Visual Cues in Manual Landing of Airplanes

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Abstract: This paper discusses recent findings in ongoing research on the visual cues that pilots use when landing airplanes. An overview is given of the many visual cues that have been proposed in literature. Some are widely accepted as 'important cue' in a certain phase or for a certain decision, others are controversial.

Specifically the cues used to time the flare maneuver are discussed in this contribution. The flare is a pitch-up maneuver a few seconds before touchdown, in order to decrease sink rate and land on the main landing gear first, and therefore its timing and accuracy of performance are critical for a safe and comfortable landing.

Analysis of human pilot control in real and simulated landings of mid-size aircraft in previous research has suggested a new cue on which the pilot seems to base the timing of the flare maneuver: the speed at which the apparent angle between the runway sidelines increases $(\dot{\theta})$. The current research further investigates the $\dot{\theta}$ cue through mathematical analysis and using data obtained from flight simulator landings.

Keywords: Visual Cues, Perception, Human Pilot, Airplane Landing, Control, Psychophysics

1. INTRODUCTION

A pilot's accurate perception and interpretation of visual cues in the out-the-window view are of utmost importance for landing airplanes safely. In extreme conditions where automated landings cannot be made and manual control is needed, this is obvious, but also for proper supervision of today's autopilot systems, the human pilot must obtain proper state-awareness mainly from visual cues. This is a skill which is developed through extensive training and experience.

The final approach to landing being one of the most demanding standard operations [1], being the phase most prone to accidents [2] and being heavily dependent on the pilot's visual perception, state awareness and decision making, it is of great interest to gain a deeper understanding of the factors determining the pilot's control. Knowledge about the available (visual) cues, the information contained in them and how and when experienced pilots use those cues is valuable for training junior pilots, increasing simulator fidelity, augmented display design, awareness of visual illusions etc. etc.

The research presented here contains two parts, the first being a review of aeromedical, pilot training, and human control modeling literature and the second part being an analysis of human piloted landing simulations. Previously reported results [3] indicated that the change of the apparent angle between the runway sidelines (due to linear perspective) may play a major role in the timing of the flare maneuver. This result has been further investigated and the findings from experimental and theoretical analysis will be elaborated on in this paper.

2. THE VISUAL PERCEPTION OF MOVEMENT AND DEPTH

The key point in vehicular guidance[1] is state awareness; one must know his position, orientation and velocities relative to the scene in order to control the vehicle appropriately. Most of this information is obtained through observation of the visual scene.

2.1 Two Approaches

Two different approaches can be found in literature considering the perception of movement. The first is 'motion perspective' (or 'optical flow') as described by Gibson et al.[4] in the 1950's and has been adopted by many other researchers ever since (e.g. [5–11]). It is based on the relative movements of all points in the visual field and thus depends on the texture of the scene. In experiments, this texture is often simplified to parallel and/or perpendicular lines or random dot patterns. The optical flow theory describes the passive perception of movement and does not take into account the fact that the observer may shift his focus of visual attention to specific objects that contain special information relevant to the task.

The second approach to modeling visual perception does focus on special features in the visual scene ('visual cues') that contain specific information. This includes for example the notion of the horizon as a cue for pitch and roll attitudes (and movements), the retinal size of known objects as a cue to distance, and shape distortion as a cue to the relative orientation of known objects. Which cues are used depends very much on the task and scene: the cues to look for will be very different for landing an aircraft on a runway, and for finding a needle in a haystack.

2.2 Depth & Distance Cues

Probably one of the most important things in aircraft landing is proper depth and distance perception. Altitude and distance (and sink rate and ground speed) awareness are essential for a smooth and safe landing. There are many cues available to estimate (relative) distance. Good overviews of generally available depth cues can be found in [12–15].

2.3 Visual Perception during Landing

Several researchers have investigated the way pilots look at the out-the-window scene and a wide variety of visual cues has been suggested for guidance during the final approach to landing.

Like many others, Riordan [16] describes the visual cues important to the pilot in relatively vague terms: 'Runway Perspec-

[1]The problem of aircraft landing discussed in this paper is closely related to that of car driving, a skill which is also learned through experience. Also in car driving the 'instrument panel' only plays a minor role and visual information is the main source of state awareness.

tive', 'Visual Rate of Change' and 'Runway Motion Parallax'.

> *Runway Perspective includes the visual combination of size (a function of horizontal distance) and shape (a function of vertical distance) to produce a slant appearance. The Visual Rate of Change combines moment-to-moment changes in the horizontal (size) and vertical (shape) distances or 'perspective.' Motion parallax includes apparent vertical displacements of the runway or target touchdown point as well as real changes in runway perspective.*

However, there is no consensus about the use of apparent length and/or width of the runway as cues [17–20]. Furthermore, often the 'size of familiar objects' (or level of texture detail) is also mentioned as an important cue [1, 16, 17, 21]

> *[...] the visual cues used most are those related to changes in runway or terrain perspective and to changes in the size of familiar objects near the landing area such as fences, bushes, trees, hangars, and even sod or runway texture. [21, Ch.8]*

Optical flow [4] can be regarded in many ways. The most essential is maybe that the focus of expansion is the heading point, which should be the touch down zone markings (TDZM) in a normal approach. Pilots also noted that flow in the far periphery of the visual field is important to correctly estimate sink rate in the final phase of landing [priv. comm.].

A cue derived from the optical flow is τ, the time to contact as defined by Lee [22], although it can also be derived from a specific feature such as the apparent runway width. τ has been suggested as a guide for the flare phase (roundout, leveloff) [20, 23], although others [24] could not confirm this and found a dependency on sink rate instead (which is consistent with [25], but sink rate is not a readily available visual cue).

For pilot modeling purposes it is important to have cues which can be translated into variables with numerical values. The main 'numerical' cues are:

- **The 'implicit horizon'**, which is the distance between the horizon and the aim point (TDZM), measured in the visual plane (Y-H in Fig.1), is especially important for keeping the preferred glide slope [18, 19, 21, 26].
- **The position of the horizon** (Y), which has a close relation to the pitch of the aircraft.
- **The perceived angle between the runway edges** (θ), which provides altitude information [18, 27, 28].
- **The width of the runway** (W), this may be seen as a 'familiar size' cue, specifying distance. Width of the near end, width of the far end and distance between the markers are sometimes considered separately. [18, 20, 29]
- **The rotation of the centerline w.r.t. the vertical** (Ψ), for lateral control [26, 30, 31].
- **The rotation of the horizon**, (φ) for roll angle control.

Figure 1 shows the above mentioned cues and a few others, but is still far from exhaustive.

This quick overview of possible cues shows that there are many visual cues available to the pilot and for most of these cues, taking the time derivative of the cue into account could also be meaningful.

2.3.1 Binocular Cues

In research on visual depth perception, often the separation between 'monocular' and 'binocular' cues is made. Monocular cues are those which can be extracted with a single eye, from an image or video. All cues described above are Monocular. Binocular cues, by definition, can only be perceived by cooperation of both eyes. The two cues specific to binocular vision

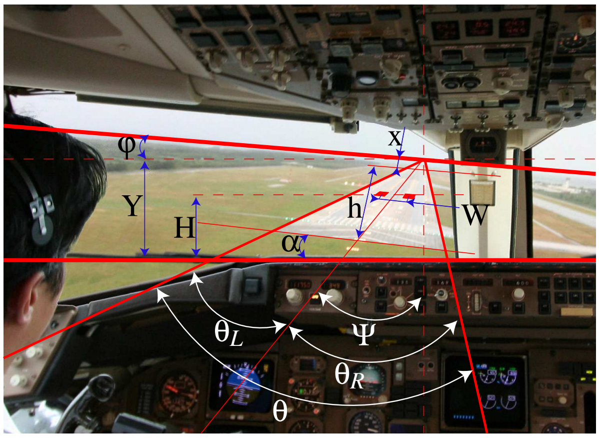

Fig. 1 Definition of visual cue variables.

are 'vergence' (the simultaneous movement of the pupils of the eyes towards or away from one another during focusing) and 'stereopsis' (depth perception based on the disparity of the two retinal images resulting from the slightly different viewpoints of the side-by-side eyes)[2].

There has been quite some discussion about whether binocular cues are useful in aircraft landing, which is the reason to mention it separately here. Three points of discussion can be found, which I will comment on subsequently:

- Do monocular pilots perform worse than binocular pilots?
- What is the limit of stereopsis?
- What is the strength of the stereoscopic depth cue in relation to monocular cues?

Several studies have compared the use of monocular and binocular cues in aviation [35–41]. For proper interpretation of the results of that research, it is important to note the difference between the phrases 'binocular cues are *needed*' and 'binocular cues are *used*', as quite a portion of the research was done to prove that pilots with bad or no stereo vision (monocular pilots) should still be allowed a license. The conclusion that, although an aircraft *can* be landed monocularly, binocular pilots still use stereoscopic cues, is generally not drawn, even when the experiment results indicate so[3].

Values mentioned for the 'limit of stereopsis' (the greatest distance at which an object can just be detected as nearer than an object at infinity) vary widely: from 6m [15, 41][4] upto 6.5km [15][5]. Much depends on the way the experiment is done, for example [42] shows that stereoscopic acuity varies widely for

[2] Apart from providing these 2 new cues, the use of two eyes extends our field of view and can improve perception of monocular cues, see for example [32–34]

[3] Monocular pilots were found to make steeper approaches and have higher sinkrates at touchdown [36, 38], pilot uncertainty and workload seemed to increase (e.g. the pilots were observed to make more head movements, probably to get more depth cues from motion parallax) [35–38], and first monocular landings were clearly inferior although pilots quickly adapted during the experiment [35, 38].

[4] References just mention the value, no experimental or theoretical basis is provided. There may have been a mixup with the limits of vergence.

[5] This is a theoretical extrapolation based on the best acuities obtained in laboratory experiments with the Verhoeff stereopter.

laboratory tests with different types of (or without) comparison stimuli. In field experiments it is practically impossible to rule out the additional use of monocular cues. Furthermore, illumination levels, the part of the retina used, stimulus size and orientation in frontal plane all influence acuity [43, §5.918], not to mention the wide interpersonal differences. The actual limit should probably be assumed to be around 500m [44–46], although the limit of practical use is about an order of magnitude lower [12, 47].

The last point of discussion, about the relative strentgth of binocular depth cues is a very difficult one indeed. It is strongly related to the pilot's stereoacuity, and the availability and strength of the monocular cues [48, 49]. In degraded vision situations, such as night approaches, bad weather, and at unknown airfields, binocular cues may prevent illusions arising from monocular cues. The U.S. Navy notes

> *Stereopsis is not an absolute must in flying an aircraft, and in fact the FAA does not require this to be tested. [...] However, the visually demanding environment of carrier aviation requires every sense a pilot can have.[50, 1999 ed., §12.4]*

As we saw, the practical limit of stereopsis is probably in the range of several decameters. With the runway outline providing very strong linear perspective cues, it is likely that binocular cues only play a supportive role. In monocular landings pilots were found to have a different landing style, but most of these experiments were carried out in small aircraft (responding quickly and flaring at very low altitude) and often the field of view of pilots was reduced in the monocular landings. It can finally be concluded that for landing small aircraft, flying helicopters, ground operations, formation flight, mid-air refuelling etc. binocular cues may play a role, but for landing midsize or larger passenger or transport aircraft they can be safely ignored[6].

3. OVERVIEW OF PREVIOUS RESEARCH

Previous research by the author [3] dealt with finding the visual cues a pilot uses, through analysis of scene and flight control data. A method was developed to construct a model of a human pilot which takes visual cues and generates longitudinal control actions during the visual approach to landing. This model was based on numerical data obtained from real or simulated landings by human pilots. Of main interest were the structure and parameters of the resulting model, i.e., the driving inputs, internal relations and thresholds, as these give insight in the pilot's (subconscious) behavior.

The research focused on two phases in the final approach to landing (see Fig. 2): the glide phase –where the pilot should maintain a constant descent which is generally about 3 degrees and keep the airplane aligned with the runway centerline– and the flare phase (also called roundout or leveloff) –where the pilot slowly pulls the column to make the aircraft pitch up in order to decrease the sink rate and land on the main landing gear first.

Proper timing and execution of the flare are critical for a soft and safe landing.

> *The rate at which the roundout is executed depends on the airplane's height above the ground, the rate of descent, and the pitch attitude. A roundout started excessively high must be executed more slowly than one from a lower height to allow the airplane to descend to the ground while the proper landing attitude is being established. The rate of rounding out must also be proportionate to the rate of closure with the ground. When the airplane appears to be descending very slowly, the increase in pitch attitude must be made at a correspondingly slow rate. [21]*

An especially interesting result of that research was that the *timing* of the flare initiation seemed to depend strongly on the 'speed of apparent rotation of the runway edges', which we call $\dot{\theta}$. This result was interesting as it had not been mentioned in literature before, although it makes sense because the apparent runway edge inclination is strongly related to altitude.

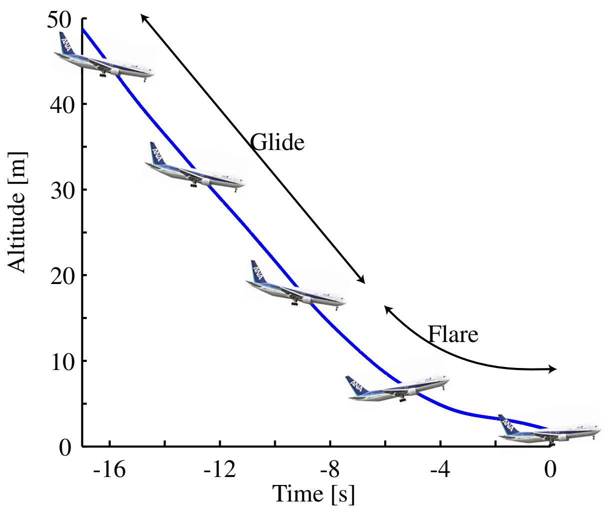

Fig. 2 In the final approach to landing, the pilot pitches up to arrest sink rate and land softly on the main gear. This maneuver is called the flare.

4. CUES FOR FLARE INITIATION

Training literature and autopilot specifications often mention the flare is initiated at a certain altitude. However, experienced pilots show a wide range in flare initiation altitudes (see for example [3, 51]), and by their more sophisticated control – taking sinkrate into account– they are generally able to make softer touchdowns [52]. Two cues which contain altitude as well as sinkrate information are detailed in this section: the time-to-contact-cue and the newly found runway-edge-rotation-cue.

4.1 Time To Contact as a Cue for Flare Initiation Timing

As discussed in §2.3, several researchers have suggested that pilots may use the time to contact (TTC) τ as a cue for the (initiation of the) flare phase, although the results were not always supporting this hypothesis.

τ, a variable originally derived from the optic flow, can be expressed in many ways. When considering aircraft states, the altitude tau is most convenient:

$$\tau_z = \frac{h}{\dot{h}} = \frac{\text{altitude}}{\text{sinkrate}}. \quad (1)$$

[6]This discussion has been limited to stereopsis as a binocular cue since the limit of vergence is generally accepted to be only a few meters. In professional flight simulators the displays are collimated to make sure no wrong vergence cues are perceived.

In case of visual cues, the TTC can be obtained from the apparent inclination of the runway edges:

$$\tau_\theta = \frac{\theta}{\dot{\theta}} = \frac{\text{angle between runway edges}}{\text{change rate of angle between runway edges}}. \quad (2)$$

It can be shown that τ_z and τ_θ are similar (see Appendix B.)

Some training literature mention a flare initiation rule slightly more advanced than the fixed altitude, for example:

Upon approaching the desired altitude, select a predetermined level off lead point. Ten percent of the vertical velocity in feet [per minute] is a good estimate for the level-off lead point.[53, Vol.1, §2.4.5]

This '10%-rule' to determine the flare altitude h_{flare} given the sinkrate $\dot{h}$ also comes down to a TTC-rule, as it can be written as

$$h_{\text{flare}} = -6\dot{h}, \quad (3)$$

for h in meters (or feet) and $\dot{h}$ in m/s (or ft/s), or alternatively as

$$\tau_{z,\text{flare}} = \frac{h_{\text{flare}}}{\dot{h}} = -6. \quad (4)$$

Although the TTC-based flare model is much better than the fixed altitude assumption, there is still a discrepancy between the model and experimental results. Grosz et al. [24] note on their experiment results:

In the first place, it is clear that our pilots did not initiate the flare at a constant height above the runway, as the height at T_f was found to be significantly correlated with sink rate at T_f At the same time, however, it is also clear that they did not initiate the flare at a constant tau-margin magnitude, specifying the time before they would make contact with the runway. [...] in the present experiment we found the tau-margin at the onset of the flare to decrease with increasing sink rate!

If we assume the runway-edge-rotation-cue (see next subsection) to reach a certain value to indicate the flare start, we see that the corresponding tau margin indeed decreases with increasing sinkrate (Fig.3).

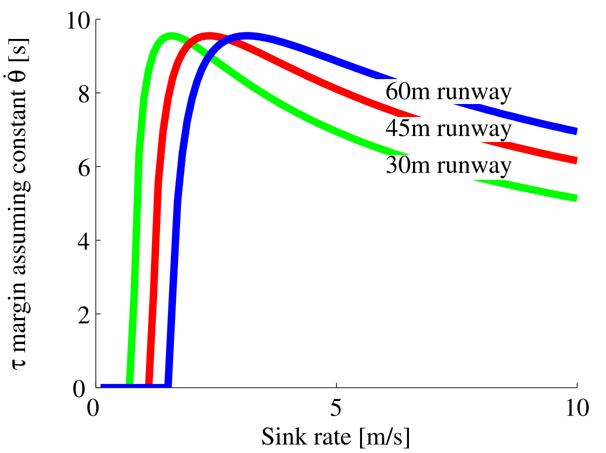

Fig. 3 Tau-margin as function of sinkrate as it would be found by Grosz et al. [24] if the real cue to flare initiation was the rotation rate of the runway edges. Different lines show values for different runway widths.

4.2 Speed of Apparent Rotation of the Runway Edges as a Cue for Flare Initiation Timing

In previous research by the author [3] the speed of apparent rotation of the runway edges $(\dot{\theta})$ was found as a cue for timing of the flare initiation, rather than the TTC (τ_θ). When analyzing the aircraft states –to compare with literature– not exactly the TTC (τ_z), but still a combination of altitude and sinkrate (or altitude and τ_z) was found. This section will look deeper into the visual cue $\dot{\theta}$ by deriving its relation to altitude and sinkrate and linking it to pilot control obtained from simulated landings.

4.2.1 Theoretical Background

Due to perspective, ground lines parallel to the line of sight seem to converge to a single point on the horizon. This makes that for instance the sidelines of the runway seem to make an angle (θ in Fig.1). The lower the altitude, the bigger this angle gets. The angle is also a function of the real distance between the ground lines (i.e. the width of the runway). It can be expressed as [7]:

$$\theta = 2 \cdot \tan^{-1}\left(\frac{\frac{1}{2}\text{Width}}{\text{Altitude}}\right), \quad (5)$$

The time-derivative of this cue is a function of both altitude and sinkrate[8]:

$$\dot{\theta} = \frac{\text{Width}}{\text{Altitude}^2 + \left(\frac{1}{2}\text{Width}\right)^2} \cdot \text{Sink rate}. \quad (6)$$

It is well know that for good flare control both altitude and sinkrate should be taken into consideration. $\dot{\theta}$ is therefore a plausible cue.

Except for containing appropriate information, the cue has to be visible with the human eye with sufficient accuracy. Several researchers have mentioned rotation thresholds of 2.5∼3°/s for similar tasks [54, 55] and [26] mentions such a cue would be 'observable below a height of about 120ft'(≈37m). Although $\dot{\theta}$ is just the speed at which an angle increases, the human observer may be even more sensitive to this cue than we would expect based on the threshold for rotation. This is because we are very sensitive to expanding objects, especially if the center of expansion is in the center of the visual field, as this normally indicates an approaching object at collision course. Even when setting the rotation threshold as a limit for detectability however, $\dot{\theta}$ can be perceived early enough to give time for observation and decision making regarding the flare initiation (cf. Figs.4 and 5).

4.2.2 Match with Experiment Results

Landing data were obtained in two different simulators:

- A high class simulator with Wide Angle Collimated display owned by JAXA (Japan Aerospace Exploration Agency) [Dornier Do228-202 turboprop airplane @20Hz]
- A certified Boeing 767 simulator owned by ANA (All Nippon Airways) [@10Hz]

The simulators were always operated by experienced pilots holding a license to fly the real plane.

First of all it is interesting to note that the maximum value of $\dot{\theta}$ is the same for all flights, as can be seen in the upper graphs in Figs.4 and 5. There is of course a difference between the two aircraft types, as the turboprop flares at a considerably lower altitude than the B767 and thus has a higher value of $\dot{\theta}$.

The point where the pilot initiates the 'pre-flare' (marked ① in the figures) varies considerably in time, value of $\dot{\theta}$, and indeed also in all the other observed cues and states. However,

[7] See App. A.1 for the derivation

[8] See App. A.2 for the derivation

this first pull of the column is slight, slow and generally the pilot holds the column or even releases it shortly before really flaring (from point ② on). This start of the real flare is found to coincide with the maximum value of $\dot{\theta}$. It seems like the pilot notices $\dot{\theta}$ increasing rapidly, slowing down this process by 'pre-flaring', and when $\dot{\theta}$ reaches the right speed of angle increase, the pilot flares the aircraft.

Also interesting is that when the value of $\dot{\theta}$ gets too high again (or stops decreasing for the B767 case), the pilot commands some additional pitch just before touchdown (marked ⑤)

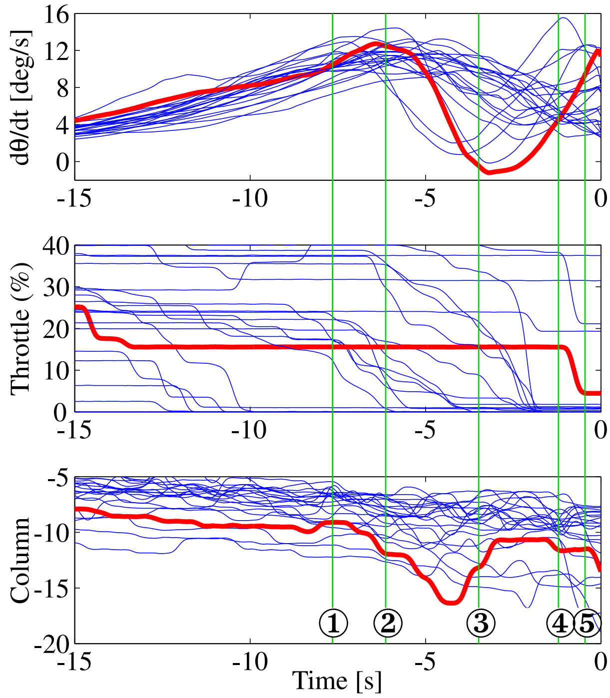

Fig. 4 In turboprop aircraft landing simulations 2 control styles were observed, the style typical for small aircraft (see [3]) is highlighted. The proposed visual cue $\dot{\theta}$=dθ/dt is shown in the upper figure, and seems to reach a constant maximum value of ca. 12°/s regardless of flare control style. ① start of 'pre-flare' ② pilot hesitates, seems to wait for/confirm proper cue value before fully flaring ③ pilot hesitates, seems to wait for/confirm no sink ④ when decreasing throttle, pilot compensates resulting pitch change ⑤ when cue value gets (too) high again, the pilot starts to pull the column more.

5. CONCLUSION

When landing his aircraft, the pilot has a wide variety of visual cues available to base his control judgments on. Over the years, researchers have identified many of the most important visual elements in the scene (runway, horizon, markers, texture), however the way these are used by the pilot (i.e. subconsciously processed in the brain) is often still unknown. It is for instance well known that the runway side lines are very important when landing as they provide altitude information, but pilots have rarely be seen to use altitude-driven control strategies.

A newly proposed visual cue –the speed at which the angle between the runway sidelines increases $(\dot{\theta})$– which is thought to be used for the timing of the initiation of the flare maneuver has been analyzed further and compared to time to contact (TTC) cues put forward by other researchers. It has been shown that, like the TTC, $\dot{\theta}$ provides combined information on the altitude and sinkrate, the two main factors determining the flare point. The cue has also been shown to be strong enough to be observed by the pilot early enough to determine the flare point.

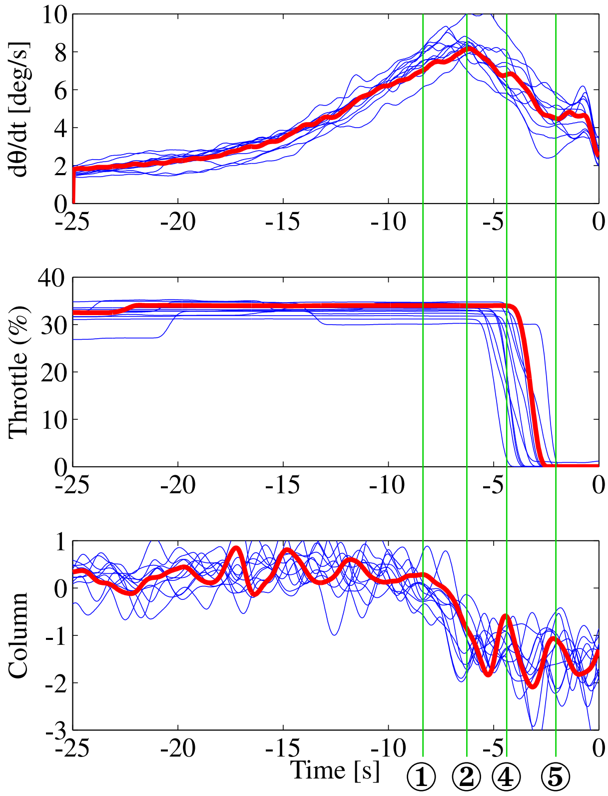

Fig. 5 Typical control as obtained from the Boeing 767 landing simulations, together with the time histories of the proposed visual cue $\dot{\theta}$=dθ/dt, which seems to reach a constant maximum slightly higher than 8°/s (the one going up to 10°/s was the first of a series of night approaches). Although the column movement is more oscillatory and the throttle is set to idle *in* rather than *after* the flare, the pilot's control shows the same characteristics as found for the turboprop landings (Fig.4).

Data obtained from simulated turboprop and Boeing 767 landings by experienced pilots revealed a constant maximum value of the proposed cue $\dot{\theta}$, coinciding with the moment where the pilot starts the main portion of the flare. Trends in $\dot{\theta}$ in later phases of the landing, just before touchdown, also seem to influence last second control adjustments by the pilots.

It can be concluded that $\dot{\theta}$ is very likely to be used by pilots for timing the flare maneuver. Further research will focus on including this finding in a global pilot model which considers visual cues for the control in the glide and flare phases and the transition between these phases.

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APPENDIX A. DERIVATION OF θ AND $\dot{\theta}$

In this appendix the equations for the apparent runway inclination θ and its time derivative $\dot{\theta}$ (Eqs. (5) and (6) in the main text) are derived using the pinhole camera model.

A.1 Derivation of θ

The pinhole camera model (see Fig.A–1 and Eq.(A1)) maps every point in the real world (such as points a and b on the runway edge) to the image plane, i.e., it defines where on the retina of the eye each point in a scene is sensed.

Matrix A contains the camera intrinsic parameters, F is a zoom matrix, and $[R\ t]$ is the rotation and translation between the real world and camera coordinate systems. s is a 'floating' variable, its value is decided by the bottom row of the equation.

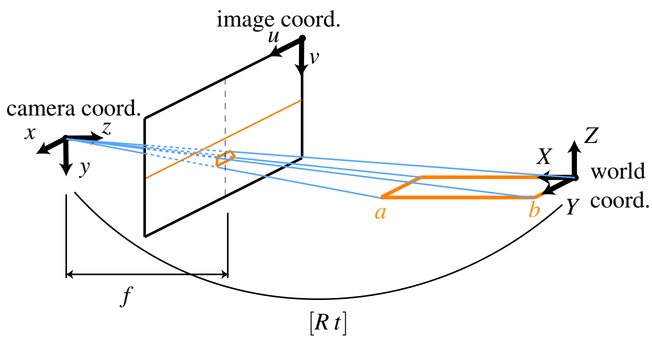

Fig. A–1 Coordinate systems and transformations in the pinhole camera model.

$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=\underbrace{\begin{bmatrix}\alpha & c & u_0\\0 & \beta & v_0\\0 & 0 & 1\end{bmatrix}}_{A}\underbrace{\begin{bmatrix}f & 0 & 0\\0 & f & 0\\0 & 0 & 1\end{bmatrix}}_{F}\underbrace{\begin{bmatrix}r_{11} & r_{12} & t_x\\r_{21} & r_{22} & t_y\\r_{31} & r_{32} & t_z\end{bmatrix}}_{[R\,t]}\begin{bmatrix}X\\Y\\1\end{bmatrix}. \tag{A1}$$

In the simple case, with no zoom, an ideal camera (square pixels, no skew, $[u_0, v_0]$ in the center of the image), and the world and camera coordinate systems coinciding, Eq.(A1) reduces to

$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=\underbrace{\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}}_{AF[R\,t]}\begin{bmatrix}x\\y\\z\end{bmatrix}. \tag{A2}$$

From this equation we can find the horizontal and vertical positions of a and b in the image plane:

$$\left.\begin{matrix}su=x\\s=z\end{matrix}\right\}\Rightarrow u=\frac{x}{z}\quad\Rightarrow u_a=\frac{\omega}{z_a},\quad u_b=\frac{\omega}{z_a+\ell}, \tag{A3}$$

$$\left.\begin{matrix}sv=y\\s=z\end{matrix}\right\}\Rightarrow v=\frac{y}{z}\quad\Rightarrow v_a=\frac{y}{z_a},\quad v_b=\frac{y}{z_a+\ell}, \tag{A4}$$

with ω half the real runway width and ℓ the real runway length.

Now the full angle between the runway sidelines can be calculated from the angle of line ab with the image vertical (i.e., the runway centerline):

$$\begin{aligned}\frac{1}{2}\theta &= \tan^{-1}\left(\frac{u_a-u_b}{v_a-v_b}\right)=\tan^{-1}\left(\frac{\frac{\ell\omega}{z_a(z_a+\ell)}}{\frac{\ell y}{z_a(z_a+\ell)}}\right)\\ &\Rightarrow \theta = 2\tan^{-1}\left(\frac{\omega}{y}\right).\end{aligned} \tag{A5}$$

A.2 Derivation of $\dot{\theta}$

The time derivative of Eq.(A5) is obtained as following (note that the runway geometry, ω, ℓ is constant over time, but relative aircraft position, y is a function of time):

$$\begin{aligned}\frac{d\theta}{dt} &= 2\frac{d}{dt}\left(\tan^{-1}\left(\frac{\omega}{y}\right)\right)\\ &= 2\frac{d}{dt}\frac{1}{1+\left(\frac{\omega}{y}\right)^2}\cdot\frac{d}{dt}\left(\frac{\omega}{y}\right)\\ &= \frac{2}{1+\left(\frac{\omega}{y}\right)^2}\cdot\frac{-\omega}{y^2}\cdot\frac{dy}{dt}\\ &= \frac{-2\omega}{y^2+\omega^2}\cdot\frac{dy}{dt}.\end{aligned} \tag{A6}$$

Note that $-\frac{dy}{dt}$ is the sinkrate.

APPENDIX B. SIMILARITY BETWEEN τ_θ AND τ_Z

Through Taylor series expansion it can easily be shown that τ_θ, the runway angle-based time to contact (TTC) is in first order approximation equal to the altitude based TTC τ_z:

$$\tau_\theta = \frac{\theta}{d\theta/dt} = \frac{2\tan^{-1}\left(\frac{\omega}{z}\right)}{\frac{-2\omega}{z^2+\omega^2}\cdot\frac{dz}{dt}} \quad \text{(cf. Appendix A.)} \tag{B1}$$

$$= \frac{\frac{\omega}{z}-\frac{1}{3}\frac{\omega^3}{z^3}+\frac{1}{5}\frac{\omega^5}{z^5}-\frac{1}{7}\frac{\omega^7}{z^7}+\cdots}{\frac{-\omega}{z^2+\omega^2}\cdot\frac{dz}{dt}} \tag{B2}$$

$$= \left(\frac{1}{z}-\frac{1}{3}\frac{\omega^2}{z^3}+\frac{1}{5}\frac{\omega^4}{z^5}-\frac{1}{7}\frac{\omega^6}{z^7}+\cdots\right)\left(z^2+\omega^2\right)\frac{-1}{dz/dt} \tag{B3}$$

$$= \left(z+\frac{2}{3}\frac{\omega^2}{z}-\frac{2}{15}\frac{\omega^4}{z^3}+\frac{2}{35}\frac{\omega^6}{z^5}+\cdots\right)\frac{-1}{dz/dt} \tag{B4}$$

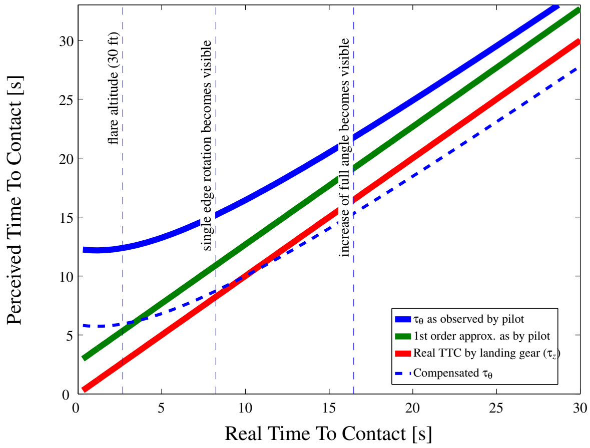

Fig. B–1 Comparison of τ_θ and τ_z. τ_z is the first order approximation of τ_θ. This graph was drawn considering a B767 landing on a 60m wide runway with 3.4m/s sinkrate. Thresholds for rotation and expansion of the angle between runway sidelines is assumed to be 2.5°/s.

This first order approximation is quite accurate for altitudes higher than about half the runway width, although there is an offset. It is thought that, through training, the pilot learns to compensate for this offset, as well as for the fact that his viewpoint is ca. 10m above the main landing gear with which he will touch down.

It is interesting to note that Palmisano et al. write in [20] on their experimental results:

> *[...] participants overestimated the time it would take until touchdown during the 4 and 6.5 second actual TTC conditions. However, they underestimated the amount of time it would take until touchdown in the 14 second actual TTC conditions.*

If we assume a constant compensation made by the pilot, we may find something like the dashed line in Fig.B–1, which can explain these under and overestimations.