Visual Features Used by Airport Tower Controllers: Some Implications for the Design of Remote or Virtual Towers

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Abstract Visual motion and other visual cues are used by tower controllers to provide important support for their control tasks at and near airports. These cues are particularly important for *anticipated separation*. Some of them, which we call visual features, have been identified from structured interviews and discussions with 24 active air traffic controllers or supervisors. The visual information that these features provide has been analyzed with respect to possible ways it could be presented at a remote tower that does not allow a direct view of the airport. Two types of remote towers are possible. One could be based on a plan-view, map-like computer-generated display of the airport and its immediate surroundings. An alternative would present a composited perspective view of the airport and its surroundings, possibly provided by an array of radially mounted cameras positioned at the airport in lieu of a tower. An initial more detailed analysis of one of the specific landing cues identified by the controllers, landing deceleration, is provided as a basis for evaluating how controllers might detect and use it. Understanding other such cues will help identify the information that may be degraded or lost in a remote or virtual tower not located at the airport. Some initial suggestions on how some of the lost visual information may be presented in displays are mentioned. Many of the cues considered involve visual motion, though some important static cues are also discussed.

Keywords Visual motion • Perceptual cues • Spatial perception

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1 Introduction

The visual cues necessary to fly and land an aircraft have been well studied over many decades (e.g., Gibson et al. 1955; Grunwald and Kohn 1994). In particular, the degradation in piloting performance and the consequent need to reduce airport capacity due to bad weather is fairly well understood (FAA 71010.65R 2006). The present report outlines a complementary side of the airport capacity-safety trade-off. It identifies and quantifies some of the visual features and properties used by tower controllers to monitor and enable safe landing and maneuvering on or near airports. These features are especially interesting now due to recent proposals for technology and procedures in which controllers work in towers without a direct view of their controlled space. Such towers are described alternatively as a remote or "virtual tower" (JPDO 2007). Work in these towers would be supported by controller displays of information about aircraft and the airport environment.

In general, two types of displays can be considered: one would present a plan-view, map-like computer-generated display of the airport and its immediate surroundings (JPDO 2007) somewhat like existing ASDE-X displays (Fig. 1). An alternative could present a composited perspective view, possibly provided by an array of radially mounted cameras positioned at the airport in lieu of a tower (Fürstenau et al. 2008) (Fig. 2). In either case, procedures and display techniques need to be developed which are cognizant of the current visual information used by controllers, which may be lost.

The following discussion initially points out visual elements of the control task facing the tower evident in previous task analyses of tower operations (Paul et al. 2000; Werther 2006). However, this earlier work appears to only provide very general descriptions of the specific visual features to which that the controllers attend. To the extent the visual functions that are important to the controllers are considered; they are generally limited to questions of detection, recognition, and identification. The following discussion will consider other visual features that go beyond these basic three elements and relate in specific ways to the individual

Fig. 1 ASDE-X airport map display

Fig. 2 Out-the-window camera or synthetic vision display format

decision processes tower controllers develop to do their job; in particular, we discuss the motion of the controlled aircraft. The preliminary conclusion of the discussion is that tower controllers use visual features to provide predictive position information allowing them to use *anticipated separation* to effectively and safely merge and space aircraft, maximizing airport capacity.

The visual cues used by controllers are important for several reasons. In the first place, there is FAA interest in increasing airport capacity so that current operations under nonvisual flight rules with reduced capacity may be modified to allow higher visual flight rule capacity during nonvisual operations. For this purpose, the currently used visual information needs to be provided by alternative means. Such "equivalent visual operations" described by FAA/NASA planning documents may be achieved with synthetic visual systems, i.e., with replacement of direct tower camera or sensor views with visualized electronic position data (Kramer et al. 2008). This replacement of the direct view, however, will not be fully successful, and may even be tragically misleading, if the useful visual affordances provided by the real scene are not appropriately included or accounted for. Although Equivalent Visual Operations has primarily been considered from the pilot's viewpoint in terms of flight displays which use new sensor data for synthetic vision, it has a flip side for which synthetic vision or camera-based displays could be used to present useful visual information within a remote or virtual tower.

Significantly, this information need not be provided in the form of an image, but could be provided in a more map-like plan-view format and conceivably could even come along nonvisual sensory channels, e.g., auditory or haptic. In fact, it could be based on data directly downlinked to ground displays from an aircraft indicating its state, i.e., spoilers deployed (Hannon et al. 2008).

The visual environment in an airport tower may be illustrated by considering the view from a specific tower such as that of San Francisco International Airport (SFO) (Fig. 3 top). Such tower views show significant perspective compression at the ~1 nmi range to runways and taxiways, making commercial aircraft subtend small visual angles and posing viewing difficulties due to background visual clutter. Interestingly, during low visibility CAT III operations at SFO, airport operations

Fig. 3 The variation of visibility within airport tower's immediate environments is shown from unlimited visibility (San Francisco International, *top*) through partial occlusion due to low clouds (Santa Barbara Municipal, *middle*) to complete whiteout (Stockholm Arlanda, *bottom*)

may be conducted with the controllers never actually seeing the aircraft. Thus, since it is already possible for the controllers to continue many of their control tasks without visual contact, albeit with fewer aircraft, the idea of a remote tower may have some prima facie feasibility. But without visual contact, controllers must inform the pilot and those monitoring their communications that visual contact has been lost. Significantly, at the SFO tower where the parallel runways are ~750 ft apart, continued operation without visual contact is associated with a loss (~50 %) of airport capacity.[1] In contrast at an airport such as Stockholm Arlanda, Sweden (ARN), with the parallel runways ~1 km (~3280 ft) apart, total loss of visual contact can have virtually no impact on capacity when the ground radar is fully functional.[2] Thus, there exist some operational examples of tower operation with total loss of visual contact. During low visibility operations, it is not always necessary for the controller to maintain visual contact with the aircraft, but for the aircraft to have enough forward visibility to safely maneuver the aircraft during ground taxi operations.

[1] Personal communication, ATCO, San Francisco International Airport, 7/7/2006

[2] Personal communication, tower supervisor, Stockholm Arlanda International Airport, 4/23/2007

1.1 SFO Operations

An analysis of the role of visual features in tower control can be developed from a more detailed discussion of operations for a particular airport, SFO. A sense of the overall strategy for some aspects of usual airport operation at SFO is best obtained from plan-view maps (see Fig. 4 for SFO map). Aircraft are taxied from their gates

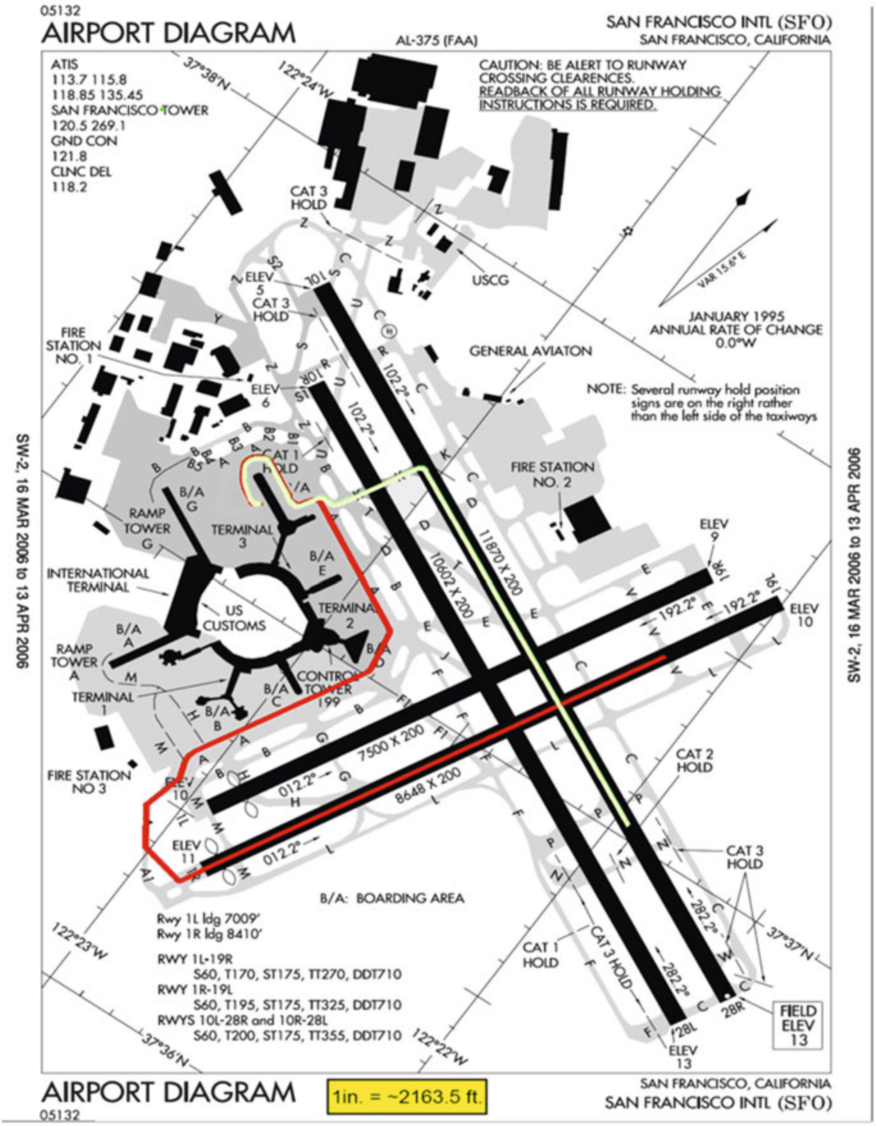

Fig. 4 SFO airport diagram showing typical movement paths for United Airlines, departures (*dark/red* paths), arrivals (*light green*/paths)

to the southwest ends of runways 1L and 1R and launched in staggered pairs to the northeast. Departing aircraft are interleaved between aircraft landing on runways 28 left and 28 right which also are treated as staggered pairs. Current winds, weather, and special operational requirements, of course, can significantly alter this pattern. For example, sometimes the longer 28 runways are needed for heavy, departing transpacific aircraft. Detailed descriptions of the alternative approach and departure procedures can be found in the standard instrument departures (SID) and standard terminal arrival routes (STARs) associated with the airport, but the local controller's responsibility for arriving traffic generally begins with radio contact somewhat before the aircraft crosses the San Mateo Bridge and ends for departing aircraft 1 nmi beyond the end of the departure runway. By FAA rules, the local controller is generally responsible for aircraft entering and leaving the runways, whereas the ground controllers handle, in a coordinated way, most of the taxiing to and from the gate. These two positions, in addition to that of the supervisor, are the ones that make the most use of the out-the-window information. The other two tower controller positions, Flight Data and Clearance Delivery, primarily use inside-the-tower information sources and voice communications.

2 Visual Information Used in the Airport Tower

The primary responsibility of the control tower is to ensure sufficient runway separation between landing and departing aircraft (FAA 2006). A back-propagating process may be used to understand the visual requirements supporting the tower controller's primary responsibility.

This process first identifies the visual affordances that the controllers' tasks involve. Affordances are the higher-level behavioral capacities that vision must support (Fig. 5). Controllers, for example, must be able to identify the aircraft type, company, and flight status. They must control and recognize aircraft speed, direction, and position. They must establish a movement plan involving a succession of spatial goals. They must communicate this plan to the aircraft, coordinate it with other controllers and pilots as necessary, establish whether aircraft comply appropriately, and recognize and resolve spatial and other conflicts that may arise. These higher-level elements are supported visually by a number of visual functions: detection, recognition, and perception of the static and dynamic state of the aircraft. These functions are supported by still lower-level visual mechanisms that underlie luminance, color, control, position, and movement processing. These three levels of analysis provide a basis for describing the controllers' visual task.

The tower controller's overall task has, of course, been analyzed within and outside of the FAA. It may be broken down to six different job subtasks: separation, coordination, control judgment, methods/procedures, equipment, and communication. The five of these subtasks which involve vision have been identified by boldface type in Table 1 (Ruffner et al. 2003; FAA 2006).

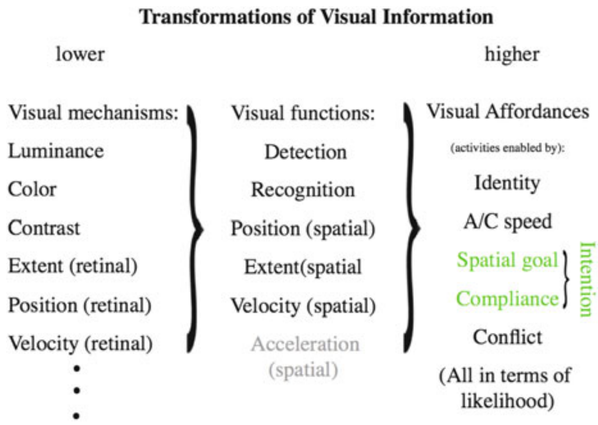

Fig. 5 Description of the dependency of the high-level spatial information needed by controllers on progressively low and lower perceptual functions and visual mechanisms

Table 1 Analysis of tower control tasks that inherently involve visual information is printed in bold

Job task	Job subtask
1. Separation	**1. Separation is ensured and maintained at all times** 2. Safety alerts are provided
2. Coordination	**1. Performs handoffs/point-outs** 2. Required coordinations are performed
3. Control judgment	1. Good control judgment is applied 2. Priority of duties is understood 3. Positive control is provided 4. Effective traffic flow is maintained
4. Methods/procedures	**1. Aircraft identity is maintained** **2. Strip posting is complete/correct** 3. Clearance delivery is complete/correct and timely 4. Letters of agreement (LOAs)/directives are adhered to 5. Additional services are provided 6. Rapidly recovers from equipment failures and emergencies 7. **Scans entire control environment** 8. Effective working speed is maintained
5. Equipment	1. Equipment status information is maintained 2. Equipment capabilities are utilized/understood
6. Communication	1. Functions effectively as a radar/tower team member 2. Communication is clear and concise 3. Uses prescribed phraseology 4. Makes only necessary transmissions 5. Uses appropriate communications method 6. Relief briefings are complete and accurate

The assurance and maintenance of spatial separation is, of course, a visual task since regardless whether separation is determined by radar or direct view, it is definitely recognized visually. Handoffs and point-outs clearly are also intrinsically dependent upon vision, though the need for the controller to adopt the pilot's spatial frame of reference to direct attention toward objects and aircraft is also a significant cognitive task. Control judgment, being essentially a mental and cognitive issue, does not have an intrinsically visual component. But its connection with maintenance of effective and efficient traffic flow does emphasize the critical importance of time in traffic control. Three general methods and procedures directly involve vision. These include establishment and maintenance of aircraft identity, posting and correct annotation of flight strips, and continual scanning of the entire control environment. Associated with these methods is the admonition to work quickly and rapidly recover from errors or off-nominal conditions. Because each tower's environment is to some extent unique, the specifics of their procedures differ from tower to tower. All control techniques are, of course, consistent with the regulations cited and described in the FAA air traffic control*, Order 7110.65R,* but unique procedures and heuristics are passed on to future controllers by on-site training. The specific visual features tower controllers use can frequently be found in these locally developed heuristic rules. Some are presented in Table 4.

The overall tower control process has been formally analyzed and modeled including visual and nonvisual components (Alexander et al. 1989; Werther 2006). For example, the MANTEA notation (Paul et al. 2000) has been applied to analyze controller activity in the tower. Some of the elements identified in the MANTEA analyses are, in fact, visual, but the visual components are only described in very general terms such as "visualize runway," "visualize meteo," etc. These descriptions really only identify the sensory modality used to gather the information and a general description of the content of the visual information, but they say nothing specific about the actual visual viewing conditions or about the specific visual stimuli. This feature is, in fact, common in other more recent and more sophisticated task analyses of visual features seen from the tower. Even the recent modeling done with Petri nets (Werther 2006) does not identify specific visual stimuli but is more concerned with estimates of time required for the precision with which various visual subfunctions maybe executed and to the logical conditions and consequences associated with the functions.

The FAA has done some analysis of the specific visual performance expected from tower controllers. The work primarily focuses on the controller's surveillance function and has been based on visual performance models developed for the military by CERDEC at Ft. Belvoir (e.g., Vollmerhausen and Jacobs 2004). These models primarily are intended to predict the probability of visual detection, recognition, and identification of known targets. "Detection" refers to users' ability to notice the presence of a particular object. "Recognition" refers to their ability to categorize the object into a general class such as a tank, light aircraft, or truck. "Identification" refers to their ability to determine the specific type of object, i.e., an Abrams tank, a Cessna 172, or a Ford refueling tanker. More modern similar visual performance models do not require same amount of calibration techniques to determine model parameters for specific visual targets and specific users (Watson et al. 2009).

The CERDEC analysis, which predicts specific object perception from towers of various heights during a variety of atmospheric conditions and object distances, has

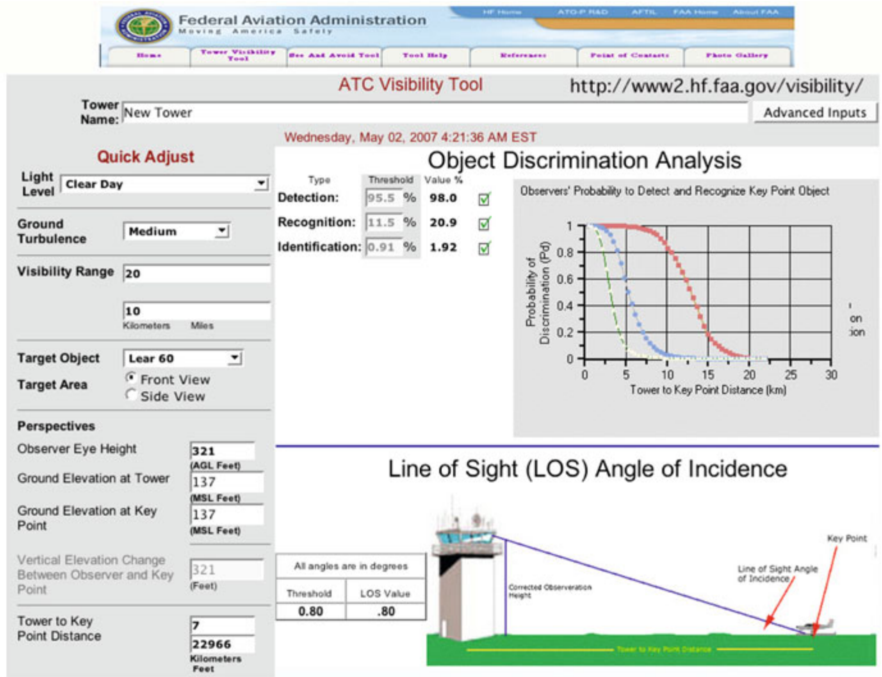

Fig. 6 The WEB interface to the FAA's tower design analysis tool that may be used by municipalities and others to test tower designs ultimately intended for FAA analysis and approval. Note website indicated in the *upper right*

been incorporated into a web tool to help tower designers ensure that specific architectural and site selection decisions for new towers will meet FAA requirements. Significantly, this tool also just focuses on the surveillance function and does not address the aspects of visual motion that tower controllers use for the information, separation, and safety tasks (Fig. 6).

In order to understand the details of the visual features used in tower control, it is first necessary to identify the range within which controllers use visual information. We can use the example of SFO. Informal voluntary discussions and structured interviews with ten active controllers and supervisors who work at this tower were analyzed for the physical locations identified as points where various types of visual references are used while controlling approaching or departing aircraft. These discussions, which were considered preliminary work, were conducted with the knowledge and approval of the SFO tower manager, his chain of command, and the local NATCA tower representative. All primary notes were taken without personally identifying markings and transcribed into secondary statistical summaries or grouped data so as to preserve the anonymity of the respondents. Primary notes were thereafter discarded.

These reported points where useful visual information could be seen primarily to include positions where visual contact with the aircraft is first or last considered to be helpful. These positions, marked in Fig. 7, include those for which aircraft come

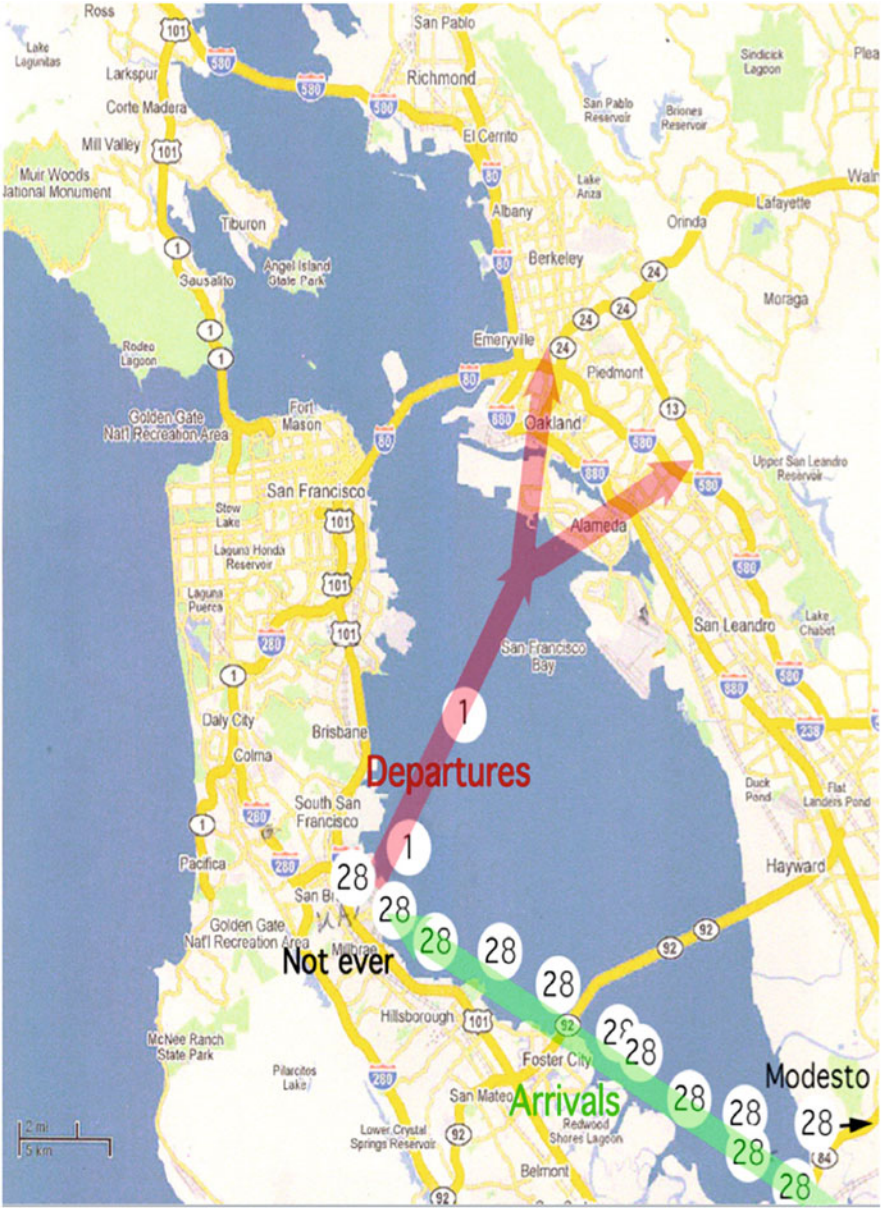

Fig. 7 The first and last positions where SFO controllers report useful visual information w/r to landing (runway 28) and departing aircraft runway 1. The *arrows* show idealized, most common approach paths (*transparent green*) to the west and departure paths (*transparent red*) to the north

under or leave tower control, where they pass important ground references or where visual contact provides other useful information. The points were determined independently from each of the controllers in response to the question, “When you are in the Local controller position, where are the aircraft when you usefully observe them visually, what visual aspects of the aircraft do you observe and why?” Controllers could designate more than one point of interest for departing and more than one for arriving traffic; only two controllers took this option. One point represents nine controllers’ overlapping responses identifying approximately the same location about 1 nmi beyond the end of the departure runway 1.

In general it is apparent from the distribution of points that controllers’ visual attention is much more spatially distributed to the aircraft approaching the 28LR runways and rather abruptly drops off about 1 mile off the end of the usual departure runways 1LR. These observations refer to the most common aircraft flow at SFO but suggest the generalization that the local controllers’ visual attention to approaching aircraft is distributed over a much large area than that corresponding to departing aircraft. A likely reason for this is that departing traffic is handed off to approach/departure control at 1 nmi beyond the end of the runway and generally not thereafter of concern to the tower.

A significant aspect of the controllers’ remarks concerning when they first start paying visual attention, or when they last pay attention, to aircraft is that they rarely mentioned the aircraft’s visual motion.[3] One reason is that for the viewing angles and distances to the aircraft approaching and departing SFO, this motion is very small in terms of degrees per second, often the azimuth rate is on the order of much less than 0.25°/s and rarely more than 0.5°/s. The visual accelerations are even much smaller and difficult to see because of atmospheric haze, thermal effects, and the visual range being beyond 5 miles. Visual rates of motion are more important for closer aircraft just seconds away from touchdown or from those on taxiways.

Probably the most obvious need for visual contact by controllers in the tower is to immediately note unusual events that are not detected by electronic sensors such as radar. Examples could be heavy bird activity or an aircraft leaking fuel onto a taxiway. But there are a wide variety of other visual features that controllers use on a more regular basis when aircraft are close enough for the visual motion to be more easily noticed. Discussions with controllers have provided a list of some that are used (see Tables 2 and 4).

A tabulation (Table 2) of the visual features mentioned in the discussions with each of the SFO controllers shows the relative frequencies with which different features were mentioned. These discussions used a “cognitive walk-through” technique in which the controllers were asked to imagine representative approaching, departing, and taxiing aircraft under a variety of visual conditions and to report what they looked for visually to assist their control tasks. The consequent discussions were guided by the elements outlined in Ellis and Liston (2011, Appendix).

[3] Visual motion is defined as the angular rate of change of the line of sight angle to an aircraft from the tower.

Table 2 Visual features identified by interviews with ten SFO tower controllers

Feature	Times mentioned	Commentary	Feature	Times mentioned	Commentary
1. Relative visual motion used to interleave takeoffs and landings	5	Controllers **verify predicted separation** using relative motion w/r stationary references to plan clearances	7. Visible wing dip predicts coming turn	3	Visible banking quickly confirms conformance to turn clearance
2. Visual check for obstacles or other A/C to verify a clearance	5	Obstacle checks include ground vehicles, aircraft, birds, and people	8. "Mike and a mile" rule for interleaving takeoffs and landings	3	**Predictive rule:** Departing A/C must be rolling across taxiway Mike on RW1 when matched landing A/C on RW28 is at least 1 mi out for required separation
3. "Taxing with authority" helps attention allocation	4	Fast and confident A/C motion allows controllers to distribute attention to pilots who maneuver hesitantly allowing **anticipation** of future problems	9. Engine smoke or heat confirms takeoff start	2	Currently less useful since modern engines don't smoke much and have cooler exhaust
4. Aircraft attitude/altitude predicts a "go-around"	4	Controllers anticipate "go-around" by checking A/C passage through various approach gates defined by altitude and attitude	10. Onset of navigation lights predicts a tower call requesting service	2	Controllers can **anticipate** coming workload
5. Visually apparent acceleration, speed, or turn rate anticipates taxiway selection	4	Controllers mentally integrate motion features to anticipate taxiway and ground route selection	11. Visual resolution of motion and position is better than by radar at airport	1	1–2 nmi from the tower; the "visual display" of the real world has more "pixels" than associated radar displays
			12. Visual double check on A/C tail to verify company	1	

(continued)

Table 2 (continued)

Feature	Times mentioned	Commentary	Feature	Times mentioned	Commentary
6. Coordinate/ cross-check visual and radar data	4	Specific visual landmarks are selected to cross-check radar	13. Check landing gear	1	Probably an isolated comment because it's checked routinely; "Gear down" isn't a problem for major airlines

Boldface marks the predictive aspect of specific visual features

The most frequently mentioned features were relative motion between landing or departing aircraft and obstacles that could be on the runway. The first of these features is probably prominent because SFO has intersecting runways commonly used for takeoffs and landings. An assessment of all of the features mentioned, however, shows what may be a more general element. Seven of the 13 features identified in the interviews note that the feature helps the controller anticipate future activity. This information provides insight into pilot intent, knowledge, and likelihood of aberrant behavior. These predictive cues help the controller with the short-term trajectory planning needed for *anticipated separation* and help them allocate their attention to pilots either unfamiliar with the airport or maneuvering in unexpected ways.

3 Visual Features at SFO

In order to examine the generality of the visual features and produce a list as complete as possible, structured anonymous interviews were conducted with controllers from an additional seven airports. Because we were not able to obtain timely agreement from the national NATCA office for the participation of line controllers, these additional discussions were limited to supervisory personnel. Anonymity was maintained since all written notes were taken without personally identifying markings, and formal questionnaires were not used. To insure anonymity, original notes were transcribed into statistical or grouped secondary notes, and the originals were thereafter discarded insuring that no personally identifiable information was recorded or could be reconstructed post hoc. In all cases, tower visits to US airports were conducted with the knowledge and approval of the specific tower's manager and FAA headquarters. US airport towers in addition to that of San Francisco International Airport (SFO) that were visited were Boston Logan International (BOS) MA; Golden Triangle Regional (GTR) MS; Santa Barbara Municipal (SBA), Santa Barbara, CA; and Norman Y. Mineta San Jose International (SJC), San Jose, CA. Supervisory controllers from Denver

Table 3 Airport tower environments discussed and evaluated

Airport tower environments discussed	Number of controllers or supervisors	Notes
Stockholm Arlanda ARL	1	Discussions were held, but visual features from the ARL tower were not analyzed
Boston Logan International (BOS)	3	Supervisors only
Denver International (DEN)	1	Supervisors only without airport view
Golden Triangle Regional (GTR)	1	Supervisors only
LaGuardia International (LGA)	1	One supervisor without airport view
Philadelphia International (PHL)	1	One supervisor without airport view
Santa Barbara Municipal (SBA)	2	Supervisors only
San Jose International (SJC)	3	Supervisors only
San Francisco International (SFO)	11	One supervisor, 10 controllers
Total	24	

International (DEN) Denver, CO; LaGuardia Airport (LGA), New York City, NY; and Philadelphia International (PHL), Philadelphia, PA, were included in the multi-airport analysis. They visited the first author at NASA Ames and provided information regarding the nature and location of visual features used by controllers while viewing airport diagrams and regional maps. The tower at Stockholm Arlanda (ARN) in Sweden was the only foreign airport tower visited but was not included in any quantitative analysis. For a summary of the airport towers considered and the personnel interviewed, see Table 3.

Figures 8 and 9 illustrate how the visual velocity of aircraft viewed from the tower could be determined for moving aircraft at or near the airport and those that were farther away in the airport vicinity but still visible. Figure 10 provides a breakdown of various classes of features as 14 general categories that were used to organize the features. Counts on the numbers in each category give some idea of their relative frequency of mention. At this stage of investigation, no systematic attempt was made to determine the relative operational importance or frequency of use of the various features. Investigations are currently underway in collaboration with Jerry Crutchfield of the Civil Aerospace Medical Institute (CAMI) to determine the frequency of use and criticality of the visual features that have been

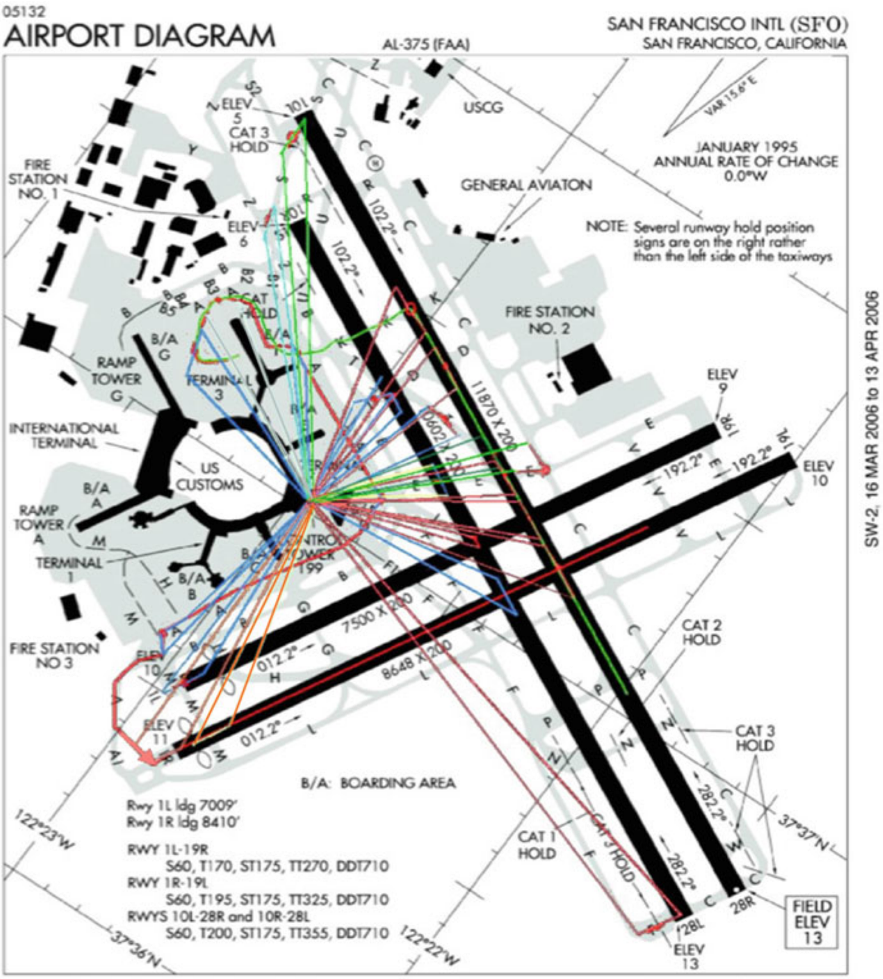

Fig. 8 Lines of sight from the San Francisco International Airport tower to positions on the airport where the visual motion was analyzed. Simple geometry allows calculation of rates of change of lines of sight from the tower to aircraft from knowledge of tower and aircraft position and aircraft velocity

identified[4] [also see van Schaik et al. (2010) and chapter "Detection and Recognition for Remote Tower Operations"]. In particular, the high frequency of mention of the points of the first and last useful visual contact is undoubtedly an artifact of their mention in the structured interview as an example of the kind of visual information

[4] The project is called Concurrent Validation of AT-SAT for Tower Controller Hiring (CoVATCH). AT-SAT stands for Air Traffic Selection and Training test battery.

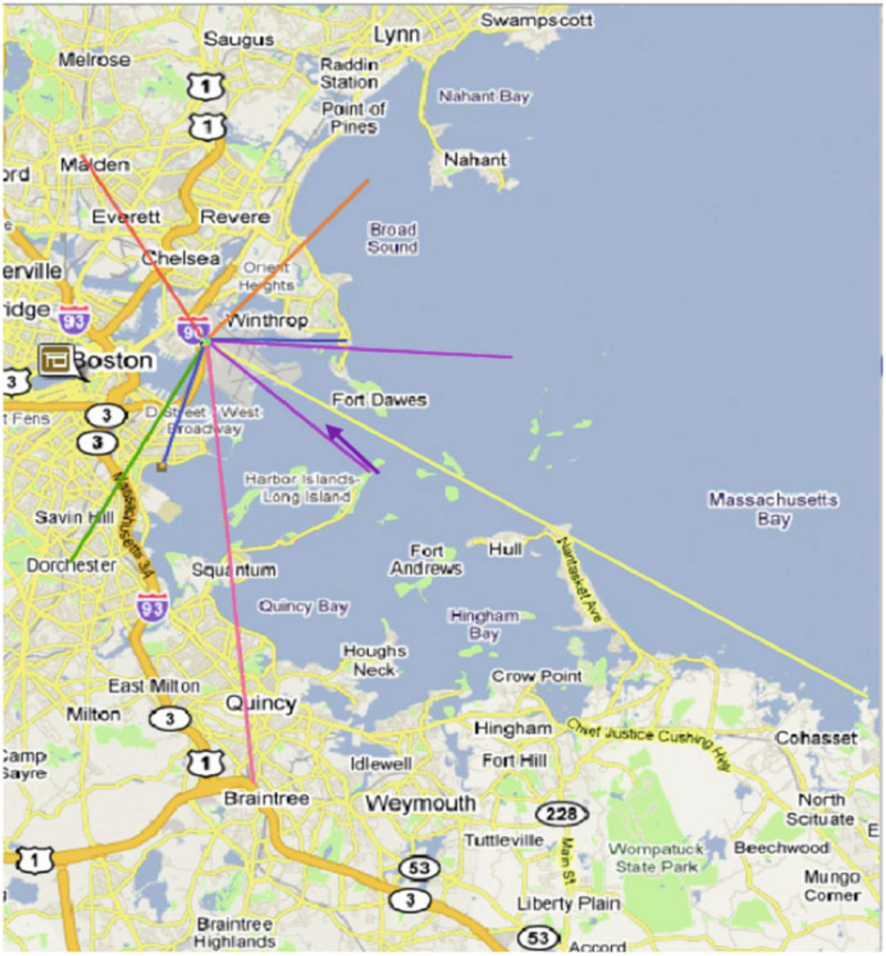

Fig. 9 Lines of sight from the Boston Logan International Airport (BOS) tower to positions in the airport region where the visual motion of moving aircraft were analyzed

being sought. The point of the investigation was to collect as broad a range of visual features as possible for further analysis in subsequent studies.

When a visual feature was identified by a controller, its location was plotted on an appropriate map. Afterward, the direction of flight and speed was determined from the appropriate airborne traffic pattern or ground path. Simple geometric analysis was then possible to determine the apparent visual rate of the aircraft as seen from the tower at the time the visual feature would have been noted. Because actual aircraft speed was not actually measured, speed was estimated

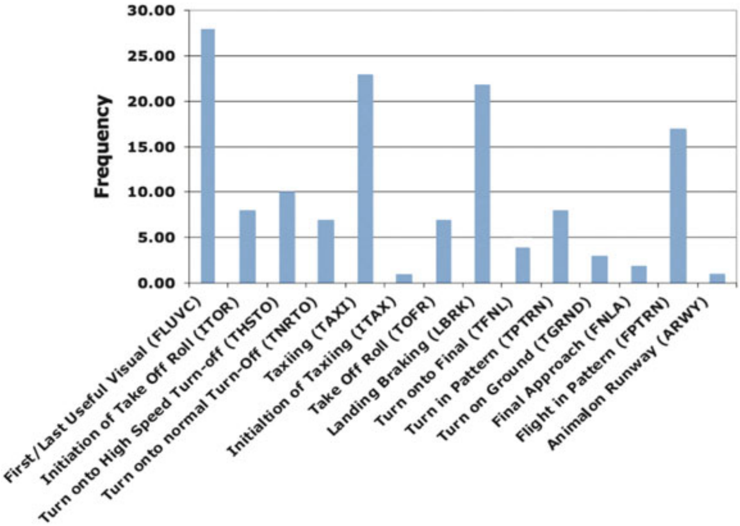

Fig. 10 Frequency of report of the use of various visual cues

from typical rates mandated by approach procedures or estimated by controllers and pilots familiar with the airport and typical air and ground aircraft motion. Some reflection on the geometry shows, however, the aircraft speed to have a comparatively small influence on visual motion. Its impact is dwarfed by the effect of relative direction of flight. An aircraft flying directly toward the tower can have virtually 0 °/s visual velocity! The relative direction of flight used for analyses was determined from the interviewees and the typical patterns of motion at and around the airport if the original notes did not include the needed information. Once the approximate visual velocity associated with each visual feature was determined, a spectrum of visual velocities associated with each of the 14 feature categories could be determined. These are shown in Fig. 11 and summed to give an overall total. These spectrums of visual velocity for each of the categories of features reflect some of the physical aspects of each category. The first and last useful visual contact rates are slowest because these are in general the farthest from the tower. Visual rates during landing deceleration are high because the aircraft are generally closer to the tower yet still moving relatively fast compared to taxiing.

For the purposes of the present inventory, the most important aspect of the distribution of motions is not its shape or arithmetic mean but its mode and range. As can be seen in Fig. 11, the vast majority of visual rates are less than 1 °/s with the mode at a small fraction of a degree per second. These visual rates are quite slow compared to those typically studied in visual psychophysics. If a concept of operations for a remote or virtual tower is to include visually presented targets that provide the information that controllers currently pick up from aircraft motion, the display techniques need to be able to represent this range of slow motion for visual cues that controllers currently use. It is important to note that the useful

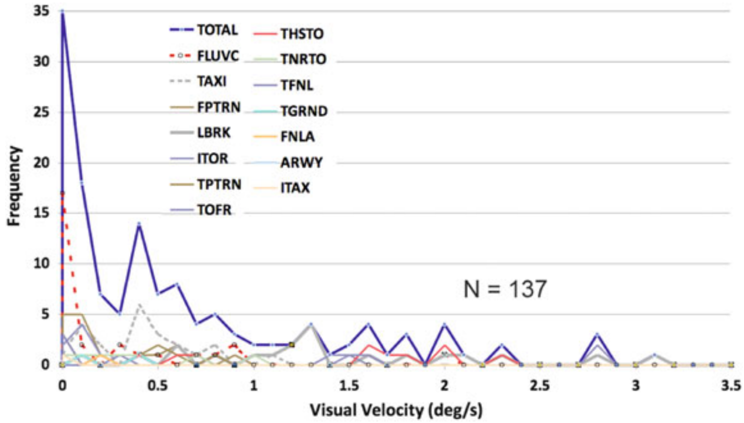

Fig. 11 Frequency distribution of rates of visual movement associated with a variety of different visual cues coming from moving aircraft. See Fig. 10 for the meaning of the letter codes of the variety visual cues identified

presentation of aircraft motion therefore benefits significantly from the use of very large-format displays. To the extent that the display scales down visual motion due to screen size, the displayed visual rates, which are already very slow, could well become imperceptible and require special signal processing to be operationally useful. An example of such processing could be the computational detection of the slow motion and its denotation by introduction of or changes in visible symbology. A second important caveat is that the visual rates are not seen in isolation but have a temporal context; in fact, the change in visual velocity itself can be an important cue which is identified for some visual features in Table 4 and discussed in more detail in the final section.

Table 4 provides a summary of all the visual features identified from discussions with controllers from all analyzed airports. It lists the identified visual feature, the information the feature provides the controller, and suggests some general information support characteristics that would be necessary to provide equivalent information on alternative displays that might be used in a virtual or remote tower: (1) A map-like display that could be driven by ground radar or other comparable positions information, e.g., ADSB. (2) An image-like display that resembles the out-the-window view from a tower and could be driven by airport cameras or other sensors and computer graphics providing synthetic vision (Figs. 1 and 2).

A better understanding of exactly how some of these cues can be used can come from examining them quantitatively. An example of such analysis is presented below with respect to landing deceleration at SFO.

Table 4 Visual and other perceptual features that aid tower air traffic control

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
Status			
1. A/C is prepositioned with an anticipatory rotation for a turn while holding short of a taxiway or runway	Pilot is correctly expecting to be cleared for a specific turn	Current and static A/C orientation should be shown on electronic map	Visual resolution of display should be sufficient for user to recognize A/C pose at crossing points
2. A/C type	Predicts likely ground acceleration, e.g., the difference between turbine and constant speed propeller. A/C type determines separation techniques used	A/C type should be indicated by icon shape or data tag to relieve controller memory load	High-resolution visual image required to support existing visual performance requirements for tower design
3. Dust up or thermal optical distortion from thrust	Applied power can confirm compliance with takeoff or other clearances that require engine spool up	Downlinked indications from A/C of engine spool up should be displayed A/C icon	Evidence of spool up should be visible on display, or A/C icon associated with the power-up should be displayed based on downlinked information
4. Smoke or spray from wheel indicates ground contact and touchdown point	Touchdown indicates landing likely unless a touch-and-go is planned. Helps to identify likely taxiway to be used to exit runway	Downlinked information from wheel sensors indicating touchdown should be displayed on A/C icon to indicate touchdown point	Visual evidence of wheel contact should be visible or downlinked information from wheel sensors indicating touchdown should be displayed on A/C icon
5. Navigation lights being turned on	Call to tower is imminent, usually to the clearance delivery controller at a big tower	Navigation lights when A/C at gate should be visible. Downlinked information regarding A/C before engine start should be displayed if visibility is insufficient before pilot calls tower	Navigation lights when A/C at gate should be visible. Downlinked information regarding A/C before engine start should be displayed if visibility is insufficient before pilot calls tower
6. A/C relation between A/C attitude and altitude	The visual relationship between A/C attitude and altitude is predictive of pilot intent such as landing or executing a missed approach	A/C pitch attitude should be displayed geometrically or numerically for comparison with speed display with short delay < ~1 s	Pitch attitude and speed need to be perceivable on display with short delay < ~1 s

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
7. Reflected "lights" on the water. Visible reflections of A/C lights-off ground features such as bodies of water or a runway surface that confirm normal or indicate deviant flight path	At some airports reflections of landing lights-off surfaces like water can independently confirm normal lateral position and orientation of landing A/C. Such information is similar to pilot reports of passing the outer marker	Provide indication of A/C passing over "virtual" markers along approach route and outer or inner marker shown on display, possibly sourced from data downlink	Visual fidelity of image of approaching A/C should include large specular reflection of landing lights
8. A/C mechanical status, gear, flaps, spoilers, and reversers	Confirms appropriate aerodynamic status of A/C. Confirms intention to land. Can be used to indicate onset and intensity of braking, predicting the A/C deceleration profile	Downlinked data from A/C should provide data for display of status of gear, flaps, spoilers, and reversers to confirm commitment to landing	Aerodynamic configuration of A/C should be visually evident or enhanced by graphic overlays based on downlinked data
11. First/last visual acquisition. The position where an approaching aircraft is normally first usefully visible or where visibility is typically lost for a receding aircraft	Confirm location of radar contact, spacing w/r to A/C in pattern	Display A/C icon corresponding to initial and final radar contact	Provide sufficient visual contrast and resolution to allow visual contact at times and positions comparable to view from a real tower
12. Movement during taxi	Verifies compliance with taxi clearance and/or detects violation	A/C motion and position need to be observable. Note: because of reduced display size and map scale, the physical motion on the display may be below perceptual thresholds	A/C motion and position need to be observable. Note: because of reduced display size, the physical motion on the display may be below perceptual thresholds

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
13. Animal obstructions or intrusions	Need to issue obstruction warning and modify approach, departure, or ground movement; offending animal could be as small as a snapping turtle or as large as a bear or alligator	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely displays of obstructions' locations and movement	Visual displays should have sufficient resolution and contrast to match out-the-window views. Airport sensor data (e.g., motion sensors or cameras) could alternatively be used to provide timely iconic or text overlays
14. Birds, flocks, large birds	Need to issue bird activity warning and modify approach, departure, and ground movement	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely iconic and/or text displays of obstructions' locations and movement	Visual displays should have sufficient resolution and contrast to match out-the-window views. Airport sensor data (e.g., motion sensors or cameras) could alternatively be used to augment display to provide timely iconic or text warning overlays
15. Inanimate obstacles on runway/taxiway	Need to issue obstruction warning and modify approach, departure, ground movement, and possible communication with user-operated vehicles	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely iconic and/or text displays of obstructions' locations and movement	Airport sensor data (e.g., motion sensors or cameras) should be used to provide timely iconic and/or text displays of obstacles or displays making them visually detectable
16. Unexpected/unanticipated event	Visual observation of event requiring non-standard/emergency procedures	Not handled well without sensors designed for unanticipated dangers consequently rare but dangerous events could be missed	High visual fidelity wide field of view surveillance with high sample rate and low latency required for unanticipated events, which likely have a visual component

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
Acceleration/deceleration			
17. A/C beginning visual acceleration of takeoff roll	Confirms compliance with clearance to takeoff	Detection of onset of takeoff roll by low-latency motion sensors needed. Downlink from A/C or other sensors needed to provide information with delays comparable to current view of the A/C. NB: physical size of map display will make initial A/C motion harder to see than direct out-the-window view (see text). A map onset of motion signal, such as making the A/C symbol double bright, would greatly assist controllers	High resolution, bandwidth, low-latency view of A/C starting takeoff roll are required for visual confirmation of compliance. Such a display could provide information equivalent to the current out-the-window view
20. A/C pitching after landing braking	Predicts landing, length of landing roll, and taxiway to be used to exit runway and is related to confirmation of understanding of assigned gate	Downlink from A/C or other sensors would be needed to provide information with delays comparable to current view of the A/C. A visual indication on the icon of the landing A/C to indicate wheel contact could provide comparable information	High resolution, bandwidth, low-latency view of A/C landing roll are required for visual detection of pitching. Since this pitch cue is smaller than that at touchdown, its visibility on out-the-window displays should be verified
21. A/C pitching during initiation of takeoff (especially B757)	Confirms compliance with clearance to takeoff	This information is redundant with the indication of onset of takeoff roll (see above)	High resolution, bandwidth, low-latency view of A/C starting takeoff roll are required for visual detection of pitching. Since this pitch cue is smaller than that at touchdown, its visibility on out-the-window displays should be verified

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
22. Banked wing predicts turn faster than change in A/C position	Confirms compliance with clearance	Aircraft symbol or data tag needs to indicate A/C pose	High resolution, bandwidth, low-latency view of A/C banking are required for visual detection of pose
23. A/C initiating turn onto taxiway, especially cue from nose wheel angle	Confirms clearance to turn onto taxiway, nose wheel angle predicts turn	Downlink from A/C or other sensors would be needed to provide information with delays comparable to current view of the A/C. A visual indication on the landing A/C icon of nose wheel angle and A/C pose w/r to taxiway and runway could provide comparable information	High resolution, bandwidth, low-latency view of A/C taxiing are required for visual detection of pose and nose wheel position
24. Timing of visible plume effects of thrust reversers and spoilers. Note: these cues are distinct from the visibility of the mechanical deployment of these devices	Predicts landing deceleration, length of landing roll, and taxiway to be used to exit runway and is related to assigned gate	Downlink from A/C or other sensors would be needed to provide information with delays comparable to current view of the A/C. A visual indication on the landing A/C icon of deployment of thrust reversers could provide comparable information	High resolution, bandwidth, low-latency view of A/C landing roll are required for visual detection of deployment of reversers and spoilers (see text)
Speed			
25. Visual deviation of glide path seen as relative motion against stationary reference. Relative motion of an A/C seen against stationary ground references, allowing its glide path to be more easily perceived	Confirms correct approach/departure paths	Graphical display of flight path against a ground-referenced map could provide some comparable visual information, but the 3D element would require ground-referenced altitude data tag for the A/C icon	High-resolution visual image is required based on existing visual performance requirements for tower design

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
26. Relative motion of visually overlapping targets. Relative motion of visually, partially overlapping objects that allow them to be perceptually separated, e.g., two aircraft along approximately the same line of sight. This cue is especially helpful at night when A/C are seen as light patterns	Breaks visual clutter, aids perceptual separation of otherwise confusing objects	Relative motion can also be displayed on a map, but the sampling rate degrades and delays motion perception. De-clutter algorithms can be employed to remove clutter. The usual plan-view format minimizes clutter due to perspective compression as seen from a tower	High resolution, bandwidth, low-latency view of visually overlapping aircraft and background are required for visual judgment of relative motion. Current specifications for tower design provide adequate visual requirements for the perception of relative motion (see text)
27. Relative motion of aircraft on crossing trajectories with respect to a fixed ground reference such as a lamp pole	Confirms correct approach/departure paths, allows estimation of safe passing through runway intersections such as those at SFO	Stationary ground reference symbols should be introduced to map displays to make the relative motion of moving symbols easier to perceive	High resolution, bandwidth, low-latency view of visually overlapping aircraft and reference objects are required for visual judgment of relative motion (see text)
28. A/C speed during taxi, "taxing with authority"	Speed indicates level of pilot familiarity with airport, and likelihood of clearance conformance improves distribution of controller's attention, unusually slow speed indicates need for special attention	Ground speed data tags should be associated with aircraft symbols. If such data tags are not provided, the physical map size needs to be large enough so that high and low speed taxiing can be distinguished by controllers	High resolution, bandwidth, view of taxi area are required for visual judgment of motion. The physical size of the display needs to be sufficient for discrimination of high and low visual rates of taxiing (see text)
Sound[a]			
29. Sound of takeoff power	Confirms compliance with takeoff clearance	Directional sound cues provided by 360° radially mounted directional microphones should be provided within a remote tower	Directional sound cues provided by radially mounted directional microphones should be provided within a remote tower
30. Sound of engine run-up	Preparing for takeoff	Directional sound cues provided by 360° radially mounted directional microphones should be provided within a remote tower	Directional sound cues provided by radially mounted directional microphones should be provided within a remote tower

(continued)

Table 4 (continued)

Visual feature A/C = aircraft	Visual information provided	Information and display techniques: map-like displays	Information and display techniques: out-the-window image-like displays
31. Loud unexpected sound	Attention directed to source, possible explosion, bomb attack, etc., is an important adjunct to visual information	Directional sound cues provided by 360° radially mounted directional microphones should be provided within a remote tower	Directional sound cues provided by radially mounted directional microphones should be provided within a remote tower
Additional observation			
32. General surveillance	Some airport towers are strategically placed so as to provide useful, excellent visual surveillance outside of the airport and relevant airspace		The field of regard may be usefully made larger than that needed for aircraft control for airports where general surveillance is needed, e.g., Boston Logan

[a]In discussions of visual features used to aid control, so many controllers spontaneously mentioned the importance of sound cues, we have included them in this table

4 Deceleration During Landing at SFO

In order to analyze the deceleration of aircraft landing at SFO, digital video images of the initial braking were recorded after touchdown. Recordings of a wide variety of landing aircraft were made to examine a wide range of decelerations. The 45 observed and reported aircraft included 747–400s; a variety of models of 767, 757, 737, A319, A320, and CRJs; and small twin turboprops. The weather was clear with light winds from the west. The landing data from all the aircraft have been aggregated as there was no intention to make a more detailed analysis by type but rather to understand the range of visual rates and visual decelerations that would be visible from the airport tower as discussed below.

The following analysis begins to determine the magnitude of this visually sensed deceleration and how it could be used by controllers. Through this process we identify one of the dynamic visual features used in traffic control from the airport tower: the change in speed evident during a single glance a controller might make toward a decelerating landing aircraft.[5] In thinking about what specific aspects of

[5] During normal vision, people make from 3 to 5 fixations per second (Rayner and Castelhano 2007). However, when studying some aspect of an ATC image, fixation duration can increase but rarely grow longer than approximately 1.3 s (e.g., Remington et al. 2004). Consequently, a reasonable constraint for modeling the duration of a controller's glance would be to insure that they are 1.3 s or less.

the visual stimulus to which the controllers might be attending, it is helpful to remember that perceptual discriminations of commonly experienced magnitudes of sensory quantities such as velocity are fairly well described by Weber's Law, which states that the just-noticeable difference (JND) is a constant proportion of the quantity's magnitude. This so-called Weber fraction is roughly constant for a variety of psychophysical parameters, but under the best conditions is ~6 % for changes in velocity viewed within a typical 0.5 s time period. For stimuli with random mixtures of spatial frequencies, i.e., mixtures of contours of different sizes, the JND grows to about 7.5 %. Very significantly for the very slow visual velocities less than 1 deg/s such as those commonly seen from the control tower for landing and departing aircraft, the JND can climb up to ~10 % (McKee et al. 1986).

It is therefore important to understand that controllers may not be directly sensing the visual velocities per se even though they may claim to do so. They may, in fact, develop alternative viewing strategies allowing them to translate speed into displacement during relatively fixed time intervals, thus making the detection of unusual rates of change easier. Additionally, alternative visual cues to quantities such as deceleration could be used. For example, aircraft pitch while moving along the ground could be equally well a clue to the onset or offset of braking.

It is not so much the visual aspect of the visual information that is important as it is the fact that the information revealed by vision is relevant, real, direct, unmediated, immediate, and continuous that makes it possible for the best possible anticipation of future action. This is why the visual input could be critical. Replacements for it need to capture the same predictive, informational features as suggested in Table 4.

In order to begin to analyze the visual features actually present in real landing in more detail, we have initially focused on the deceleration profile of aircraft landing on the 28 left and 28 right runways at SFO. Controllers report that they use their sense of degree and timing of this specific deceleration to anticipate which taxiway would be needed for the aircraft to exit the active runway. Their decision is time critical during heavy runway use since landing aircraft are staggered in pairs and interleaved with departures on crossing runways 1R/1L.

We have made 15 frame/s video recordings at 1024×768 resolution of the braking phase of 45 aircraft landing on 28L and 28R and processed the recordings to measure changes in visual velocity. We have used a custom MATLAB image processing technique that isolated the moving contours across a set of two frames and averaged them to localize the aircraft and provide their screen velocity in degrees per second. Using the viewing geometry described in Fig. 12, we have recovered the aircraft braking profile and computed the changes in its visual velocity as viewed from the control tower by re-projecting the movement, as it would have been seen from the tower. Thirty of these velocity profiles (low-pass filtered with a 1 Hz cutoff) are shown in Fig. 13.

Because of the noise present in our current recording technique, we were unable to obtain velocity and acceleration values with acceptable noise levels. We were,

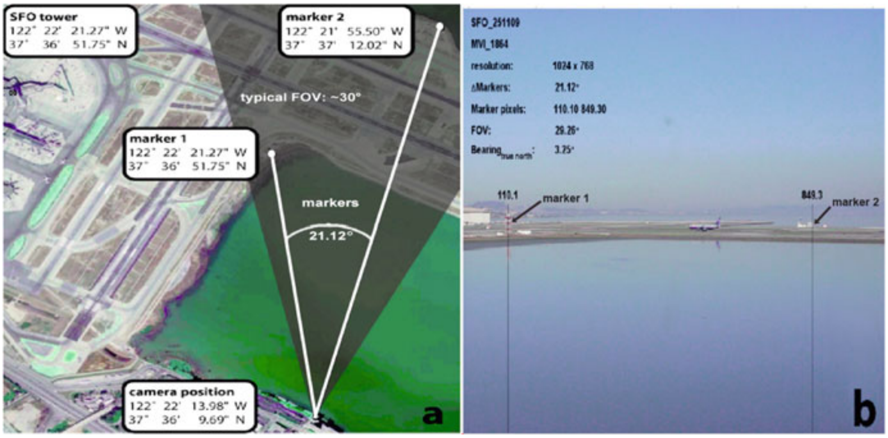

Fig. 12 Camera parameters and view at SFO. Markers at known ground positions determined from Google Earth ground images were used in combination with the known geometry of the runway to convert line of sight angles to aircraft from the camera position into position along the runway, thereafter into line of sight angles from the airport tower and thereafter into visual velocities as seen by controllers

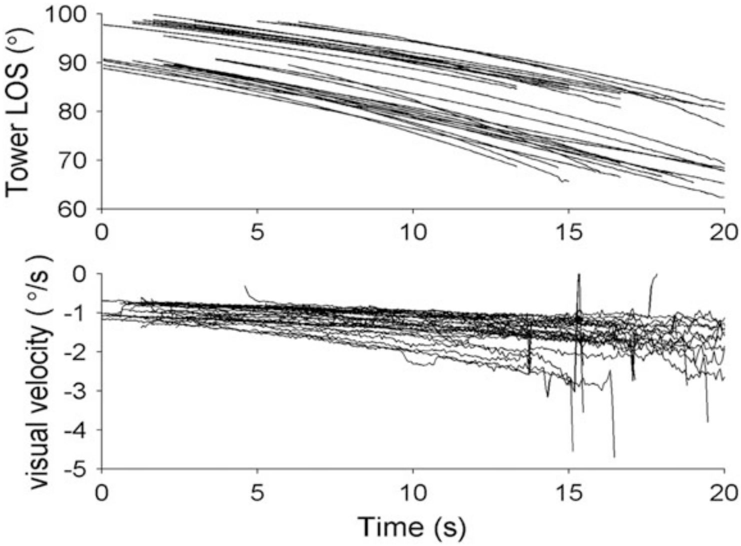

Fig. 13 Line of sight direction change and visual velocity

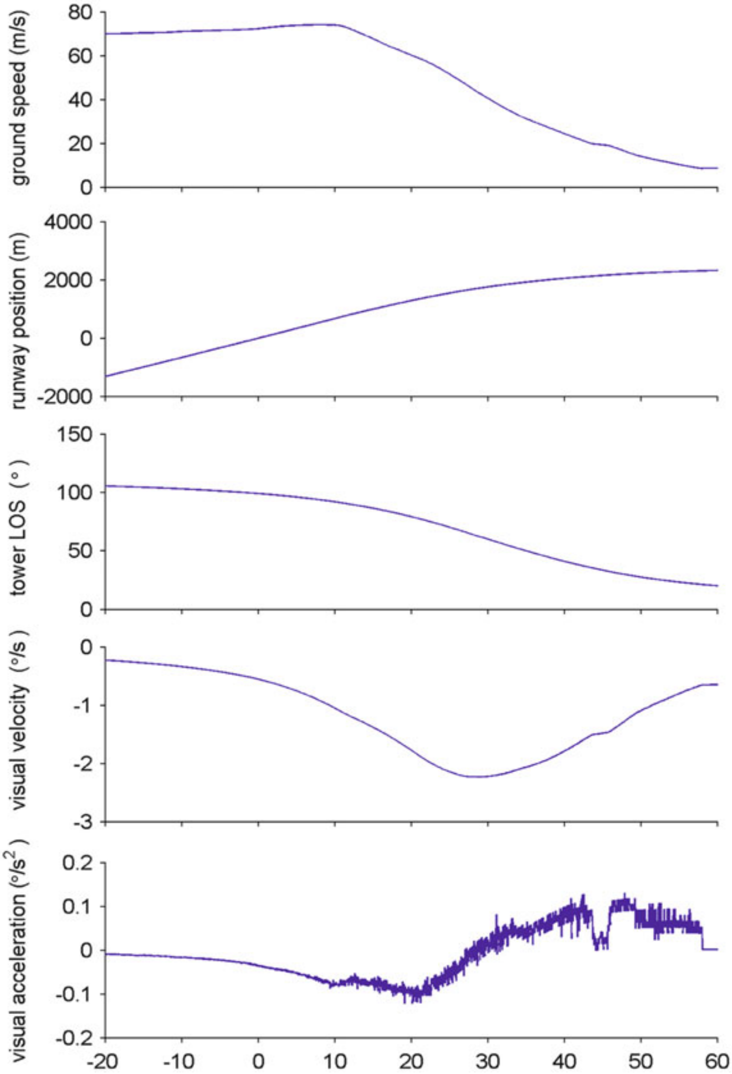

Fig. 14 Line of sight (LOS) changes

however, able to obtain a directly recorded braking deceleration profile[6] for another A319 aircraft landing on runway 28L from the same company, comparably loaded and flying in the same wind and weather conditions as one of the aircraft we had recorded visually. Since we knew the touchdown points for these two A319 landings, we've combined the two trajectories to produce what we believe to be a fairly accurate landing profile as seen from the tower (Fig. 14).

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[6] The aircrafts' deceleration was recorded just after touchdown using an arm rest-stabilized iPhone in airplane mode running an application called Motion Data with sampling rates at 30 Hz.

The deceleration profile in Fig. 14 shows the aircraft approaching and passing the tower as it decelerates. In fact, during the approach the visual velocity actually increases during the deceleration because of the decreasing distance between the aircraft and the tower. It is clear from the deceleration profile that there are several phases of braking due to deployment of the thrust reversers, spoilers, and mechanical brakes and further data collection and processing needs to be done to more precisely identify these periods. However, the very smooth velocity plot in Fig. 14 (third panel from top) already shows that the amounts of velocity change in the braking within any short-time window 2 s or less are well less than the ~6 % usual Weber fraction for a just-noticeable difference of midrange psychophysical quantities such as perceived speed. This level is defined by convention to be that difference in a sensory quantity that can be detected correctly 75 % of the time and is therefore not evidence of a very strong sensory stimulus. This observation leads to some skepticism that the controllers are detecting velocity change per se because controllers would likely wish to be more certain regarding their judgments than 75 % correct. Accordingly, they may have developed a strategy to detect speed change by some other means, perhaps by comparing displacement for approximately equal time periods. Such a timing strategy might be evident in eye-tracking records of controllers judging aircraft deceleration. Of particular interest will be future analyses and experiments to determine how well the controller's sense of aircraft deceleration can be maintained with airport imagery spatially degraded by pixilation and sensor noise and temporally degraded by low sampling rate. The sampling rate issue has been addressed by research first published by Ellis et al. (2011) and more extensively analyzed in chapter "Videopanorama Frame Rate Requirements Derived from Visual Discrimination of Deceleration During Simulated Aircraft Landing" of this volume.

5 Summary

1. Airport tower controllers use visual features observed during aircraft operations to provide information beyond simple detection, identification, and recognition of aircraft.
2. Twenty-eight useful visual features have been identified from discussion with 24 controllers and supervisors. Some involve the static pose of the aircraft of interest, but many of the most useful involve aircraft motion, especially aircraft acceleration and deceleration.
3. The visual features provide predictive or lead information regarding future aircraft position, pilot intention, and pilot airport familiarity that enable controllers to appropriately distribute their attention during operations and to anticipate possible conflicts.
4. The very slow rates of visual motion in terms of subtended visual angle suggest that the change in velocity reported by controllers is not directly sensed but must be observed by learned viewing strategies developed from tower experience.
5. Directional aircraft sounds audible in the tower are also used to assist operations.

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