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PRELIMINARY INVESTIGATION OF MOTION REQUIREMENTS FOR THE SIMULATION OF HELICOPTER HOVER TASKS

FOR REFERENCE

NOT TO BE TAKEN FROM THIS ROOM

RUSSELL V. PARRISH

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

SUMMARY

This paper presents data from a preliminary experiment which attempted to define a helicopter hover task that would allow the detection of objectively-measured differences in fixed base/moving base simulator performance. The addition of heave, pitch, and roll movement of a ship at sea to the hover task, by means of an adaptation of a simulator g-seat, potentially fulfills the desired definition. The feasibility of g-seat substitution for platform motion can be investigated utilizing this task.

INTRODUCTION

Both the military and civilian segments of aviation are placing an increasing reliance on flight simulators for pilot training and proficiency maintenance. This fact, combined with the increasing sophistication and associated costs of available simulation devices, has raised the issues of the numerous trade-offs between simulation fidelity and costs to highly visible levels. In specifying the simulation configuration, the designer must consider the need for particular cueing devices as well as the requisite level of fidelity. Unfortunately, little data is available on either point.

Some of the factors affecting the fidelity of a flight simulator are the mathematical model of the flight vehicle, the cockpit hardware (control system, instrumentation, etc.) and the visual, motion, and aural cues provided to the pilot. The final three factors are thought to be of considerable importance in the simulation of a helicopter, particularly when low-altitude maneuvering is

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simulated.

The importance of visual cues to the helicopter pilot is well understood (ref. 1), although disagreement exists as to the exact nature of the visual requirements for simulation. The addition of motion cues seems intuitively important in a vehicle possessed with the capabilities of rapid movement within three-dimensional space. Aural cues should also be significant in providing the pilot with information relative to his vehicle's performance.

A current target of fidelity versus cost arguments has been the requirement for simulator platform motion. In evaluating the need for the provision of platform motion in several future tactical fighter simulators, an Air Force Scientific Advisory Board ad hoc committee reported in reference 2 that:

> "Based on the motion/no motion studies and experiments which have been run to date, a convincing case cannot be made for either including or excluding platform motion in flight simulators for tactical fighters."

A similar situation exists in the field of helicopter simulation. A typical example from the available literature is reference 3, which describes an evaluation study of combined visual, motion, and aural cues for a helicopter engaged in visually conducted slalom runs at low altitude. The evaluation of the visual and aural cues was subjective, whereas the motion cues were evaluated both subjectively and objectively. Subjective opinion and objective data conflicted in the detection of differences in the performance of a primary and secondary task under motion and no motion conditions. Subjectively, differences in performance were expected, and objectively, no significant differences were detected. However, subjective and objective results coincided in the area of control activity. Generally, less control activity is present under motion conditions than under fixed-base conditions, a fact attributed subjectively to the feeling of realistic limitations of a machine (helicopter) given by the addition of motion cues.

This paper will present data from a preliminary experiment which attempted to define a helicopter hover task that would allow the detection of objectively-measured differences in fixed base/moving base simulator performance. With such a task definition in hand, a further experiment to investigate the feasibility of g-seat substitution for platform motion for this task would be initiated. A comparative evaluation of fixed-base, platform motion, and g-seat conditions for various visual delays would be the culmination of this research effort.

In the task definition process, the supposition was advanced that the most difficult hover task would probably have the greatest requirement for platform motion. Hover above a heaving ship's deck, in which the pilot's task is to remain above a mean ship-deck position without tracking the ship's movements, requires information that allows the separation of ship movement from helicopter motions. Most of the visual content provides only relative information. The addition of platform motion cueing might provide the necessary separation information.

Because a moving ship model was not available at Langley, the preliminary experiment was first attempted with the heliport model available on a terrain model board. A technically innovative approach was used to provide a moving ship model. By utilizing a simulator g-seat as a mounting base for the ship model, pitch, roll, and heave motion are provided by synergistically inflating and deflating the seat compartments.

This paper will present the objective data collected during both phases of the preliminary experiment, along with a description of the simulator, including the g-seat mechanization for ship movement.

SIMULATOR DESCRIPTION

The simulator was assembled with the elements: mathematical model, visual system, motion system, simulator cockpit, and aural cueing.

Mathematical Model

A six-degree-of-freedom total force and moment mathematical model of a helicopter, including a modified blade element rotor model, was used in the study. It was a modified model of a Huey-Cobra helicopter with a stability augmentation system tuned so that the handling characteristics of an S-61 helicopter are closely duplicated. The development of the program of the helicopter model is documented in reference 4, and the first application of the model is documented in reference 5. The control system was of the rate command/attitude hold type.

Computer Implementation

The mathematical model of the aircraft and the simulation hardware drives were implemented on the Langley real-time simulation system. This system, consisting of a Control Data CYBER 175 and appropriate interface equipment, solved the programmed equations 32 times a second. The average time delay from input to output (1.5 times the sample period) was approximately 47 milliseconds.

Visual System

The visual system consists of a state-of-the art TV camera transport system used in conjunction with a sophisticated terrain model board. (See fig. 1) The model board, 7.32 m (24 ft) by 18.3 m (60 ft), offers terrain at a 750/1 scale and a 1500/1 scale. The approximate second-order transfer function parameters for the camera transport system are presented in reference 6, and show translational lags of 15 msec or less and rotational lags of 22 msec or less. The "out-the-window" virtual image system, located nominally 1.27 m (4.17 ft) from the pilot's eye, presented a nominal 48° width by 36° height field of view of a 525 TV line raster system and provided a 46° by 26° instantaneous field of view. The system supplies a color picture of unity magnification with a nominal resolution on the order of 9 minutes of arc.

The scene depicted in the virtual image system consisted of a Heads-Up Display (HUD) video-mixed with a terrain-board scene of either a heliport or a ship. Total visual delay, consisting of computational delay plus visual hardware lags, was less than 70 msec. An additional 62.5 msec delay could be added to both the HUD and the terrain scenes in order to investigate visual delay effects on pilot/vehicle performance.

The HUD.- The absence of side windows made determination of altitude and fore-and-aft position practically impossible with that portion of the terrain board scene utilized. The HUD display shown in figure 2 was provided to supply this information. Deviation of the circular bugs from the cross-hairs represented an error in longitudinal and/or lateral, and altitude positions. However, because over-control was induced by an attempt to fly this display, rather than the terrain scene, the brightness of the HUD was decreased to a level at which it was barely visable to the pilot. At this level, the HUD did not intrude into the active, higher frequency portion of the task, and yet provided necessary reference information to the pilot.

The heliport scene.- Figure 3 depicts the 750 to 1 scale heliport scene that was used in the no-ship movement portion of this study. The pilot task was to hover at a point 15.23 meters away longitudinally and 9.16 meters above the maltese cross.

The ship scene.- The 525 to 1 scale aircraft carrier model used in the ship-movement portion of this study is shown in figure 4. The hanger was added to the model to simulate the deck structure of a destroyer in the landing area. Ship movement was provided in heave, roll, and pitch by an innovative use of a g-seat. A g-seat is a device intended to be used to provide acceleration cues to a simulator pilot through the seat pressures (refs. 7 and 8). The application of the seat to provide ship-movement visual cues is illustrated in figures 5, 6, and 7. The drive equations are presented in the appendix of this paper.

A constant forward velocity for the ship was simulated by driving the visual probe with relative longitudinal and lateral velocity and position information. The helicopter was thus required to maintain constant forward speed while performaing a relative hover.

Motion System

The Langley visual-motion simulator (VMS, fig. 8) is a six-degree-of-freedom synergistic motion base with performance limits as listed in table I, although conservatism must be exercised in use of these limits for multiple degree-of-freedom applications. References 9, 10, and 11 document the characteristics of the system, which possesses time lags (around 50 msec) that are close to those of the visual system. The washout system used to present the motion-cue commands to the motion base is nonstandard. It was conceived and developed at Langley Research Center, and it is documented in references 12 and 13. The basis of the washout is the continuous adaptive change of parameters to minimize a cost functional through continuous steepest descent methods, and to produce the motion cues in translational accelerations and rotational rates within the motion envelope of the synergistic base. The specific parameters of the nonlinear coordinates adaptive washout used in this helicopter study are presented in table II. Figure 9 presents a block diagram of the washout system. It should be noted that the heave cue supplied to the pilot was based only on the rate of change of collective stick position rather than on normal acceleration. This arrangement allowed for significant vertical onset cueing without the phasing and amplitude problems that arise when trying to present the cue based on normal acceleration. Simulation of vibration, obtained from the aural-cue drives, was also presented in the vertical motion channel.

Simulator Cockpit

The general-purpose transport cockpit of the VMS was modified to represent a helicopter by installing a two-axis center-stick controller to supply cyclic inputs. The cyclic controller was loaded, as were the rudder pedals, by a hydraulic system coupled with a special-purpose analog computer.

The collective stick in the VMS is a counter-balanced, friction-controlled stick, and it is representative of a helicopter collective.

Primary instrumentation consisted of an attitude indicator, vertical speed indicator, an altimeter, an RPM indicator, a turn and bank indicator, a compass card, and an airspeed indicator. The airspeed indicator was driven with V when V was above 20 knots, and with $+u$ when V was below 20 knots.

A sine wave of 100 Hz was multiplied on a general-purpose analog computer with a half-rectified sine wave of controlled amplitude and frequency generated on the digital computer to provide the aural cues to the simulator. The 100-Hz sine wave provided a realistic tone, the half-rectifying of the second sine wave provided the pulsing desired, and amplitude and frequency variations of the second sine wave provided the rotor loading cues desired. The empirical equations for the control of amplitude and frequency of the second sine wave used within the digital computer were

$$\text{Amplitude} = 0.203 \times |\Theta_a + 0.13| + 0.002 \times |\text{RPM} - 290| + 0.00002 \times |h| + 0.15 \times |\phi_a| + 0.317\delta_c$$

$$\text{Frequency} = \omega_p$$

$$\omega_p = \begin{cases} \omega_p & |\omega_n - \omega_p| \leq 0.1 \\ \omega_n & |\omega_n - \omega_p| > 0.1 \end{cases}$$

$$\omega_n = 0.112 \times \text{RPM}$$

The half-rectified sine wave was also introduced into the heave channel of the motion base to simulate vibration levels.

PARTICIPATING PILOTS AND TASKS

Two operationally-experienced Navy helicopter pilots participated in this preliminary study. One pilot "flew" all of the no-ship motion cases, and both pilots participated in the ship-motion portion of the study.

In the no-ship-motion portion, the pilot task is illustrated in figure 10. RMS deviation from the fixed point in space, 15.23 meters away longitudinally and 9.16 meters above the maltese cross, was measured radially for two levels of air turbulence, two levels of visual lag, and the two motion conditions (fixed base and moving base).

The ship-movement portion of the study was conducted for only the larger levels of visual delay and of air turbulence. Both motion conditions (fixed base and moving base) were used. The task is again illustrated in figure 10, if the maltese cross can be envisioned as pitching, rolling and heaving in a sea state 3 condition. The pilot task was to hover at the point fixed relative to the mean deck position. While the point was moving at a constant forward speed, it was not affected by deck pitch, roll, or heave.

EXPERIMENTAL RESULTS

The preliminary experiment to define a helicopter hover task that would allow the discrimination of simulator motion condition from objective performance data was conducted in two parts. The first portion of the experiment was conducted with an out-the-window view of a ground-based heliport (that is, without ship movement). The second portion of the experiment utilized a ship model mounted on a g-seat that presented a realistic scene of a ship underway at sea.

Without Ship Movement Results

In addition to examining the motion factor at two levels (fixed base and moving base), two other factors at two levels each were examined in order to investigate their interaction with the motion condition. That is, whether the effect of motion was more pronounced under certain levels than other levels. The additional factors were turbulence (on and off) and visual lag (the local-optimal and degraded). A full factorial was not carried out in this preliminary experiment, but rather a sampling at each cell, with the major emphasis placed on the most difficult combination.

The results of this portion of the study are presented in table III in terms of means and standard deviations of the RMS distance between the helicopter center-of-gravity and the desired fixed point. The sample size is also shown, with only one pilot available for all cases. Student's t-tests on the means and homogenuity-of-variance tests on the standard deviations revealed no significant motion effects under any of the conditions. Turbulence and visual lag are both significant effects. No motion interaction terms are significant.

Ship Movement Results

The second portion of the experiment was conducted with ship movement under only the more difficult conditions of turbulence and visual lag. Table IV presents these results in the same format as table III, with an additional pilot (pilot 2). In the ship movement case, the performance with motion is clearly superior to the fixed based performance. The pilots subjectively attribute this difference in performance to the additional information obtained from the platform motion cues, which apparently enable them to separate the relative visual motions into ship movements and helicopter motions.

Contrasting the Results

A comparison of the performances of pilot 1 across portions of the experiment (table III to table IV) indicates that, as expected, the addition of ship movement to the task adds to the pilot workload and the task difficulty. The fact that the detection of differences in fixed base/moving base performance occurs only with this additional difficulty tends to verify the supposition that the requirements for platform motion increase with task difficulty.

RECOMMENDATIONS

The intended comparative evaluation of fixed-base, platform motion, and g-seat conditions that would be the culmination of the present research was to be shaped by the objective results obtained in this preliminary experiment. In addition to identification of a suitable task, the objective data indicates that pilot variability, ship movement effects, and visual delay effects are factors that, in addition to the central motion cueing question, may be worthy of further investigation.

Suggestions from the two participating pilots included changing from the rate command/attitude hold control system of the simulated S-61 helicopter of this study to the acceleration command control system of an available Cobra model. This proposed change would further increase the task difficulty and is consistent with the original supposition that requirements for platform motion increase with task difficulty. An acceleration command control system is the type with which the available pilot pool is more familiar, also.

The pilots also recommended, if possible, changing the ship model to a destroyer (the operational problem), rather than the carrier model utilized (such a change would probably involve a lesser scale size, which may not be desirable). The hover point should be changed, on the pilots' recommendation, from the British-type approach path position parallel to the bow/sternline of the ship to a position on the American-type diagonal approach path. Further interest as to the necessity of the HUD display, in light of the increased altitude cues available from the hanger structure, was expressed by the pilots, although the restricted field-of-view may still make its use desirable.

CONCLUDING REMARKS

A helicopter hover task which potentially allows the detection of objectively-measured differences in fixed-base/moving base performance has been identified in the subject preliminary experiment. Differentiation of the motion condition was not possible under the less demanding task of no ship movement. A formal comparative evaluation of fixed-base, platform motion, and g-seat conditions for various visual delays, and the two ship movement conditions (no movement and simulated sea movement) can be based on these preliminary results.

APPENDIX

Ship Movement Drive Equations

The g-seat has four bladders that are controlled independently. The bow of the ship was connected to bladder #2 and the stern to bladder #4. Bladders 1 and 3 provided roll and heave motion by means of a cross-brace connected to the center of the ship. The bladder drive equations were:

$$\text{drive } 1 = K_z z_s + K_\phi \Phi_s + \text{ref}$$

$$\text{drive } 2 = K_z z_s + K_\theta \theta_s + \text{ref}$$

$$\text{drive } 3 = K_z z_s + K_\phi \Phi_s + \text{ref}$$

$$\text{drive } 4 = K_z z_s + K_\theta \theta_s + \text{ref}$$

where K_z is the gain on the vertical motion, z_s

K_Θ is the gain on the pitch motion, Θ_s

K_ϕ is the gain on the roll motion, Φ_s

The pitch, roll and heave motion equations were adapted from reference 14. As adapted, the equations were:

$$m_i = \sum_{j=1}^{4} A_{ij} \cos\left(\omega_j t - \Phi_{ij} + \varepsilon_j\right)$$

where i = axis identification (pitch, roll, or heave)

j = component number

m_i = ship motion about mean position in i<u>th</u> axis (Zs, Φs, Θs)

A_{ij} = amplitude associated with j component of i<u>th</u> axis

ω_j = encounter frequencies associated with j<u>th</u> component

t = time

$\emptyset_{ij}$ = phase angle for j<u>th</u> component in i<u>th</u> axis

ε_j = uniformly distributed random phase, $\pm 180^\circ$, selected at the beginning of each run for the four components.

The following amplitudes, frequencies, and phases were utilized for sea state 3, condition 11, ref. 14:

j		1	2	3	4
ω_j, rad/sec		.70	.89	1.10	1.32
Amplitude, A_{ij}	pitch, deg	.175	.339	.293	.112
	roll, deg	.537	.572	.342	.136
	heave, m	.179	.275	.240	.051
Phase, ϕ_{ij}	pitch, deg	-62.95	-44.14	-4.82	27.56
	roll, deg	-82.25	-63.80	-62.17	-72.97
	heave, deg	-1.39	2.13	40.13	81.84

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TABLE I.- PERFORMANCE LIMITS FOR SINGLE-DEGREE-OF-FREEDOM OPERATION WITH A NEUTRAL POINT OF 0.6161 m (2.02 ft)

Degrees of freedom	Performance limits		
	Position	Velocity	Acceleration
Longitudinal, x	Forward 1.245 m Aft 1.219 m	±0.610 m/sec	±0.6g
Lateral, y	Left 1.219 m Right 1.219 m	±0.610 m/sec	±0.6g
Vertical, z	Up 0.991 m Down 0.762 m	±0.610 m/sec	±0.8g
Yaw, ψ	±32°	±15°/sec	±50°/sec^2
Pitch, θ	+30° -20°	±15°/sec	±50°/sec^2
Roll, ϕ	±22°	±15°/sec	±50°/sec^2

TABLE II.- NONLINEAR WASHOUT PARAMETER VALUES

Variable*	Value in SI Units	Program value in U.S. Units	Variable*	Value in SI Units	Program value in U.S. Units
b_ψ, per sec^2	1.0	1.0	e_y, per sec^2	0.81	0.81
e_ψ, per sec	.3	.3	$K_{y,1}$, sec^3/m^2 (sec^3/ft^2)	.51668	.048
K_ψ, sec	100	100	$K_{y,2}$, sec^5/m^4 (sec^5/ft^4)	0	0
W_x, m^2/sec^2 (ft^2/sec^2)	61.686	664	$K_{y,3}$, sec^3/m^2 (sec^3/ft^2)	.2691	.025
b_x, per sec^4	.1	.1	b_z, per sec^4	.5	.5
c_x, per sec^2	2	2	c_z, per sec^2	.1	.1
d_x, per sec	1.2727	1.2727	d_z, per sec	1.2727	1.2727
e_x, per sec^2	.81	.81	e_z, per sec^2	.81	.81
$K_{x,1}$, sec^3/m^2 (sec^3/ft^2)	.51668	.048	K_z, sec^3/m^2 (sec^3/ft^2)	10.764	1.0
$K_{x,2}$, sec^5/m^4 (sec^5/ft^4)	0	0	$K_{c,1}$, per sec	.05	.05
$K_{x,3}$, sec^3/m^2 (sec^3/ft^2)	.75348	.07	$K_{c,2}$, per sec	.5	.5
W_y, m^2/sec^2 (ft^2/sec^2)	.00929	.1	$K_{c,3}$, per sec	.05	.05
b_y, per sec^4	.1	.1	$K_{c,4}$, per sec	1.5	1.5
c_y, per sec^2	2.0	2.0	$K_{c,5}$, per sec	.1	.1
d_y, per sec	1.2727	1.2727	$K_{c,6}$, per sec	.05	.05

*Where two sets of units are given, the first is the SI Unit and the second is the U.S. Unit.

TABLE III. - MEANS AND STANDARD DEVIATIONS FOR WITHOUT-SHIP-MOVEMENT-PERFORMANCE

VISUAL LAG,ms	MOTION CONDITION	RMS TURBULENCE 0 m/sec	RMS TURBULENCE .524m/sec
70	FIXED BASE	2.16 ,n=1	4.57±.94,n=5
	MOVING BASE	1.95 ,n=1	4.60±.46,n=5
132.5	FIXED BASE	3.69±.49,n=5	5.33±.94,n=10
	MOVING BASE	3.62±.82,n=5	5.18±.91,n=10

TABLE IV. - MEANS AND STANDARD DEVIATIONS FOR SHIP MOVEMENT PERFORMANCE

n=5	MOTION CONDITION FIXED BASE	MOTION CONDITION MOVING BASE
PILOT 1	8.20±1.10	6.40±.95
PILOT 2	16.73±3.02	9.66±1.71

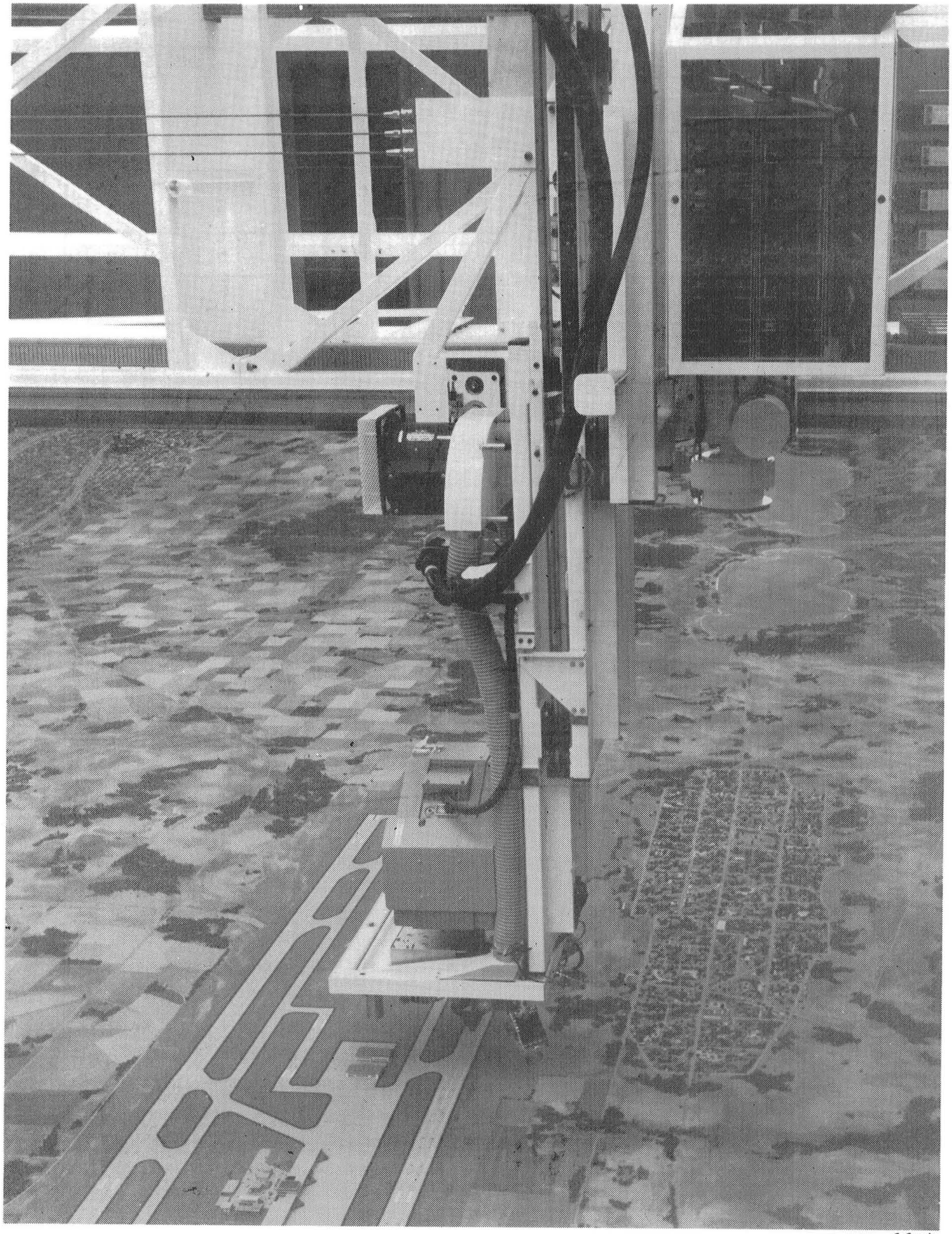

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Figure 1.- The visual landing display system.

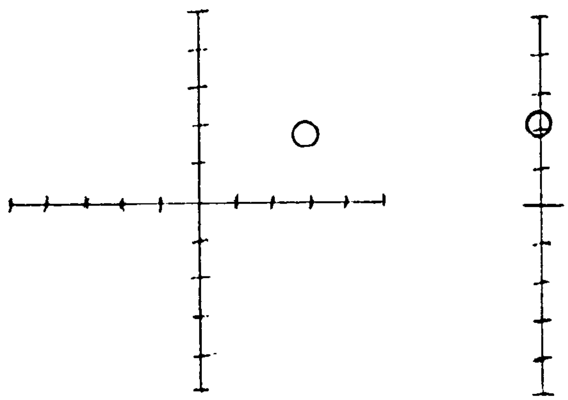

Figure 2.- The heads-up display (HUD)

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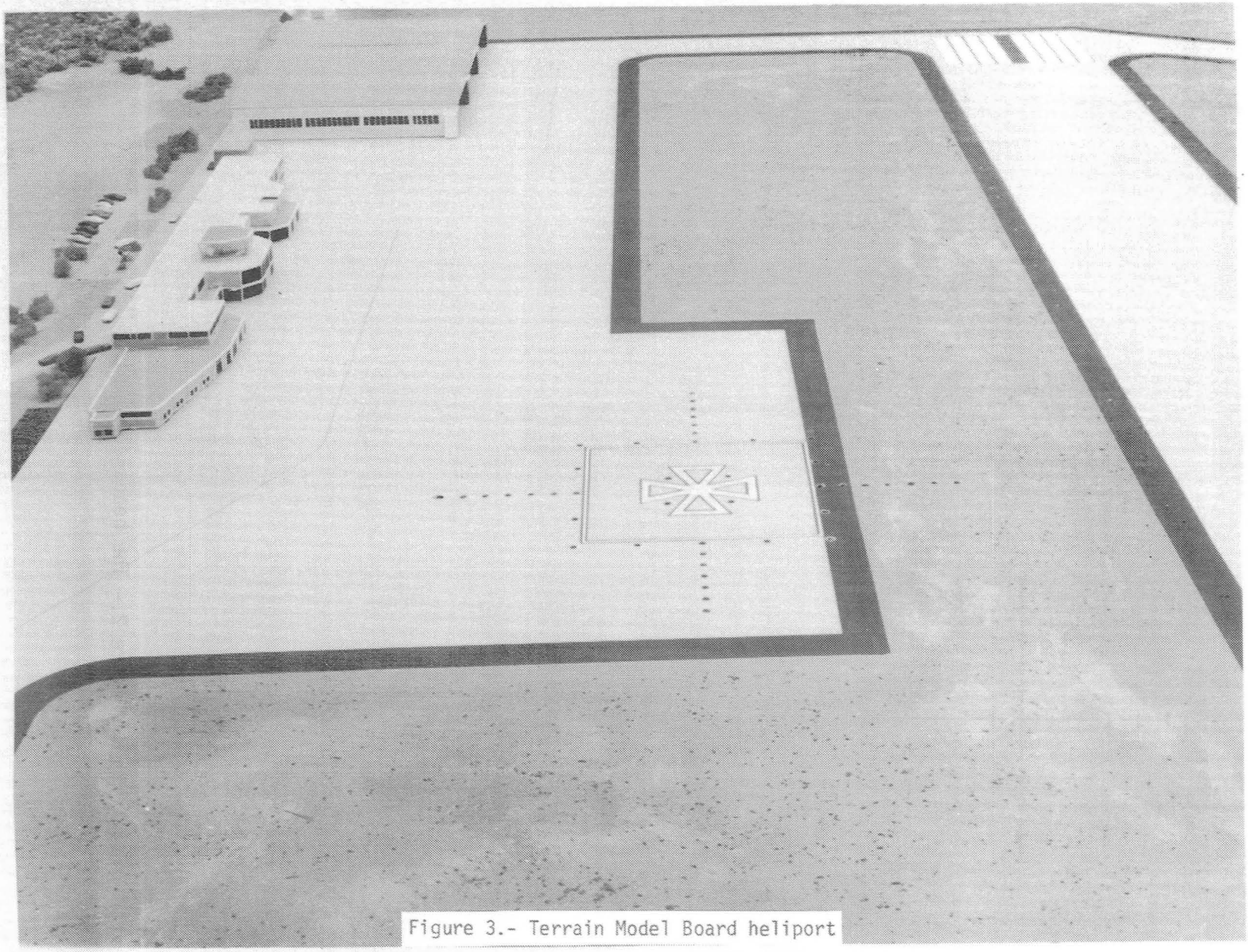

Figure 3.- Terrain Model Board heliport

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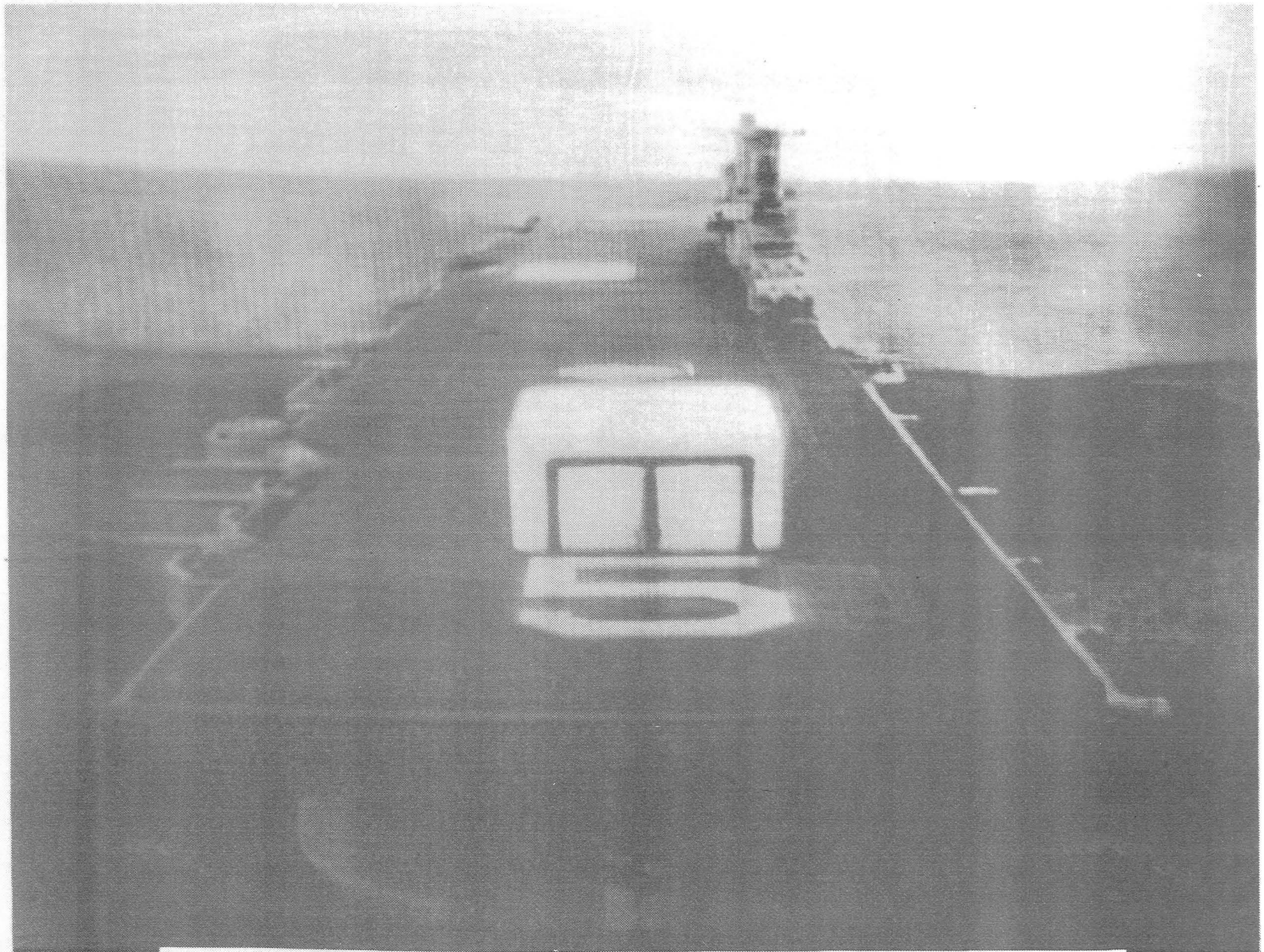

Figure 4.- Visual scene of aircraft carrier with simulated destroyer helicopter hanger

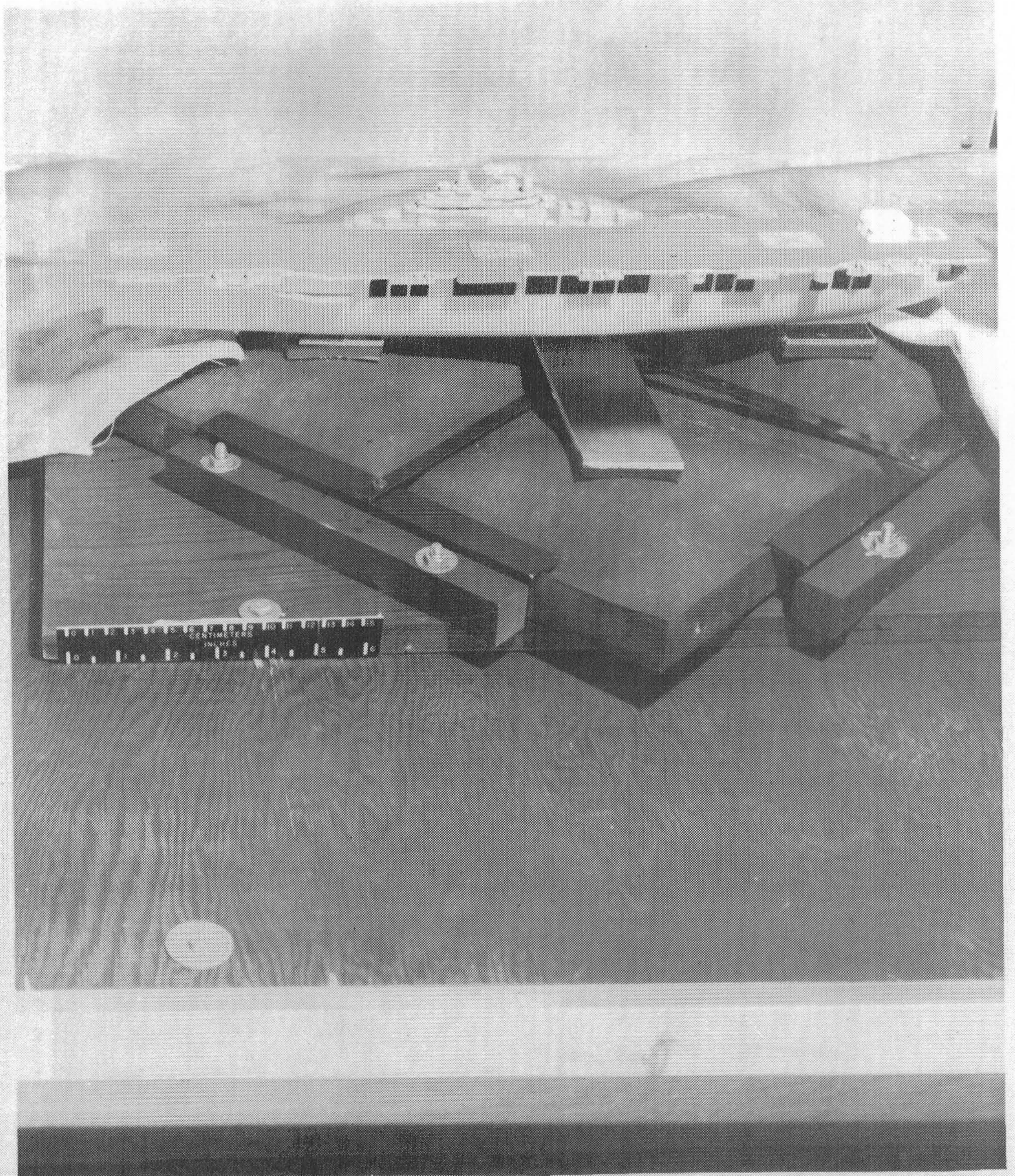

Figure 5.- Aircraft carrier mounted on g-seat

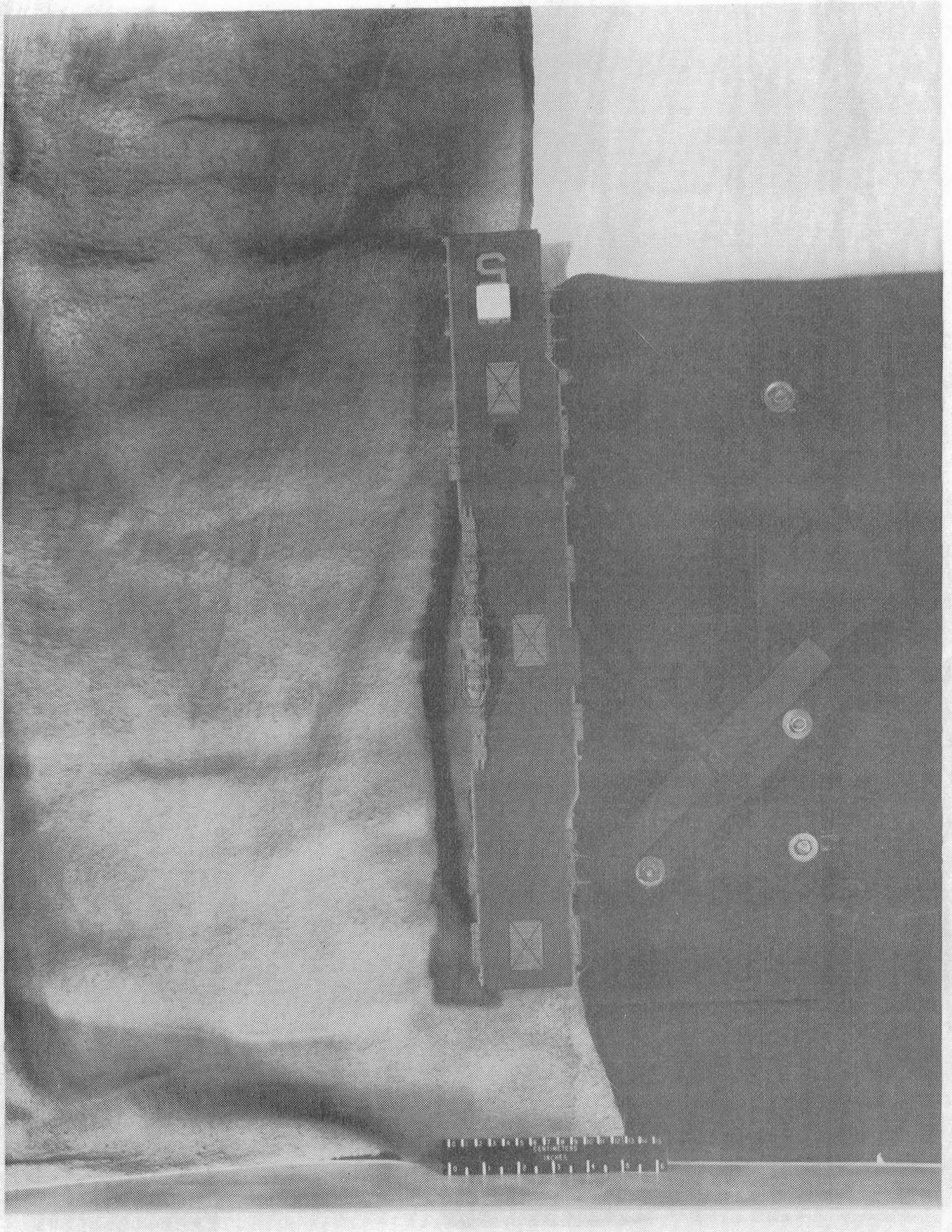

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Figure 6.- Top view of g-seat, carrier mounting

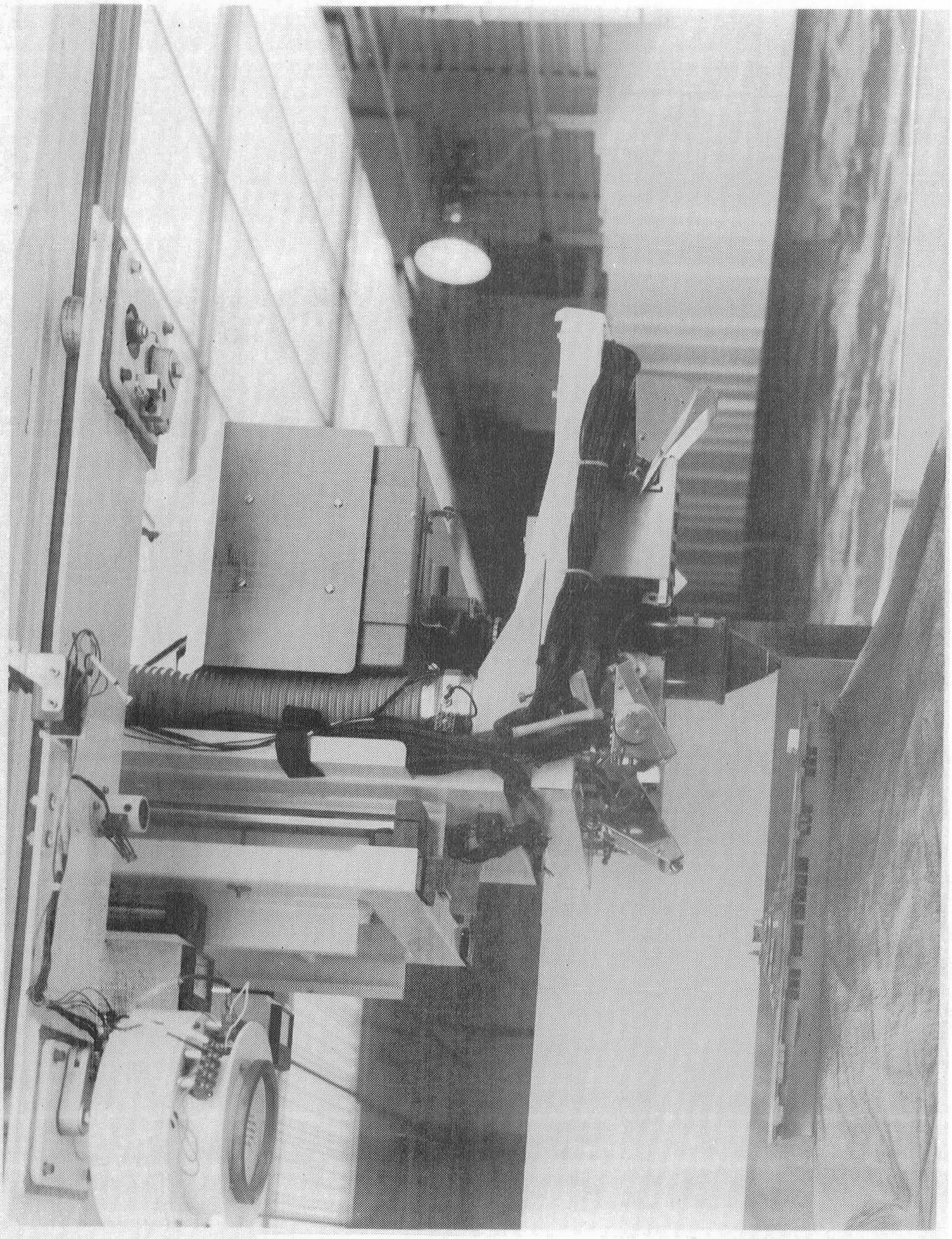

Figure 7.- Probe viewing the ship model

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Figure 8.- Langley six-degree-of-freedom motion simulator.

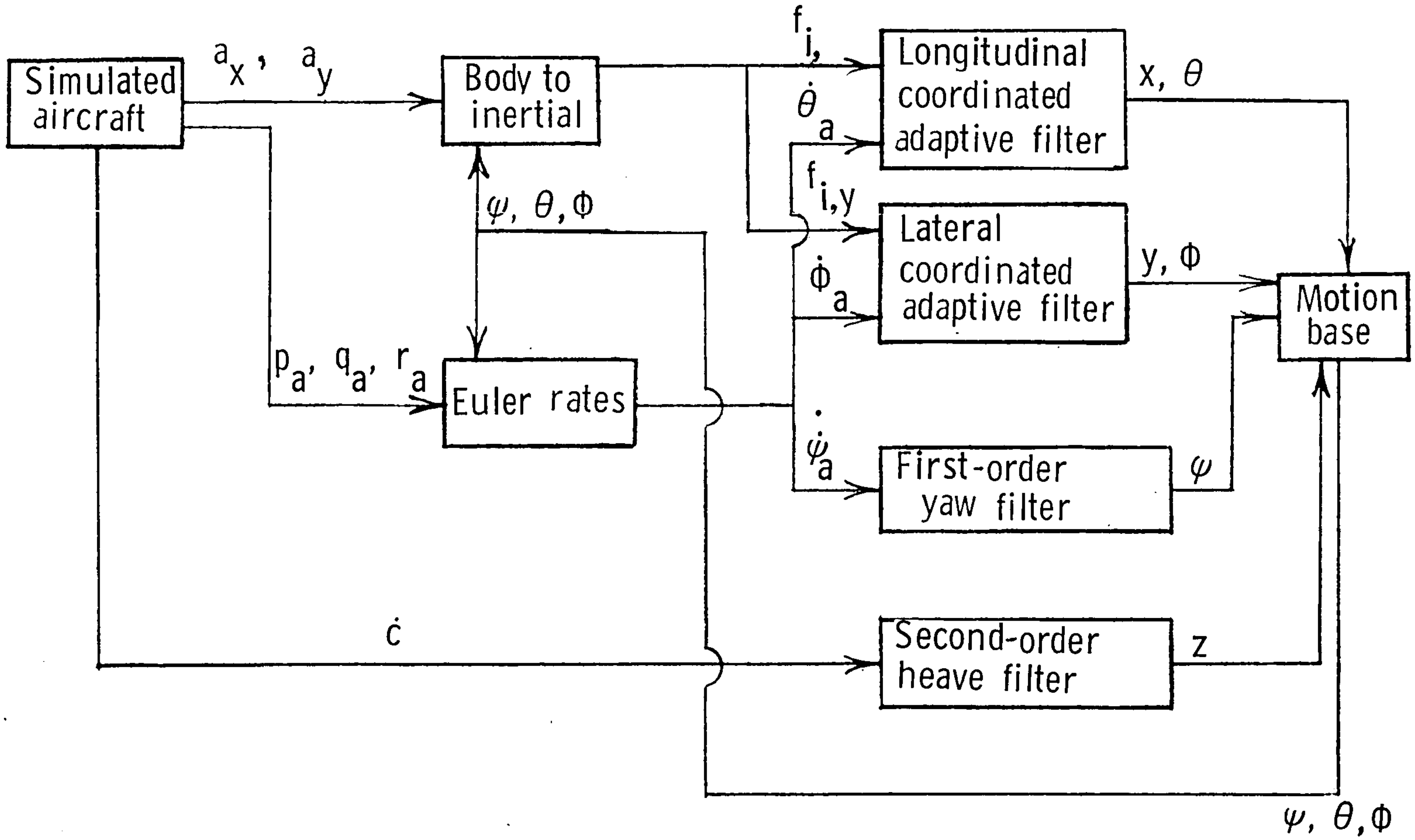

Figure 9.- Coordinated adaptive washout.

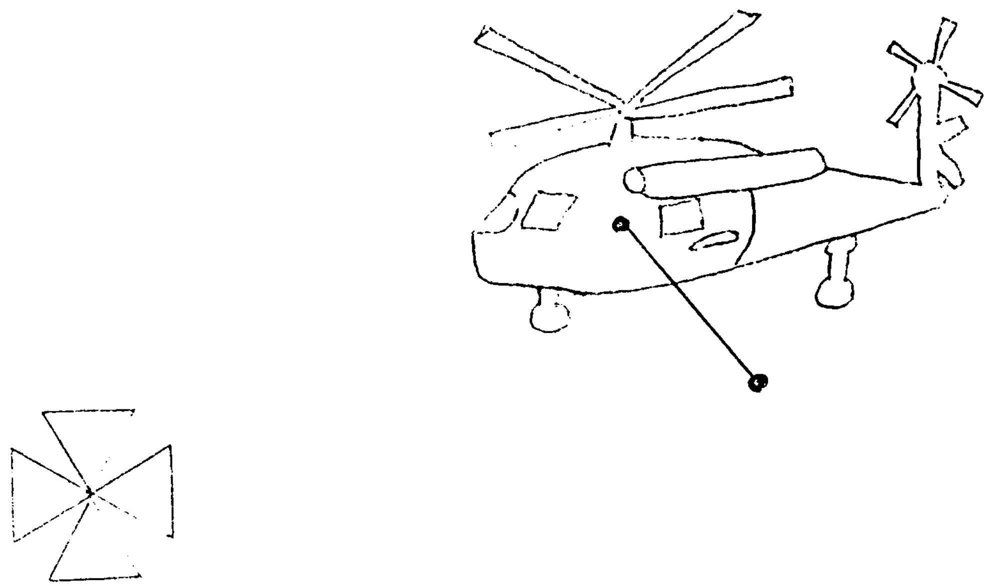

Figure 10.- The hover task

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16. Abstract

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