Measurement of Takeoff and Landing Performance Using an Airborne Motion Picture Camera

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A method is presented which will obtain the attitude and position of a conventional or V/STOL aircraft utilizing a motion picture camera mounted in the test vehicle and viewing a runway or some equivalent ground reference. With the use of photogrammetric techniques, the lateral and longitudinal spacing of the runway boundary lights is used to obtain vehicle position. The parallel lines formed by the runway lights are used to obtain vehicle attitude by means of the geometry of perspective. Employing standard numerical techniques, one can obtain the velocity and acceleration derivatives of roll, pitch, and heading angle and longitudinal, vertical, and lateral displacement. An instrumentation-quality camera with timing and pilot event lights may be mounted anywhere on the aircraft, which permits a view of the runway forward or aft. Calibration of the attitude and position of a camera with respect to a simulated runway has proved the validity of the method throughout a wide variation of attitude and position. Airborne qualitative and quantitative results indicate that the method has practical applications for selective tests involving either V/STOL or conventional aircraft.

I. Introduction

THE standard ground camera systems consisting of phototheodolites or utilizing a calibrated grid have become inadequate for obtaining takeoff and landing performance data from tests of modern aircraft. The greater takeoff and landing distances of today's aircraft cause a more serious loss of accuracy at the increasing camera angles required. Furthermore, the increased complexity of today's aircraft requires, for complete evaluation, more information relative to total aircraft movement and attitude.

The concept of an airborne camera that is mounted in the test vehicle and views the runway as a reference base is not new. The growing problems associated with the ground camera systems led Lockheed to develop a split-image airborne camera system in 1957[1,2] which has since been used extensively by Lockheed and others.

The technique presented in this paper is a further development of the concept of an airborne camera system that views the runway as a reference base. It will obtain more information with less restrictions than the original airborne system. This technique will obtain longitudinal, vertical, and lateral displacement of the vehicle as well as roll, pitch, and heading angles. Employing standard numerical techniques, one may obtain the velocity and acceleration derivatives of each of these parameters.

II. Analysis

A. Application of Perspective Geometry

The runway is used as a reference from which all information is derived. The motion picture camera will be mounted in such a manner in the test vehicle as to permit a view of the runway either forward or aft. The lateral distance between runway lights is used as a stadiametric reference to obtain distance data. The position of the runway lights along the runway is used as a longitudinal position reference for the test vehicle. The parallel lines formed by the runway lights are used to obtain attitude information by means of the geometry of perspective.

In Fig. 1, points W_1 and W_2 are runway lights on opposite sides of the runway. The line W_1W_2 is perpendicular to the runway sidelines and thus represents the true runway light lateral separation. An imaginary plane σ is constructed through W_1W_2 perpendicular to the runway plane. The camera is formed by the lens L and the optical plane σ_1. The optical plane in Fig. 1 is parallel to the imaginary plane and therefore perpendicular to the runway plane. The perspectives of the parallel runway light lines when projected through L will form converging lines on the projection planes σ and σ_1. The converging lines, if extended, will meet at the vanishing points P and P_1 on planes σ and σ_1, respectively. Points R_1, R_2, and P_1 on plane σ_1 correspond to W_1, W_2, and P on plane σ. Since P and P_1 are projections of a point on the horizon of the runway plane, which would be a point at infinity, it follows from Euclidean concepts that the projection ray through P, L, P_1 is parallel to the runway plane. A line F_2P is constructed through P perpendicular to the runway plane and therefore intersects line W_1W_2. The height of the triangle W_1W_2P is F_2P, which also represents the normal height of the lens L above the runway plane. The position of the vanishing point P with respect to W_1W_2 will define both the vertical and lateral position of the camera lens L. When the optical plane σ_1 is parallel to the imaginary plane σ, the triangles $R_1R_2P_1$ and W_1W_2P are similar triangles and directly proportional in all respects. Since, in the actual case, σ_1 will seldom assume a parallel condition with respect to σ, the infinite variety of pitch and yaw conditions that σ_1 will assume

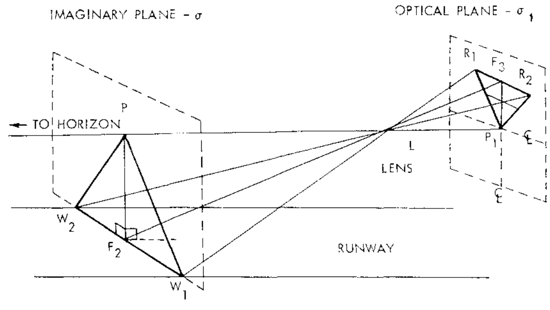

Fig. 1 Application of perspective geometry.

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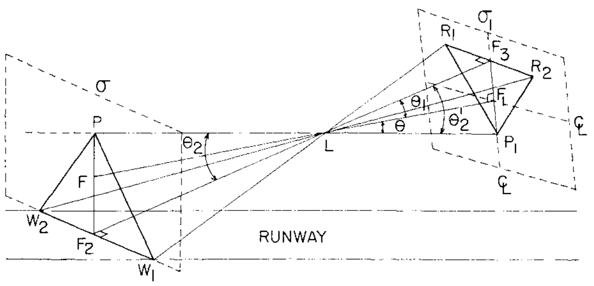

Fig. 2 Pitch angle derivation.

with respect to σ will have to be resolved in order to obtain horizontal and vertical distances.

The angle between the optical axis F_1L of the camera and the projection ray P_1L from the runway vanishing point, when resolved into its component angles, represents the yaw and pitch angle of the optical axis with respect to the projection ray. From the previous discussion, the projection ray P_1L is parallel to the runway light lines. This angle is determined from the position of P_1 with respect to F_1 on the film image. In Fig. 1 F_1 and P_1 coincide because the optical axis is parallel with the runway plane.

B. Pitch Angle Derivation

The analysis of this system and the derivations of basic formulae for the determination of attitude and position is presented initially with only a pitch condition. The analyses for yaw, roll, and off-center deviations are made in subsequent individual steps.

In Fig. 2 the optical plane σ_1 is pitched so that an extension of the optical axis F_1L intersects the line F_2P at a point F. From the previous discussion, F_2P is the height of the lens above the runway plane, F_2P is perpendicular to PL forming a right triangle F_2PL, and PL represents the horizontal distance of the lens to a viewable runway light line W_1W_2. By obtaining the angle θ_2 and the hypotenuse F_2L, one can determine the two sides F_2P and PL of the right triangle. Thus the vertical and longitudinal position of the lens, with reference to the runway, can be determined.

In Fig. 2 the two triangles W_1W_2L and R_1R_2L lie in the same plane; F_3 is the projection of F_2 through L. Since this is a no-yaw condition, W_1W_2 is parallel to R_1R_2. The two triangles W_1W_2L and R_1R_2L are similar. The runway width W_1W_2 is known; F_3L can be obtained from the optical length and a film measurement F_1F_3. The runway light width image, R_1R_2 on the optical plane, can be measured. Thus the distance F_2L can be determined stadiametrically:

$$F_3L = (F_1L^2 + F_1F_3^2)^{1/2} \tag{1}$$

$$F_2L/F_3L = W_1W_2/R_1R_2 \tag{2}$$

Substituting and rearranging yields

$$F_3L = (W_1W_2)(F_1L^2 + F_1F_3^2)^{1/2}/(R_1R_2) \tag{3}$$

If Fig. 2 is referred to, the component angles of θ_2' are θ and θ_1:

$$\theta_2' = \theta + \theta_1 \tag{4}$$

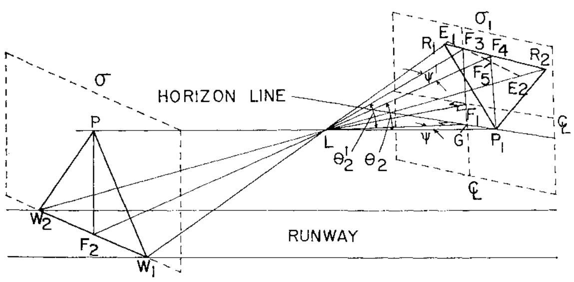

Fig. 3 Yaw angle derivation.

The pitch angle θ is the angle included between the projection ray P_1L and the optical axis F_1L:

$$\tan\theta = F_1P_1y/F_1L \qquad \theta = \tan^{-1}(F_1P_1y/F_1L) \tag{5}$$

The angle θ_1 is

$$\tan\theta_1 = F_1F_3/F_1L \qquad \theta_1 = \tan^{-1}(F_1F_3/F_1L) \tag{6}$$

Substituting yields

$$\theta_2' = \tan^{-1}(F_1P_1y/F_1y) + \tan^{-1}(F_1F_3/F_1L) \tag{7}$$

In the no-yaw condition in Fig. 2, $\theta_2 = \theta_2'$. With a yaw condition, $\theta_2 \neq \theta_2'$. This will be resolved with the yaw angle correction. To determine vertical distance,

$$F_2P = F_2L \sin\theta_2 \tag{8}$$

Substituting yields

$$F_2P = \left[\frac{(W_1W_2)(F_1L + F_1F_3^2)^{1/2}}{(R_1R_2)}\right] \times \sin\left(\tan^{-1}\frac{F_1P_1y}{F_1L} + \tan^{-1}\frac{F_1F_3}{F_1L}\right) \tag{9}$$

The longitudinal distance is obtained by making the same substitutions in the following equation:

$$PL = F_2L \cos\theta_2 \tag{10}$$

C. Yaw Angle Derivation

Figure 3 shows a combination pitch and yaw condition. The projection of F_2P onto the optical plane forms F_4P_1. The optical axis will not intersect F_4P_1 when a yaw condition exists; F_3 is the intersection of R_1R_2 with a line through F_1 perpendicular to the optical plane image of the horizon line at point G. Therefore, LG is perpendicular to the optical plane horizon line or to P_1G. The angle of yaw is included between P_1L and LG:

$$\psi = \tan^{-1}(P_1G/LG) \tag{11}$$

$$LG = (F_1L^2 + F_1G^2)^{1/2} \tag{12}$$

Substituting yields

$$\psi = \tan^{-1}\left(\frac{P_1G}{(F_1L^2 + F_1G^2)^{1/2}}\right) = \tan^{-1}\left(\frac{F_1P_1x}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right) \tag{13}$$

D. Yaw Correction

In Fig. 3, the orthographic projection of the yaw angle ψ from the plane P_1LG will result in angle ψ' in plane R_1R_2L. It will be convenient to have ψ' in terms of ψ in the derivation of the yaw angle correction. Being an orthographic projection, ψ' may be stated in terms of ψ and θ_2 as follows:

$$\psi' = \tan^{-1}(\tan\psi \cos\theta_2) \tag{14}$$

In Fig. 3, θ_2' has the same relationship to θ_2 as ψ' has to ψ. Also, θ_2' lies in the vertical plane through the optical axis and is the angle included between F_3L and LG; θ_2 lies in the vertical plane through P_1L and is the angle included between P_1L and F_4L; θ_2 is obtained in terms of θ_2' and ψ:

$$\theta_2 = \tan^{-1}(\tan\theta_2'/\cos\psi) \tag{15}$$

An orthographic view of the plane formed by the two triangles W_1W_2L and R_1R_2L is shown in Fig. 4. Since the optical plane is yawed with respect to the runway, R_1R_2 will not be parallel to W_1W_2. Instead, R_1R_2 is resolved to a parallel condition by constructing a line E_1E_2 through F_3 perpendicular to F_4L. The triangles E_1E_2L and W_1W_2L are now similar, and a direct proportion can again be established. In Fig. 4,

$$E_1E_2/F_5L = W_1W_2/F_2L \tag{16}$$

In order to solve for F_2L, it is necessary to determine E_1E_2 and F_5L:

$$\tan\delta_1 = F_3R_2/F_3L = [F_1R_2x^2 + (F_1R_2y - F_3y)^2]^{1/2}/F_3L \tag{17}$$

$$\tan\delta_3 = F_3R_1/F_3L = [F_1R_1x^2 + (F_1R_1y - F_3y)^2]^{1/2}/F_3L \tag{18}$$

$$\delta_2 = \delta_3 + \psi' \tag{19}$$

$$\delta_4 = \delta_1 - \psi' \tag{20}$$

$$F_5E_1 = F_5L\tan\delta_2 \tag{21}$$

$$F_5E_2 = F_5L\tan\delta_4 \tag{22}$$

$$E_1E_2 = F_5E_1 + F_5E_2 \tag{23}$$

Substituting Eqs. (21) and (22) into (23) yields

$$E_1E_2 = F_5L\tan\delta_2 + F_5L\tan\delta_4 \tag{24}$$

Substituting Eqs. (19) and (20) into (24) and rearranging yields

$$E_1E_2 = F_5L[\tan(\delta_3 + \psi') + \tan(\delta_1 - \psi')] \tag{25}$$

From trigonometric functions of sums of angles,

$$\tan(\delta_3 + \psi') = (\tan\delta_3 + \tan\psi')/(1 - \tan\delta_3\tan\psi') \tag{26}$$

and

$$\tan(\delta_1 - \psi') = (\tan\delta_1 - \tan\psi')/(1 + \tan\delta_1\tan\psi') \tag{27}$$

Substituting (26) and (27) into (25) yields

$$E_1E_2 = F_5L\left[\frac{\tan\delta_3 + \tan\psi'}{1 - \tan\delta_3\tan\psi'} + \frac{\tan\delta_1 - \tan\psi'}{1 - \tan\delta_1\tan\psi'}\right] \tag{28}$$

Substituting Eqs. (13, 14, 17, and 18) into (28) yields

$$E_1E_2 = F_5L\left[\frac{\left(\dfrac{F_3R_1}{F_3L}\right) + \left(\dfrac{F_1P_1x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)}{1 - \left(\dfrac{F_3R_1}{F_3L}\right)\left(\dfrac{F_1P_1x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)} + \frac{\left(\dfrac{F_3R_2}{F_3L}\right) - \left(\dfrac{F_1P_1x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)}{1 + \left(\dfrac{F_3R_2}{F_3L}\right)\left(\dfrac{F_1P_1\,x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)}\right] \tag{29}$$

Substituting Eqs. (1) and (29) into (16) yields

$$F_2L = \frac{W_1W_2}{\left[\dfrac{\left(\dfrac{F_3R_1}{(F_1F_3{}^2 + F_2L^2)^{1/2}}\right) + \left(\dfrac{F_1P_1x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)}{1 - \left(\dfrac{F_3R_1}{(F_1F_3{}^2 + F_1L^2)^{1/2}}\right)\left(\dfrac{F_1P_1x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)}\right] + \left[\dfrac{\left(\dfrac{F_3R_2}{(F_1F_3{}^2 + F_1L^2)^{1/2}}\right) - \left(\dfrac{F_1P_1x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)}{1 + \left(\dfrac{F_3R_2}{(F_1F_3{}^2 + F_1L^2)^{1/2}}\right)\left(\dfrac{F_1P_1x\cos\theta_2}{(F_1L^2 + F_1P_1y^2)^{1/2}}\right)}\right]} \tag{30}$$

To determine vertical distance, substitute Eqs. (7, 15, and 30) into (8). To determine longitudinal distance, substitute Eqs. (7, 15, and 30) into (10).

E. Off-Center Distance

Off-center distance is defined as the lateral displacement or deviation of the aircraft from the center of the runway. Referring to Fig. 4, one obtains C as the midpoint of runway width W_1W_2. The off-center deviation is F_2C:

$$F_2C = (W_1W_2/2) - W_2F_2 \tag{31}$$

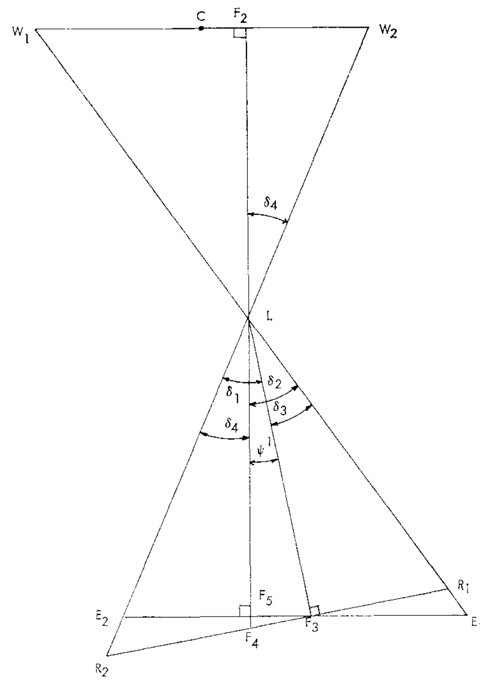

Fig. 4 Yaw angle correction and runway off-center deviation.

and

$$W_2F_2 = F_2L\tan\delta_4 \tag{32}$$

Substituting yields

$$F_2C = (W_1W_2/2) - F_2L\tan\delta_4 \tag{33}$$

Note that F_2L and δ_4 have been previously derived.

The distance equations that have been developed to this point have been corrected for pitch and yaw angle. The final step is to correct for roll angle.

F. Roll Angle Derivation

Before deriving an equation for a roll condition, it should be noted that, in perspective, a common vanishing point exists for every set of parallel lines. When these sets of parallel lines lie in the runway plane, their vanishing points will lie on, and thus define, the horizon line of the runway plane.

Figure 5 is the projected image of a runway when viewed from a yaw condition. When viewing the runway from a yaw

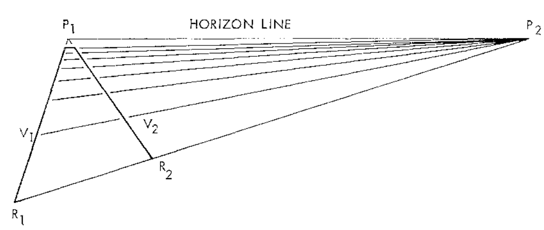

Fig. 5 Determination of horizon line.

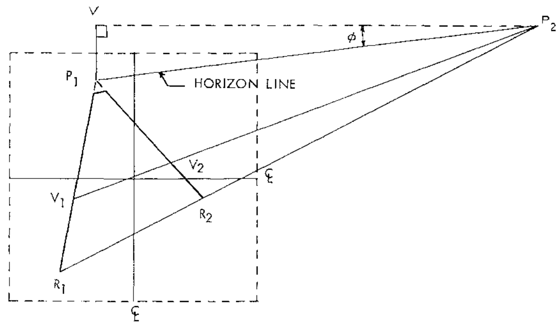

Fig. 6 Roll angle derivation.

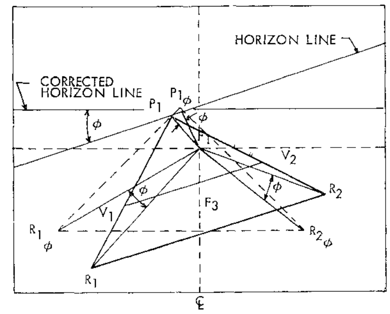

Fig. 7 Roll angle correction.

condition the runway light lines R_1R_2 and V_1V_2 will not be parallel with the horizon line P_1P_2 as in a no-yaw condition. The parallel runway light lines R_1V_1 and R_2V_2, when extended, will converge at the primary vanishing point P_1 on the runway plane horizon line. The parallel runway light width lines R_1R_2 and V_1V_2, when extended, will converge at a secondary vanishing point P_2, also on the runway plane horizon line. These two vanishing points define the horizon line of the runway plane. The runway plane horizon line may not coincide with the true horizon line, but this presents no problem since runway slope information is readily obtainable.

Figure 6 is the same view as Fig. 5 except that there is a roll condition in Fig. 6. Line P_1P_2 is the horizon line, and P_2V is parallel to the x axis of the film image. The angle included between these two lines is the roll angle φ:

$$\tan\varphi = P_2V/P_1V \tag{34}$$

In terms of the coordinates of P_1 and P_2 this equation would be written as

$$\varphi = \tan^{-1}[(P_2y - P_1y)/(P_2x + P_1x)] \tag{35}$$

The coordinates of P_1 are determined by solving for the intersection of the runway light lines, R_1V_1 and R_2V_2.

Substituting the coordinates of R_1 and V_1 into an equation for a straight line and letting $x = P_1x$ and $y = P_1y$ yields

$$(P_1y - R_1y)/(V_1y - R_1y) = (P_1x - R_1x)/(V_1x - R_1x) \tag{36}$$

Similarly, with the coordinates of R_2 and V_2,

$$(P_1y - R_2y)/(V_2y - R_2y) = (P_1x - R_2x)/(V_2x - R_2x) \tag{37}$$

Solving the two equations simultaneously yields

$$P_1x = \frac{R_1x\left(\dfrac{V_1y - R_1y}{V_1x - R_1x}\right) - R_2x\left(\dfrac{V_2y - R_2y}{V_2x - R_2x}\right) + R_2y - R_1y}{\left(\dfrac{V_1y - R_1y}{V_1x - R_1x}\right) - \left(\dfrac{V_2y - R_2y}{V_2x - R_2x}\right)} \tag{38}$$

and

$$P_1y = (P_1x - R_1x)(V_1y - R_1y/V_1x - R_1x) + R_1y \tag{39}$$

The coordinates of P_2 are obtained in the same manner by solving for the intersection of R_1R_2 and V_1V_2:

$$P_2x = \frac{R_1x\left(\dfrac{R_2y - R_1y}{R_2x - R_1x}\right) - V_1x\left(\dfrac{V_2y - V_1y}{V_2x - V_1x}\right) + V_1y + R_1y}{\left(\dfrac{R_2y - R_1y}{R_2x - R_1x}\right) - \left(\dfrac{V_2y - V_1y}{V_2x - V_1x}\right)} \tag{40}$$

and

$$P_2y = (P_2x - R_1x)(R_2y - R_1y/R_2x - R_1x) + R_1y \tag{41}$$

G. Roll Correction

The next step is to incorporate the roll angle correction into the basic equations. Figure 7 shows the film image of the runway light lines R_1V_1 and R_2V_2 extended to the vanishing point P_1 with an assumed roll angle φ. It also shows the same image after it has been rotated $\varphi°$ to correct for roll angle. Point F_1 is the optical center of the film image and is shown with the vertical and horizontal centerlines passing through it. The runway image is rotated around this point to correct for roll angle. Point F_1 will also be considered the origin of the coordinate system used in the derivation of the equations. From the basic distance equations [i.e., Eq. (30) and the proposed equations for vertical and horizontal distances mentioned at the end of Sec. 2D], the following points will require rotational correction: R_1x corrected to $R_1x\varphi$, R_2x corrected to $R_2x\varphi$, P_1x corrected to $P_1x\varphi$, P_1y corrected to $P_1y\varphi$, R_1y corrected to $R_1y\varphi$, and R_2y corrected to $R_2y\varphi$.

Substitution of the coordinates of R_1, R_2, and P_1 into standard derived equations for the transformation of coordinates around a fixed origin will result in the following equations:

$$R_1x\varphi = R_1x\cos\varphi + R_1y\sin\varphi \tag{42}$$

$$R_2x\varphi = R_2x\cos\varphi + R_2y\sin\varphi \tag{43}$$

$$P_1x\varphi = P_1x\cos\varphi + P_1y\sin\varphi \tag{44}$$

$$P_1y\varphi = P_1y\cos\varphi - P_1x\sin\varphi \tag{45}$$

$$R_1y\varphi = R_1y\cos\varphi - R_1x\sin\varphi \tag{46}$$

$$R_2y\varphi = R_2y\cos\varphi - R_2x\sin\varphi \tag{47}$$

The point F_3y is the intersection of the primary runway width line with the vertical axis after rotational correction and can be determined by substituting the coordinates of $R_1\varphi$ and $R_2\varphi$ into the equation for a straight line:

$$(y - R_1y\varphi)/(R_2y\varphi - R_1y\varphi) = (x - R_1x\varphi)/(R_2x\varphi - R_1x\varphi) \tag{48}$$

Letting $y = F_3y$, setting $x = 0$, and re-arranging yields

$$F_3y = [(R_2y\varphi - R_1y\varphi)/(R_2x\varphi - R_1x\varphi)](-R_1x\varphi) + R_1y\varphi \tag{49}$$

H. Final Equations

The coordinates, corrected for roll, are then substituted into the basic distance and attitude equations. With these final substitutions, the basic equations will then be corrected for yaw, pitch, and roll angle. The derivations of the equations for the various parameters were developed without regard to a sign convention in reading the data. By using the center of the film image as the origin of the coordinate system and using standard quadrant signs, the final equations for attitude and position are presented as follows. These equations are for a forward-looking camera installation. If the camera looks aft, the signs of the results for roll, pitch, and off-center deviation should be reversed.

Roll angle: right roll = +

$$\varphi = \tan^{-1}(P_2y - P_1y/P_2x - P_1x) \tag{50}$$

Pitch angle: nose up = +

$$\theta = -\tan^{-1}(P_1y\varphi/F_1L) \tag{51}$$

Yaw angle: nose right = +

$$\psi = -\tan^{-1}[P_1x\varphi/(F_1L^2 + P_1y\varphi^2)^{1/2}] \tag{52}$$

Longitudinal distance:

$$D_L = \frac{W_1W_2\cos\theta_2}{\left[\dfrac{-\tan\psi' + \left(\dfrac{F_3R_1\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right)}{1 + (\tan\psi')\left(\dfrac{F_3R_1\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right)}\right] + \left[\dfrac{\left(\dfrac{F_3R_2\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right) + \tan\psi'}{1 - \left(\dfrac{F_3R_2\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right)(\tan\psi')}\right]} \tag{53}$$

Vertical distance: the formula for vertical distance is the same as for longitudinal distance except that the cosine function becomes a sine function.

Off-center distance: deviation to right of runway center = +

$$D_{0c} = \frac{W_1W_2}{2} - \frac{W_1W_2}{\left[\dfrac{-\tan\psi' + \left(\dfrac{F_3R_1\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right)}{1 + (\tan\psi')\left(\dfrac{F_3R_1\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right)}\right] + \left[\dfrac{\left(\dfrac{F_3R_2\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right) + \tan\psi'}{1 - \left(\dfrac{F_3R_2\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right)(\tan\psi')}\right]} \left[\dfrac{\left(\dfrac{F_3R_2\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right) + \tan\psi'}{1 - \left(\dfrac{F_3R_2\varphi}{(F_3y^2 + F_1L^2)^{1/2}}\right)(\tan\psi')}\right] \tag{54}$$

III. Data Retrieval and Information Processing

Retrieval of the data from the film may be accomplished on any of a number of film measurement systems available. A semiautomatic film reader is recommended that is capable of measuring x-y coordinate displacement of selected reading points from an arbitrary fixed reference point. The machine should have automatic digitizing capability with readout into IBM cards for subsequent computer processing.

As the equations for the various parameters stand, no angular measurements are read. Only coordinate readings are made. Figure 8 shows the film image of the runway as it would appear under a certain attitude and position condition. Any convenient reference or zero-reading position may be used; however, it must be resolved to the optical center of the film image, since all of the equations are based on the optical center of the film image as the reference point. In Fig. 8, the optical center is F_1. A total of four points are read to provide input for all equations, i.e., point reading: R_1, R_2, V_1, and V_2; readout: x and y (at each point). Time is, of course, read at each reading frame.

In the reading of the film, R_1R_2 should be the closest pair of opposing lights, and V_1V_2 should be the next set of opposing lights beyond R_1R_2. As the aircraft moves along the runway, successive sets of lights are read. Identification of the runway lights will be necessary to determine the distance traveled along the runway. A runway survey map will provide runway light longitudinal spacing and also lateral separation. Information can be obtained as long as there are two sets of runway lights that can be read. Most runway lights are spaced approximately 200 ft apart along the runway, which will result in good takeoff and landing performance data if read at this interval with a timing system accurate to 0.01 sec. Any frequency of data can be read up to the total number of film frames used in recording the data, provided that the timing system is accurate enough to obtain good velocity and acceleration data. Standard numerical techniques may be employed to smooth and differentiate the displacement data in order to obtain the velocity and acceleration derivatives. Camera installation corrections and runway slope corrections will have to be made.

In Fig. 9 there are four film image views under various attitude conditions and an off-center condition. With no attitude deviation, the vanishing point coincides with the image center. With a pitch condition, P_1 will deviate along the y axis of the film image. The last illustration shows an off-center deviation.

IV. Camera System and Installation

A 35-mm instrumentation-quality motion picture camera with good film registration is recommended. A 16-mm camera is not precluded from use in this technique. Timing and event lights are recorded as a secondary image along the

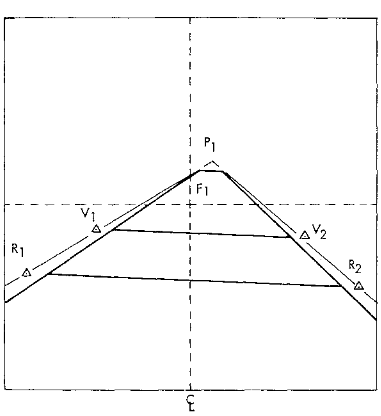

Fig. 8 Data reading points on film image.

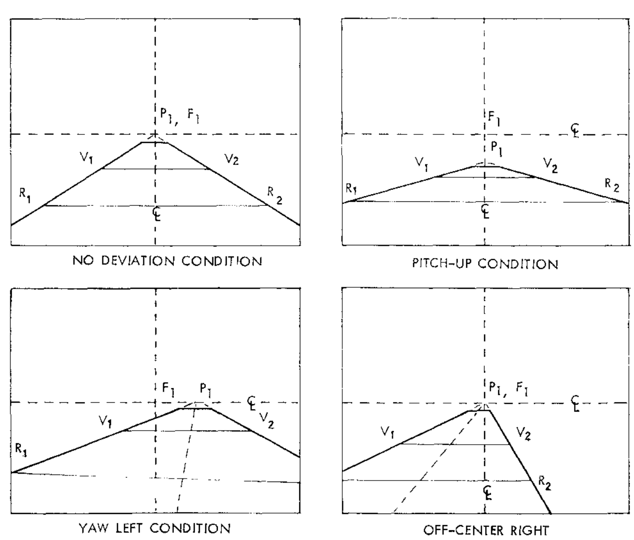

Fig. 9 Film image runway views.

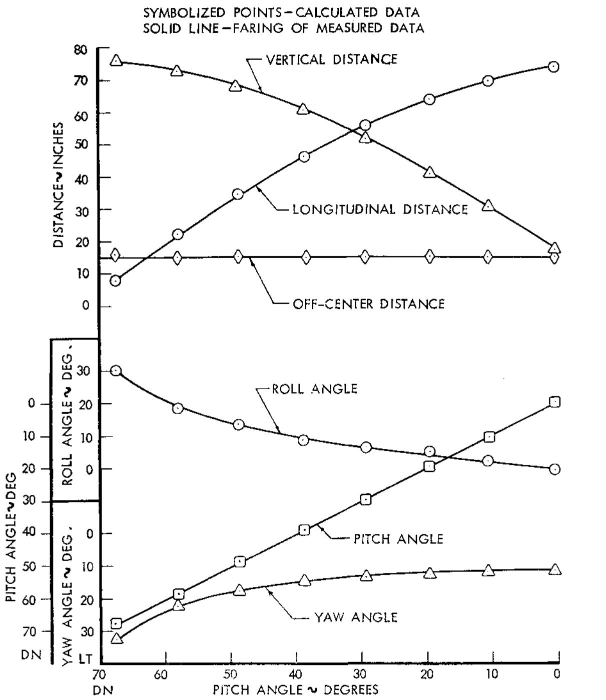

Fig. 10 Attitude and position calibration of camera with respect to a simulated runway.

edges of the film frame. A normal lens with good linearity is recommended for best quantitative results. Any suitable framing rate may be chosen dependent upon the test requirement and the timing system, and sufficient to provide good continuity in viewing the runway lights.

The camera may be installed anywhere on the aircraft as long as there is an unobstructed view of the runway either forward or aft. The camera mounting angles may also be varied to meet a particular installation requirement. A mounting underneath the fuselage with the main gear in view would provide precise unstick and touchdown points. Initial and final aircraft movement could also be determined.

V. Application

The development of this technique has been pointed primarily towards the determination of aircraft takeoff and landing performance data. The technique, however, is not restricted to this application. It is believed that there may be other areas of testing and development work where this technique may be applied.

Besides conventional aircraft takeoff and landing tests, the technique would have application for V/STOL vehicles including hovering tests, height-velocity tests, transition between horizontal and vertical flight, maneuvering tests, etc. Another obvious utilization of this technique in aircraft flight testing is airspeed and altimeter calibrations. Fly-bys over the runway with this camera system will obtain the velocity and altitude information necessary to calibrate the airspeed and altimeter systems. Higher altitude calibrations could be performed, provided that the reference base were of sufficient magnitude.

Ground tests or laboratory tests where it is desired to obtain data describing the attitude, position, and movement of a test article would be feasible. If the test did not permit mounting the camera on the test vehicle, a target reference could be placed on the test vehicle and the camera placed on a stationary mounting viewing the target reference. This technique could obtain data from one camera which normally would require three cameras with the inevitable correlation problems. It may have application for evaluation of the initial launch phase of missile or satellite first-stage rocket boosters.

VI. Calibration Results

To check the validity of the technique, a calibration was performed in a laboratory by positioning a camera with respect to a simulated runway. The simulated runway was laid out on a flat surface that was hinged across the runway width, so that the runway plane could be rotated about this line. Thus, the camera was fixed, and the runway was rotated about the primary runway width line permitting simpler and more accurate measurements. With the camera optical axis initially yawed with respect to the runway heading, rotation of the runway about the hinge line results in a smooth variation of both the attitude and position of the camera with respect to the runway plane and hinge line. Initial camera attitude and position measurements were made with respect to the runway prior to rotation. Subsequent measurements required only an inclinometer measurement of the runway plane at each rotation point. All attitude and position parameters were then calculated from the initial measurements plus each runway slope measurement.

The plot of the calibration is shown in Fig. 10. For this calibration, the camera was placed completely off the runway in a lateral sense. The pitch angle was varied from 0° to almost 70° nose down. The solid lines represent the true position and attitude of the camera with respect to the runway as calculated from the measurements. The symbolized points represent calculated output from the computer program of the technique.

VII. Qualitative Results

The primary concern, qualitatively, was the ability to see the runway lights during daylight hours. It is likely that there may be some airports where it is difficult to see the runway lights, depending upon the intensity of the lights and the background behind the lights. Difficulty was encountered in viewing runway lights at a desert airport during midday hours apparently because of the lack of contrast. Any difficulty in

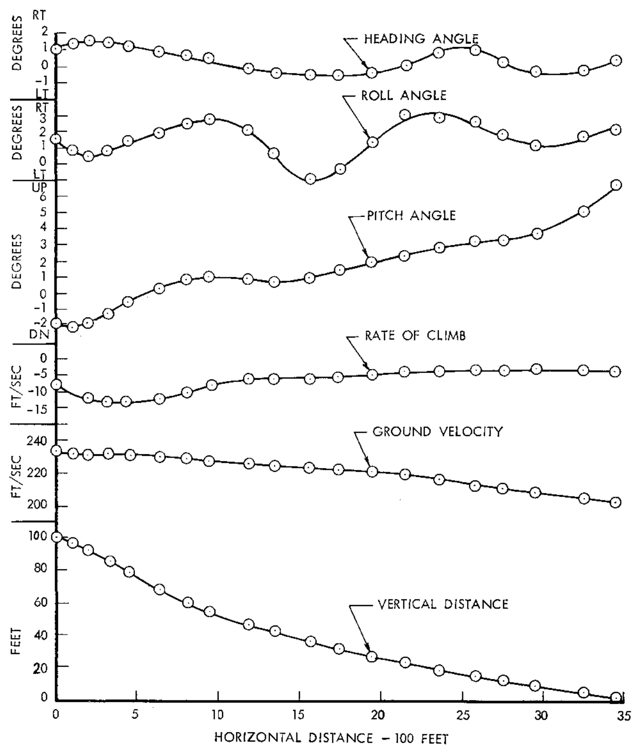

Fig. 11 Aircraft landing.

viewing the runway lights because of light intensity or lack of contrasting background can be overcome by performing the tests during the early morning hours or late afternoon hours when there is better contrast. Color film is considered a necessity in this technique. It may be possible, however, that some type of marker could be constructed and placed along the runway which would be visible on black and white film.

VIII. Quantitative Results

A 35-mm motion picture camera was mounted vertically within the underside of a transport aircraft fuselage. Camera lens to ground distance was 5 ft. A prism attachment in front of the lens permitted a view of the runway ahead of the aircraft. The camera was mounted 8 ft behind the main landing gear with the optical axis pointed 8° down from the airplane longitudinal axis. Camera position was corrected to an airplane reference point midway between the main landing gear. Camera attitude was corrected to the airplane axes.

A landing was made at Palmdale Airfield, Calif. on runway 25, which has a runway light lateral separation of 210 ft and a longitudinal spacing averaging 192 ft. The results are shown in Figs. 11 and 12, which are ground distance histories of the landing. Data are presented from a vertical distance of over 100 ft to approximately the touchdown point.

The camera was also mounted underneath the fuselage facing aft in the same airplane with the optical axis pointed down about $12\frac{1}{2}°$ from the airplane longitudinal axis. Its position was $12\frac{1}{2}$ ft behind the main gear. A "touch and go" was made at Van Nuys Airport, Calif. on runway 16, which has a runway light lateral separation of 170 ft and a longitudinal spacing averaging 200 ft. The results are shown in Figs. 13 and 14, which are ground distance histories of the takeoff from the touch and go. Data are presented for approximately 3500 ft of ground distance with the airplane accelerating on the runway through takeoff and climb to over 60 ft vertical distance.

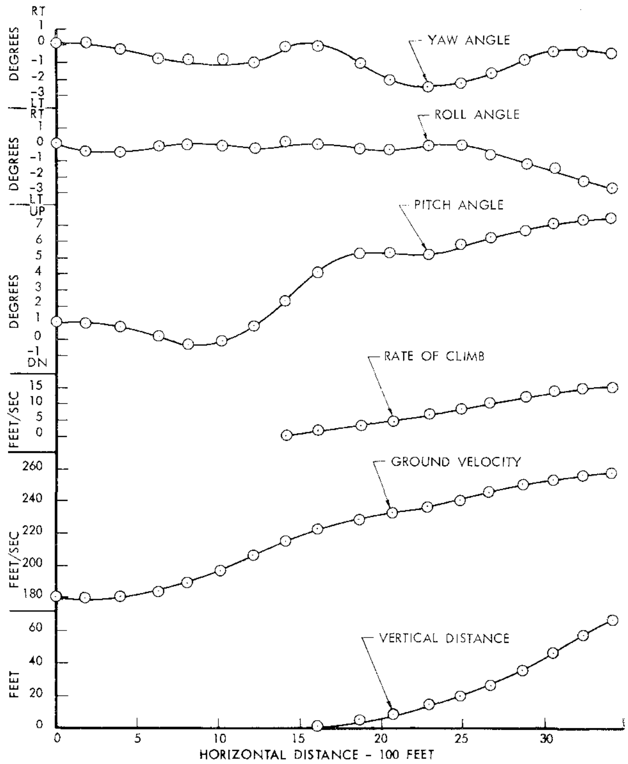

Fig. 13 Aircraft takeoff from touch and go.

IX. Comparison with Ground Camera Systems

The airborne system permits flexibility in the choice of airports where the tests are to be conducted. If it is desired to do takeoff and landing performance tests at a high-altitude airport, it is only necessary to fly to the airport and conduct the tests. Although it is possible to set up the ground camera systems at some remote airport, it entails considerable preparation before the tests can be conducted, and the problem of obstructions blocking the view of the runway is frequently encountered.

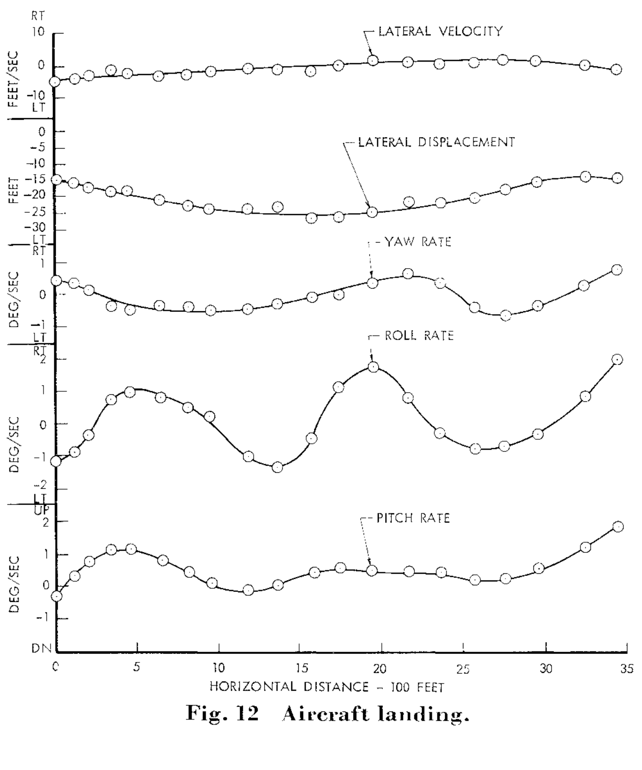

Fig. 12 Aircraft landing.

Experience with the original Lockheed Airborne system (L^2ORI) has shown that tests may be conducted more efficiently with less delays than with ground camera systems. There is no reason to believe that this airborne system would be any different in that respect. Coordination with ground camera crews is eliminated.

The airborne camera may be mounted underneath the fuselage in such a manner as to permit a view of the main gear

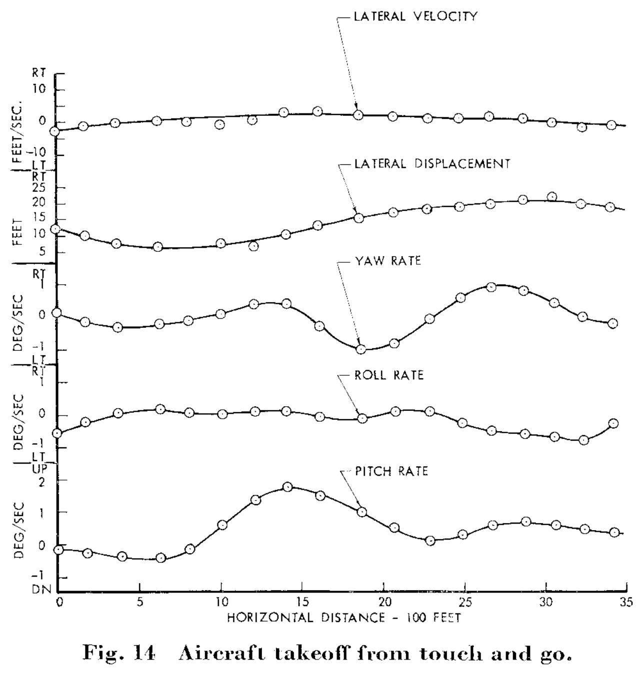

Fig. 14 Aircraft takeoff from touch and go.

Table 1 Standard deviation of errors

Parameter	Vertical distance = 50 ft σ	$3\sigma_{max}$	Vertical distance = 90 ft σ	$3\sigma_{max}$
Longitudinal displacement, ft	0.28	1.05	0.26	0.98
Vertical displacement, ft	0.34	1.27	0.38	1.42
Lateral displacement, ft	0.97	3.60	0.89	3.30
Longitudinal velocity, fps	0.15	0.54	0.18	0.68
Vertical velocity, fps	0.17	0.65	0.25	0.94
Lateral velocity, fps	0.60	2.22	0.52	1.94
Longitudinal acceleration, ft/sec^2	0.13	0.49	0.13	0.49
Vertical acceleration, ft/sec^2	0.19	0.17	0.22	0.82
Lateral acceleration, ft/sec^2	0.56	1.70	0.58	2.16
Pitch angle, deg	0.07	0.27	0.09	0.33
Roll angle, deg	0.27	1.00	0.30	1.10
Yaw angle, deg	0.17	0.63	0.11	0.39
Pitch rate, deg/sec	0.04	0.14	0.06	0.20
Roll rate, deg/sec	0.17	0.63	0.17	0.64
Yaw rate, deg/sec	0.11	0.41	0.06	0.23
Pitch acceleration, deg/sec^2	0.04	0.16	0.05	0.17
Roll acceleration, deg/sec^2	0.13	0.48	0.19	0.70
Yaw acceleration, deg/sec^2	0.08	0.29	0.07	0.27

and the runway. With this installation, it is possible to precisely determine the touchdown, unstick, brake release, and final stop points. These points are not determined with precision with ground camera systems.

The ground systems will obtain longitudinal and vertical displacement and their respective velocity and acceleration derivatives. The airborne system will completely define the attitude and displacement of the aircraft and their respective velocity and acceleration derivatives. If it is desired to coordinate the camera with other on-board instrumentation, it is an easy job for an airborne camera and a more difficult task for a ground camera.

There is a diminution of accuracy of the ground camera systems with the increasing camera angles that occur at the initial and terminal phases of the test run. With the airborne camera, accuracy is maintained at the initial and terminal phases of the test run as the runway reference base advances along with the aircraft.

X. System Limitations and Operational Restrictions

An increase in yaw angle runway off-centerness or vertical distance will move the nearest viewable set of runway lights further away from the camera, increasing the error. Restriction in vertical displacement is dependent upon accuracy requirements.

Runway off-centerness of 40 to 50 ft while the airplane is on the runway may make it difficult to view the runway lights on the far side of the runway and to pair them with lights on the near side. This problem diminishes with vertical distance.

The technique will obtain all of the data for any angle and position that the camera optical axis may assume with respect to the runway light plane, provided that the reference runway lights are in the field of view of the lens except when the optical axis lies within the same plane as the runway lights. Opposing runway lights must be evenly spaced laterally and longitudinally along the runway to achieve valid results. The pattern of evenly spaced lights is frequently broken at runway crossings and taxiway intersections, and it is necessary, under these circumstances, to view lights further down the runway with some loss in accuracy.

Care must be exercised in the installation of the camera to prevent engine exhaust from entering into the field of view of the lens. This is a restriction, primarily, in an aft facing camera installation.

XI. Error Analysis

A reading error and program calculation precision analysis was performed for a simulated landing from a 90-ft vertical distance to touchdown. The objective of the analsis was to determine the standard deviation of error and the maximum error of the 18 translational and rotational parameters that are calculated by this technique in a range of vertical distance from 5 to 90 ft.

An analytical set of expressions was derived which defined a simulated landing in terms of the coordinates of the reading points on the film for each set of time and distance conditions during the simulated landing. Random film reading errors were determined at each vertical distance input and applied to the analytical coordinates, which were then used as input to the computer program for the technique. Input to the analytical model was considered as the true value of the parameters. Output from the computer program for the technique was evaluated in comparison to the input to the analytical model for the error analysis.

Monte Carlo techniques were employed in this analysis. The generation of 1000 simulated landings resulted in a level of confidence of 94.5% that the true standard deviation of the error σ_T was within 24% of the calculated value of the standard deviation of error σ. There is a level of confidence of 94.5% that the maximum error is less than or equal to $3\sigma_{max}$ where σ_{max} is defined as 1.24σ. Standard deviations of the error and maximum values of the error for vertical distances of 50 and 90 ft are presented in Table 1.

XII. Conclusions

This technique has the capability to provide accurate longitudinal, vertical, and lateral displacement of a conventional or V/STOL airplane as well as roll, pitch, and yaw angle. This includes the capability to obtain the respective velocity and acceleration derivatives as well. Tracking, tangential and flight path velocities, and accelerations may be obtained.

The technique was developed, primarily, for the determination of airplane takeoff and landing performance data of conventional aircraft, but it might well be used to satisfy any test requirement for attitude and position information of any flight vehicle. Additional applications may include airspeed and altimeter calibrations, VTOL hovering, and autorotational characteristics.

No special camera system or equipment is required other than a good instrumentation quality motion picture camera with timing and pilot event lights. Data retrieval from the film requires no special techniques. The film may be read quickly with minimum instruction. A fairly extensive computer program is required.

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