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A review of space perception applicable to artificial intelligence robots

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인공지능 로봇에 적용할 수 있는 공간지각에 대한 종설

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Abstract Numerous space perception studies have shown that Euclidean 3-D structure cannot be recovered from binocular stereopsis, motion, combination of stereopsis and motion, or even with combined multiple sources of optical information. Humans, however, have no difficulties to perform the task-specific action despite of poor shape perception. We have applied humans skill and capabilities to artificial intelligence and computer vision but those machines are still far behind from humans abilities. Thus, we need to understand how we perceive depth in space and what information we use to perceive 3-D structure accurately to perform. The purpose of this paper was to review space perception literatures to apply humans abilities to artificial intelligence robots more advanced in future.

Key Words : Convergence, 3-D space, shape perception, robotics, artificial intelligence, computer vision

요 약 수많은 공간지각 연구 결과, Euclidean 3-D 구조는 양안 입체시, 움직임, 입체시와 움직임의 결합, 또는 여러 광학 정보의 결합으로도 복구될 수 없다는 사실이 밝혀졌다. 그러나 인간은 이러한 부정확한 공간지각에도 불구하고 특정 과제를 수행하는 데는 어려움이 전혀 없다. 우리는 인공지능과 컴퓨터 비전에 인간의 기술과 능력을 적용해 왔지만 이러한 기계들은 여전히 인간의 능력보다 훨씬 뒤떨어져 있다. 따라서 우리는 인간이 공간의 깊이를 어떻게 지각하는지, 과제를 수행하기 위해 어떠한 정보들을 사용하여 3차원 공간을 정확하게 지각하는지 이해해야 한다. 이 논문의 목적은 미래에 더욱 발전된 인공지능 로봇에 인간의 능력을 적용하기 위해 공간지각 문헌을 검토하는 것이다.

주제어 : 융합, 3차원 공간, 구조 지각, 로봇공학, 인공지능, 컴퓨터 비전

1. Introduction

It is important to receive massive visual information about our surroundings to perceive our world as well as to act in our environment. An accurate space perception, thus, is needed for even a simple movement, such as reaching and grasping an object, heading to a target location, avoiding an obstacle, and etc. Recently, robotics, artificial intelligence and computer vision have been dramatically developed and utilized in our life, but active perception dealt with the perceptual-motor loop must be included to apply robotic perception systems to our real life[1]. The virtual reality (VR) and augmented reality (AR) market, and even autonomous vehicle also have

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been grown rapidly. Although VR, AR, and autonomous vehicle relevant to robot vision have been technically improved, how human perceive space in our 3-dimensional (3-D) world should be understood to make those technologies being useful. Yi and Cho[2] proposed the real-time method to compute enormous amount of computation using the continuous data of an RGB-D camera to estimate a 3-D plane faster. AR has a problem to track the fast moving marker because the images flicker while uploading images captured from cameras. Lee and Kim also proposed an improved Simultaneous Localization & Mapping (SLAM) type algorithm for tracking dynamic objects[3]. It is clearly important not only to estimate the 3-D plane for a robot vision and AR applications also to need a proper interaction between human (or devices used by humans) and 3-D virtual environment. Shape perception can be relevant to the ability of recognizing objects but also to the general domain of space perception, such as the geometry of visual space. Numerous shape perception studies have shown that the geometry of visual space is generally acknowledged not to be Euclidean, but instead, elliptical, hyperbolic or affine. In other words, space can be distorted. To apply humans' space perception to robotics including VR and AR system, this review paper provides a historical overview of the shape/space perception literature.

2. Overview of space perception studies

2.1 Alley Experiments

Visual space is metric, mathematical space. The mathematical theory of binocular visual space questions whether the geometry of visual space is Euclidean. Euclidean geometry is the study of flat space which claims that there is the shortest straight line between every pair of points. When the surface is curved or bent, however, there are many possible shortest curves between any pair of points on a curved surface. Also, some shortest curves can be extended to lines but most of them start to wrap around the surface (e.g., a cylinder) and cannot be extended further. Riemannian geometry is the study of curved space, which is non-Euclidean and includes hyperbolic and spherical geometries. It has been found that the geometry of visual space is not defined by the geometry of flat space (i.e., Euclidean geometry), but defined by geometry of curved space. Alley experiments have shown how the geometry of visual space deviates from Euclidean space. In Blumenfeld also showed the non-Euclidean space[4]. In the distance alley experiment, a pair of lights was placed first. Then, that pair of lights was turned off and another pair of lights was placed closer to the observer to be adjusted to have equal physical distance from the first placed lights. In both parallel and distance alley tasks, observers adjusted the distance between closer lights less when compared to the distance between farthest lights. Extending the results of Blumenfeld[4], Luneburg suggested that binocular visual space is Riemannian space of constant curvature which requires hyperbolic geometry[5]. Indow, Inoue, and Matsushima elaborated this geometry by computing K, a generalization of Gaussian curvature[6,7]. The Euclidean geometry is obtained for $K=0$, the elliptic geometry for positive K ($K>0$), and the hyperbolic geometry for negative K ($K<0$). In the parallel and distance alley experiments, Indow et al. found that estimated value of K were between 0 and -1 as expected from the Luneburg's theory[6,7]. Blank provided an additional experiment to support Luneburg's mathematical theory[8]. He investigated whether the visual space is hyperbolic or spherical curvature. Two lights were placed closer to an observer and one light was placed farther from the observer so that three lights formed a triangle. Two closer lights were placed equally from the sagittal plane. The observer had to place a test light to be evenly spaced from the end point of the triangle. Observers placed the test light inside the triangle, which indicates that the visual space is curved hyperbolically not spherically.

Luneburg's theory of binocular visual space is based on the assumption that visual space is a homogeneous space of constant curvature. This assumption implies a zero disparity at all points, that is, the horizontal angular separation between the retinal images of the two points is the same in both eyes. On the other hand, Foley's studies showed inconsistent results with Luneburg's assumption of homogeneity[9,10]. Foley studied locus of perceived equidistance as a function of viewing distance[9]. In his experiment, he used five point-like lights incompleted arkness and varied a viewing distance from the observer. All five lights were placed in the horizontal eye-level plane in front of the observer. There was one fixed light on the sagittal plane and four variable lights on both sides of the fixed point were placed at angles of 12 and 24 degrees with respect o the sagittal plane. An observer was then asked to replace four variable lights to make the distance from the observer to each light equivalent to the distance from the observer to the fixed light. Although the locus of perceived equidistance had a concave curvature toward to the observer at all distances, the disparity, the difference between the visual angle subtended by the two points in one eye, and the visual angle in the other eye decreased as viewing distance increased. Furthermore, the concave curve was not symmetric about the sagittal plane, with one side being drawn in closer to the observer than the other. The curves were also flatter at the angle of 12 degrees than at the angle of 24 degrees. These results led him to conclude that the locus of perceived equidistance cannot be described by one single curve, which is to say, the visual space is not homogenous.

2.2 The systematic compression of depth perception

The past alley experiments showed that visual space cannot be Euclidean, no matter how visual space is distorted, hyperbolically or elliptically, homogeneously or nonhomogeneously. However, in the alley experiments, stimulus and viewing conditions were constrained because only a few point-like lights were used in the complete dark background and head movement was restricted. Under natural conditions these constraints could be violated. In outdoor experiments under natural conditions (i.e., using larger objects and head movement in an open field under daylight), visually perceived sagittal distance (i.e., depth) has been found to be systematically compressed as a function of physical distance[11-14]. Observer's judged distance is smaller than the physical distance of the target as the distance from the observer to the target increases. For example, Loomis et al. asked observers to match the distance between two objects presented along the line of sight a given frontoparallel distance[11]. They found that observers consistently made the sagittal distance 50 to 90 percent larger than the frontoparallel distance because of the compression of the sagittal distance. If the sagittal and the frontoparallel distance were physically the same, observers would perceive the sagittal distance smaller than the frontoparallel distance. In order to make the perceived sagittal distance equivalent to the frontoparallel distance, observers had to make it larger than the frontoparallel distance. Furthermore, Koenderink et al. measured the pointing angles to investigate the curvature of visual space[12]. In a natural outfield, the pointing device and the sphere shaped target mounted on a tripod were placed in front of the observer. The size of the target was varied such that the different distances appeared to be the same size. Both pointer and targets were always at the observer's eye height. The observer was instructed to point the arrow of the pointer to the target using a transmitter while looking back and forth between target and pointer. The angle subtended by the visual direction to the target and the visual direction to the pointer was 120° and the distance from the observer to the target was equal to the distance from the observer to the pointer. Thus the veridical pointing angle subtended by the visual direction to the target and the pointing direction from the pointer to the pointer was 30°. The results showed that the judged pointing angles were larger than the veridical pointing angle, 30° at the near distance and smaller at the far distance. As the triangle configuration, the optical space is elliptical (positively curved) in the near field but hyperbolic (negatively curved) in the far field. Thus, the curvature of visual space changes systematically with the distance from the observer.

The previous studies of space perception have postulated continuous distortions in visual space. Although perceived depth is systematically compressed as a function of distance, humans can perceive 3-D structure from the patterns of light projected onto the 2-D retina. What sources of optical information lead this ability to perceive 3-D structure? There are many potential sources of information available in the visual system to perceive 3-D structure. Some of these optical sources are texture gradients, linear perspective, and patterns of shading which are mainly accessible within individual static images. Other sources of optical information are described by the changes among multiple images including binocular disparity and structure from motion. Since binocular stereopsis and motion are considered the most effective source of optical information for the perception of 3-D structure, these two methods have been highlighted and expansively investigated.

3. Perception of 3-D structure

3.1 The perception of 3-D structure from binocular stereopsis

One of the most robust sources of optical information to perceive 3-D structure is binocular disparity. In previous studies, the observers binocularly viewed the stimuli but the stimuli used were widely spaced, isolated points, as well as rods or planes in both laboratory and outdoor environment. Johnston examined 3-D structure from binocular disparity using the shape of continuous smoothly curved surfaces presented as random dot stereograms[15]. Here, circular cylinders were displayed and the half-heights of their base were varied at three different viewing distances. The task was to judge whether the depth of cylinders was greater than or less than the half-height between 1 (flattened) to 5 (elongated). Similarly, the observers' judgments were systematically distorted with the viewing distance from the observer. The observers overestimated the depth of circular cylinders at a near viewing distance and underestimated at a far viewing distance. In other words, truly circular cylinders appeared elongated at a near distance, close to veridical at an intermediate distance, and flattened at a far distance.

3.2 The perception of 3-D structure from motion

It has been also considered that another robust source of optical information for the perception of 3-D structure is motion. Wallach and O'Connell found that the stationary 2-D shadows of some forms, solid or wire frames, appeared as 3-D structures only when stationary shadows were observed in rotation[16]. They referred to this phenomenon as the kinetic depth effect. As computer technology advanced, researchers created 3-D structure from motion displayed on a computer monitor. Also, mathematical analyses for computing structure from motion has been developed to figure out what type of perceptual mechanism would allow observes to determine the 3-D structure under projected motion. Ullman analyzed this, using configurations of discrete points rotating in depth under parallel projection in which a small number of points could be identified across a small number of discrete temporal “views”[17]. He showed that 3-D structure could be recovered when four non-coplanar points are moving rigidly over at least three successive views under parallel projection. However, Todd and Bressan[18] and Todd and Norman[19] found that observers' performance to discriminate 3-D lengths or angles between lines oriented in 3-D space and to distinguish between rigid and nonrigid 3-D motion was not improved even with increased number of views. In contrast to Ullman's theory that 3-D shape could be determined by at least three distinct orthographic views, they suggested that perception of 3-D shape could be defined by two successive orthographic views. They also suggested that 2 successive orthographic views are theoretically sufficient to resolve the structural properties of any object that remain invariant under affine transformations, but 3 or more orthographic views are needed to determine the properties of Euclidean structure. Thus, humans can use only limited information available from 2 motion sequences, and cannot take additional information available from 3 or more motion sequences.

Then, what are the properties of Euclidean and affine structures? Klein categorized geometry visual space into a hierarchy based on how different transformations affect different aspects of object structure: Euclidean, similarity, and affine geometries. Any geometric transformation of an object allows that some of its structural properties are changed, while preserving other properties. Euclidean geometry allows rigid rotation and translation, which preserve size and shape of an object. Similarity geometry allows also scaling size isotropically, which preserves only shape of the object. Affine geometry allows scaling size differently in different directions, that is, frontoparallel and the line of sight, which preserves “relief shape” of the object. For example, one cannot discriminate two objects related by a stretching transformation along the line of sight. Two such objects are referred as being “affine equivalent along the line of sight”. However, from the information of two successive views, it is possible to discriminate between flat and curved surfaces because they are affinely different which means that any type of uniform stretching transformation cannot make flat surface to curved surface.

Cornilleau-pérès and Droulez asked observers to discriminate between flat plane and curved cylinder from their motions[20]. A cylinder was curved either along vertical axis (i.e., perpendicular to the image plane) or along horizontal axis (i.e., parallel to the image plane). They found that observers detected curved surfaces more sensitively when cylinders were curved in the perpendicular direction of rotation than when they were curved in the same direction of rotation. Furthermore, Norman and Lappin investigated the observer's ability to discriminate shapes of surfaces other than cylinders and planes using four different types of surfaces: spherical surface, horizontally and vertically oriented cylindrical surfaces, and planar surface[21]. The surfaces were rotated around the vertical axis tangent and centered at the front of the surface. They also found that the accuracy of observer's discrimination between shapes of surfaces decreased when surfaces were curved along the direction of rotation. In other words, observers discriminated between the vertically curved cylinder and the plane less accurately than between the sphere or horizontally curved cylinder and the plane. Observers discriminated between spheres and the vertically curved cylinder more accurately than between the sphere and the horizontally curved cylinder. Thus, observers perceived the horizontally curved cylinder as more close to the sphere, while they perceived the vertically curved cylinder as more close to the plane. The last finding was that increases in the number of points from 9 to 91 or the number of views from 2 to 15 had little or no effect on the accuracy of discriminations. Again, observers showed impressive visual sensitivity to surface curvatures from two successive views.

The main difference between Euclidean and affine geometries is the ability to discriminate distance intervals oriented in different directions. In Euclidean geometry, one can discriminate distance intervals in different directions, but in affine geometry, one can discriminate distance intervals in parallel directions, but not in different directions (see [22]). Norman and Todd examined the observer's ability to discriminate between rigid and nonrigid motions[22]. Observers perceived nonrigid stretching transformations of a rotating 3-D object along the frontoparallel axis as a nonrigid motion, whereas nonrigid stretching transformation along the line of sight was perceived as a rigid motion. This result suggested that the human visual system may be limited to first-order temporal information (e.g., velocity) which is available within two successive views, but not be sensitive to second-order temporal information (e.g., acceleration) which is available within three or more successive views. Humans may not be able to accurately detect the magnitude of second-order temporal relations that is required to recover Euclidean properties related to shape.

3.3 The perception of 3-D structure from combination of multiple sources

All studies focused on 3-D structure from binocular stereopsis and structure from motion have indicated that neither stereo nor motion alone provides enough optical information to perceive 3-D structure in space accurately and consistently over changes in viewing distance or orientation. It could be the problem of restricted source of optical information, because humans in natural vision have multiple sources of optical information. Thus, it could be possible to perceive 3-D structure more accurately if stereo and motion are presented in combination.

Richards has shown that Euclidean structure of an object can be recovered from two stereo views of 3 or more points when presented stereo is combined with motion[23]. Theoretically, in a combination of stereo and motion, motion could eliminate the ambiguity in stereo or vice versa. Other researches, however, have shown that there is no benefit from the interaction between stereo and motion. Tittle and Braunstein found that stereo and motion are not interacted to process depth information[24]. Instead, stereo information determines the judgment of the shape when stereo and motion are presented in combination. Consistently, Tittle, Todd, Perotti, and Norman found that there was no significant improvement on observer's judgments when 3-D object was specified by binocular stereopsis and structure from motion[25]. There were three judgments tasks to investigate the geometric relation between physical and perceived space from combined sources of optical information. First, observers had to adjust the shape of the cylindrical surface so that its cross section appeared circular using a mouse. Second, observers had to adjust the magnitude of a dihedral angle until it appeared to be 90°. The last task was to adjust the angle between the two planes until it appeared to be 180°. To examine the influence of other variables on judgments of shape, they varied viewing distance, average slant relative to the frontoparallel plane, and stimulus display type (monocular motion, static binocular stereopsis, or combined motion and stereo). Overall, judgments of 3-D shape from motion did not exhibit consistency over changes in the orientation of an object in depth and judgments of 3-D shape from stereo and combination did not exhibit consistency over changes in viewing distance. These results showed that stereo and motion determine 3-D structure differently and are affected by changes in viewing distance and orientation, respectively. Also, the results replicated the results of Tittle and Braunstein[24], which stereo dominates motion when two sources of optical information are conflicted.

Although it has been found that stereo and motion do not interact with each other, different types of information such as shading, texture, or highlights could interact with one another. However, this is not the case. Research showed that the integration of multiple sources including shading, texture, highlights, stereo, and motion had no significant improvement on the judgments of 3-D structure[26,27]. In the experiments of Norman and Todd, the task was to discriminate whether the depth or orientation difference between the two highlighted surface regions was greater than or less than the standards[26]. The displays were specified by many redundant sources of optical information, including stereo, motion, texture and shading with sufficient lighting. The observer's performance was not accurate, despite the availability of all this optical information

4. Possibility for accurate space perception related to action

When considered as a whole, shape perception (space perception) studies have shown that Euclidean structure cannot be recovered from perception of stereopsis, structure from motion, even structure from combination of various sources of visual information (e.g., stereopsis and motion or full cue condition). However, there is no problem for humans to perform complex visually guided actions accurately despite of inaccurate space perception. Then, the question is how?

4.1 Large visual angle

One possible to explain that shape cannot be perceived accurately is crucial sources of optical information might be missing in the laboratory experiments compared to our natural environment. Börjesson and Lind tested whether polar projection could provide enough information to recover Euclidean structure from apparent motion sequences[28]. A simulated triangle oscillating about a vertical axis (i.e., in depth) was used under parallel or polar projection. The observers had to identify which of the two lower sides of the 3-D triangle had the longest length. In summary of length judgments, observers performed poorly regardless of the type of projection. Although there was no improvement of judgments of Euclidean structure with polar projection, Börjesson and Lind investigated the effect of large visual angle under polar projection[28]. They used a sinusoidal protuberance simulated with a continuous dot surface which directed toward the observer from polar-projected motion. Observers had to judge the height of the protuberance relative to its width at the base by moving the vertical line on the screen to reproduce the height to width ratios. Whereas the observers could not judge the height to width ratios correctly at the small visual angle, they consistently performed correct judgments of the ratio at the large visual angle. Although the large visual angle yielded more precise space (depth) perception compared to the small visual angel, the height to width ratios were still underestimated as the simulated ratios increased. Thus, Euclidean structure was not fully recovered even with the large visual angle. Still, however, we know that the large visual angle on the polar project could provide additional optical information to perceive the depth dimension.

4.2 Calibration of the task-specific actions

Although it is possible to perceive Euclidean structure accurately under polar projection with the large visual angel, it is still limited to explain our actions without any difficulties in real environment. Recent studies investigated the relation between perception and action have suggested that task-specific actions can be calibrated by visual or haptic feedback[29-32]. Bingham, Zaal, Robin, and Shull found that haptic feedback calibrated reaches-to-grasp but the feedback drifted away after time[29]. They suggested that we do not need consistent haptic feedback for correct reaches-to-grasp but it is important to have regular feedback within a period of time to calibrate the action. Although haptic feedback calibrated object distance and size, shape of objects was not calibrated by haptic feedback. Another way to calibrate the desired action is online guidance. Lee, Crabtree, Norman, and Bingham found that observers judged the aspect ratios of the object accurately under the closed-loop condition (when their hand was seen) compared to open-loop condition (when their hand was not seen)[33]. Thus, shape perception should be continuously guided online to be accurate and to modulate the desired action.

4.3 Applying space perception to robotics

Any developed machine (robots, AI, etc.) even with today's technology is far from behind compared to the human capabilities. Thus, to make advanced robots, researchers have tried to mimic human capabilities. Farag, Saad, Emara, and Bahgat presented an automated system with a five-axis articulated robot arm to reach objects in 3-D space[34]. They used a particle swarm optimization (PSO) algorithm and customized stereo vision so that the estimated object coordinates error is minimized. "The accuracy of the stereo vision with respect to the depth was evaluated by calculating the root mean square error between the physical points coordinates with respect to the camera coordinates system after transformation to the robot arm coordinate system and the coordinates of these physical points with respect to the robot arm coordinate system"[34, pp. 2739]. Lin and Woldegiorgis investigated the interaction of space perception and performances in stereoscopic environments[35]. Judgments of egocentric distance were inaccurate in stereoscopic displays but direct pointing provided calibration and thus, improved performances.

5. Conclusion

As a computer vision and intelligent robots are dramatically developed these days, it is important to understand humans' perception and action because humans ability to perceive and perform is much advanced than machines even with cutting edge technology. Numerous space and shape perception studies, however, have been found that judgments of depth in space are systematically compressed and we cannot perceive Euclidean 3-D structure accurately. We cannot recover Euclidean 3-D structure even with various sources of optical information, such as binocular stereopsis, structure from motion and combinations of both. It is, however, possible to recover Euclidean 3-D structure to perform in real environment without any difficulties. First, the large visual angle could yield more accurate space perception. Second, space perception can be calibrated by visual or haptic feedback. The continuous on-line guidance also can provide important information to yield the task-specific action. In the virtual environment which requires interaction with human[36], virtual reality users modified their perceptions of the virtual environment space when distorted virtual body, such a long or short virtual arm was provided (open loop). Having a distorted body, however, required experiences of reaching to calibrate their movements. Thus, visual-motor feedback of reaching was necessary for perceiving distance in space accurately.

In conclusion, to understand how humans perceive Euclidean 3-D structure to perform complex visually guided actions accurately is necessary to develop the modern machines, including computer vision, robotics, VR and AR, etc.

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