# 21. Control Information in Visual Flight* 

J. M. Naish<br>Douglas Aircraft Company


#### Abstract

The purpose of the inquiry is to determine how precisely a pilot can estimate the movements of his vehicle, and thus exercise control, during an unaided visual approach. The method is to relate changes in the forward view, due to movements along and across the approach path, to human visual thresholds and errors. The scope is restricted to effects of inclination, expansion, size, and rotation in runway features during approaches at small angles of elevation.

Quantitative relations are given which provide a basis for ranking the several information mechanisms. Alignment by inclination of a ground line is found to be an accurate lateral mechanism, probably superior to the expansion mechanism. Vertical control mechanisms are complex, of questionable accuracy, and difficult to rank. The results throw some doubt on the usefulness of a runway symbol as a source of displayed information.


## INTRODUCTION

When an approach is made without the help of flight instruments or ground aids, the pilot depends heavily on observations of the external visual world. If he is able in these circumstances to make good a selected flight path, his control actions must be in some way related to visual information derived from external sources. On the other hand, an erratic approach would indicate the absence of an adequate relation between what is seen and what is done.

Previous investigations of this subject have perhaps given the impression that much information is available for control purposes in visual flight. For example, Gibson (ref. 1) has stated that the pilot is able to see accurately a continuous visual world in which he moves with precision, and this view has frequently found embodiment in displays which imitate the forward view in flight. But it must first be asked how precisely the pilot moves in his visual flight path, if a complete description of the control process is to be given. Unfortunately, the quanti-

[^0]tative aspect of visual flight has attracted very little attention.
Another feature of previous work is the variety of visual characteristics considered able, through dependence on the position or speed of an observer, to contribute to the control of visual flight. But not all visual characteristics are equally admissible, because of variability under differing meteorological conditions. Thus, color, contrast, and sharpness of detail can vary markedly with changes in weather, while the form, size, and apparent movement of visible ground objects are hardly affected. The latter characteristics are therefore more likely to provide a quantitative basis for a process which, obviously, may take place under a range of weather conditions.

It is not difficult to establish relationships between the form, size, and apparent movement of ground objects and the observer's position, or change of position. For example, Belik (ref. 2) has recently shown the relationship of position and speed to the size and apparent velocity of ground objects, for differeht sighting angles. What is needed for control purposes, however, is to relate the visual changes, due to movements along or across the approach path, to known visual capabilities of the human observer. If this can be done, it will be possible to determine the
smallest changes of the observer's position and speed causing detectable effects in the external scene and, thus, to estimate the precision with which a vehicle may be controlled in purely visual flight.

Another limitation desirable in selecting material from the external visual scene is in choosing only those ground objects suitable for building up quantitative relations for all visual approaches. Clearly, an invariable feature of the pilot's forward view is the outline shape of the runway, to which approaches are made over varying, or even featureless terrain. This geometrical pattern, or one of its component sides, will therefore be taken as providing the basic visual characteristics of the external scene, which are to be related to the observer's state variables, of position and speed. (The attitude of the observer's vehicle will not be considered as a state variable because it is without effect on the shape, size, and apparent velocity of ground objects.) The appearance of a ground line, such as a runway side, provides characteristic effects of inclination, expansion, size, and rotation, which will be considered for a conventional approach at a small elevation of the flight path, and without considering any secondary effects due to the windshield frame.

## INCLINATION EFFECTS

## Lateral Alignment

A prominent runway feature during the approach is the appearance of a side or centerline. It is evident from figure $\mathbf{1}$ that each appears as a more-or-less straight line which is inclined to the vertical at an angle depending on the position of the observer. Ground lines to the left of the observer extend from lower left to upper middle, and those to his right are inclined in the opposite sense. It is not difficult to show that the apparent inclination of the ground line increases with the lateral offset of the observer, but decreases with an increase in height of the observer's eye. This relation is important in the lateral alignment of an approaching vehicle.

Let $A$, figure 2 , be the origin of a rectangular coordinate system, of which the x-axis $A D$ and the y-axis $A B$ lie in a horizontal plane containing the rectangle $A B C D$. Let the observer be at the


Figure 1.-Appearance of runway during approach.


Figure 2.-Inclination of ground line.
point $E(x, \mathrm{y}, \mathrm{z})$ lying in a vertical plane through $D C$. Then the observer's horizon $H H^{\prime}$ lies in a horizontal plane through $E$, which also cuts the z-axis in a point $F$, and the parallel lines $A B$ and $D C$ appear to meet at a point $V$ on $H H^{\prime}$.

Suppose a transparent reference plane is held between the observer and the scene before him, at a convenient distance, and inclined so as to be perpendicular to the y-axis. The points $A, F$, and $V$ will be seen by the observer at the points $a, f$, and $v$, where the lines $E A, E F$, and $E V$ intersect this plane. Now the ground line $A B$ will
be seen in this plane as the line $a \nu$, extending from the position of $A$ to the position of the vanishing point $V$. The apparent inclination of $\boldsymbol{A B}$ will therefore be the inclination of $a v$, or the angle $f a \nu$, since $a f$ is a vertical line formed by two intersecting vertical planes, $a f v$ and $E A F$. Then by similar triangles,

$$
\begin{equation*}
\tan f a \nu=\tan \phi=f \nu / f a=x / z \tag{1}
\end{equation*}
$$

It follows from this simple relation that, for any height of eye, $z$, the inclination of the ground line is zero when the observer's lateral offset, $x$, is zero. In practice, however, it is difficult to observe zero inclination because it is not always possible to estimate the vertical with great precision, as can be seen in figure 1 . The process of lateral alignment will therefore be inexact to an extent depending on the ability to estimate the vertical, in field conditions. Laboratory studies, such as those of Werner and Wapner (ref. 3), suggest that this kind of estimation may be made to better than $1^{\circ}$, but a larger error, perhaps as great as $5^{\circ}$, would no doubt occur in the less settled conditions of flight. The quantitative relationship governing lateral alignment of the observer's vehicle is therefore of the form

$$
\begin{equation*}
\Delta(\phi)=\Delta(\tan \phi)=\Delta x z=k_{1} \tag{2}
\end{equation*}
$$

where $\Delta(\phi)$ is the error in estimating zero value for the inclination of the ground line, and $k_{1}$ is a constant expected to be about $1 / 12$. With this value for $k_{1}$, the minimum detectable lateral offset will be about 42 feet at a height of 500 feet, or a range of 10000 feet on a $3^{\circ}$ approach. Smaller offsets are discernible at smaller ranges, and the order of magnitude of the result suggests an accurate means of lateral control.

## Vertical Alignment

Since the runway is essentially a plane surface, it does not readily lend itself to the vertical alignment of an observer, by showing whether he is above or below a chosen approach path. Few features of vertical extent are available which reveal the kind of differential inclination so easily observed in the lateral plane. It may nevertheless be possible to gain some control information in the vertical plane from the absolute value of the inclination of a ground line.


Figure 3.-Approach at constant included angle.

In the special case where the observer's height of eye is equal to the lateral offset from a ground line, its apparent inclination is $45^{\circ}$ (eq. (1)). Thus, at an eye point 100 feet above the centerline of a runway, $\boldsymbol{A}$, figure $\mathbf{3}$, the included angle between the runway sides would be 90 " for a runway width of 200 ft . Given an ability to judge an absolute value of $90^{\circ}$, it would thus be possible to make an oblique approach to this point, at a constant glideslope angle, by passing over points equispaced in the ground plane and offset from a runway side by amounts increasing in arithmetical progression, $P, Q$, etc. But no very precise control could be expected by this method because an error of only $5^{\prime \prime}$ in estimating the included angle would result in a height error of about 8 percent; moreover, accuracy of alignment in the lateral plane would be sacrificed by using an oblique approach.

The more commonly practiced method of making an approach along a line of constant offset, such as the runway centerline, leads to the condition that inclination of the ground line varies only with height

$$
\begin{equation*}
\tan \phi=k / z . \tag{3}
\end{equation*}
$$

The trained observer may then be able to estimate height from inclination, and this technique, with the further stipulation that distance to touchdown is known, may be sufficient to control the flight path in the vertical plane. But without knowledge of position along the approach path this method cannot yield usable information.

Estimation of range to touchdown is obviously influenced by the existence and visibility of


Figure 4.-Runway width and range.
recognizable ground features. This visual information is not always available, however, or it may not be usable because of unfamiliarity with the terrain. The pilot may nevertheless estimate range to touchdown from the apparent size of ground objects. For example, in a centerline approach to a runway of width $2 x$, figure 4 , the nearest edge subtends an angle $\theta$ such that

$$
\begin{equation*}
\tan \theta / 2=x / R \tag{4}
\end{equation*}
$$

where R is the visual range to the midpoint of the edge. At the same time, either side of the runway appears inclined to the vertical at an angle $\phi$ such that

$$
\begin{align*}
\tan \phi & =x / z \\
& =x / R \sin \mathrm{y} \tag{5}
\end{align*}
$$

where $\gamma$ is the elevation of the sight line to the same midpoint. It follows from equations (4) and (5) that

$$
\begin{equation*}
\tan \theta / 2 / \tan \#=\sin y \tag{6}
\end{equation*}
$$

so that the elevation of the sight line may be held constant if this ratio of tangents can be observed always to have the same value. This suggests a possible mechanism for controlling a straight-line approach in elevation along the centerline of a runway.
The judgment required in maintaining a constant relationship between the apparent width of the runway and the apparent inclination of a runway side is more complicated than the simple judgment needed in observing alignment with a ground line. Accuracy in the vertical plane may
therefore be more difficult to achieve than in the lateral plane, if the supposed mechanism is responsible for mediating the control information. And it is hard to relate this mechanism to known human capabilities. But if it is assumed that a measurable value may be given to the ability to estimate an angular ratio of this type, the governing relation for vertical control by means of the width/inclination ratio is

$$
\begin{equation*}
k_{2}=\mathbf{A}(\tan \theta / 2 / \tan \#)=\mathbf{A}(\sin \mathrm{y}) \tag{7}
\end{equation*}
$$

where $k_{2}$ is the error in estimating the angular ratio. If this error is 10 percent, the height error at a range of 10000 ft , or a height of 500 ft on a $\mathbf{3}$ " glideslope, would be about 50 ft . That is, this angular ratio would need to be held constant to within one part in ten in order to achieve a control accuracy similar to that calculated for the lateral plane by equation (2). This possibility is conjectural.

## EXPANSION EFFECTS

It is well known that objects near the path of a vehicle appear to move outward as the vehicle advances. During an approach, for example, the runway appears to expand in all directions about the (inertial) flight path. This phenomenon suggests a mechanism providing information about the probable outcome of the pilot's control actions. Clearly, its usefulness depends on the quality of information provided, and this can be judged for the visual approach situation by calculating the apparent expansion in the region of the touchdown zone.

## Lateral Aim

Suppose the observer at $\boldsymbol{E}$, figure $\mathbf{4}$, is moving with velocity v , and approaching the point D , which is on the centerline of a runway of width 2s. A diameter through this point subtends the angle $\theta$ at the observer's eye, and each of its ends, such as $\boldsymbol{A}$, appears to move outward from the approach path at an angular rate given (with sufficient accuracy) by

$$
\begin{align*}
\frac{d}{d t}(\theta / 2) & =-\frac{s}{R^{2}} \frac{d R}{d t} \\
& =s v / R^{2} \tag{8}
\end{align*}
$$

(an increase in angle corresponding to a decrease in range).

If the observer fixates on the center point $\boldsymbol{D}$ and observes both extremities to move outward, he may conclude that his vehicle is proceeding to a point lying between them. Further, if the outward velocities are observed to be equal and opposite, it may be concluded that the destination is in fact point $D$, although this kind of judgment may be almost impossible to make at the limit of perception. Assuming that only the simpler type of observation is made, this will first be possible when the lateral angular velocity given by equation (8) exceeds the human threshold for perceiving movement. This threshold is quite large when the observation has to be made without the help of a fixed visual reference, as may be the case during a visual approach, and under these conditions the threshold will probably not be less than 10 min of arc per see, or $1 / 344 \mathrm{sec}$ (ref. 4). The impact point, at a range $R$, will then be estimated simply as lying somewhere within the runway width; that is, there will be an uncertainty of aiming position, $\pm A x$, where

$$
\begin{equation*}
A x=R^{2} / 344 v \tag{9}
\end{equation*}
$$

Then at a range of $\mathbf{1 0 0 0 0}$ feet and with an approach speed of 200 ft per sec, the aiming uncertainty is $\pm \mathbf{1 4 5 0} \mathrm{ft}$, or an angular uncertainty of $\pm 8^{\circ}$. Because this value is a predicted or future offset, it cannot be compared directly with the lateral offset of 42 ft calculated by equation (2), which is a presently detectable offset. It is nevertheless clear that the expansion mechanism is less sensitive than the alignment mechanism because, at the same range of 10000 ft , the alignment mechanism can show an acceptably small error but the expansion mechanism can only show ambiguity. It cannot even show whether the impact point is within a $200-\mathrm{ft}$ runway until the range is very much reduced (to about 2600 ft ), according to the assumed threshold.

## Vertical Aim

Basic features of the forward view which are significant to the expansion mechanism, for aiming the flight path in the vertical plane, aie shown in frontal elevation in figure 5. The near and far ends of the runway, $N$ and $F$, respectively, are
the two relevant ground lines. There is also a visible horizon $V$ and this is displaced below the true horizon $\boldsymbol{T}$ by the angle of dip 6 according to the approximate relation

$$
\begin{equation*}
\delta=\sqrt{z} \tag{10}
\end{equation*}
$$

where 6 is expressed in minutes of arc, and the height $z$ is in feet.

Since the true horizon is invisible, the largest observable vertical angle is $N V$. The rate at which this angle increases can be calculated by noting that the angle $\boldsymbol{N T}$ is nearly constant for a good approach, when the vehicle moves along an approximately straight line to touchdown, so the angle $N V$ increases at about the same rate as the angle $\boldsymbol{V} \boldsymbol{T}$ decreases. This is easily obtained from equation (10),

$$
\begin{equation*}
\frac{d}{d t}(\delta)=\frac{1}{2 \sqrt{z}} \frac{d z}{d t} \tag{11}
\end{equation*}
$$

and for a typical descent rate of 10 ft per sec, the angle $N V$ increases at less than 0.5 min of arc per second at heights above 100 ft , and only changes at an observable rate when the height is reduced to about 0.25 ft . In other words, the near end of the runway is not seen to move away from the visible horizon during a normal visual approach.

The rate at which the runway length $N F$ appears to expand can be calculated from the geometry of figure 6, which shows the visual


Depression of TDZ (y)
$\Delta \gamma=\Delta(\gamma)+k_{3} \sqrt{z}$
Figure 5.-Expanding runway features in frontal elevation.


Figure 6.-Runway features in side elevation.
features of figure 5 in side elevation through the eye point $E$. If the visual range to the near end is $R$, and the runway length is $L$, the vertical angle a subtended by the runway is given to the first order of accuracy by

$$
\begin{equation*}
\alpha=P N / E N=\frac{L \gamma}{L+R} \tag{12}
\end{equation*}
$$

where $P N$ is a vertical through $N$ and $\gamma$ is the elevation of the inertial flight path. The expansion rate is then

$$
\begin{equation*}
\frac{d \alpha}{d t}=-\frac{L \gamma v}{(L+R)^{2}}=\frac{L}{(L+R)^{2}} \frac{d z}{d t} \tag{13}
\end{equation*}
$$

which, for a typical runway length of 8000 feet and the same descent rate of $\mathbf{1 0} \mathrm{ft}$ per sec, increases to a maximum of only about 4 min of arc per sec as $R$ reduces to zero, and is thus never usefully observable. This result means that the expansion mechanism does not allow the flight path to be aimed within the length of the runway during an approach at a small glideslope angle (where the approximation of eq. (12) is valid). It does not even show that the flight path lies below the horizon.

## SIZE EFFECTS

## Lateral Position

In a conventional approach, the ratio of visual range to height is large, of the order of twenty to one, and the runway therefore subtends only a small visual angle until quite a low altitude is reached. Thus, when the elevation of the approach path is $3^{\circ}$, a $200-\mathrm{ft}$ runway subtends less than $\mathbf{6}^{\prime \prime}$ until height is decreased to $\mathbf{1 0 0} \mathrm{ft}$. Under such small-angle conditions, it is possible to be offset from the centerline by quite large amounts, of
the order of half the runway width, without appreciably altering either the visual range or the projected width of the runway. The apparent width of the runway is therefore an insensitive clue to lateral position, except at very short range, and is unable to provide information for control purposes during the greater part of a normal visual approach.

## Vertical Position by Height and Range

It has already been suggested that the flight path may be controlled in the vertical plane by maintaining a relationship between the inclination of a ground line, which can be related to height, and the apparent size of the runway, which is related to range. But height may sometimes be estimated directly from the apparent size of a known object beneath the airplane, such as a motor vehicle, and this kind of judgment is not dependent on local topographical knowledge. If such objects are available, position in the vertical plane may be known by combining this type of observation with the estimation of range: that is, by combining two observations of apparent angular size.

The path accuracy achieved in attempting to maintain a constant ratio of height to range is then given directly,

$$
\begin{equation*}
\frac{\mathrm{Ay}}{\gamma}=\frac{\Delta z}{z}-\frac{A R}{R} \tag{14}
\end{equation*}
$$

If estimates of height and range can be made within 5 percent of the true values, the flight path will be accurate to within $\mathbf{1 0}$ percent, according to this mechanism, and the result will be commensurate with the lateral accuracy achieved by the alignment mechanism, equation (2). Such accuracy in judging distances is perhaps possible when the intermediate space is a continuum of observable detail; for example, a golf shot of $\mathbf{2 0 0}$ yd can probably be estimated within $\mathbf{1 0}$ yd. But there are no intermediate objects in the airborne situation. Moreover, the two distance judgments are to be made in different directions, and can hardly be simultaneous. For these reasons, the vertical accuracy achieved by a height and range mechanism based only on angular size, is likely to be less than the lateral accuracy achieved by alignment.

## Vertical Position by Depression of Touchdown Zone

A more direct method of locating the flight path in the vertical plane may consist in observing the depression of the touchdown zone below the true horizon. Thus, if the angle TEN, figure 6, has the value y, the aircraft is on the line $\boldsymbol{E N}$, since from any other position the ground point $N$ is depressed by a different amount. If this value is maintained, the vehicle is also proceeding along the straight line $E N$ and the flight path is known if the angular values are correctly judged.

Unfortunately, more is involved than estimation of an absolute angular value. It is also necessary for the angle to be judged with respect to an invisible horizon. Thus, in figure 5, the position of T has to be established before the subtense of $\boldsymbol{N T}$ can be given a value. Clearly, angular estimation can be practised, and the associated error might be reduced to an acceptable level. But it is less straightforward to compute mentally, and estimate visually, the position of the true horizon, especially as the visible horizon may itself be displaced through changes of visibility and local variations of terrian. The total error in estimating the flight path by this mechanism is thus:

$$
\begin{equation*}
\Delta \gamma=\Delta(\gamma)+k_{3} \sqrt{\bar{z}} \tag{15}
\end{equation*}
$$

where $\Delta(\gamma)$ is the error in judging the absolute value of a small angle, and the second term is derived from equation (10). If the factor $k_{3}$ has a value as great as unity, as may happen if the significance of the angle of dip is not appreciated, the second term contributes nearly three-fourths of a degree during an approach from 1600 ft , and no great accuracy is achieved. On the other hand, if time is available and care is taken to establish the true horizon, it may perhaps be possible to operate with the accuracy typical of the lateral alignment mechanism, assuming accurate angular judgment within 10 percent. The true situation may lie between these two cases.

## ROTATION EFFECTS

Since the inclination of a ground line depends on lateral offset and height of eye, according to equation (1), each runway side will appear to
rotate during lateral and vertical movements of the observer. The consequent motions are distinguished by the sense in which the sides appear to rotate. For an observer on the centerline, the offsets and therefore the inclinations are opposite in sign, as in figure 7(a). As he moves laterally, one offset increases as the other decreases, and the inclinations change in the same algebraic sense. The lines thus appear to rotate about the vanishing point in the same sense. For an observer moving vertically above the centerline, figure 7 (b), the offsets are constant, and as height changes, each inclination of opposite sign changes in opposite algebraic sense. The runway sides thus appear to rotate in opposite sense. In the general case, lateral and vertical motions occur together, and the total rotational effect is a combination of the two kinds of apparent rotation.

## Lateral Motion

If the observer is assumed simply to move laterally at constant height, the apparent rotation of a runway side may be estimated by differentiating equation (1), using the small-angle approximation

$$
\frac{d \phi}{d t}=\frac{1}{x} \frac{d x}{d t} .
$$

This is a rotation in the observer's frontal plane of a line having an apparent (angular) length given by equation (12), with sufficient accuracy, so that either end appears to move about the other at the approximate rate

$$
\begin{align*}
\alpha \frac{d \phi}{d t} & =\left(\frac{L \gamma}{L+R}\right) \frac{1}{z} \frac{d x}{d t} \\
& =\frac{L}{R(L+R)} \frac{d x}{d t} . \tag{16}
\end{align*}
$$


(A) OBSERVER MOVING FROM LEFT TO RIGHT
$a \dot{\phi}=L \dot{x} / R(L+R)$
-
Figure 7.-Apparent rotations of runway sides.

But during an approach, the observer's sink rate must also be taken into account, and the apparent rotation of a runway side is

$$
\begin{array}{ccc}
d \phi & 1 d x & x d z \\
d t & z d t & z^{2} d t
\end{array}
$$

so that either end appears to move about the other at approximately

$$
\begin{equation*}
a \frac{d \phi}{d t}=\frac{L}{R(L+R)} \frac{d x}{d t}-\frac{L}{R(L+R)} \frac{x}{z} \frac{d z}{d t}, \tag{17}
\end{equation*}
$$

This is the speed at which the far end of the runway will appear to move if the near end is fixated. It is an angular speed at the eye, and will be discernible if it exceeds about $1 / 344$ sec.

It can be seen that until the approach is far advanced, the second term of equation (17) is unimportant, and the combination of lateral and downward motion of the observer yields a rotational effect adequately described by equation (16). Thus, for an observer on the centerline of a runway 200 ft wide and 8000 ft long, the second term first exceeds the value $1 / 344 \mathrm{sec}$ when height is reduced to about 120 ft , for a sink rate of 10 ft per sec. The minimum discernible lateral speed can therefore be estimated as

$$
\begin{equation*}
\frac{d x}{d t}=\frac{R(L+R)}{344 L} \tag{18}
\end{equation*}
$$

which, at a range of 10000 feet from the same runway, gives a value of about 65 ft per sec. Clearly, this is a large fraction of a typical approach speed of 200 ft per sec and gives a drift angle of about $18^{\circ}$, so that this mechanism of detecting lateral motion is scarcely adequate for control purposes.

## Vertical Motion

It has already been shown that vertical motion of the observer during the approach results in a negligible rotation effect, for normal sink rates, until the airplane is quite close to the ground. Departures from an optimum sink rate will not therefore result in observable effects during most of the approach, unless the departures are large. Moreover, a consequent rotation may be concealed by contrary rotation due to lateral motion. The apparent rotation of a runway side thus
provides insufficient information for controlling vertical speed.

## DISCUSSION

It is evidently possible to derive quantitative relationships 'connecting the information available in the pilot's forward view with the position and motion of his vehicle. Several mechanisms can be advanced which allow calculable changes in the visual scene to be linked with human capabilities of visual judgment. These depend on the apparent inclination, expansion, size, and rotation of prominent runway features, and their magnitudes throw light on the accuracy of the control process in visual flight.

Results of the analysis, for an approach of conventionally small elevation, are collected in table 1. An important mechanism depends on the inclination of a ground line, at a given position of the observer, which yields a simple and direct method of control in the lateral plane. With a conservatively estimated ability to judge vertically within $5^{\circ}$, alignment within less than 50 ft is possible at a range of 10000 ft , and within smaller offsets at shorter ranges. In other words, it is readily possible to place the vehicle within the width of the runway during most of the approach. A connection may also be traced between the appearance of the runway and the position of the observer, for control in the vertical plane. But for this to be used it is necessary to propose an ability to make a somewhat complicated comparison of apparent size and apparent inclination. The supposed ability has not been linked with human performance data, and the accuracy of the mechanism has not therefore been ranked.

Contrary to expectations, the expansion mechanism is unable to provide an accurate basis for controlling the flight path. Without the help of a stabilized reference mark, angular velocities less than 10 min of arc per sec can scarcely be discerned, and calculation shows that this level of visual performance will only support a crude estimation of the impact point. In the lateral plane, there is an aiming uncertainty of $\pm 8^{\circ}$ at a range of 10000 feet, for an approach at 200 ft per sec. And it only becomes possible to tell whether the vehicle will arrive within the width of the runway when the range is reduced to about

Table 1. -Information Mechanisms of Visual Flight

| Visible effect | Application | Quantitative relation | $\begin{gathered} \text { Rank } \\ \text { Lateral } \end{gathered}$ | order <br> Vertical |
| :---: | :---: | :---: | :---: | :---: |
| Inclination | Lateral alignment | $\mathrm{Ax}=k_{1} z$ | 1 |  |
|  | Vertical alignment | $k_{2}=\Delta(\tan \theta / 2 / \tan \phi)$ | $\ldots$ | ? |
|  |  | $=\mathrm{A}(\sin \gamma)$ |  |  |
| Expansion | Lateral aim | $\mathrm{Ax}=R^{2} / 344 v$ | 2 | $\cdots$ |
|  | Vertical aim | $L_{i}=(L+R)^{2} / 344$ | ... | u* |
| Size | Lateral positionVertical position by |  |  |  |
|  |  |  |  |  |
|  | Height and range | $\Delta \gamma / \gamma=\Delta z / z-\Delta R / R$ | $\ldots$ | 1 |
|  | Depression of TDZ | $\Delta \gamma=\Delta(\gamma)+k_{3} z^{1 / 2}$ | $\cdots$ | 2 |
| Rotation | Lateral motion | $x=\boldsymbol{R}(\boldsymbol{L}+\boldsymbol{R}) / 344 L$ | 3 | ... |
|  | Vertical motion | $\dot{z}=2 R(L+R) / 344 x L$ | $\ldots$ | U |

* u Signifies unusable.
one-half mile. The expansion mechanism thus provides less information in the lateral plane than the alignment mechanism, which allows continued monitoring of the offset from runway centerline. In the vertical plane the situation is worse: the flight path cannot be observed to lie below the horizon, or to fall within the length of the runway till after touchdown. The vertical expansion mechanism is therefore unusable, according to the assumption made about velocity perception.

The apparent size of the runway provides little clue to lateral position, except at short range, but yields two possible mechanisms for the vertical plane. In one of these, combined estimations of height and range may perhaps be used to determine the elevation of the flight path. But since these estimations are made in different viewing directions, and largely without the help of intermediate objects, it may be difficult to achieve optimum judgments of distance, which might otherwise yield an overall accuracy of 10 percent. An alternate vertical mechanism is based on the angular size of the depression of the touchdown zone, and this is subject to errors of estimating an angle and of establishing the position of the true horizon. Because of the unpredictable, and potentially large influence of the horizon effect, it seems necessary to rank the touchdown depression mechanism below the height and range mechanism in which, at least, the objects to be judged are visible.

Information mechanisms can also be described which depend on the apparent rotation of run-
way sides, but their yield is insufficient for control purposes. Rotation due to lateral motion of the observer is only discernible for cross track speeds capable of causing drift angles of $18^{\circ}$ in either direction at $\mathbf{1 0} 000$-foot range, and this mechanism is ranked below the lateral expansion mechanism. Rotation due to vertical motion is only observable below a height of about 120 ft and is scarcely usable, especially as it may be masked by contrary rotation due to lateral motion.

In brief, it is clear that a more satisfactory situation exists in the lateral plane than in the vertical plane. According to the analysis, the alignment mechanism provides a simple and accurate basis for lateral control and is superior to other mechanisms, including the expansion mechanism. But in the vertical plane, all of the usable mechanisms involve some kind of double judgment, whether of width and inclination, of height and range, or of depression and horizon position, and a simple mechanism of unquestionable accuracy has not been found. Without experimentation, there is some uncertainty about the visual performance data which apply, and some difficulty in determining rank order.

Finally, an important application of the results is to displays which include a runway representation. For although this kind of symbol may inspire a certain amount of confidence, through the familiarity of its shape and the ease with which it can be understood, it may be less than satisfactory as a source of information for control purposes.

## SYMBOLS

$x$ displacement perpendicular to runway side (length)
$y$ displacement along runway side
$z$ height
$\boldsymbol{\phi}$ apparent inclination of ground line to vertical
$\boldsymbol{k}_{\mathbf{1}} \quad$ error in judging vertical
e subtense of runway width
$\boldsymbol{\gamma}$ elevation of flight path (or sight line)
$k_{2}$ fractional error in estimating angular ratio
$\boldsymbol{R}$ range to touchdown or ground point
$s$ half width of runway
$v$ vehicle velocity
at apparent (angular) length of runway
$L$ length of runway
$k_{3}$ fractional error in estimating dip angle

## REFERENCES

1. Gibson, J. J.: Perception of the Visual World. Houghton Mifflin (Cambridge, Mass.), 1950, p. 129.
2. Belik, Ya. Ya.: Modelling of the Optic Distance Perception in Vertically Taking-Off and Landing Aircraft. Kosmicheskaya Biologiya i Meditsina, vol. 3, no. 3, May-June 1969, pp. 66-70.
3. Werner, H.; and Wapner, S.: Experiments on Sen-sory-Tonic Field Theory of Perception. Vol. IV Effect of Initial Position of a Rod on Apparent Verticality. Jour. Exp. Psychology, 1952, pp. 68-74.
4. Graham; Bartlett; Brown; Hsia; Mueller; and Rigas: Vision and Visual Perception. J. P. Wiley and Sons, 1965, p. 575.

[^0]:    * This paper summarizes work performed at the Douglas Aircraft Company under the sponsorship of the Independent Research and Development Program (IRAD) of the McDonnell Douglas Corporation.

