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EVALUATION OF TERMINAL CONSTRAINT ON ERROR STATE VECTOR FOR VTOL LANDING GUIDANCE

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TABLE OF CONTENTS

ABSTRACT

The analysis shows that for all weather reliability of operation of 99.5% (visibility 350 feet and ceiling 80 feet) and for the assumed configuration of the terminal, the allowable error in the position of VTOL aircraft at 350 feet from the terminal is less than 50 feet in range, 25 feet across range and 10 feet in height (all one sigma values). The ceiling decides allowable vertical error while visibility and terminal configuration determine allowable range and cross range errors.

For the maximum allowable errors, the breakout point should be as far away from the landing pad as the visibility and ceiling will permit. To take advantage of increased visibility and ceiling, a glide slope of about 15-18° might be preferable between 350 feet and 1,400 feet from the pad. The glide slope during other phases of landing is free.

The use of IMU eliminates the limitations on the glide slope and significantly improves the controllability of the aircraft. With an integrated sensor package consisting of an IMU and SAILS, it is feasible to achieve the desired accuracy along the range and across the range. Accuracy along the vertical remains unsatisfactory.

SECTION I
INTRODUCTION

For all weather and intra-urban operation of VTOL aircraft, the requirement of its position accuracy is very stringent in the terminal area. The position accuracy should be nearly one hundred percent for complete instrument touchdown. However, in practice the cloud base is about 60-80 feet above sea level for a significantly large probability. For a terminal at sea level it is, therefore, possible that even in cat III operation the instrument flight could break out into a short visual flight at the end. At the end of the instrument flight a non-zero position error could be tolerated without loosing safety or reliability of operation.

VTOL aircraft landing guidance is a multivariable control problem with a terminal constraint. There are inflight constraints also. The control can be achieved suboptimally or nonoptimally. The object of this analysis was not to deal with this control problem, but to estimate in numbers the allowable as well as the actual value's position error at the terminal. To estimate the allowable error, mainly safety and operation reliability are considered. While for actual error evaluation an onboard inertial measuring unit (IMU) with the simplified aircraft instrument landing system (SAILS) radio landing aid is assumed. A number of benefits accrue in using the inertial system. However, the major objection that still remains is that of the high cost of the inertial system.

The useful elements of the state vector $\underline{x}$ are as follows:

$$\underline{x}^T = [\delta\underline{R} \quad \delta\underline{V}] = [\delta R_r \quad \delta R_c \quad \delta R_h \quad \delta V_r \quad \delta V_c \quad \delta V_h]$$

where $\delta\underline{R}$ is the position error vector with components δR_r along the range (horizontal), δR_c across the track, and δR_h along the height (vertical). Similarly $\delta\underline{V}$ is the velocity error with components along range, cross track and height. Only position elements are evaluated here.

The analysis assumes the worst error criterion instead of the root summed square criterion. The uncertainty region is, therefore, a parallelepipied as shown in fig. 1 with its center at the ideal point of visual breakout and with semisides of δR_r, δR_c and δR_h. Now if $\delta R_r = 2\sigma_r$, $\delta R_c = 2\sigma_c$ and $\delta R_h = 2\sigma_h$, where σ_r, σ_c and σ_h are standard deviation of range, cross track and height errors respectively, then it is 95% probable that the aircraft would be inside the constraint parallelepipied.

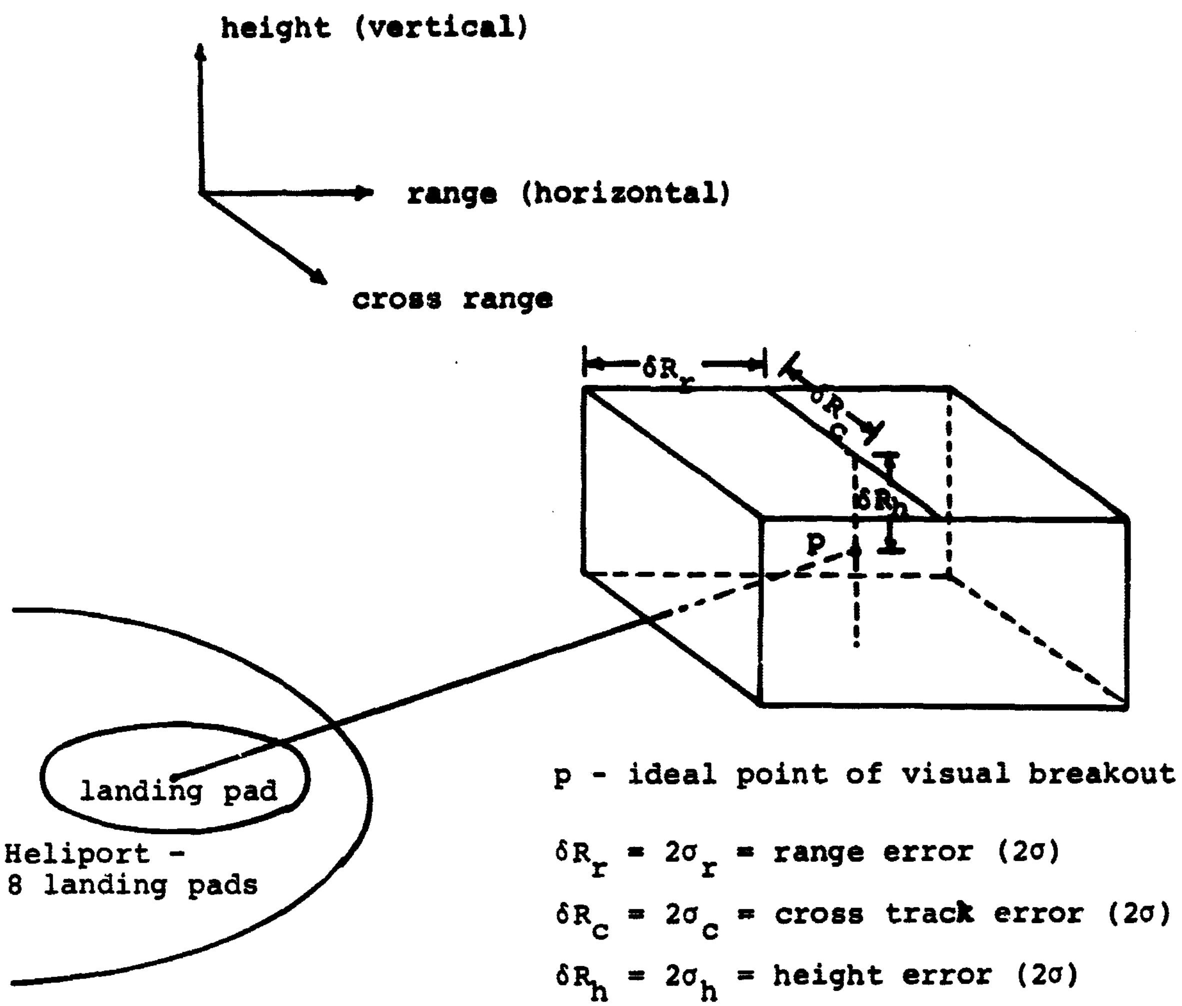

Fig. 1: The constraint box for position error vector at the terminal

The position of VTOL aircraft in fig. 1 is represented by a point which either corresponds to the position of the pilot's eyes or the position of the microwave antenna.

SECTION II

FACTORS THAT INFLUENCE THE POSITION ACCURACY REQUIREMENT AND EVALUATION OF THE ALLOWABLE ERROR

Significant factors that influence the requirement of VTOL aircraft's position accuracy at the point of visual breakout are as follows:

A. Conditions at Landing Sight

a) Weather conditions at the terminal and weather minima operation capability desired

b) Configuration of the landing area

c) Surrounding terrain features

B. Characteristics of the pilot (auto or manual), which result in so-called "pilot error" or "flight technical error." This error will be elaborated upon subsequently.

The pilot also has limitations to control the aircraft at high glide slopes and low speeds. However, the M.I.T. Instrumentation Laboratory has developed (Ref. 4) a velocity command system (VCS) using an IMU. With the VCS the pilot is able to command directly the vehicle's linear velocity with respect to the ground and the pilot can control the aircraft at all glide slopes between horizontal and vertical.

2.1 Weather Minima Capability Desired

Weather minima capability is measured in terms of all weather reliability of operation. Ref. 7 shows that in the northeast corridor 99.5% of all weather operations will have the visibility and the ceiling greater than 350 feet (1/16 mile) and 80 feet respectively. If higher visibility and ceiling are assumed as design criteria, then all weather reliability of operation is reduced. The minimum ceiling directly decides the allowable height error while the minimum visibility significantly influences the permissable range error.

2.2 σ_h Evaluation

For a reliability of operation of 99.5% in the northeast corridor, the ceiling is limited to 80 feet. If a reasonable breakout height of 60 feet is assumed, then with one sigma height error of 10 feet, it is 95% probable that the aircraft would be between 40 feet and 80 feet. The chance that error would be $6\sigma_h$, which is the probability that the aircraft would crash land, is about one in 10^8. Similar calculations were made for two other reliabilities of operation and are listed in

Table I below. Notice that with the same decrease in the reliability, the ceiling does not increase as fast as the visibility.

Table I

Reliability %	Visibility Ft.	Ceiling Ft.	Height Error ($1\sigma_h$) Ft.
99.5	350	80	10
98.8	700	120	20
98	1,400	180	30

2.3 Configuration of the Landing Area

The larger the landing pad, the larger the range and cross track errors can be. However, for an intra-urban heliport, the size of the landing pad should be as small as possible. The size of VTOL aircraft could be estimated to be as high as 120 feet in span. Allowing 20 feet for pilot error in either direction, a landing pad of 160 feet in diameter is assumed.

A heliport can be configured in two ways shown in Fig. 2. This is a schematic and does not represent the actual construction of the heliport. In the first arrangement shown in Fig. 2 a there are only two large pads which can be used for landing and takeoff while there are six standing pads. Only one aircraft can take off and land at a time. As the size of the pad is much larger than the size of the aircraft, a larger position error is allowable. However, with this configuration the traffic handling capacity is limited. On the other hand, in the arrangement shown in Fig. 2-b all eight pads can be used for landing or takeoff. With this arrangement delays due to traffic density would be almost eliminated. However, the position accuracy requirement is much higher because of the smaller landing pad.

2.4 σ_c Evaluation

From Fig. 2-b we have

$$AA' = \frac{\pi \times 400}{16}$$

equating AA' with $3\sigma_c$

$$AA' = 3\sigma_c = \frac{400\pi}{16}$$

$$\sigma_c \simeq 25 \text{ ft.}$$

2.5 Surrounding Terrain Features

Buildings and structures surrounding the vertiport, especially in urban areas, such as the northeast corridor, severely limit the allowable error along the track and in the vertical direction. However, this limit is assumed not to exceed the limit set by the worst weather,

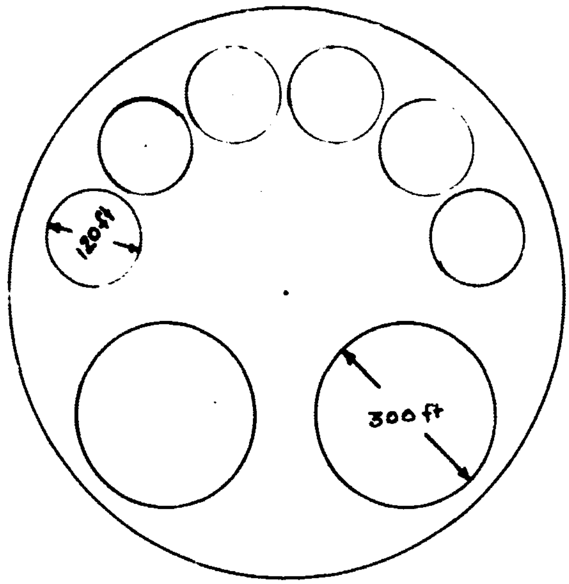

Fig. 2-a

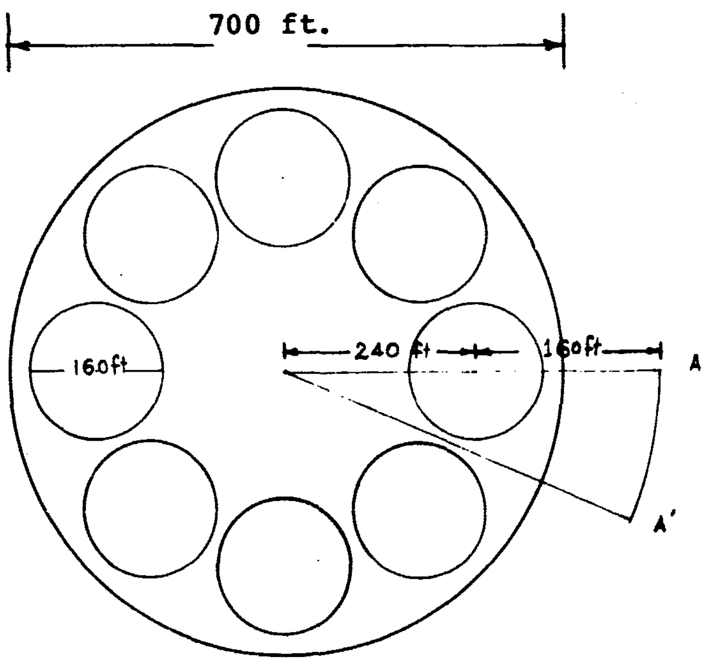

Fig. 2-b

Fig. 2: Preparation of landing area

i.e., by the minimum visibility and ceiling.

2.6 Estimation of Range Error σ_r (See Fig. 3)

With the use of IMU there is no restriction on the allowed glide slope. For determination of allowable range error we use two criteria. First, the landing pad must be visible from the point of visual breakout. Hence, the distance AC must be less than 350 feet. Secondly, the aircraft should never go beyond the center of the landing pad as this would be most dangerous for the configuration of the heliport with the eight landing pads that we have assumed. Hence, AB is fixed to $5\sigma_r$ so that the probability is negligible that the aircraft would ever cross the center of the pad. Then AC $\simeq 7\sigma_r = 350$ feet. Hence, $\sigma_r = 50$ feet.

2.7 Summary

The results of the allowable error calculations can be summarized as follows. For the larger one sigma allowable error in the position at the point of breakout, it should be as far from the pad as possible. At the same time, it should be within the minimum visibility and ceiling limits even after allowing for the error. A similar conclusion is obtained by a probabilistic approach. For a fixed sigma value for the instrument error, the probability that the pilot would be able to identify the visual scene immediately after the visual breakout decreases as the point of visual breakout moves closer to the pad. This is true because small deviations in the position of the aircraft could cause significant angular deviations in the position of the pad with respect to the pilot. As the breakout point moves away, the probability of seeing the pad decreases because of limited visibility and ceiling. The ideal point of breakout should be such that the joint probability at it is maximum.

For increased visibility and ceiling, the point of breakout moves away from the pad as shown by points P_1, P_2 and P_3 in Figure 4. Compare the two approaches at different glide slopes. For the same ceiling the pilot with a low approach angle can break out further than the pilot with a vertical approach. A glide slope of about 15°-18° may be preferred between 350 feet (cat III) and 1,400 feet (cat I) from the pad. The glide slope in other phases of landing trajectory is free for this analysis and should be chosen from other considerations, e.g., the fuel consumption and the gravity loading, etc.

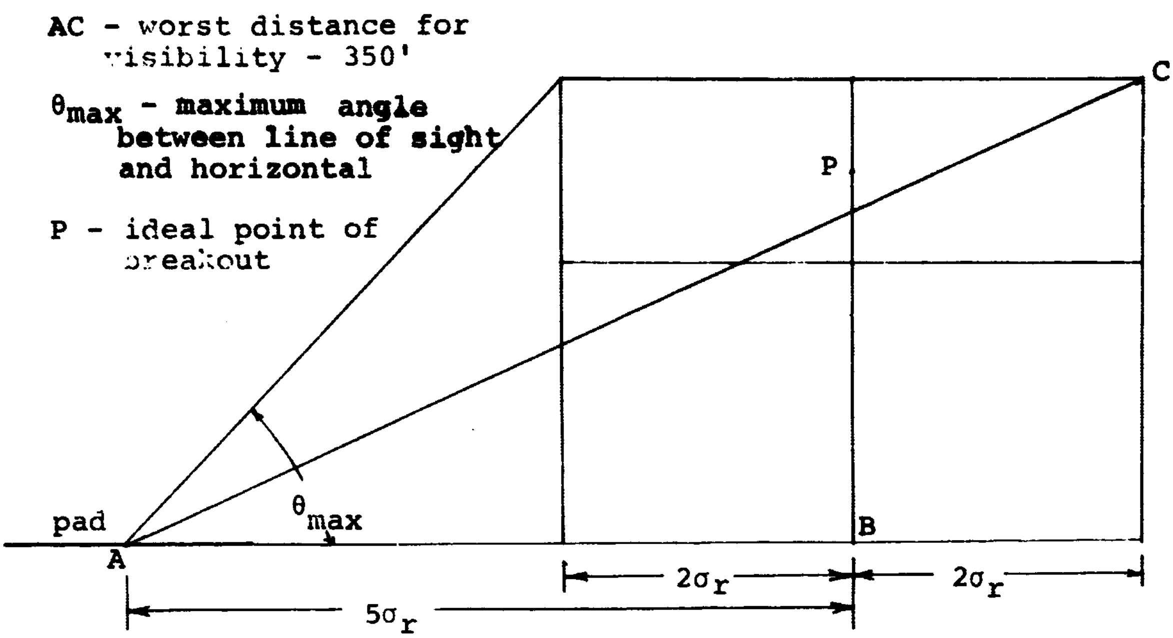

Fig. 3: Estimation of allowable range error (σ_r)

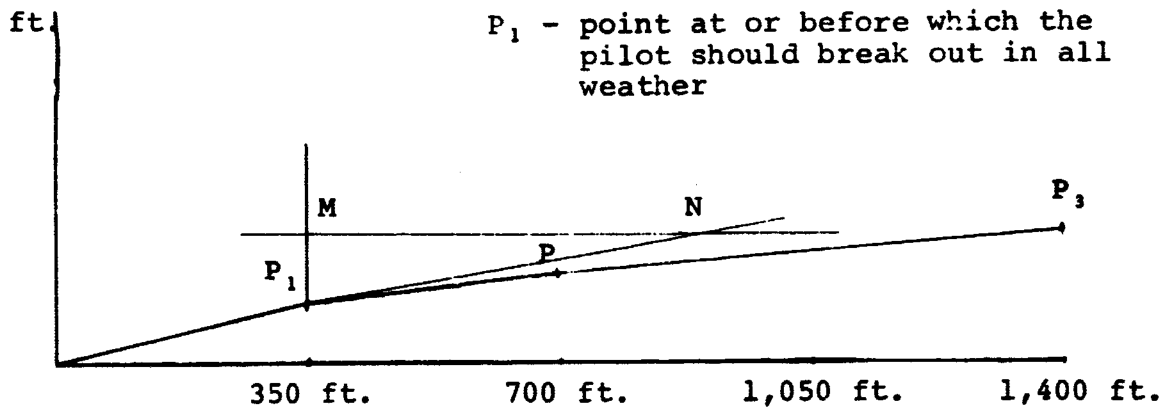

Fig. 4: Glide slope consideration near the point of breakout.

SECTION III

EVALUATION OF ACTUAL POSITION ERROR AT THE TERMINAL

Having determined the allowable error at the terminal, here it is determined whether it is possible to achieve this with the available instruments.

The calculation assumes an onboard IMU with r.m.s. error along the path of about 2 knots (3 ft/sec) and SAILS type radio aid, with a range error of 23 feet + 3.3% of range (Ref. 1).

There are three significant error sources at the terminal point of instrument flight.

A. Finite Time of Transition from Instrument to Visual Flight

The pilot needs finite time to go from instrument to visual flight (Ref. 5). For VTOL operation it is assumed that 3-5 seconds are required to establish wholly adequate visual reference. This time of transition, coupled with the error in velocity measurement, can create an unexpectantly large position error at the visual breakout.

Uncertainty in position = Uncertainty in velocity x time of transition

$$= 3 \times 4 = 12 \text{ feet}$$

As the glide slope can be 0-90°, this error is equal along all three directions.

B. Radio Update Uncertainty

As given in reference 1, the SAILS has a position uncertainty equal to 23 feet + 3.3% of the range. At a distance of 350 feet position uncertainty is equal to $23 + 3.3 \times 3.5 \simeq 35$ feet. With $\theta_{max} \simeq 20°$ (see fig. 3) resolving this error into components, the range error $\simeq$ 35 feet, the cross range error $\simeq$ 10 feet and the height error $\simeq$ 10 feet.

C. Pilot Maneuvering or Flight Technical Error

The random deviation of the aircraft from its assigned path is defined as the flight technical error. The flight technical error under autopilot control depends on the type of aircraft, the accuracy of the autopilot and atmospheric conditions. Even with the VCS and autopilot, the magnitude of this error along the vertical could be of the order of the allowable error. No statistical figures are available and it may be worthwhile to carry out an experiment to determine this.

Conclusions

From the analysis it can be concluded that it would be feasible to get the desired accuracy along the range and across the range with the instrument accuracies that we have assumed. Accuracy along the vertical cannot be met with these instruments, indicating a need for an additional investigation in this area.

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