STUDIES OF PILOTING PROBLEMS OF ONE-MAN FLYING UNITS OPERATED IN SIMULATED LUNAR GRAVITY

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SUMMARY: Current interests in small flying units to extend the range capabilities of lunar explorers coupled with a serious lack of information on the flight behavior of such vehicles have stimulated a series of studies of the handling qualities and often piloting problems of this type of vehicle by the Langley Research Center of the National Aeronautics and Space Administration. This paper briefly reviews earlier experimental studies of small earth-based vehicles and illustrates several configurations that have evolved in recent preliminary design studies of possible small lunar flying devices. These configurations include back-mounted, stand-up, and sit-down arrangements that are being, or soon will be, evaluated in the Langley studies made possible by the recent development of lunar gravity simulation techniques that permit the use of full-scale man-operated flying test-bed vehicles. The general nature of these fundamental studies as well as a few of the preliminary findings are described in this paper.

INTRODUCTION

Much attention in the field of advanced planning for future lunar missions has been focused on small manned flying devices as a means for extending the range capabilities of the lunar surface explorers. Although several such devices have been studied over the past several years with various degrees of effort, there has been little information obtained concerning the handling qualities and other critical piloting characteristics of such devices, due primarily to the lack of practical methods and facilities with which to undertake meaningful investigations of experimental operational hardware.

The purpose of this paper is to discuss briefly a recently initiated series of pertinent flight investigations some of which have been made possible as a result of the successful operation of the lunar landing research facility (LLRF, ref. 1, fig. 1) and new techniques being applied to it at the Langley Research Center of the National Aeronautics and Space Administration. In these studies, pilot evaluation of the flight behavior of full-scale test devices are being obtained under conditions of "real-live" operations in simulated lunar gravity during take-off, landing, and near hovering flight maneuvers, using research pilots experienced in lunar gravity simulations. The information gained from these flight investigations should be directly applicable to the design and development of specific lunar flying units, and should help

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approach maximum assurance of astronaut safety in the performance of the flying activities.

RECENT DESIGN EFFORTS AND PRIOR FLIGHT EXPERIENCE

A brief summary chart is presented in table I, in order to show the relation of the current Langley studies to recent design studies of small lunar flying devices as well as to prior efforts with experimental flying vehicles akin to these lunar designs. These various devices are categorized with respect to the stance of the pilot, general location of the main thrusters and the mode of attitude control. A list of some of the physical characteristics of the lunar designs is given in table II, and is accompanied by sketches and photographs in figures 2 through 7 to illustrate the various configurations.

The geneses of most of the actual flight experiments are in the pioneering works of Wendell Moore of Bell Aerosystems who developed the flying belt concept (ref. 2), and Charles Zimmerman of the Langley Research Center who conceived the balance reflex or kinesthetically controlled flying platform (ref. 7). Although most of these flight experiments were more or less successful, the information gained was only exploratory in nature and, of course, applied only to flight behavior in earth gravity. One exception, however, is the project involving piloted flight in simulated lunar gravity carried out at Langley Research Center in about 1962 using a simple sit-down configuration with manually operated air jets for pitch and roll control, and foot-operated air jets for yaw control (ref. 12). Some pilot handling evaluation was performed; however, the maneuvering capabilities of the vehicle and system were very limited.

The design studies listed in tables I and II, and depicted in the accompanying figures, illustrate the many possible approaches which can be taken to integrate a pressure-suited man with any of several different propulsion, control, and landing systems. The overall objective of the current Langley studies is to explore these various approaches using test-bed equipment which are representative of the various design concepts and whose systems can be readily modified in an attempt to identify characteristic handling qualities of each type. Of course, subsequent efforts can be directed toward refining our knowledge of those system approaches which appear most promising. Those Langley studies related to the differing design approaches are listed in the final column of table I and are described in the following discussion.

PROJECT ICARUS

The current Langley study of the backpack propulsion unit, which probably represents the minimum-sized flying system, that can be used for lunar locomotion was initiated with the in-house design and construction of the experimental hardware (depicted in fig. 8) about 2 years ago. This project, nicknamed "ICARUS" (after the mythical minimum flying system that suffered system deficiencies due to the lack of updated technical information) was based in part on the earlier design studies carried out by Bell Aerosystems for the Langley Research Center and discussed in reference 3, as well as on their experience with the flying belt system which had been developed with funds from the Army.

Exploratory studies of man's self-locomotive capabilities in lunar gravity using the Lunar Walking Simulator at Langley, revealed that loads up to 500 earth pounds could be carried on the back with relative ease (ref. 14); consequently, a target weight somewhat below this value was selected. The completed unit, which includes a built-in life-support system for the pressure-suited subject, weights about 300 pounds with 110 pounds of hydrogen peroxide for a maximum flight time of about 3 minutes. Existing off-the-shelf hardware was used inasmuch as this experimental unit was not intended as a finalized space-qualified system. The unit consists of two main hydrogen peroxide fuel tanks and two nitrogen pressurizing tanks which feed two independently controlled thrusters, each mounted on the end of an arm pivoted near the pilot's shoulder. The thrust level and direction of each thruster are controlled by motions of the arm and hand adjacent to each thruster. The manually operated controls are readily adjustable through a range of linkage settings giving the pilot a selection of control sensitivities.

This project is divided into two phases, the first of which involves flight attempts with three-degrees-of-freedom motion in the pitch plane only, as provided by the previously mentioned Lunar Walking Simulator (LWS). A photograph showing the installation of the test unit on the back of the test subject suspended in the LWS is shown in figure 9. The subject and propulsion unit are supported by separate cables attached to two lightweight trolleys free to roll along an overhead track that is parallel to the 200-foot-long walkway on which the test subject is standing. The walkway is displaced from directly beneath the overhead track so that the cables are at approximately 9.5^{o} from the vertical. In this manner the component of the weight of the subject and his flying unit equal to their equivalent lunar weight is acting in the plane of motion so as to simulate lunar gravity. The subject with his flying unit is free to rotate in pitch but is restrained in roll and yaw and, also, he is free to travel 200 feet in his fore-and-aft direction and 30 feet in his up-and-down direction. For the initial flight attempts, tether cables are attached to the flying unit and are handled by ground crewmen who keep the cables slack except in the case of an emergency.

The specific objectives of phase I are: (1) to evaluate the feasibility of the new flight technique involving the inclined-plane lunar gravity simulator, (2) to determine if the pilot can use his legs effectively to replace a structural landing gear that would otherwise be required, and (3) to evaluate pilot handling qualities in this flying mode of limited degrees of freedom for both "shirt-sleeve" and pressure-suited conditions. Several test sessions have been completed and the initial results indicate that the technique is feasibile and that the pilot can use his legs, at least in the "shirt-sleeve" conditions, quite effectively to absorb the landing impacts.

The second phase of the ICARUS project will involve testing the unit with six degrees of freedom using a vertical suspension technique similar to that which had been developed for the next project to be described. The objectives of the second phase effort are: (1) to explore in depth the handling qualities of the back-mounted unit, and (2) to determine the significance of the differences between the two testing techniques.

PROJECT POGO

Project POGO, which has been already completed, is an exploratory study undertaken jointly by the Marshall Space Flight Center and the Langley Research Center, using the experimental POGO flying device provided by Bell Aerosystems and space suits provided by the Manned Spacecraft Center. A photograph of the experimental unit flown in simulated lunar gravity using the lunar landing research facility is shown in figure 10, and a complete description of this project is covered in reference 4. This stand-up unit represents a somewhat larger size vehicle than the ICARUS unit and incorporates an elementary type landing gear. All controls are manually operated. The flying unit is mounted in a gimbaled-whiffletree system attached to an overhead constant-tension unit suspended on cables from the servo-controlled traveling bridge crane of the LLRF. The gimbaled support system permits the vehicle to rotate with the three degrees of angular freedom, and the constant tension unit allows the vehicle to travel vertically over a distance of about 10 feet above the ground. A force equal to about five-sixths of the total system weight is applied to the vehicle by the constant-tension unit. Cable angle sensors attached at the top of the cables cause the bridge crane to stay directly over the rocket-powered vehicle so that the cables remain vertical at all times.

The basic vehicle was flown first in earth gravity at Bell facilities and then in simulated lunar gravity at Langley by two experienced pilot subjects. The conclusion was drawn that lunar flight with such a vehicle was feasible although a number of shortcomings with the particular design and hardware were noted. Furthermore, it was found that lunar gravity provided a generally favorable effect by slowing down all of the vehicle's responses to pilot control inputs so as to give him more "think time" while performing low altitude, near hovering maneuvers. Although use of pressurized "soft" and "hard" type space suits produced some unfavorable effects, no major problems were experienced as long as the suits were fitted properly to the pilot and the vehicle was fitted properly to the suits. Because of the exploratory nature of this project no instrumentation was provided, and no detailed studies of the handling qualities were undertaken.

PROJECT OMPRA

This project, utilizing the hardware shown in figure 11, is directed toward the study of a waist-mounted propulsion system and was developed primarily for zero gravity space applications. Downward firing thrusters have been provided, however, so that the system can be adapted to the lunar gravity application. The system utilizes clusters of cold gas thrusters operated in either on-off or proportional fashion through hand-operated electronic control systems with optional use of different types of stabilization systems. The pilot and propulsion unit are gimbal-supported from a cable system which is attached to the Rendezvous and Docking System (RDS, ref. 15) through a constant-tension unit which either fully or partially supports the suspended weights. The RDS uses cable angle sensors in the same manner as the LLRF so as to track the flying unit and keep the cable vertical. The status of this project is that the hardware, built under contract by Bell Aerosystems, is currently being installed and checked out for system performance.

PROJECT FLEEP

This fourth project involving a vehicle intended to be representative of larger flying units is currently in its preliminary design and fabrication stages at Langley. A conceptual sketch of this flying test bed is illustrated in figure 12, showing the stand-up version used to study the balance reflex (kinesthetic) as well as other control system concepts. It is anticipated that the unit will be convertible to a sit-down version for evaluation of the other possible configurations. The unit will be tested using the LLRF to achieve six degrees of freedom within a flight envelope of about 360 feet long, 42 feet wide, and 150 feet high. A special servo-controlled vertical cable system to support five-sixths of this approximately 1300-pound unit will be attached to the bridge system which normally operates with a 12 000-pound vehicle.

Special attention to the problem of lunar-gravity simulation is required for the case of the kinesthetic control configuration because for this control concept the body weight is shifted to produce the desired control moments for the pitch and roll axes. The weight of the pilot must, therefore, be reduced to his equivalent lunar weight in order that the resulting control moments produced by shifting his body relative to the thrust vector will be of the proper magnitude. Consequently, five-sixths of the pilot's weight must be suspended independent of the vehicle. Various schemes for achieving this unusual requirement are currently being evaluated so as to find an arrangement that will have a minimum interference with the pilot and the flying unit. Flight testing of this unit is expected to be underway in about 1 year. The objectives of this project are, of course, essentially the same as those of the previous projects.

LUNAR LANDING RESEARCH VEHICLES

Although not mentioned previously in this presentation, the recent and continuing studies of the Apollo lunar landing mission using full-sized lunar landing research vehicles operating in simulated lunar gravity provide some very useful information relative to their "little brother" counterparts, inasmuch as these larger vehicles are involved in lunar "flying" while they are being landed. One of the research vehicles is the LLRV (fig. 12) which had been flown originally as a research vehicle at the Flight Research Center (ref. 16) and was more recently flown as a training vehicle at MSC until being completely demolished in the recent crash. A second type vehicle is the one continuing to be used at Langley with the LLRF (ref. 1, fig. 14). The LLRV weighed about 4000 pounds and was equipped with a pilot's compartment in a sit-down configuration, whereas the LLRF vehicle weighs about 12 000 pounds and is equipped with two interchangeable cabs; one a sit-down version (somewhat similar to the LLRV), and the other a stand-up version duplicating the flight commander's portion of the Apollo lunar module's manned compartment. Both research vehicles incorporated sophisticated control systems which had different modes of operation.

This type of vehicle, of course, will provide our first experience in actual lunar flying during the Apollo mission and, consequently, will provide the initial opportunity for correlation of simulated lunar gravity flight experience with that of actual lunar flight. It should be noted that the buildup for the Apollo mission involves cross training of the astronauts and MSC pilots in LLRV-type vehicles and the LLRF vehicle which should provide pertinent information in this correlation. A further consideration is the fact that the Langley and MSC pilots and astronauts who have gained experience in simulated lunar flying with these vehicles will be able to apply this experience to the evaluation of the smaller vehicles which are of more direct interest in this particular paper.

CONCLUDING REMARKS

Emphasis has been placed on studies of handling qualities and other piloting problems as applied to general types of lunar flying units. However, the techniques and experience developed in carrying out these particular studies should also be directly applicable to the training program for the astronauts involved in the actual lunar flying activities with the newly developed devices.

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TABLE I.- SUMMARY OF ONE MAN FLYING UNITS AND DESIGN STUDIES OF LUNAR FLYING UNITS

Pilot Stance	Point of Thrust Application	Attitude Control	Source	Prior Flying Experience	Design Studies	Current Lunar Flight Studies
Stand	Back	Manual rotation of thrust	Bell Aero.	Flying Belt. Reference 2.	———	———
			LRC-Bell	———	Reference 3	———
			LRC	———	———	ICARUS
	Chest	Manual rotation of thrust.	LRC-MSFC-Bell	Free flight. POGO Reference 5	Reference 4	POGO
	Waist	Auxiliary thrusters	Hamilton Standard	———	Reference 6	———
			LRC - Bell	———	———	OMPRA
	Floor	Pedal rotation of thrust.	LRC	Flying platforms. References 7&8	———	FLEEP
			Hiller	Airborne personnel platform Reference 9.	———	———
			Delackner	Aerocycle. Reference 10	———	———
			North American Rockwell	OMLTD test bed. Reference 11.	OMLTD Reference 11.	———
		Auxiliary thrusters.	LRC - Bell	———	Reference 3	———
			LRC	———	———	FLEEP
Sit	Back	Manual rotation of thrust.	Bell	Flying Chair	———	———
	Floor	Auxiliary thrusters.	LRC	*Simulated Lunar Flying Vehicle. Reference 12.	———	———
			LRC- Bell	———	Reference 3	———
			MSFC-Bell	———	Reference 13	———

* Simulated Lunar Gravity

TABLE II - PHYSICAL CHARACTERISTICS OF ONE MAN FLYING UNITS DEVELOPED IN VARIOUS DESIGN STUDIES.

Configuration	Waist mounted OMLS	Stand-on platform (OMLTD)		Advanced Pogo	Back-pack ΔV-4000fps	Two-man sit-down ΔV-2000 fps	One-man stand-on ΔV-8000fps	Two-man sit-down ΔV-6000 fps	Lunar Flying Vehicle	Simulated Lunar Flying Vehicle.
Source	Ham. Stand. MSC	North American Rockwell		Bell Aero. MSFC	Bell Aero. LRC	Bell Aero. LRC	Bell Aero. LRC	Bell Aero. MSFC	Bell Aero. MSFC	LRC
Type of pitch and roll control.	Differential main thrust.	Balance reflex		Manual thrust gimbal.	Manual thrust gimbal.	Auxiliary thrusters.	Balance reflex	Auxiliary thrusters.	Differential main thrust.	Auxiliary thrusters
Pilot weight, lb.	260	260	260	294	200	245	245	245	293	185
Empty weight, lb.	114	83	83	146	201	208	300	310	448	175
Fuel weight, lb.	59	150	150	273	230	170	770	740	635	———
Payload, lb.	0	0	260	100	30	245	30	245	300	———
Gross weight, lb.	433	493	753	813	636	868	1344	1540	1677	360
Thrust-to-lunar weight ratio	1.1	7.3	4.8	1.8	3.0	3.0	3.0	3.0	1.8	1.06
Pitch inertia, slug ft.^{2}	———	———	———	———	35	74	175	163	195	17
Landing gear, span, ft.	Feet	5	5	5.5	Feet	7.0	8.5	7.0	7.3	2.5
Platform height, ft.	None	1.5	1.5	1.0	None	3.2	1.0	3.5	3.5	1.0
Design range, miles	0.8	24	———	5.7	———	———	———	———	15	———
Figure number	2	3		4	5				6	7
Reference number	6	11		5	3				13	12

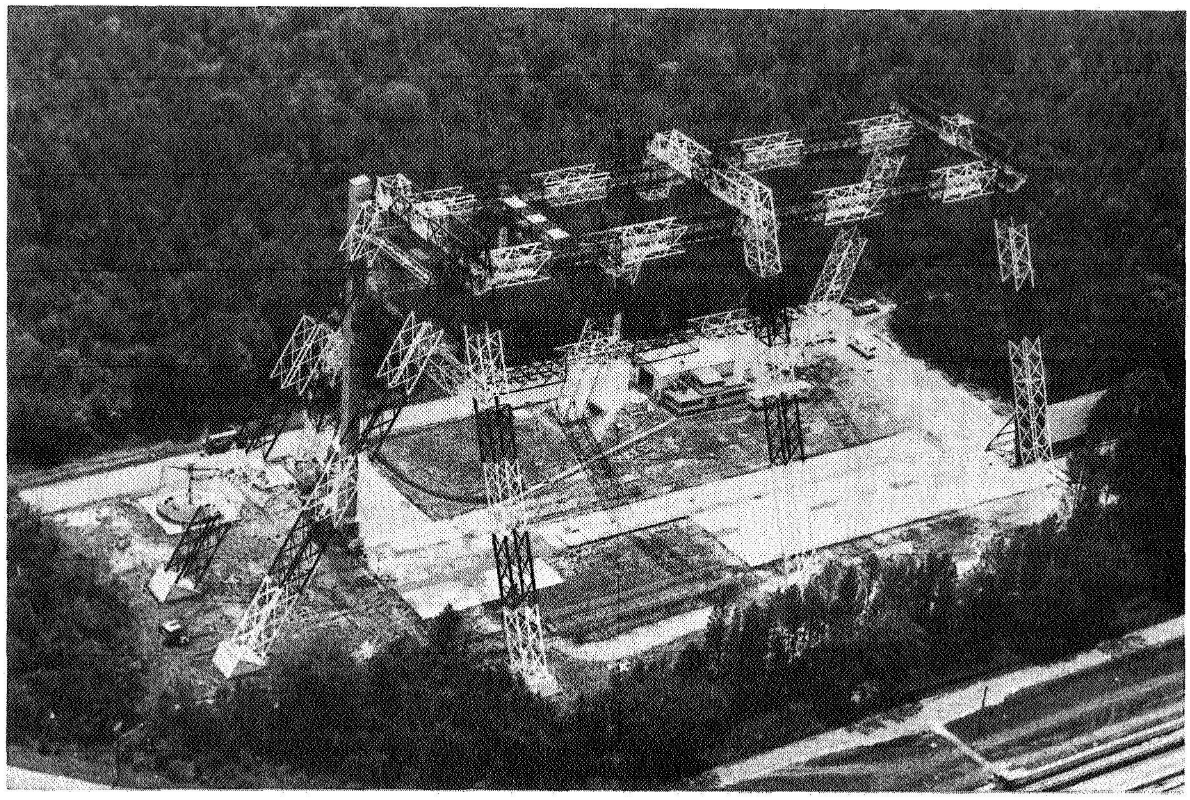

Figure 1.- Photograph of the Langley lunar landing research facility (LLRF).

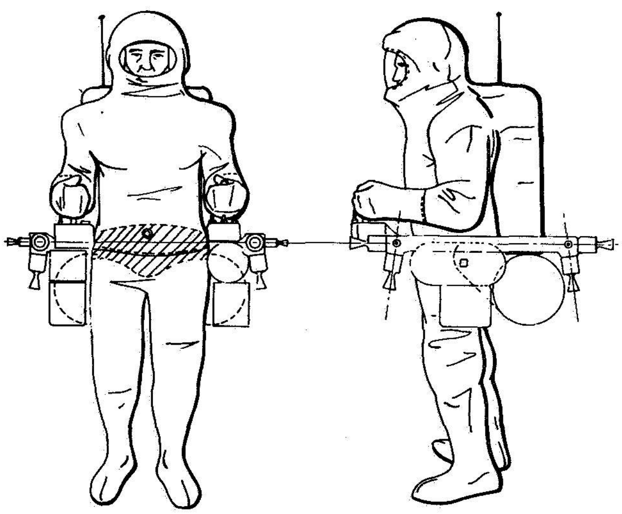

Figure 2.- Sketch of the Hamilton standard one-man location system developed for Manned Spacecraft Center (ref. 6).

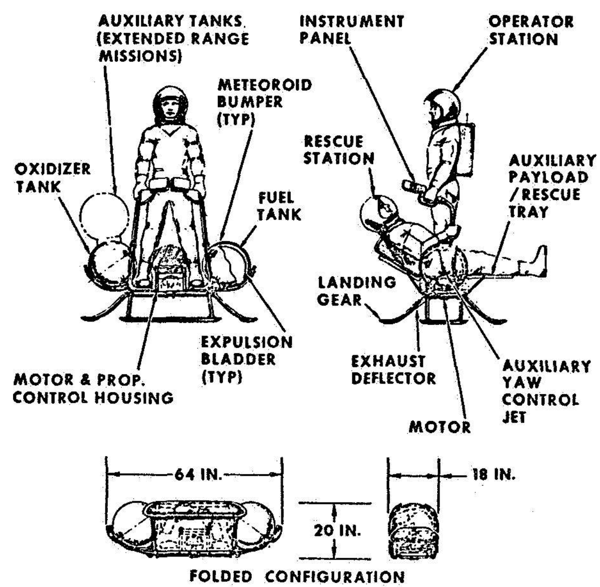

Figure 3.- Drawing of North American Rockwell's one-man lunar transportation device (ref. 11).

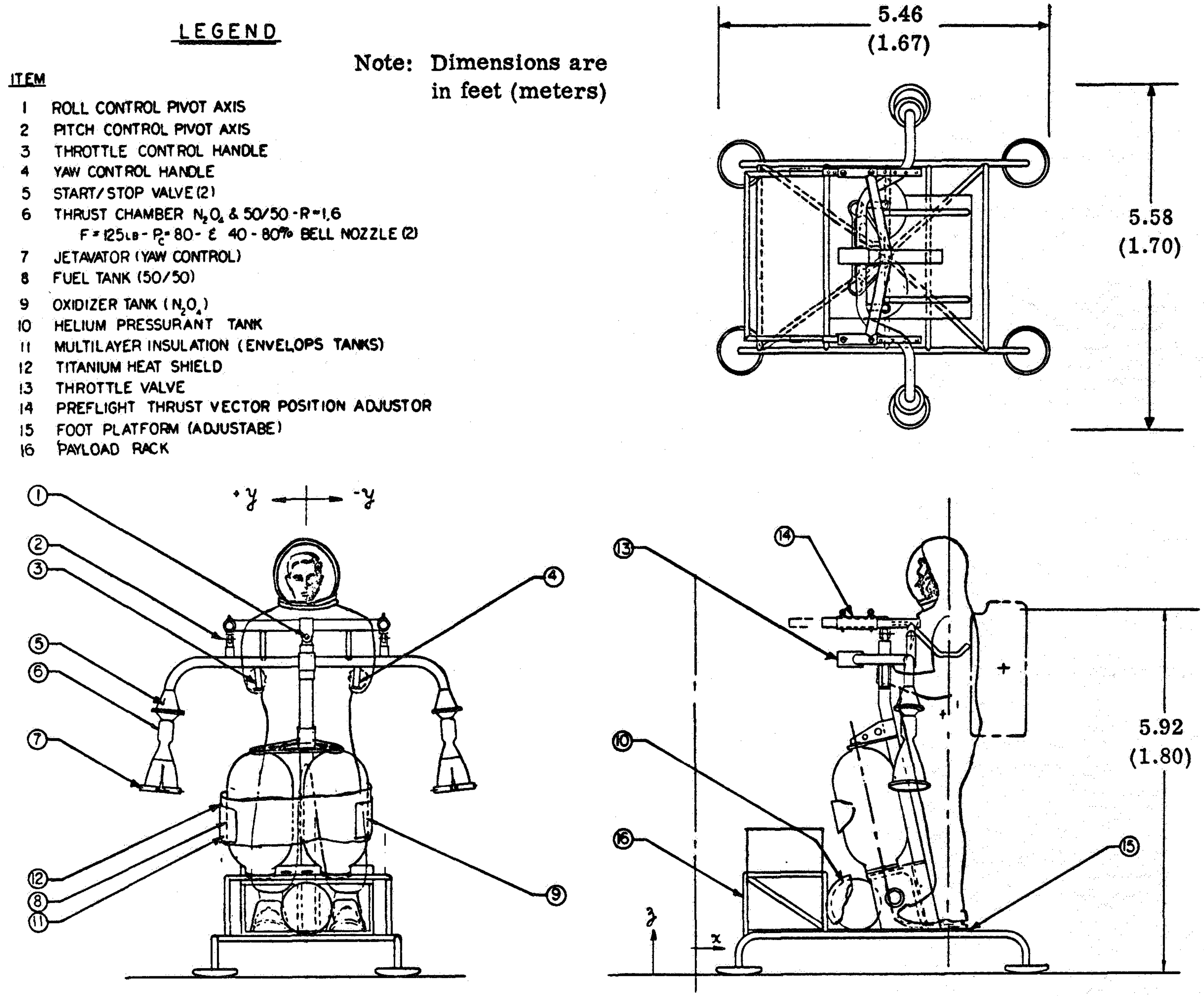

Figure 4.- Drawing of Bell Aerosystems advanced POGO based on early flying belt and original POGO experience (ref. 5).

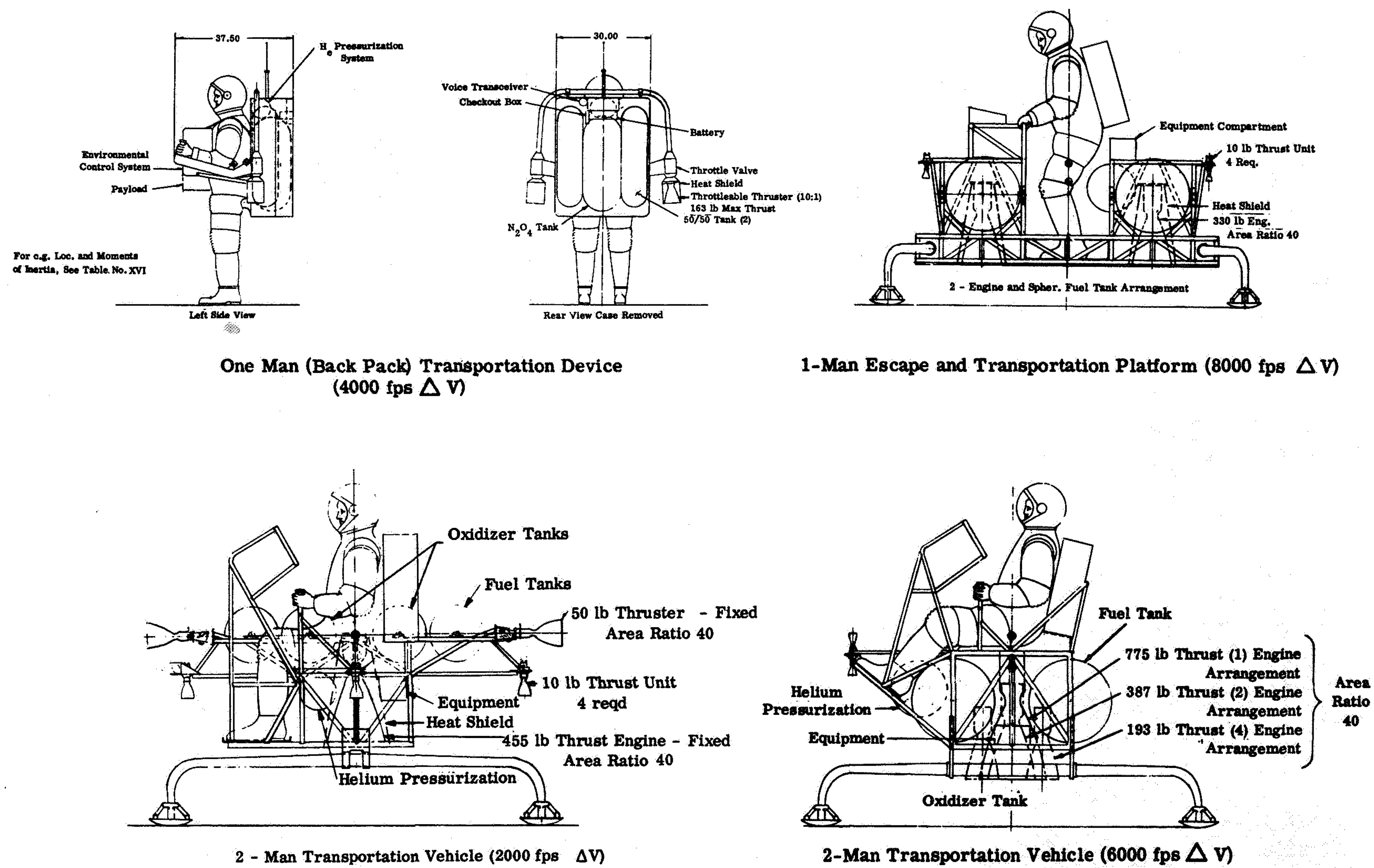

Figure 5.- Drawings of various one-two man lunar flying vehicle configurations developed in a design study by Bell Aerosystems for Langley Research Center (ref. 3).

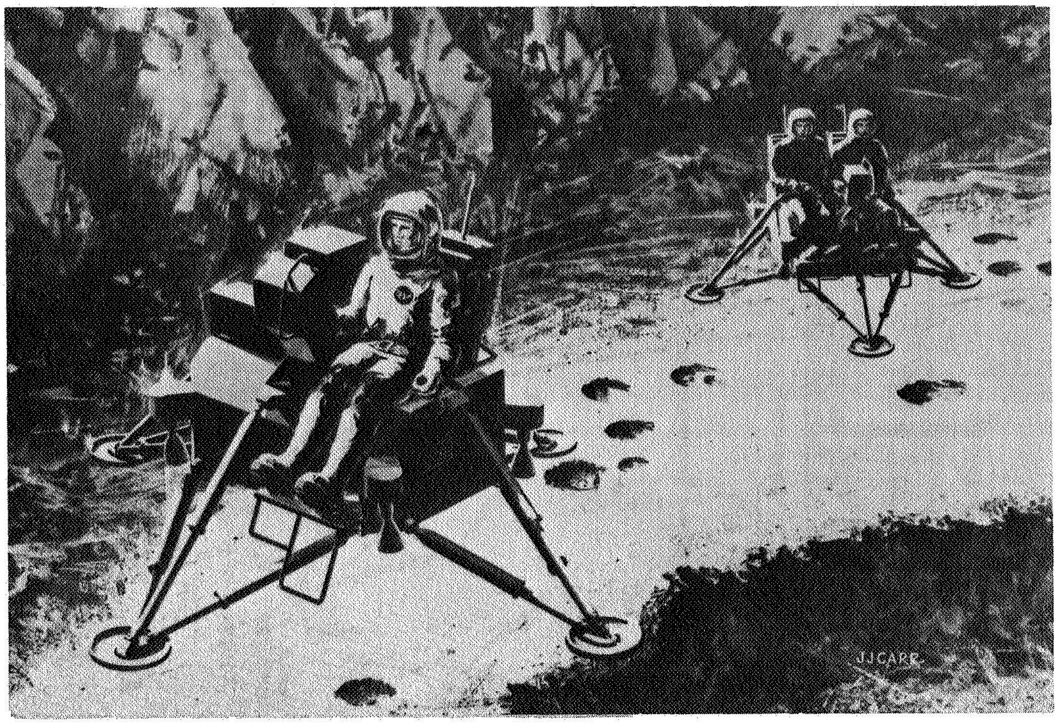

Figure 6.- Drawing of the Bell Aerosystems lunar flying vehicle "sit-down" configuration developed for Marshall Space Flight Center (ref. 13).

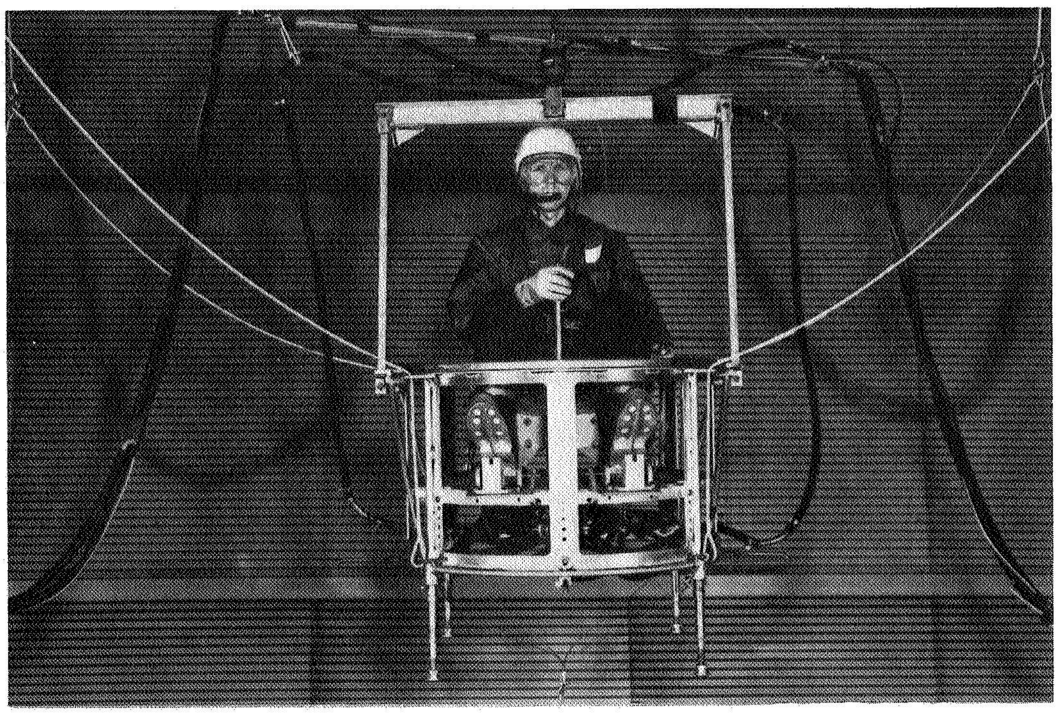

Figure 7.- Photograph of one-man test vehicle used in evaluating servo-controlled suspension system for lunar gravity simulation (ref. 12).

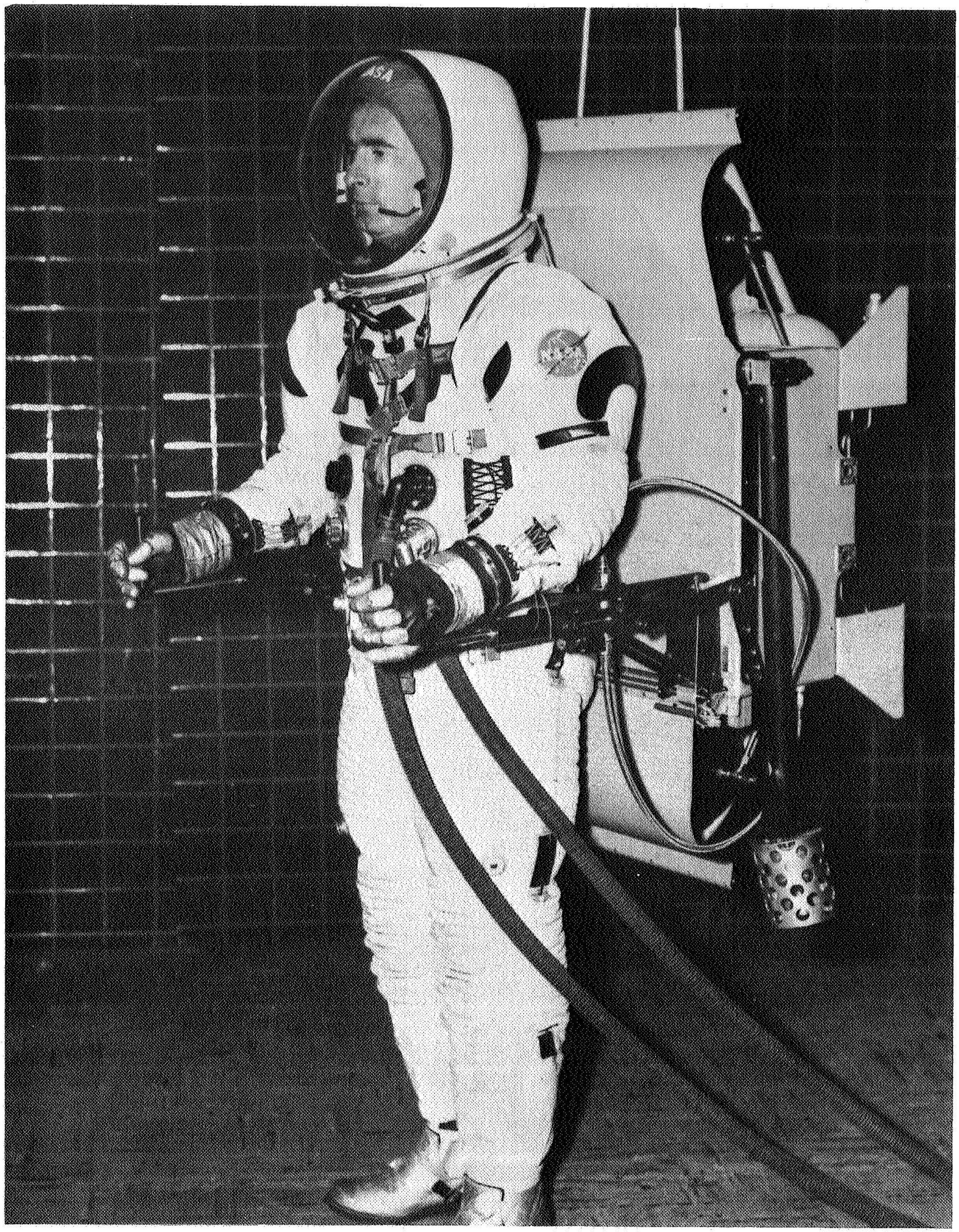

Figure 8.- Photograph of the Langley lunar flying backpack mounted on the research pilot wearing a pressurized space suit. During test flights a personnel life support system will be housed within the backpack assembly.

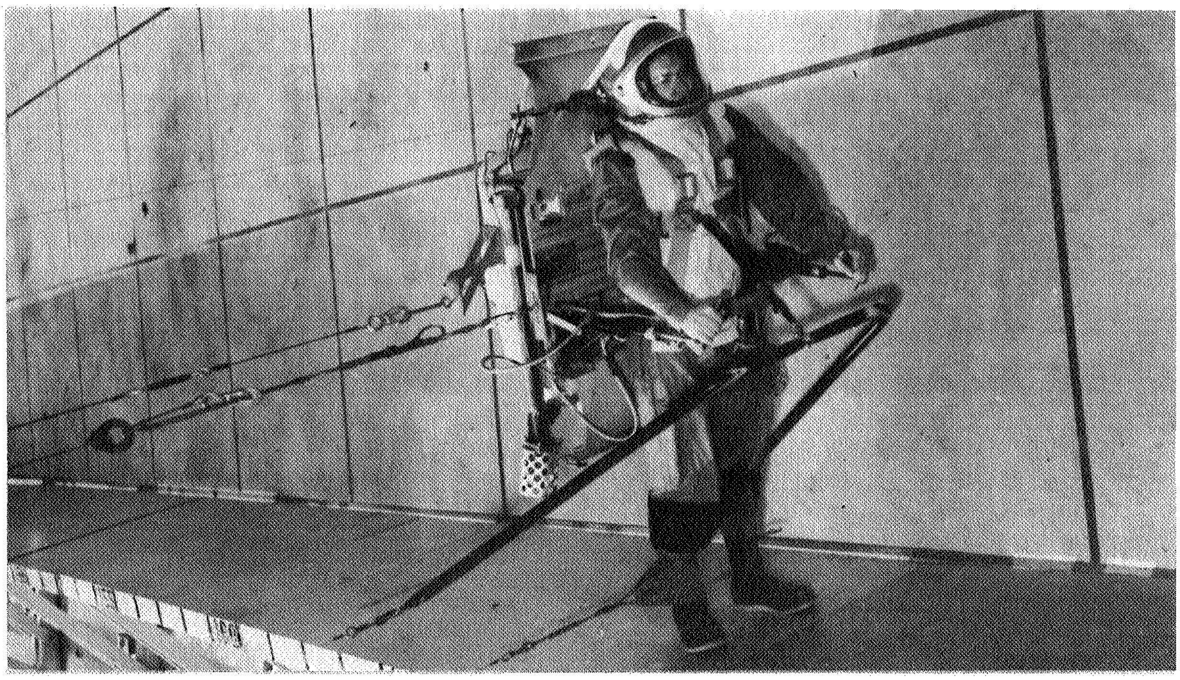

Figure 9.- Photograph of ICARUS flying unit and subject mounted in the Langley lunar walking simulator. The subject is shown in the "shirt-sleeve" condition.

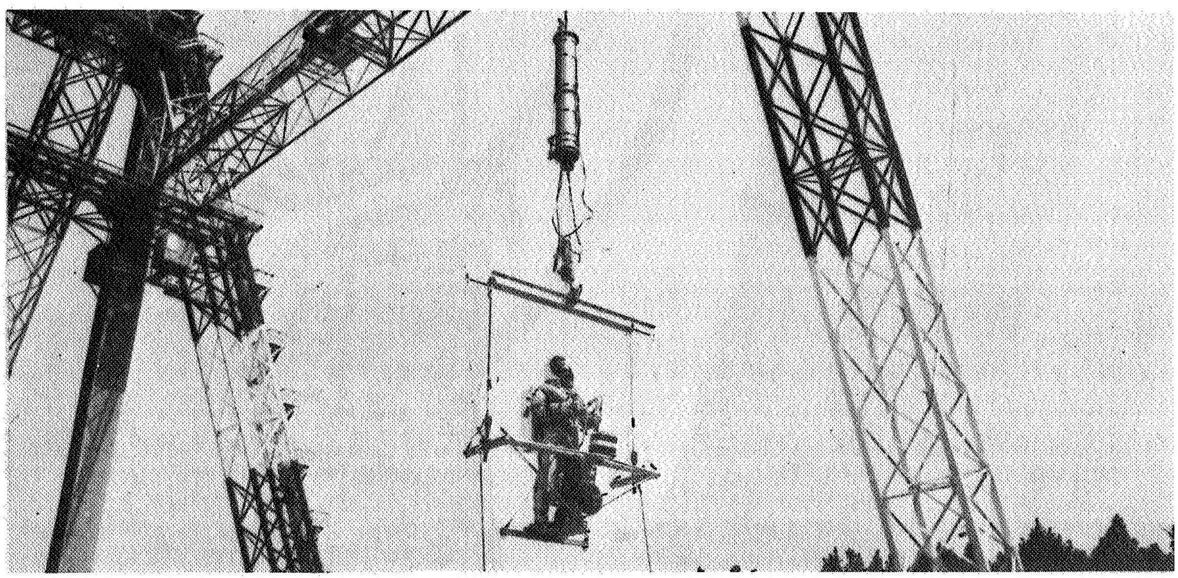

Figure 10.- Photograph of the Bell Aerosystems "POGO" lunar flying research vehicle as tested at the Langley lunar landing research facility. The operator is wearing a pressurized space suit and life support backpack. Vehicle is partially supported by the whiffletree attached to the overhead constant tension unit (ref. 4).

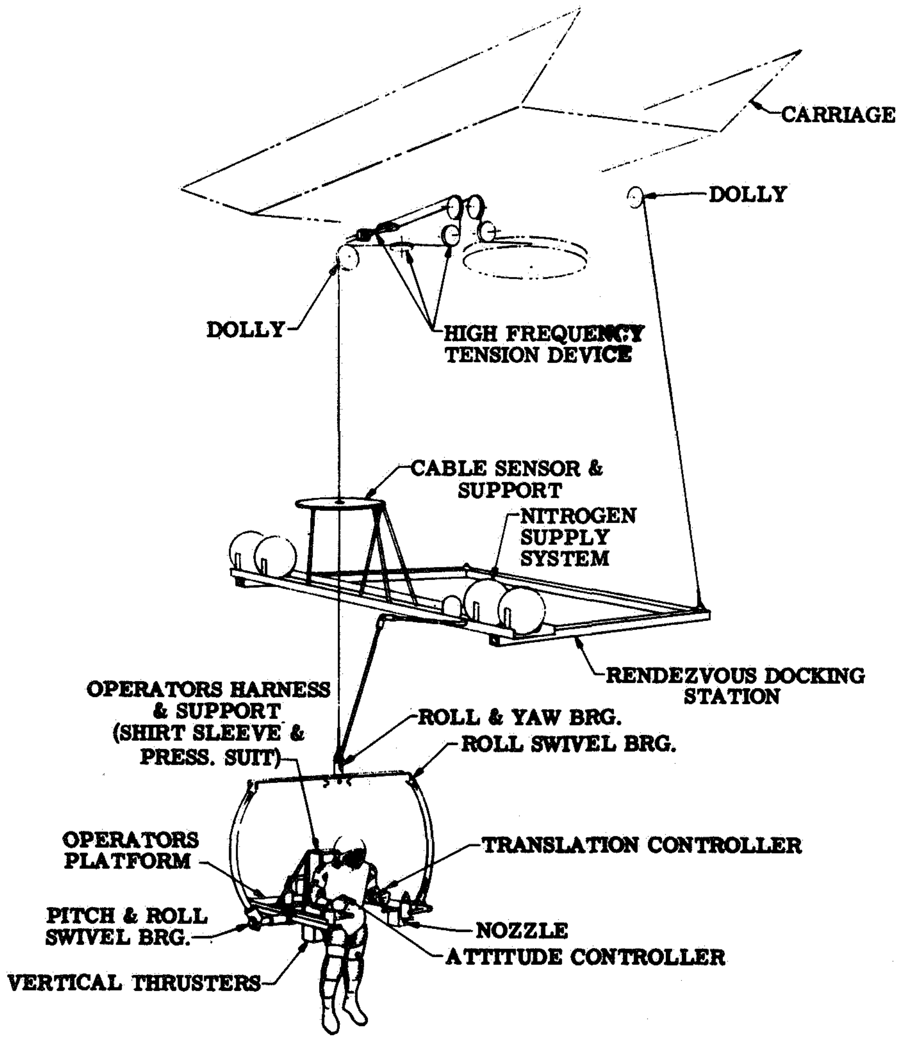

Figure 11.- Sketch of the general arrangement of the OMPRA flying unit suspended from the Langley rendezvous and docking simulator (RDS).

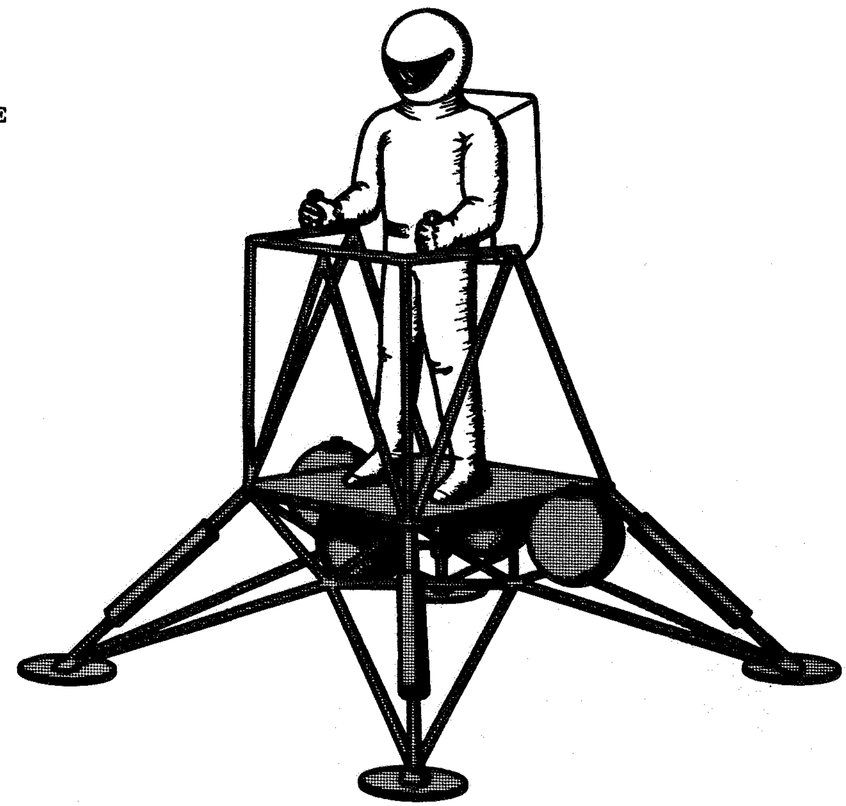

Figure 12.- Sketch of proposed "stand-on" configuration for the one-man lunar flying research vehicle.

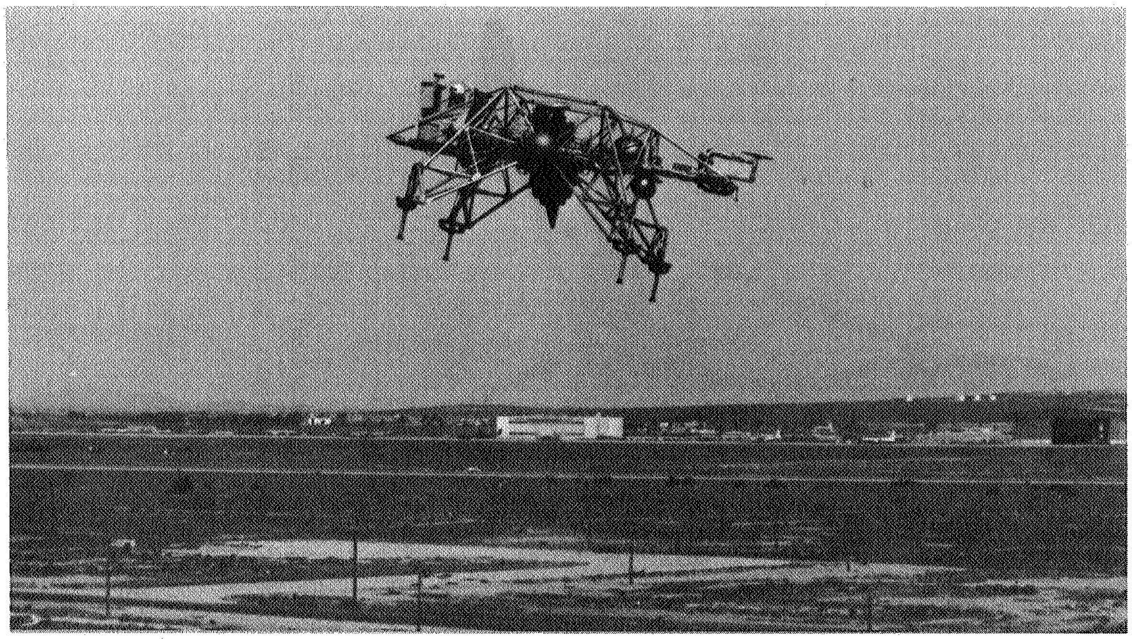

Figure 13.- Photograph of the lunar landing research vehicle (LLRV) flying at Flight Research Center.

Figure 14.- Photograph of the Langley lunar landing research facility showing the research vehicle with a "stand-up" pilot's compartment in the flying attitude. The pilot's compartment simulates many of the features of the Apollo lunar module.

NASA-Langley, 1968