3D datasets can be explored in virtual reality allowing researchers and practitioners to understand and manipulate the volumetric reality of urban spaces from a world away.

Efforts are currently underway in New York City to utilize Hinks et al.'s techniques to begin to collect data of the quality and resolution seen in the Dublin dataset above but for New York City. An initial pilot dataset will be collected over $1km^2$ in Sunset Park, a neighborhood in southwest Brooklyn, and will include the added value of hyperspectral data collected alongside the LiDAR data for use in materials identification, vegetation health analysis, and surface texture information. As increasingly many vehicles are being equipped with LiDAR sensors to facilitate navigational autonomy, street side data may also become available for inclusion in city scale models and to enhance the resolution of aerial datasets at street level. In combination with operational data, data from stationary sensors, and a range of census and research data, such 3D data promises to open a whole new, not only vertical, but fully volumetric, 3D understanding of the urban environment.

Conclusions

As urban researchers become ever more interested in understanding the verticality and volume of the built environment, the limitations of traditional 2D plans and 2.5D GIS models are becoming evident in more striking ways. For example, one of the most critical limitations of 2D and 2.5D representations is their inability to accurately represent entities that have different footprints at different elevations. Additionally, overhead utility wires and seasonal decorations as well as sky bridges and elevated pathways have no footprint on the ground level but are highly significant for aerial operations, disaster planning, maintenance, city planning and more. Buildings with overhangs or protruding sections on higher floors and even balconies are similarly unable to be fully represented in 2D space and so buildings with overhangs and those without are represented identically in cadastral maps and traditional GIS, thus losing valuable information not only about the built environment but also the human experience of moving through it. In order to facilitate a full appreciation of the 3D spaces that compose the urban environment, a truly 3D mode of conceptualization and modeling must be embraced. At present, the most promising candidate for this new form of modeling is LiDAR data. Whether collected from the air or from vehicles, the inherently 3D nature of the geo-referenced LiDAR point clouds enables researchers and practitioners to ask questions and seek solutions in a volumetric environment that more accurately represents the real world, while still allowing the flexibility of a virtual environment wherein elevation and positioning can be adjusted to allow the researcher to explore areas of particular relevance. Emerging data collection, integration, and querying methods hold great promise for empowering urban planners, architects, data scientists, and other urban researchers and practitioners to answer critical urban questions at city scale without dimensional limitations.

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