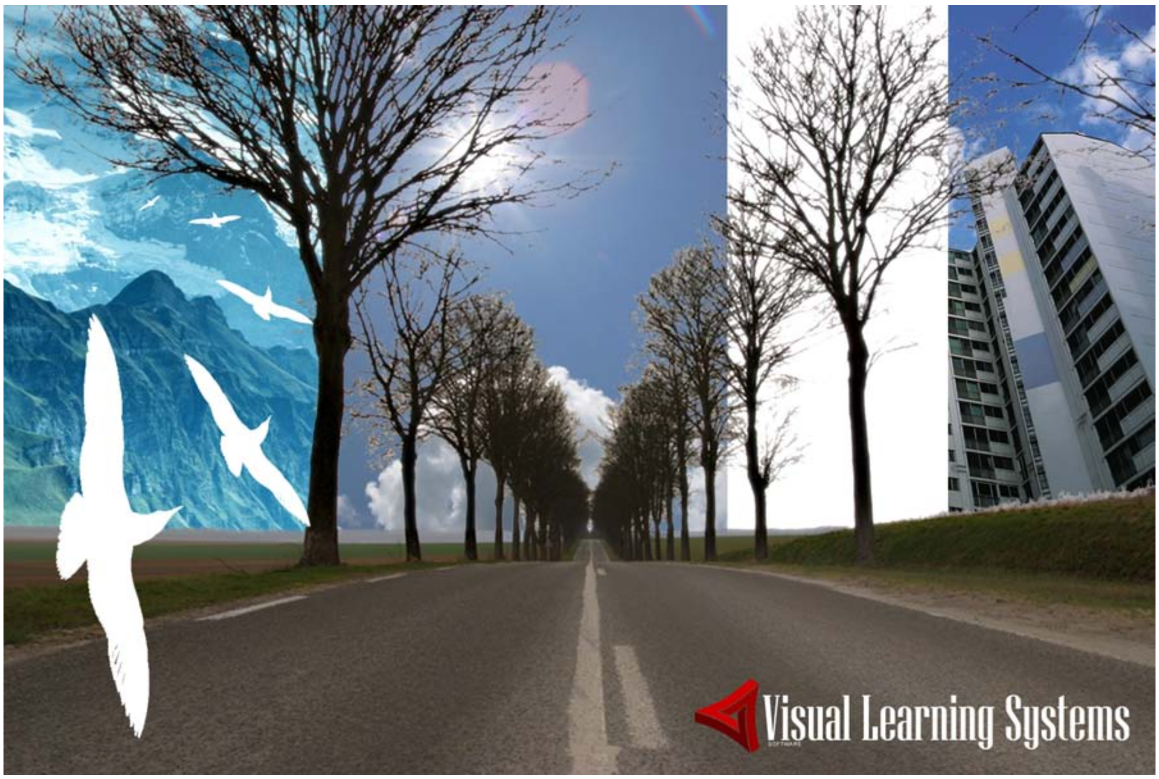
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Linear Perspective: Creating 3D Simulation from Side Profile Photography

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ABSTRACT

Geographic intelligence systems (GIS) analysts have wrestled with the task of representing three-dimensional images on a two-dimensional picture plane. There has been a rapid movement for GIS analysts to use 3D illusions to create lifelike city models for purposes such as Homeland Security. ESRI's ArcScene™ and other GIS software have made 3D geospatial simulations possible using the same principles of linear perspective originally practiced by artists in the 1400s.

Linear perspective techniques would allow GIS analysts to create 3D models in a progressive way. The laws of linear perspective do not apply easily to the standard types of bird's eye imagery used in the GIS industry: aerial, satellite and now light detection and ranging (LIDAR). Instead, linear perspective methods would work best with side profile imagery. Not only is profile imagery more accessible than bird's eye imagery, but it is also more accurate because it presents multiple sides of an object instead of only the top view.

The evaluation of various linear perspective methods for the purposes of this paper consisted of both drafting three-dimensional objects from scratch and testing each theory on existing profile photographs. These studies indicated that all of the height, width and depth information necessary to create 3D visualization became available through the use of linear perspective, requiring two visible sides in the single profile image. These findings would lead one to believe that 3D modeling could be achieved

easily using standard profile images with a computer software program designed to find vanishing points.

INTRODUCTION

The images most commonly used in GIS studies are collected from overhead via airplane or satellite. Aerial and satellite photography allow GIS analysts to survey large areas quickly, and they are becoming easier to obtain and more affordable all the time. Local governments use these types of images to build 3D maps for economic development, disaster management and environmental preservation.

The main disadvantage of using bird's eye imagery for the basis of 3D models is that it generally provides only one side of any feature: the top view. This one-sided viewpoint offers height and width, but not depth. More recently, LIDAR imagery has further enabled GIS analysts to obtain information for 3D models by providing the third dimension: depth. Alas, overhead images fail to show what exists beneath the roof.

Side profile images, on the other hand, reveal height, width and depth information plus a great deal more: doors, windows, texture, etc. Ground-level profile photographers can easily capture images from multiple viewpoints. Profile photography requires only basic knowledge, making it available with few restrictions to anyone at any time and place. Film-based camera technology has been easily understood and used for more than a century while digital photos can be viewed in the field, allowing immediate verification of image quality.

Experimenting with linear perspective involves close observation of objects photographed from every angle. Wherever converging parallel lines are perceptible, the points of intersection can be collected by extending the imaginary lines that make up the edges of the object. After finding the intersection points, called vanishing points, one can use that knowledge to identify the hidden edges of the object, thus creating building blocks for 3D simulation.

Understanding how 3D illusions work is a key to developing new innovations in 3D, and linear perspective explains it all. With the correct mix of feature extraction, art and mathematics, one can achieve the same 3D city models using side profile photography as were previously only available through aerial and satellite photography.

A firm understanding of linear perspective allows for the creation of software that collects vanishing points to build 3D simulations from, with imagery that anyone can obtain.

Automating the process of data collection for side profile imagery requires the use of linear perspective techniques. It is feasible to develop accurate, logical and consistent 3D city models using a computerized process of plotting visible coordinate points, following converging lines to vanishing points, and then discovering hidden coordinate points. The aim of this study is to inspire the design of software capable of finding vanishing points to enable the 3D representation of ground-level photography.

USING LINEAR PERSPECTIVE FOR 3D MAPPING

The human eye is a small sphere, and in order to view what the eye really sees one must simplify the facts of sight. If a viewer used only one eye, the viewpoint would begin slightly behind the center of the lens. Rotating the eye, looking in different directions, reveals the extent of the visible area, called the cone of vision. Using both eyes, the viewer would discover that the actual viewpoint differs from one eye to the other, and the cone of vision is simply the average of two retinal images, so it is arbitrarily located near the center of the head. The cone of vision can be thought of as the range of visibility that exists within the peripheral vision of the eyes (see Figure 1). Linear perspective simplifies the world in order to create logical visual representations of the world.

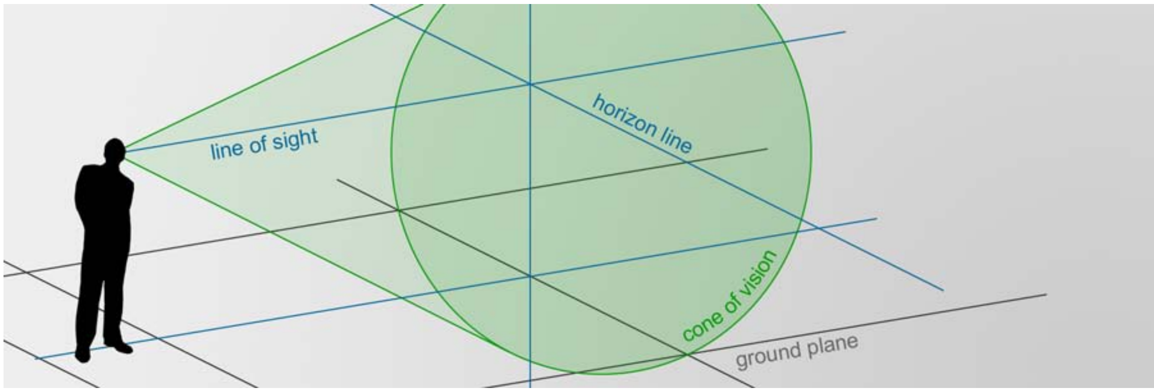

Figure 1: Cone of Vision

GIS analysts can capture a high degree of detail from side profile imagery and then simplify their findings using linear perspective techniques. Knowledge of linear perspective greatly enhances the ability to represent shapes in 3D. With the ArcScene application, GIS analysts can identify basic information about the landscape and deal with it quickly. ArcScene is not suitable for all purposes, though, because it is somewhat inaccurate, based solely on the feature's upper surface. Analysts may turn to side profile imagery when a higher level of detail is required. The level of detail desired in these representations depends on the purpose of the 3D model. Linear perspective presents the ability to influence the level of detail or simplicity.

Although the rules of linear perspective apply to all shapes, square or round, a common simplification is to illustrate theories using rectangular boxes, the most basic of all three-dimensional shapes. This benefits the GIS community for a number of reasons. First, rectangular cubes represent the simple shapes of buildings: LEGO land shapes such as those represented in ArcScene. All edges are straight lines and all angles are 90 degrees, making the 3D forms easy to visualize. Cubes illustrate the basic strategy of plotting only significant points: one can create the whole form with only eight corner points. This is precisely the strategy in map making. Finally, GIS analysts can easily plot rectangular forms on grids, providing the foundation for automated 3D representation.

Linear perspective originated during the Italian Renaissance in the fifteenth century, as a method of adding greater wisdom to representational art. Artists such as Leonardo da Vinci and Raphael were among the first to explore the subject. It is a geometrical system that creates the illusion of three-dimensional space, representing height, width and depth. While two-dimensional illustrations such as building blueprints depict only width and height, three-dimensional illustrations add depth. Linear perspective can be defined as the appearance of depth on a two-dimensional plane, such as a canvas or computer screen, through the use of converging lines. The rule is this: all parallel planes that recede in space meet at a vanishing point.

The vanishing point is the apparent intersection at which all of the parallel imaginary lines of perspective converge. A rectangular cube has horizontal parallels at the top and bottom edges, with vertical parallels on the side edges. Since distant objects appear smaller while nearer objects appear larger, the distant ends of any 3D object must appear smaller than the nearest ends. Therefore, the parallel lines of the rectangular cube appear to draw narrower at the distant ends while remaining wider at the nearest ends. Extending the converging parallel lines infinitely beyond the ends of an object yields a point of intersection: the vanishing point.

Convergence lines, also called orthogonals, trace the parallel edges of a cube and travel infinitely toward or away from a vanishing point. In the side edges of buildings, parallel lines appear wider apart from a close range or nearer together from a distance, depending on the angle of the viewer's frame of view. On the canvas, as well as on the computer screen, all objects are confined to a frame of view: the cone of vision. As previously stated, the cone of vision can be thought of as the range of visibility that exists within the peripheral vision of the eyes as well as the viewing frame of a camera, or the edges of a photograph. Convergence lines do not fit within the boundaries of the cone of vision because the length of these lines is infinite.

The horizon line is the axis around which a perspective drawing is created. In linear perspective, the horizon is represented by a straight, theoretical line appearing at the viewer's eye level. In reality, the horizon is not necessarily a straight line; it can take the saw tooth shape of mountains, for example. Figure 2A illustrates the difference between the conceptual horizon line and the actual horizon. The road offers several convergence lines that lead to a vanishing point, represented by the blue target. Although the true horizon may be hidden by walls, buildings, or hills, the imaginary horizon line in linear perspective is always visible somewhere, even if it lies beyond the extent of the viewer's cone of vision.

Leonardo da Vinci's *The Last Supper*, shown in Figure 2B, is arguably the greatest example of one-point perspective ever created. The artist's study of mathematics can be seen in the converging parallel lines in the painting. These imaginary lines can be drawn from every angle in the room, and they all lead straight to the eyes of Christ. Da Vinci's use of linear perspective is accurate and well ahead of its time. The technique is also purposeful, intending to direct one's attention to the focal point. No matter where the viewer beholds the massive painting, 15 x 29 feet, the eyes are drawn straight to the area of importance. Not only was Leonardo da Vinci talented as an artist, but he was clever beyond his time.

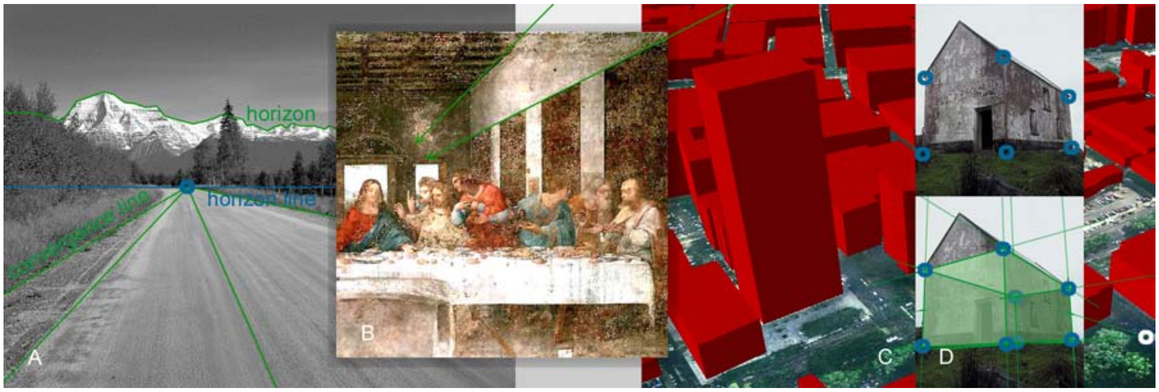

Figure 2: History of Linear Perspective

Presently, with a single side profile image of a building, one can achieve 3D simulation with results equal to or better than a typical representation in ArcScene: Figure 2C. Viewing two sides of a cube, such as a building, one can locate six corner points, called target points, and then connect these points to define building edges as shown in Figure 2D. The lines that define these edges can be extended infinitely, and eventually they will intersect. The white target point located at the bottom right-hand side of Figure 1 is an example of a vanishing point. From these points of intersection, one can achieve all of the information regarding the other four sides of a cube. Using standard ground photography and the principles of linear perspective, one can find all of the information necessary to create 3D simulation. This knowledge can be used to create a software package that enables analysts with any budget to build 3D models.

ONE- TO SIX-POINT LINEAR PERSPECTIVE AND MORE

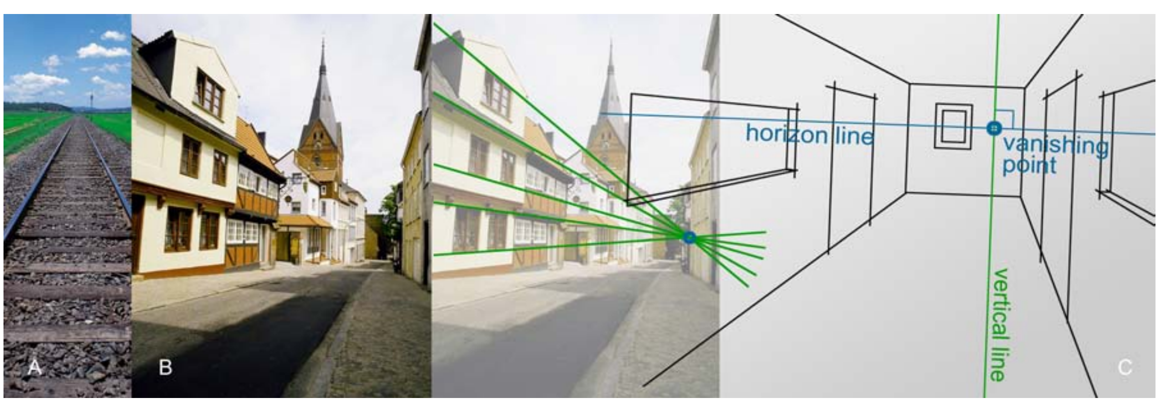

Figure 3: One-Point Perspective

Looking down a long stretch of railroad tracks, the parallel steel rails seem to join together at some point in the distance: the vanishing point. The cross ties, running perpendicular to the rails appear smaller and closer together in the distance. One-point perspective explains this phenomenon. It is the most basic technique in linear perspective. In this method, the parallel edges of objects seen straight ahead, such as the rails in Figure 3A, are drawn to a single vanishing point along the horizon line. Meanwhile, the parallel edges of perpendicular objects, such as the cross ties, remain parallel to the horizon line, growing proportionally smaller in the distance.

Viewing railroad tracks from above is like viewing a building from an aerial view in that depth is not easy to discern. A better way to see depth is to view an object from an angle near the middle of the object. In side profile images that feature three-dimensional, above the ground objects, the parallel lines that define the horizontal edges will appear to converge at a vanishing point along the horizon line. In one-point perspective, the parallel lines that define the vertical edges are always perpendicular to the horizon line. Since the verticals always correspond at 90 degrees from the horizon line, they are recognized as y-axis values while the horizon line is the x-axis.

Similarly, objects that are positioned parallel to one another share the same vanishing point. In Figure 3B, the buildings are lined up side-by-side, roughly parallel to each other. Even the sidewalks and road appear to be lined up, each parallel edge converging toward the same vanishing point. Since only one side of each building lies within the cone of vision, all of the horizontal parallel lines, shown in green, appear to travel toward the same imaginary point, shown in blue. The converging parallels found along the edge of the sidewalk, the rooftops, the gutter lines and the tops and bottoms of the window panes all appear to intersect at this point. If the buildings had been positioned at different angles each building would have its own set of vanishing points.

In linear perspective, the same laws that pertain to exterior views apply to interior views. Indoors, the horizontal parallel lines that define the edges of the floor, the tops and bottoms of windows and doors, cabinets, counters, etc. all travel toward the same vanishing point on the horizon line (see Figure 3C). The horizon may or may not be visible, but there is always a theoretical horizon line, shown in blue, that represents the point of view of the observer. The observer's point of view is also represented by a vertical line that naturally runs perpendicular to the horizon line. The intersecting point, called the zero point, represents the viewer's central focus point. In some cases, the horizon line lies beyond the frame of the image.

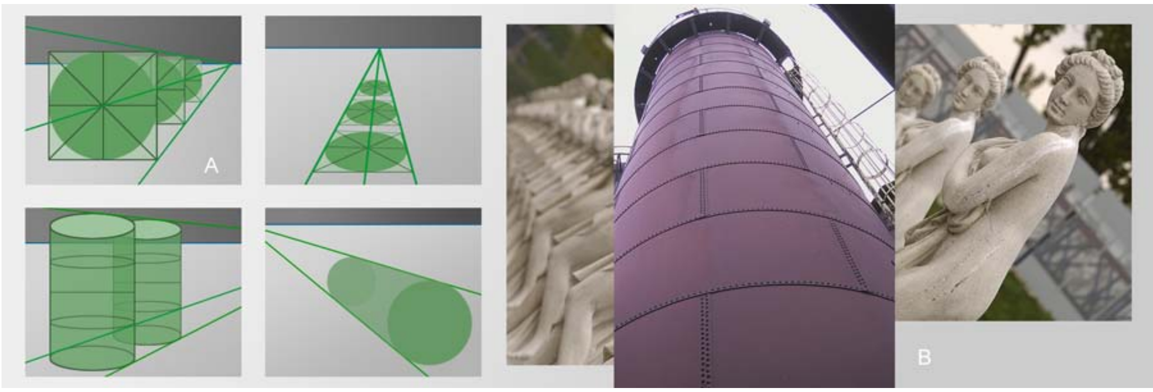

Figure 4: Round Objects and Irregular Shapes in Space

Likewise, the same laws that pertain to rectangular cubes apply to circular objects and all other shapes. Figure 4A illustrates the technique of visualizing proportionally correct round objects in 3D. This approach involves using a grid. In the first frame, a rectangle traces the edges of an oval. Using convergence lines aimed at a vanishing point, the grid can be reduced to scale as the object diminishes through space. Drawing an X between the corners of the rectangle yields the center point. The three remaining frames show what happens to round objects as they follow the laws of perspective.

Linear perspective is visible everywhere, even when no defining edges or corners are present. Spheres and cylinders move through space the same way as cubes do, according to the laws of perspective. All of the defining features in the cylindrical tower and statues in Figure 4B grow proportionally smaller in the distance. Looking up at a high object is the same as looking far ahead at a long road. The same is true with every object in every shape: features nearest to the viewer appear largest while the same features appear to fade proportionally smaller as they occur farther away from the viewer.

One-point perspective is the most primitive form of linear perspective, and it offers the least accurate depiction of three-dimensional reality. There are, however, two instances in which 3D objects appear in one-point perspective: (1) the observer is directly facing the object and the side planes are not visible; or (2) the objects are positioned at a considerable distance from the viewer. Two-point perspective occurs when at least two sides are visible at eyelevel. Instead of converging to one point along the horizon line, all of the parallel horizontal lines on the object viewed at an angle converge toward two vanishing points.

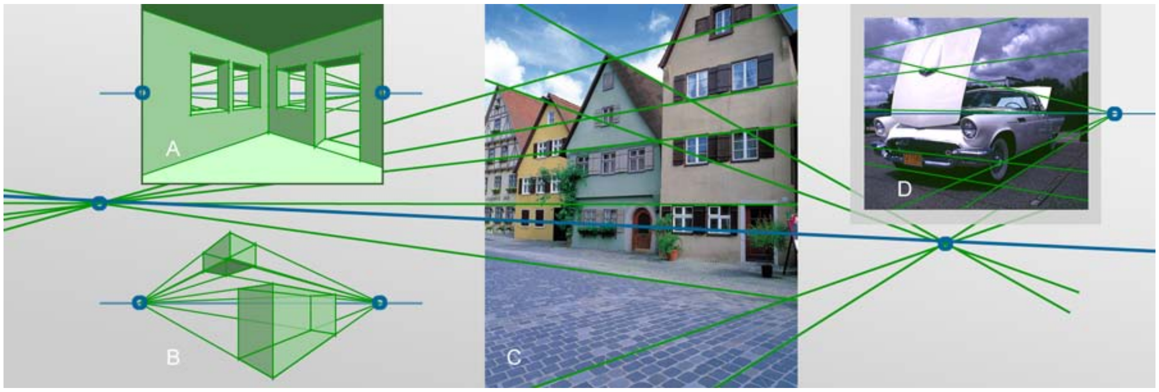

Figure 5: Two-Point Perspective

When viewing an object at its corner, two-point perspective is a more accurate way of visualizing objects in 3D. The method of two-point perspective is probably the most commonly used in 3D illustration. The same rules of one-point apply, except that parallel lines will converge onto one of two vanishing points, both of which fall on the horizon line. Figures 5A and 5B simplify the construction of three-dimensional interior and exterior shapes. One can create 3D models of actual objects using the same principles. The parallel edges that define every object converge in space toward a vanishing point. This point is the origination or destination of all related parallels.

To be more specific, the left side wall in Figure 5A features several sets of parallel edges: the ceiling, floor and window sills, each of which converges toward the point at the right. A second set of parallel edges exists on the same wall: the side depth of the window sills appear to converge toward the point at the left. On the right side wall, the top and bottom sides of the doorway and window converge to the point at the left, while the side edges converge to the right. Any interior photograph would yield the same results: horizontal edges converge toward the vanishing point at the opposite side. By comparison, an exterior photograph would yield the opposite results: horizontal edges converge toward the vanishing point at the same side, as illustrated in Figure 5B.

Figure 5C shows that each of the parallel exterior features that define a house: windows, ledges, corner points, etc. appear to converge toward the associated vanishing point. In this case, that vanishing point appears to the left of the cone of vision. To the right of the cone of vision lies a second vanishing point, found at the intersection of the convergence lines from a different set of parallel horizontal lines: the edges of rooftops and cobblestone. As seen in Figure 5C, the horizon line is not always perfectly horizontal. The horizon line, shown in blue, can take any angle because it depends entirely on the viewer's perspective, but it is usually somewhat level. A photograph taken with a level camera will always yield a 180 degree horizon line.

Objects seen at an angle, such as the car in Figure 5D, reveal two sets of converging parallel lines and consequently: two vanishing points. As highlighted in Figure 5D, the following parallel edges appear to converge to a vanishing point on the left: the top of the hood, the top and bottom edges of the license plate and the bottom of the tires. The long side of the car reveals a second set of parallel edges that appear to meet at a point to the right: the roof of the interior, the bottom of the frame, the tires, etc.

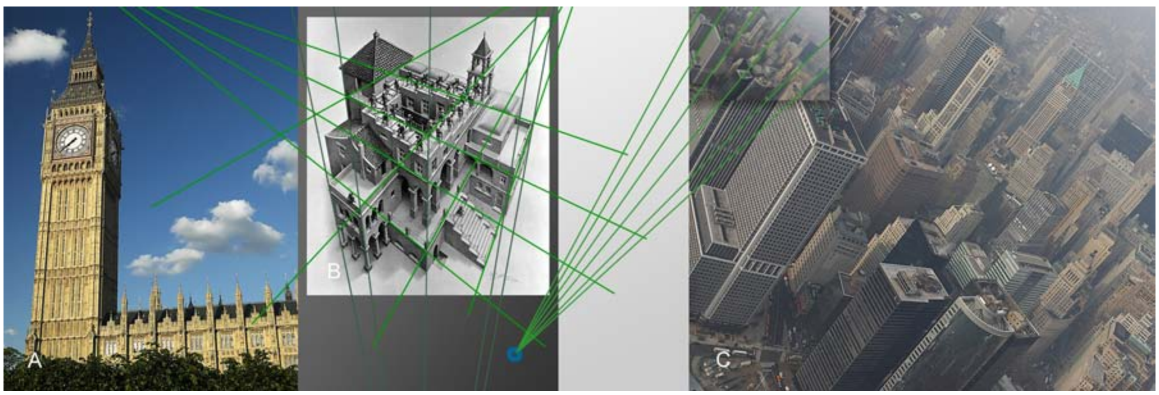

Figure 6: Vertical Depth


Figure 7: Three-Point Perspective

The two-point perspective framework is suitable for nearly all points of view except for extremely low or high angles which require three-point perspective. The third vanishing point, for the vertical edges and lines parallel to them, is invisible in most cases because the vertical parallels do not appear to converge in any direction. The distortion in vertical proportions is somewhat insignificant. If a camera on a level tripod focuses on an object straight ahead, the vertical side edges would appear at right angles to the ground, as shown in two-point perspective. As the camera tilts back to look up at a tall object, such as a skyscraper, the vertical side edges no longer appear at right angles to the ground. Instead, the edges seem to draw narrower toward the top, while remaining wider at the bottom. These vertical convergence lines indicate vertical depth.

The low eye level in the clock tower image, Figure 6A, reveals that the vertical parallel lines that make up the sides of the building are convergence lines. These lines will eventually intersect, of course, in an area high above the frame of the photograph. When looking up at a tall building from the ground, the side edges appear to grow narrower as one's eyes travel toward the rooftop. Likewise, the higher eye level in the image with multiple skyscrapers, Figure 6C, depicts parallel lines that converge in the opposite direction. These converging parallel lines lead to a third point of perspective appearing below the shape, in addition to the two vanishing points that appear on the horizon line. The worm's eye view as well as the bird's eye view allows one to recognize vertical depth, and although it is not always visible to the human eye, it always exists.

Figure 6B, M.C. Escher's *Ascending and Descending*, shows the artist's mastery of linear perspective. Escher's print displays an overhead view of an unusual building. Even though the staircase involves some deception, vertical depth is unmistakable in the downward narrowing sides along with two other sets of converging parallels, leading to a total of three vanishing points. Analyzing the print, one can see that each vanishing point exists outside of the cone of view in addition to the horizon line, high above the image frame.

Essential to the curiosity of Escher's print is the impossible, never-ending staircase with steps that appear to go up and down in either direction. To accomplish this, he rejected the linear perspective laws regarding incline vanishing points (explained later in the advanced linear perspective discussion). Depicting inclines and declines, such as staircases, shadows, rooftops or anything else, requires locating the incline vanishing point that naturally corresponds to one of the two vanishing points on the horizon. Instead of regarding the incline vanishing point that would have corrected the slope of the stairs, Escher treated the staircase as a flat plane. To prove that the oversight was intentional, he added a second set of stairs at the bottom of the building that utilizes the incline vanishing point theory perfectly.

Using three-point perspective, in contrast to one- and two-point perspective, the true vertical edges that define an object are not completely parallel to the y-axis. Three-point perspective recognizes that vertical parallel lines follow the same rule as horizontals: all parallel planes that recede in perspective meet at a vanishing point. A GIS analyst can collect three vanishing points from almost any building, tall or short. Figure 7 demonstrates the technique of extending parallel edges so that the vanishing points can be reached. The green horizontal lines converge to two vanishing points to the left and right of the cone of vision. The blue vertical lines converge to the third vanishing point far below the cone of vision.

Even without a single vanishing point that exists within the cone of vision, a GIS analyst can create 3D shapes the same way that they are represented in ArcScene. Since side profile images reveal more of the characteristic features, such as the intricate levels of the building in Figure 7, the analyst can decide the level of detail that he or she wishes to invest in the 3D representation. The right-side green box in Figure 7 illustrates a typical ArcScene representation, and shows the amount of detail that ArcScene lacks while revealing the greater potential of a 3D simulation derived from side profile imagery.

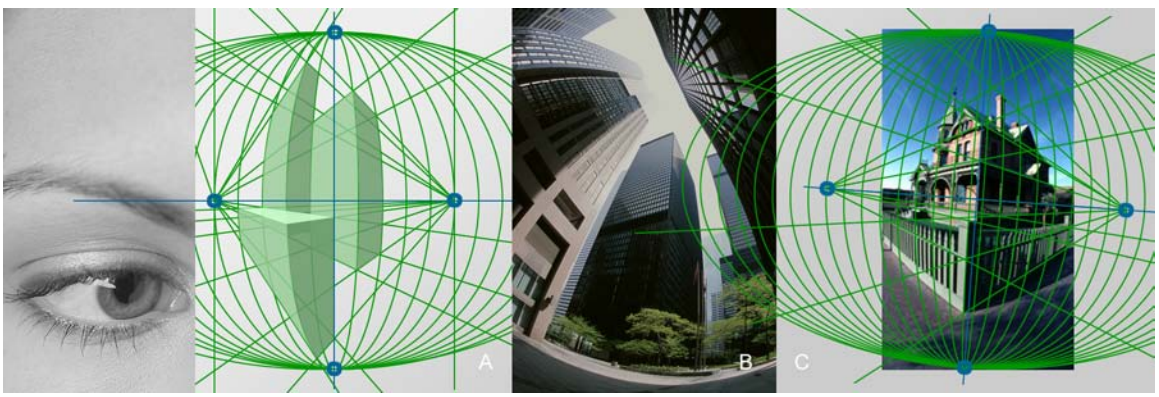

Figure 8: Four-Point Perspective

Four-point, also called curved-line or curvilinear, perspective uses the same logic as applied in three-point perspective. The only difference is the observer's point of view. When looking at a tall skyscraper, for example, from tenth floor of a medium building, part of the skyscraper at eye level appears fat in the middle. The up and down parallel lines of the building cube appear to curve in like a football with the side edges appearing to converge as they approach two vertical vanishing points called zenith (above) and nadir (below). In this case, vertical depth is seen both above and below the horizon. Figure 8A illustrates basic four-point perspective.

Fisheye camera lenses exaggerate these perceptual curves. Figures 8B and 8C illustrate the result of the fisheye lens. This effect works the same way the eyes do, and it provides a truer representation than a “corrected” wide angle lens that attempts to make straight edges look straight. Compared to the “corrected” wide angle lens, the fisheye is actually a more natural perspective for a 180 degree extreme wide angle view. The laws of perspective would agree: an object directly in front of an observer bulges in the center, appearing largest at the point nearest to the viewer while its sides converge in the distance.

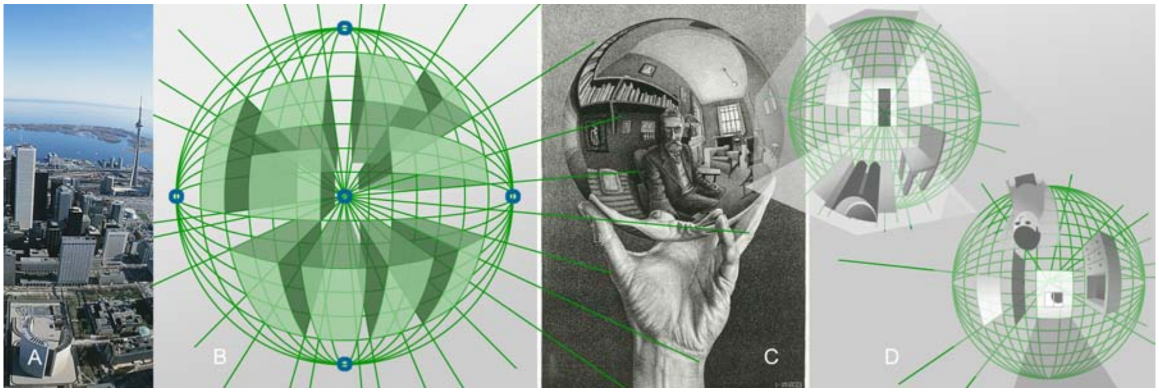

Figure 9: Five- and Six-Point Perspective

The aerial photograph in Figure 9A captures the bending of the Earth, a trait that is captured only in five- and six-point perspective. Five-point perspective means looking through a transparent hemisphere, and six-point perspective is looking through a transparent sphere. Five-point perspective takes the same concept of four-point and adds the curvature of Earth or any curved plane in one’s frame of view, as shown in Figure 9B. A fifth vanishing point can appear in front of the viewer’s eye, and a sixth one can appear in back of the viewer’s eye (see Figure 9D). Six-point perspective indicates the view ahead and behind the eye of the observer.

Figure 9C is M.C. Escher’s self portrait, *Hand with Reflecting Sphere*. This image demonstrates the general form of spherical reflections and, more importantly, it shows the way light curves around the surface of the eye. Escher’s reflection displays the curvature of perspective lines in the edges of the ceiling, walls and bookcase. His hand, which is closest to the reflective surface, is the largest object in the frame of view.

The hand is proportionally smaller at the wrist, and smaller still at shoulder, more distant from the reflection. Like all of the objects in Figure 9, objects resting on a spherical surface, even on the human eye, appear largest at close distances and diminish at far distances.

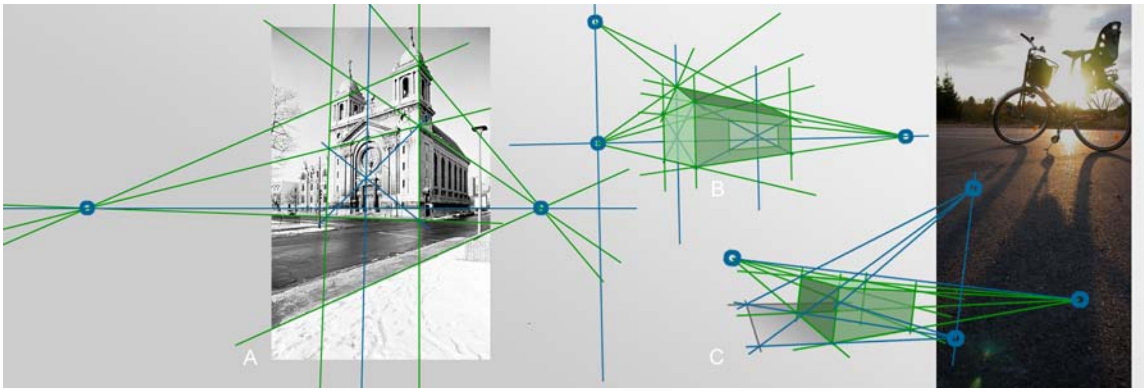

Figure 10: Advanced Linear Perspective

One of the advantages of using side profile photography for GIS purposes is the ability to see the front, back, and side views of a building instead of only the top. Mathematical principles make it simple to find center points, angles of interest such as rooftops, and even shadows. Side profile imagery enables GIS analysts to obtain more detailed representations in 3D. Instead of the simplistic LEGO land block models, houses can take more realistic shapes, including chimneys and triangular rooftops. Linear perspective explains the science of any building structure as well as the shadows cast by objects of any shape.

The center of a roof pitch, or any other feature, is found by drawing an X to connect the corners in the appropriate side of the building cube (see Figure 10A). A line drawn through the vertical and horizontal centers of the X, corresponding to the y-axis or x-axis will indicate the center of the side. After locating the appropriate center lines, angular sections of buildings, such as rooftops or arches, can be illustrated in 3D using incline or decline vanishing points. As shown in the angle of the rooftop in Figure 10B, the incline congruence line travels through the centerline of the side, reaching a vanishing point that appears along the same y-axis as the corresponding vanishing point on the horizon line.

Shadows can be explained using the principles of light and shadow vanishing points. Light radiates out from the light vanishing point, the source of light, while shadows radiate out from the shadow vanishing point, the surface where the shadow is being cast. To find the source of lighting and shading, one must pinpoint the light vanishing point, such as the sun, and the shadow vanishing point. The shadow vanishing point represents the surface plane on which the shadow appears. Figure 10C shows that the light and shadow vanishing points lie on the y-axis, perpendicular to the horizon line and the shadow edge is defined by the intersection between the light and surface planes. Shadows, explained easily by linear perspective principles, facilitate the enhanced reality of a 3D representation.

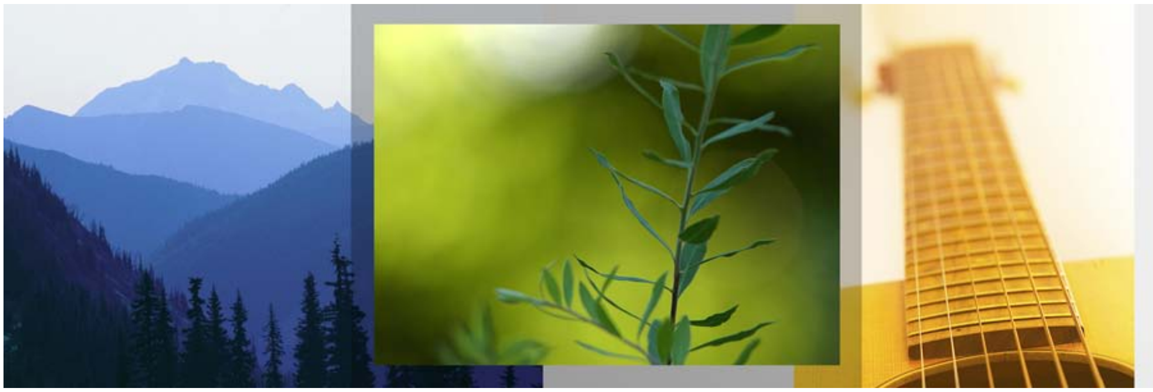

Figure 11: Atmospheric Perspective

In 3D representation, a tree seen from far away is not just a miniature image of a tree close up. The difference is explained by a different type of perspective effect, called atmospheric perspective. Atmospheric perspective gives the illusion of depth by showing the loss of contrast as distant objects appear more blue-gray as a result of the Earth's atmosphere; air contains finite particles of water vapor, dust and so on. Da Vinci called it "the perspective of disappearance." Atmospheric perspective is normally discussed in conjunction with landscape painting since its true effect is often illustrated by mountains blanketed in dark green trees that appear blue or purple in the distance and grow increasingly faint in the farthest reaches of the horizon. The same effect is seen elsewhere by adjusting the focus on a camera lens, for example, to enhance the clarity of a feature of interest.

AUTOMATING THE PROCESS

The first step in using linear perspective to create 3D simulations from side profile photography is to find the end points that make up the outer corners of an object. As shown repeatedly, one can create the whole form of a 3D rectangular cube with only eight corner points. In order to find all of the target corner points, at least two sides of the typical 6-sided building must be visible. One can collect six target points whenever two sides are shown, and these points create at least two sets of converging parallel lines. Extending the converging parallels yields three vanishing points. A computer will be able to extend these lines indefinitely to vanishing points that may be far beyond the eye's reach. From these three vanishing points, the hidden target points become available, completing the 6-sided, 8-cornered, three-dimensional rectangular cube.

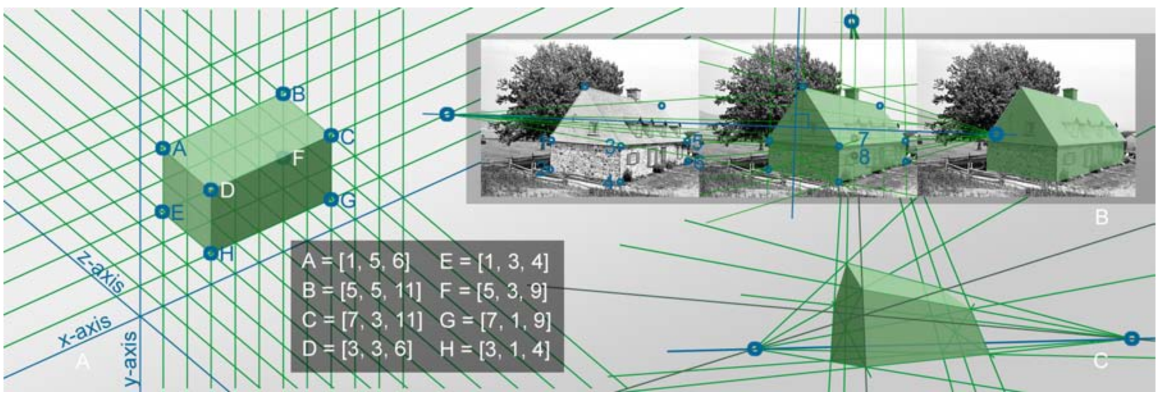

Figure 12: Automating the Process

Collecting hidden target points is simple. Figure 12B shows the process of locating target points, vanishing points, hidden target points and then creating the 3D representation. Once again, the first step is to collect the six target corner points, numbered 1-6. Next, connect the dots and extend the appropriate convergence lines until they reach the vanishing points, indicated by the larger blue targets. Then, lines must be drawn from each of the two vanishing points that lie on the horizon line through the two target points on the opposite far side. For example, lines must be drawn from the left vanishing point to points 5 and 6 in the diagram. Likewise, lines must be drawn from the right vanishing point to points 1 and 2 in the diagram. These lines intersect at points 7 and 8, finalizing the cube.

Linear perspective is simple, and the GIS industry would be smart to capitalize on it for 3D modeling purposes. The only thing missing is a computer software program that automatically locates the three vanishing points. In order to locate these vanishing points, one would first need to map the object on a coordinate system. In 3D objects, the coordinate system requires three coordinate axes. In Figure 12A, the x- and y-axes correspond to width and height, and z-axis corresponds to depth. Therefore, a point in space has three components: [x, y, z] where x, y and z are the coordinates of the x-, y- and z-axes, and each axis has its own vanishing point.

In Figure 12A, note the coordinates of point H = [3, 1, 4] and the coordinates of point G = [7, 1, 9]. Using these coordinates, one can find the lines between points and then extend the lines infinitely until they intersect with the appropriate parallels at the perspective points. By connecting end points, one can also find slope, angles, distance and other measurements that can contribute to the automation of 3D modeling from terrestrial imagery. A simplified house, such as the one shown in Figure 12C, consists of ten sets of coordinate points [x, y, z] which define the eight corners of a box plus two gable points on the rooftop.

Remember, the camera is limited by its cone of vision. The eyes view an object as they see it, but it may exist beyond the reaches of one's vision. A close up photograph of a building, for example, may not reveal all of the necessary endpoints of its sides. For the purposes of plotting points for 3D using three-point perspective, images must be captured from a frame of view that shows all of the necessary slopes (at least two parallels for each direction of perspective). The actual vanishing points do not need to appear in the camera's frame of view, however, because the computer is able to plot points outside the cone of vision. In most cases, some of the vanishing points will not be visible in the camera's frame of view, but they will all be discovered on the computer as long as two parallels from each of the three axes are shown.

There are two limitations that need to be considered when attempting to analyze side profile imagery for the sake of 3D simulation. First, buildings are not perfectly rectangular cubes. There are often slight inconsistencies between the blueprint plan and the constructed product. One of the problems is that the ground surface is not always level with the horizon line, making it difficult in some cases to define the bottom edge of a building. Fortunately, this line can be determined in most cases by using linear perspective estimates; and although buildings are not perfectly square on all sides, vanishing points can still be approximated. Similar to aerial photography, the imperfect shapes of buildings prevent absolute perfection in 3D simulation, but accurate representation is always possible.

A second limitation is that groups of buildings are not always positioned parallel to each other, preventing mass 3D feature analysis in some cases. Streets are generally not aligned in a perfect grid pattern, and homes may be staggered along curvy roads. As mentioned before, objects that are placed parallel to one another use the same vanishing points, but those set at different angles each have their own vanishing points. For that reason, one can rarely use the exact same vanishing points for all buildings. However, buildings are usually lined up with each other in some way, and a block of buildings often yields near-perfect parallels and perpendiculars. In many cases, the same vanishing points will correspond to all of the visible buildings, making 3D simulation incredibly simple. In cases of extremely dissimilar alignment, vanishing points must be collected separately for each individual building.

In urban cities, searching for common vanishing points will be an important part of reducing the time required to create the 3D model. Locating vanishing points is comparable to finding features of interest such as roads, buildings or vegetation, and the process is just as simple as using an automated feature extraction software such as Feature Analyst®. After creating a training set and specifying the parameters, a GIS analyst will be able to identify vanishing points quickly and accurately. If buildings are generally aligned, the same vanishing points apply to all. If not, then the analyst will promptly collect different sets of vanishing points. Either process will produce the same results in a timely manner.

CONCLUSION

Using side profile imagery to create three-dimensional models using linear perspective methods offers some significant advantages when compared with existing processes. Each process requires locating all of the target points that define the corners of an object. Since 8 target points compose a basic rectangular cube, all 8 must be present in order for the 3D model to occur. By comparison, 6 of the required target points are available in side profile photos while only 4 are available in aerial photos. Linear perspective techniques yield the 2 missing target points in side profile images while the 4 missing points in aerial photos require data attribution.

With the exception of LIDAR imagery, the depth dimension is unknown in aerial and satellite photography because only the top side of the rectangular cube is visible in most cases. Even though LIDAR data indicates depth, the distance of this depth is not directly proportional to the height and width of the rooftop. Only the linear perspective method allows the viewer to achieve correctly proportional height, width and depth. Plus, bird's eye images reveal only the surface top, so any feature that exists underneath the top is purely guesswork. Only side profile images reveal the true building shape.

Not only do side profile photographs present a superior vision for lifelike 3D models for GIS applications, the imagery is more affordable and easily reached. Creating 3D models from side profile imagery using principles of linear perspective is of utmost importance because it provides the same benefits of existing 3D simulations while offering every advantage of accessibility. Staying competitive in a GIS industry that is shifting from 2D maps to 3D necessitates a firm understanding of linear perspective.

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