A New Approach to Visual Simulation

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The need for realism in visual simulation, particularly for the critical maneuvers of aircraft takeoff and landing, has long existed and has increased enormously with new requirements to operate under extreme conditions of low visibility. Not only is it difficult and dangerous to train for these conditions in the actual airplane, but the training problem is compounded by the fact that a mission in the aircraft must wait for the combination of the desired weather conditions and the availability of air space to occur. This paper describes the various approaches that the industry has taken in the attempt to solve the visual problem and provide the necessary training value. A new approach to the problem is described also which exploits the philosophy of limited corridor simulation and exercises the tradeoffs of limited freedom of maneuver in order to provide superior picture quality.

Ideal Visual System

THE ideal visual system for takeoff and landing can be described very simply. It should contain the following two basic capabilities: 1) Unlimited freedom of maneuver—the ideal system should have unlimited capability to simulate aircraft maneuvers in six degrees of freedom over any portion of terrain within a 15- to 20-mile radius around the airport where the landing will take place. 2) High quality presentation—the picture quality displayed to the pilot should contain real-world fidelity in full color over the entire field for every portion of the flight path. If these two fundamental parameters are achieved, various subsystems can be devised to degrade or fog the picture, simulate weather effects, and, thereby, provide a true visual simulation.

How Good is Good?

The acuity of the normal human eye often has been described as one minute of arc. This acuity is obtained under conditions represented by a man lying on his back in an open field, after having been thoroughly dark-adapted, looking at the stars against a black cloudless sky. Under these conditions, which approach infinite contrast, the eye is barely capable of distinguishing two stars that are separated by an angle of one arc minute from a single star having a larger subtense. Observing the same contrast through an aircraft window under clear air visibility unlimited conditions, the normal eye will resolve approximately three minutes of arc. In common terms, this means that two white posts on a hill which subtend an angle of three minutes of arc at the eye, can barely be distinguished as separate entities.

However, the significance of poor resolutions in the presentations must be stressed from the standpoint of picture quality rather than data content. As the resolution content degrades appreciably beyond three arc minutes, the observer sees the entire picture as one that is defocused rather than one in which he cannot separate small objects and cannot resist the urge to adjust the focus control.

The picture quality of any form of visual simulation system can be expressed in television lines per picture height (Radio Electronics and Television Manufacturers Association definition), per picture width, optical line pairs, or minutes of arc. Typically, the means of resolution measurement is the use of a test pattern containing equally spaced alternate black and white lines of variable size and spacing. The numerical resolution is measured at the point where alternate lines can barely be distinguished. The only meaningful measurement for visual simulation systems is that obtained in minutes of arc (the subtense of two alternate white lines in the pattern), since this is the method that relates directly to the acuity of the eye. This relationship becomes clear when one recalls the common experience of watching television at home. The presentation looks reasonably good from a distance, but relatively poor from only one or two feet away. In this example, of course, the resolution of the television system is constant when measured in lines of picture width or height, but varies in angular terms with the viewing distance. Generally, the point at which the picture looks sharp and clear is the point where the resolution is about three arc minutes.

Considering a picture with a resolution content of three minutes of arc measured at the eye with a nominal forward field of view of 50 deg, the resolution content in television lines per width is equal to

$$\frac{60 \text{ min/deg}}{3 \text{ min}} \times 50 \text{ deg} \times 2 \text{ TV lines/line pair} = 2000 \text{ TV lines}$$

If a film presentation with a picture content of 50 lines per millimeter is used, the total picture format required for three arc minutes resolution is

$$\frac{60 \text{ min/deg}}{3 \text{ min}} \times \frac{50 \text{ deg}}{50 \text{ line pairs/mm}} = 20 \text{ mm}$$

Thus, considering resolution as the governing criterion, a minimum film format of 20 mm is required for a 50-deg presentation, whereas the television resolution required for the same clarity is beyond the state-of-the-art.

Another factor that must be considered in evaluating picture quality is contrast, which is defined as the ratio of the brightness of the lightest object to that of the darkest object in the field. While a home television receiver has a resolution content of three arc minutes when viewed from approximately 10 ft away, and a motion picture presentation viewed from a front seat in the theater has the same, it is generally conceded that the subjective quality of the motion picture is superior. The reason is that the typical maximum contrast ratio from a television presentation is approximately 20:1, whereas that of a motion picture is approximately 100:1. For this reason, the motion picture provides a sharper image than television.

Systems Providing Unlimited Maneuverability

The subject of the medium of transmission has been discussed from the standpoint of limitations imposed on the de-

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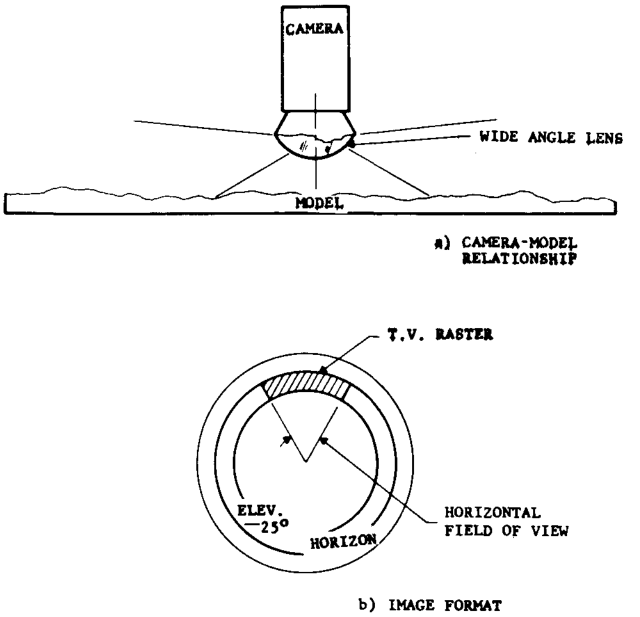

Fig. 1 Direction analog systems—wide-angle approach.

sired quality of presentation. However, in general, this has not been the most severe limitation of systems that have been developed to provide complete freedom of aircraft maneuver. Other limitations, caused by optical pickup systems, diffraction effects, and physical size of the storage medium, are more severe. Following is a discussion of each approach that has been employed and the results of its most severe limitation. In general, the effects have been that of poor definition in the foreground that gradually improves (although limited by the medium of transmission) in the background—a phenomenon that is the opposite of natural observation.

1. Three-Dimensional Terrain Model and Television Camera

The earliest approach taken to this problem is a direct analog of the real-world situation. This design uses a three-dimensional model of the terrain in conjunction with a television camera that is "flown" in six relative degrees of freedom. Systems utilizing this approach have been built at scale reductions ranging from 1:150 to 1:3000. Paradoxically, from the standpoint of model size, the best picture quality is obtained with the lowest scale reduction, 1:150. This is apparent when it is realized that the greatest picture degradation occurs when the aircraft is at its lowest altitude and, therefore, the optical probe of the television camera is closest to the model. In general, the degradation results from the inability of the lens to focus on the near foreground when the attempt is made to focus from infinity to a few millimeters away.

Recently, stimulated more by the desire for wide-angle display than by the need for picture quality, this system approach has been implemented using a wide-angle or "fisheye" lens. In this approach, the lens picks up a solid angle of greater than 180 deg with its axis positioned at nadir. Figure 1a shows the relationship between the lens and the model, which are relatively positioned in the three translational degrees of freedom, while attitude effects are provided by electronic manipulation of the raster shape and position. This full solid angle is reduced to the plane of the camera tube with the inherent high level of distortion that is prevalent in all wide-angle lenses. Although this distortion can be removed from the final display by electronic raster shaping on the camera tube, probably the most critical problem determining final image quality is in the resolution capability of the lens itself. It is apparent from the geometry of Fig. 1b that the area of best lens resolution, which is the portion along the lens axis, is never used in a display except in the seldom-used condition of a 90-deg downward pitch attitude. The area of principle interest, unfortunately, is the portion of the lens in the extremes of its angular field where the resolution is poorest. Typically, the performance of a lens of this type results in an angular system resolution at the best point in the field of 15 arc min, if problems of depth of focus can be completely ignored. Although the depth-of-focus problem associated with this type of lens is not as severe because of the smaller pupil size, some degradation for close viewing should be expected. Although the small pupil size that results from practical element sizes relieves the depth-of-focus problem, it causes over-all picture degradation.

2. Transparency Models

Another approach to providing completely unlimited freedom of maneuver is the use of the orthophotograph transparency. This transparency utilizes a photographic emulsion for storage. It contains the area over which the aircraft is to be flown as a vertical photograph taken from "infinity." One approach to image generation from this type of storage is the use of a flying spot scanner with keystone distortion introduced into the raster, so that the resultant display shows the correct perspective of a flat earth. In other words, the shape of the raster on the flying spot scanner is equivalent to a projection of a rectangular windshield (display) onto the ground from the aircraft position, as shown in Fig. 2.

If the limit of the television system employed is 1000 lines, it can be assumed that performance limited by television can be preserved as the 20-mm format, established earlier, is reduced to 10 mm. This slight degradation allows the transparency to be built at a scale of 1:1000, which permits a 15-mile approach to be reproduced on a transparency only 90 ft long. However, another limitation of this approach is the spot-size capability of the flying spot scanner. In this case, it must be realized that the horizontal line nearest the apex of the triangle in Fig. 2b represents the entire foreground of the picture, the quality of which is limited by the number of spots that can be resolved across its dimension. Thus, in a flying spot scanner transparency system, the foreground is again severely defocused, but in this case not as a result of optical limitations in the lens system. It should be noted that this spot-size limitation is completely independent of transparency scale factor, since the total line length along any azimuth line on the cathode ray tube must represent a given ground range at any scale. Using a system capable of displaying 5-mile visibility utilizing a 5-in. cathode ray tube as the flying spot scanner under the best of conditions, the 5-in. dimension must correspond to the five miles of terrain that can be seen at one time, since the magnification of the optical

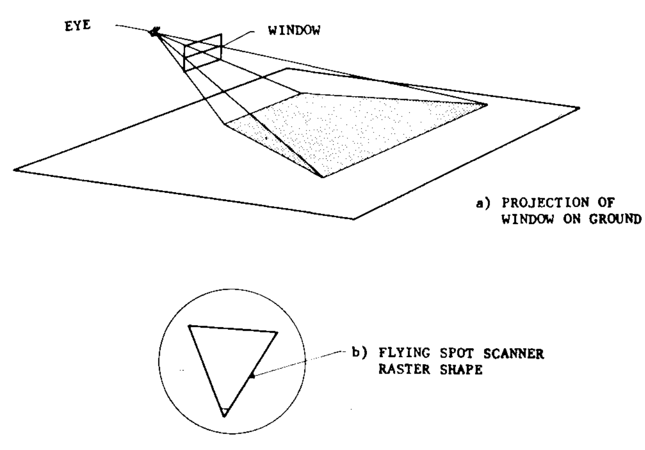

Fig. 2 Orthophotographic transparency geometry.

system used to image the tube on the transparency will determine the scaling. Thus, if 5 in. corresponds to 5 miles, the closest point that can be observed on the runway (35 ft away) corresponds to approximately 0.006 in. at any scale. Considering a tube with a spot size of 0.001 in., which approaches the best attainable, a total of six spots of six "TV lines" is resolvable across the bottom of the widescreen. Extending this shows that 1000 TV lines, or six arc min resolution over a 50-deg field, is only obtained at a distance of 1 in. (one mile at scale) from the apex of the triangular pattern.

Systems have also been produced using the same type of transparency storage, but avoiding the medium of television. In this approach, a point source of light is positioned to the scale analog coordinate of the aircraft, and the necessary keystone distortion for correct perspective viewing is introduced by direct projection on a screen. This arrangement is illustrated in Fig. 3a. This approach is limited by both the quality of the transparency and by the physical dimensions of the point source, as illustrated in Fig. 3b. This sketch shows how a point source with physical dimensions causes a sharp line in the transparency to be focused over a substantial area on the screen as a result of the physical size of the "point" source itself. Beyond this restriction, the optical wavefront at the plane of the transparency causes an additional resolution limitation that results from the diffraction effects inherent in the wave character of light. Strangely enough, this limitation, even for relatively small scale reductions, is often more significant than the geometric limitation measured in lines per millimeter at the photographic transparency. As a result, the foreground appears defocused again, while the background contains greater clarity.

The VAMP†

To provide real-world fidelity, the presentation through the windscreen should have approximately three arc min of resolution over the entire field, be in full color, and contain an image contrast approaching 100:1. In addition to these parameters, the picture should also be very bright so that sufficient light is available in the cockpit for map reading, etc., without appreciably degrading the contrast in the picture. To date, it has not been possible to provide anything approaching this level of picture quality in a system capable of unlimited freedom of maneuver. The foregoing paragraphs illustrate the approaches that have been taken, all of which have fallen substantially short of achieving the high-quality presentation needed for all portions of the mission.

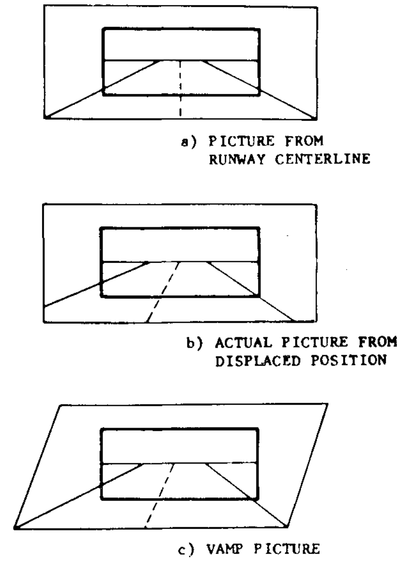

Fig. 4 Lateral position change.

Another approach that is capable of freedom of motion within a more limited corridor does have the capability of providing the necessary realism from approach through touchdown and rollout on the runaway. This system, called Variable Anamorphic Motion Picture, or VAMP, utilizes an actual motion picture of an aircraft approach and landing as input storage. This picture, combined with servo-controlled distortion optics, enables the picture to be altered to provide realistic simulation of displacements from the ideal approach in true perspective. The use of motion pictures obtained during real-world flight assures the required realism in playback, whereas the envelope within which freedom of maneuver is enabled, is sufficient for adequate training in the approach, landing, and takeoff maneuvers. For the majority of the mission, the excursion envelope is considerably greater than the limits of instrument landing systems commonly employed in most aircraft.

Figure 4 illustrates the principle underlying this approach by depicting a scene taken from the runway centerline in Figure 4a, and an actual picture taken from a position to the right of runway centerline, as shown in Fig. 4b. In both of these illustrations, the small rectangle represents the field of view displayed before the pilot; the larger rectangle represents the total format contained on the film. Figure 4c illustrates the effect of anamorphic lenses in distorting the rectangular format on the film to that of a parallelogram.

While this distortion is effective over the entire picture format, the slanted edges are not apparent in the field observed by the pilot. Since the image contained in the smaller rectangle is identical in Figs. 4b and 4c, the pilot observes a true illusion of the position change which follows his commands, thus creating the feeling that he is flying the airplane. Illustrating the principles by which a change in altitude is simulated, Fig. 5a represents a normal picture from altitude $h1$, while Fig. 5b represents a picture taken from an altitude higher than $h1$. In Fig. 5c, the method by which the distortion optics stretch the entire picture in the vertical dimension is shown. Again, in all three illustrations, the inscribed rectangle represents the pilot's field of view showing that portion of the picture in Figs. 5b and 5c to be identical. Thus, the illusion of altitude change is created, which can be combined with the lateral changes shown in Fig. 4 to provide freedom of maneuver anywhere within the prescribed envelope. The parallelogram distortion illustrated in Fig. 4 and the vertical

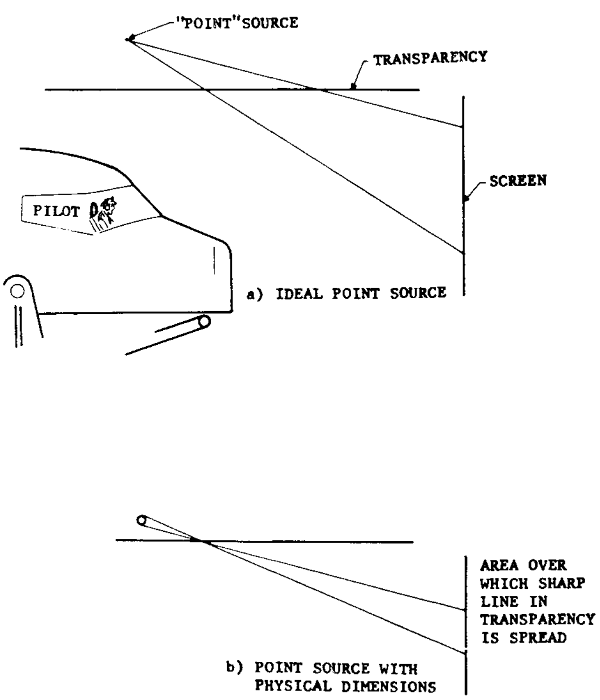

Fig. 3 Point source system.

† Trademark General Precision Systems Inc.

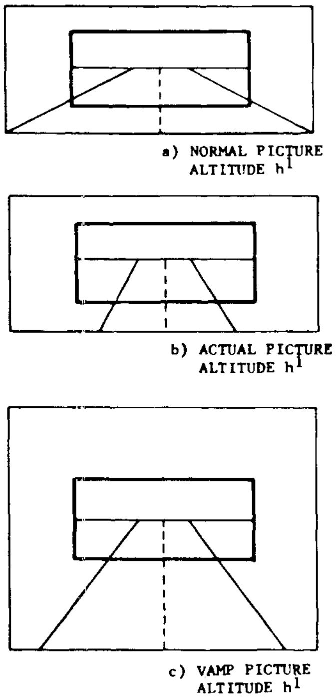

Fig. 5 Altitude change.

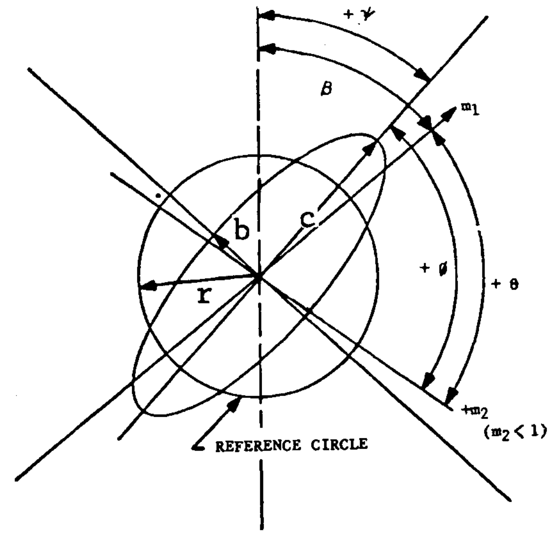

Fig. 6 Alteration of circular image into ellipse.

stretch, illustrated in Fig. 5, are accomplished by means of a servo-controlled lens assembly associated with a 70-mm motion picture projector.

The VAMP optical train utilizes both zoom-type lenses and anamorphosers. The zoom lens provides variable magnifications in different meridians. A circle, as viewed through a zoom lens, will appear as a circle with a larger or smaller radius, depending upon the magnification. The same circle, as viewed through anamorphic elements, appears as an ellipse with its major axis along the axis of greatest power in the anamorphic element. Alternation of a circular image into an ellipse is illustrated in Fig. 6, showing a reference circle with radius r imaged into an ellipse with major and minor axes of a and b, respectively. This is accomplished by two anamorphosers having powers m_1 and m_2 ($m_2 > 1$) with the maximum power axis of m_1 being oriented as defined by angle β and the maximum power axis of m_2 as defined by θ. The major axis of the ellipse is defined by the angle ψ. The lengths of the two axes of the ellipse and its angular position are determined by the relative powers of the two anamorphic elements and by their orientation as defined β and θ. Motion of the viewpoint toward or away from the scene is accomplished in the actual filming of the movie. The VAMP system, in projecting the movie, therefore, provides an accurate apparent displacement of the viewpoint in three degrees of translational freedom. Angular freedom is added by displacement and rotation of the transformed image. Closed-loop operation is accomplished in use with the flight simulator by appropriate interconnections between the VAMP projector and the simulator computer, providing simulator flight path and altitude information projector servos.

Optical System

The optical system of the VAMP projector consists of a zoom lens, followed by two cylindrical anamorphic elements, each having a fixed power of two along its principal axis. The zoom power is variable as well as the angle of the power axis of each of the two anamorphics with respect to the projected frame. Since the anamorphic elements produce picture rotation in addition to the required distortion, a K mirror assembly is included following the optical train to remove this inherent rotation.

Figure 7 shows an optical schematic of the system beginning with the film plane following through the zoom lens, the anamorphics, and the K mirror. Beginning at the film frame, the zoom lens is positioned at its focal distance from the film so that the light emerging from its pupil is collimated. Both anamorphics are afocal so that a decollimating lens (not shown) is required to image the frame at the correct projection distance on the screen.

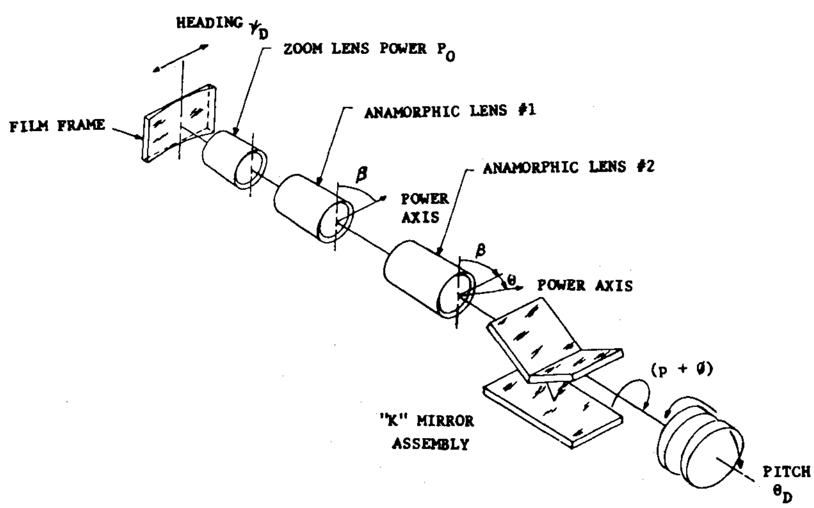

Fig. 7 Optical schematic.

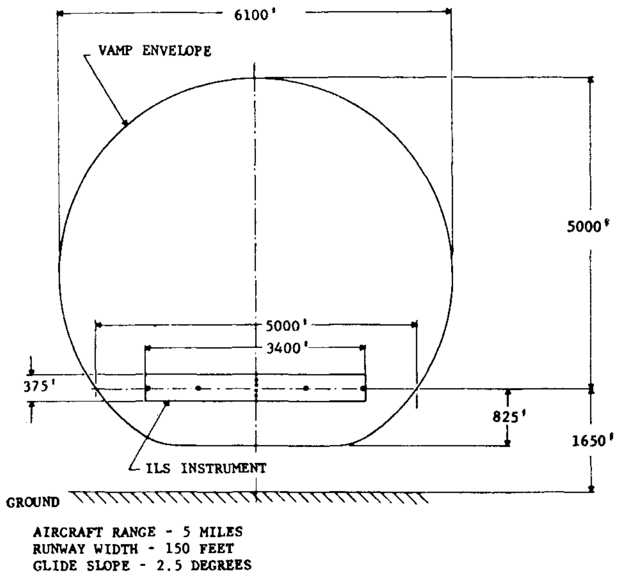

Fig. 8 VAMP envelope of correct perspective presentation vs ILS instrument limits at a range of 5 miles.

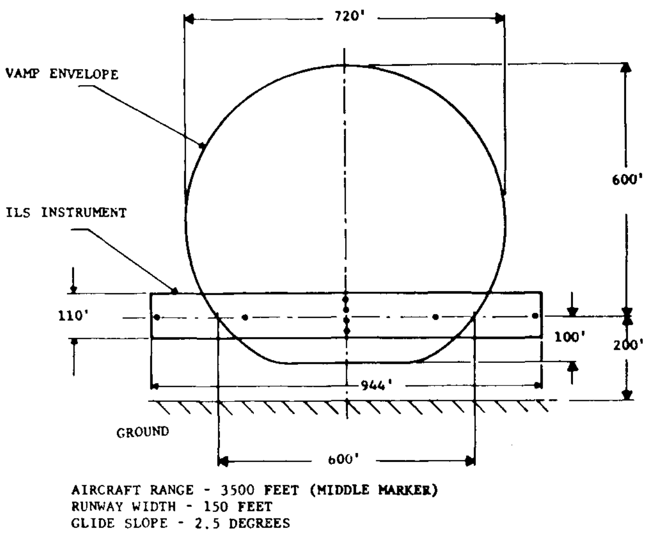

Fig. 9 VAMP envelope of correct perspective vs ILS instrument limits at the middle marker.

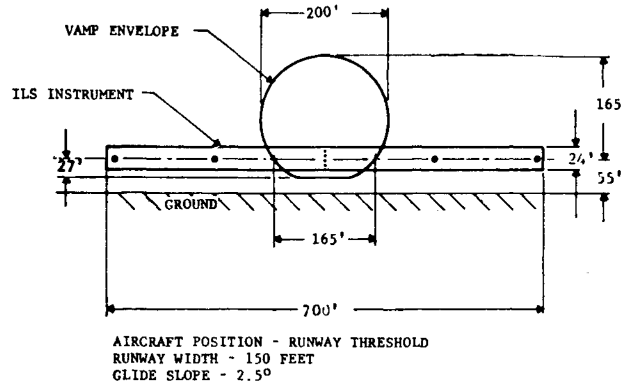

Fig. 10 VAMP envelope of correct perspective presentation vs instrument limits at runway threshold.

Lateral and vertical displacements from the camera path are accomplished by a combination of drives on the zoom lens magnification, the angular position of the two anamorphic lenses, and the angular position of the K mirror assembly. The third degree of translational freedom is provided by progression on the film. Heading and pitch variations are provided by means of translation of the distorted picture with respect to the screen. Roll is provided by means of an additional signal driving K mirror assembly.

Positional Latitude

For a task as specific as an approach and landing sequence, as it applies to an aircraft in proximity to an airfield, the determination and recognition of safe maneuvering limits is of major importance. The VAMP system attempts to establish these corridors of safe performance in accordance with real-world conditions. Where desired, the VAMP system limits can be reduced to any level desired, as pilot proficiency in precision flying is improved. It is of primary interest, however, to relate these corridor limits to flight procedures normally practiced at the present time.

Figures 8–10 show the operational envelope that can be provided by the VAMP system at three readily identified points in a straight-in ILS approach. Full-scale deflections of the localizer and glideslope bars are interpreted as equivalent air space in feet. The VAMP system limits are superimposed.

Examination of the figures shows that in the vicinity of the outer marker (Fig. 8), the VAMP visual presentation will be correct for a space envelope considerably in excess of the ILS

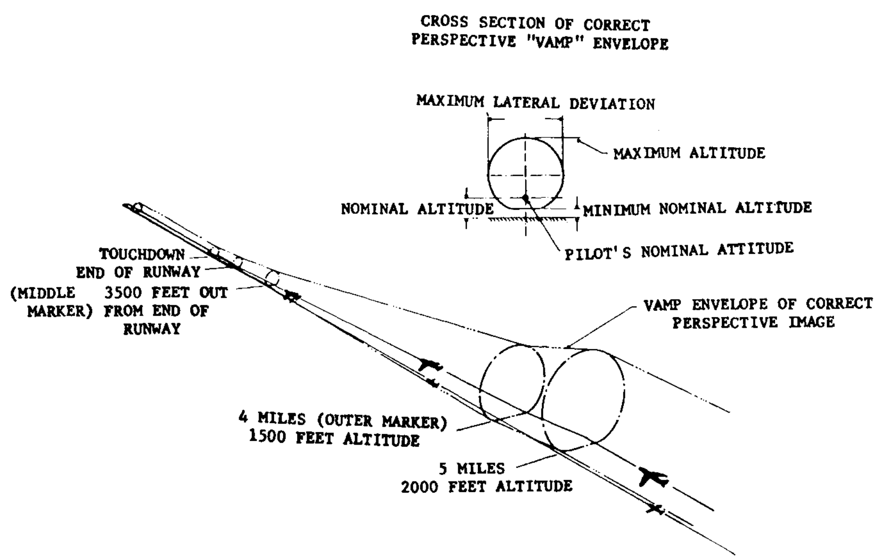

Fig. 11 Typical approach and landing limits.

limits. From this point on, the pilot in the real world must progressively reduce his deviation from optimum performance if he is to land successfully. Similarly, this tolerance is reduced also in the VAMP system. Figure 9 shows the permissible deviation at the middle marker.

Finally, when crossing the runway threshold (Fig. 10), the pilot must be essentially in his final alignment with respect to the touchdown point. At this time, the ILS limits have little meaning (and vary according to the particular airfield installation). What is significant in Fig. 9 is that the vertical and lateral deviation limits within which the VAMP projector can generate a correct perspective view far exceed the tolerances permissible for the aircraft itself. Consequently, the VAMP system is able to simulate any approach and landing that could actually be completed in practice. Figure 11 clarifies the corridor limits by illustrating a typical approach and landing in a perspective drawing.

Conclusion

This paper illustrates an inevitable conclusion that a tradeoff must be made between picture quality and freedom of aircraft maneuver when selecting a system approach to simulate the scene to be observed through an aircraft windscreen. Various approaches that provide unlimited freedom are described, all of which, in practice, have fallen considerably short of the goal of providing real-world fidelity in the presentation. Trading off motion excursion for picture quality, a system is described which has freedom of maneuver only within a prescribed envelope, but is, without question, capable of displaying the real world through the windscreen. Accepting as fact the condition that real-world fidelity cannot be obtained unless completely unlimited freedom of maneuver is somewhat sacrificed, an evaluation must be made as to which is more critical for a particular application. Since the approach and landing as well as the takeoff maneuvers are generally confined with a specific envelope by ILS requirements or airport regulations, this approach appears well suited for this problem. Other simulation problems for which maneuvers cannot be confined to a reasonable corridor, must select the tradeoff of greater aircraft mobility at a sacrifice in picture quality, the extent of which generally depends on the minimum altitude at which the aircraft must be flown.