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OFF-ROAD LOCOMOTION ON THE MOON AND ON EARTH*

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ALMOST two decades ago Gabrielli and von Kármán discovered an impenetrable borderline which limits the speed and specific power of vehicles for land, sea and air [1].

In work published shortly thereafter, I tried to show similar, though less immediate, limitations with reference to vehicular concepts prevailing in off-the-road locomotion [2, 3]. I have since felt that Gabrielli and von Kármán's paper was a timely reminder of the inevitability of 'diminishing returns' which attenuate evolution of present ground transport—a reminder that the problem is one of concept rather than engineering.

This feeling was not really new. I think that Morin [4], Bernstein [5], Letoshnev and his colleagues [6], Swiezawski [7], Garbari [8] and Micklethwait [9] felt the same way a long time ago, when they embarked on an evaluation of the concept of a wheel and track rather than on technological improvement of hardware.

It seems to be certain, however, that the need for a conceptual generalization of ground locomotion solutions was never more spectacular than approximately five years ago, when we first were confronted with the question of lunar surface locomotion. Until then there had been no requirements—only general expectations of things to come. Educated guesses dwelled on exotic modes of locomotion, and at the 1961 Meeting of the American Rocket Society, held in New York, one could only marvel at science-fiction-like models of lunar surface vehicles that walk, jump and crawl.

When mission and operations requirements became known, I had the opportunity to analyze the problem in a more rigorous manner and propose solutions which, perhaps unexpectedly, led to the conclusion that on the moon a wheeled vehicle is the most plausible [10, 11], in spite of all the uncertainties involved in the physical and geometrical properties of the surface.

The method which led to this conclusion was reported in depth at the First International Conference on the Mechanics of Terrain–Vehicle Systems, held at Turin-Saint Vincent in June 1961, under the auspices of the Politecnico di Torino and the Italian and American Armies [12]. Although four years have since elapsed, the method still appears to serve successfully the needs of both the National

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Aeronautics and Space Administration and American automobile and aerospace industries. This may justify a discussion of some of the latest developments and their possible significance.

Among events which have affected surface locomotion progress since 1960, exposure of extra-terrestrial problems to the automotive and aerospace industries has, in my opinion, had the most far-reaching effect. Not only have these industries shown how the existing concepts of the mechanics of off-road locomotion [2, 3] can be used in a selection of optimum terrain vehicle systems for extra-terrestrial mission objectives, they also have introduced computerized techniques for optimizing systems from engineering, operational, and mission viewpoints [13–22]. This amounted to superseding the qualitative and purely empirical methods of mobility evaluation which cannot be programmed for a parametric analysis.

As a consequence, I believe, similar methods will be gradually expanded in numerous applications on this planet. Progress is slow, however, because numerical input data concerned with terrestrial locomotion are scarce, and the mathematical models for predicting performance and design parameters are not always accurate. Although this statement may seem incompatible with the previously mentioned value of the method for evaluating locomotion on the lunar surface where knowledge of mechanical properties of soil is, to a large extent, conjectural, the paradox can be explained easily.

When selecting a solution among a large number of possible solutions with the given constraints of lunar locomotion, we were interested in a comparative rather than a determinative evaluation. To this end, a common denominator and a number of yardsticks were needed for assumed environmental and operational input. The arrived-at order of merit of differing systems was thus not necessarily an absolute one. It told, however, which was better and which was worse; its validity depended only on the practicality of the basic assumptions, on which the mathematical models for predicting design and performance were based, and on the band width of the assumed environmental data.

The practicality of equations available for evaluating terrain–vehicle systems on earth has been demonstrated repeatedly in both field and laboratory during the past decade [12]. On the other hand, we could plausibly assume a restricted range of lunar soil properties by eliminating 'soils', like swamps, organic–mineralogical mixtures, or snow, which do not exist on the moon, and including some exotic ones, which do not exist on earth. The methods thus arrived at have had a general applicability providing performance yardsticks for relative terrain–vehicle evaluation for any planet.

This, I believe, is the principal merit of the methods used in the evaluation of lunar surface locomotion. The fact that they do not necessarily yield absolute values proved to be of less significance, for what was, and is, primarily needed is the comparative evaluation of locomotion systems, and this can be accomplished within the 'state of the art'. If and when the methods of analysis are perfected then, and only then, will the more complete evaluation of the systems on an absolute rather than relative basis be fully attainable.

Even when the methods of analysis are perfect, however, the determinacy of prediction will never be complete, for the reason that optimum performance and design parameters depend on engineering, environment, mission, and operational constraints, and even though some of the pertinent data are fixed by the best 'know-how' in technology (engine power–weight ratio, efficiency of power transfer, etc.), other data, which are related to environment and operations, are statistical in nature (i.e. are expressable only in terms of probability, or in cost-effectiveness numbers based on the assumed probability distributions of the input data) [23].

Problems like this have been abundant in lunar surface locomotion, prompting the development of a new trend toward a better understanding and definition of terrain–vehicle system analysis, as based on the available notions of the mechanics of locomotion. Out of this will emerge, I hope, a much clearer picture of the critical areas and what improvements will make the mathematical models of terrain–vehicle relationships more accurate. Naturally, before better tools are developed, we urgently need to use those that are already available. This I have outlined, in more detail, in Ref. [24].

The impact which space requirements have had upon the development of techniques for ground mobility study is not limited to research strategy or to the general implications discussed in the preceding paragraphs. Specific developments in engineering have emerged.

To present these in wider perspective, I should mention the classical, but little known work by Neesen [25] who wrote, in 1940, about the architecture and economy of air, sea, and land vehicles, developing, in my opinion, the first approach to modern system and cost analysis. Neesen has shown that vehicle form is essential to its performance; the same conclusion could be drawn from the study by Gabrielli and von Kármán. This led me to believe that a morphological change of ground vehicles may offer more promise than improvements in materials, components, and processes.

It was a long time ago that I noticed the irrationality of form of conventional tracked vehicles [26] and called attention to Diplock's 1917 patent, a two-unit vehicle steered through articulation of the joint. Not until 1950, however, did my search for improved vehicle forms reveal great promise, in what I call the 'train concept' [2, 3, 27]; this soon was followed by a proliferation of types of multi-unit 'articulated' vehicles [28, 29].

Nevertheless, articulated vehicles developed for use on this planet have been limited by the traditional size–form configuration of individual units, and by the conventionality of joint design (Fig. 1). Although I tried to overcome the latter, in 1951, by designing a novel two-hinge joint [30], not until the advent of lunar surface locomotion was the full potential of articulated vehicles, both tracked and wheeled, fully understood by me.

Two of the problems we faced in lunar surface locomotion were: the impossibility of obtaining maximum mobility in soft ground and crossing obstacles with conventional ground vehicles, both created by restricted volume of stowage in the space ship which will transport the vehicle to the moon.

Analysis has shown that an articulated, six-wheeled vehicle is, perhaps, the best answer to the mobility problem [10, 11]. The question of the joint between units remained unresolved, however, not only because of volume limitations of the space ship, but also because the lunar environment defies the maintenance of conventional joints with rubbing surfaces.

Fortunately, the design of lunar roving vehicles has not been restricted by require-

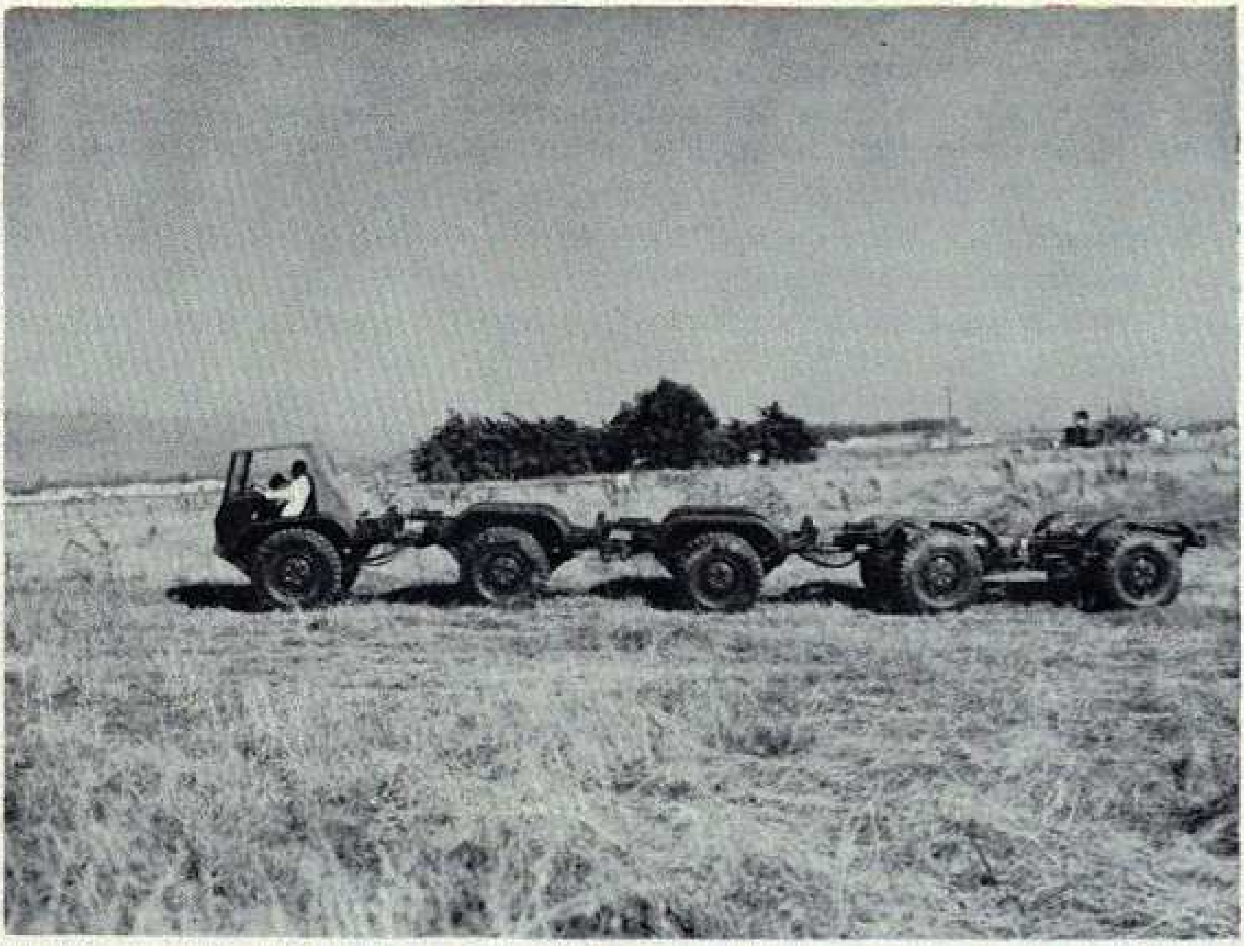

FIG. 1. Experimental model of a 5 unit articulated vehicle by General Motors Defense Research Laboratories. Each unit powered by an individual powerplant, and connected with a Cardan type joint which was stabilized with a helical spring.

ments which must be satisfied on our planet. This enabled me to introduce a flexible joint which consists of a series of elastic rods, or flat springs, between the axles (Fig. 2).

The flexible joint has provided much more freedom of motion and load distribution than the conventional joint, thus increasing beyond the standards of conventional vehicles the ability of the articulated vehicle to cross soft ground and obstacles (Fig. 3).

The studies have shown also that one rigid link between two axles does not much impair performance, as long as the third axle is linked by the elastic joint (Fig. 4). In addition, an elastic joint can be deformed to fit the vehicle into space on the carrier. Figure 5 shows a small, unmanned lunar vehicle, folded and mounted on the carrier frame, in this manner.

The study of lunar locomotion has thus shown that elastic-joint articulated vehicles or, as I call them, elastic-frame vehicles, present a new promise of higher mobility and versatility in adapting to new tasks.

Since the 'train concept' appears to offer a radical improvement in mobility, the elastic-frame articulated vehicle has acquired new significance in off-road locomotion, not only on the moon, but also on earth [28, 29].

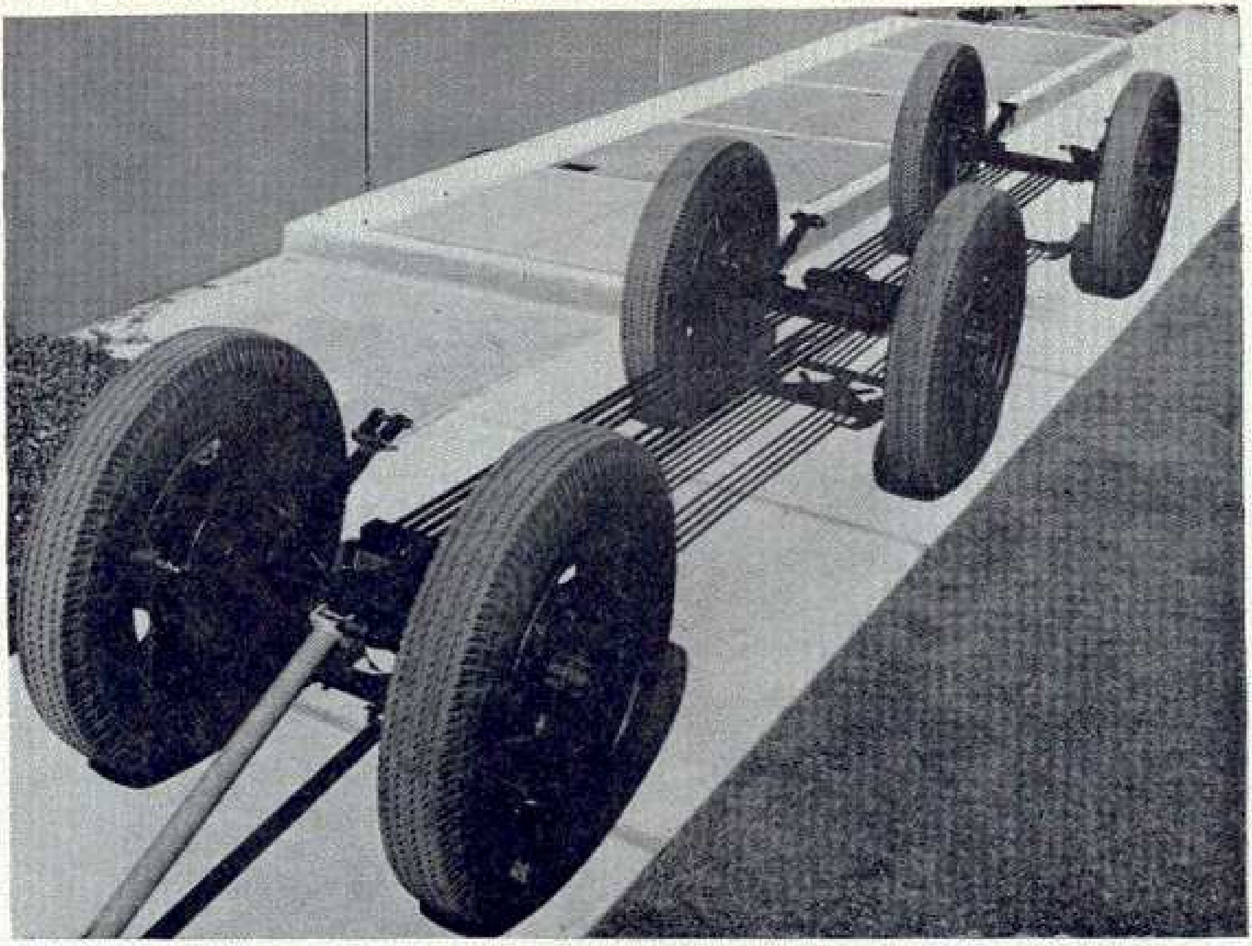

FIG. 2. Flexible joints connecting the axles of a three unit articulated vehicle; the joints form an 'elastic frame'.

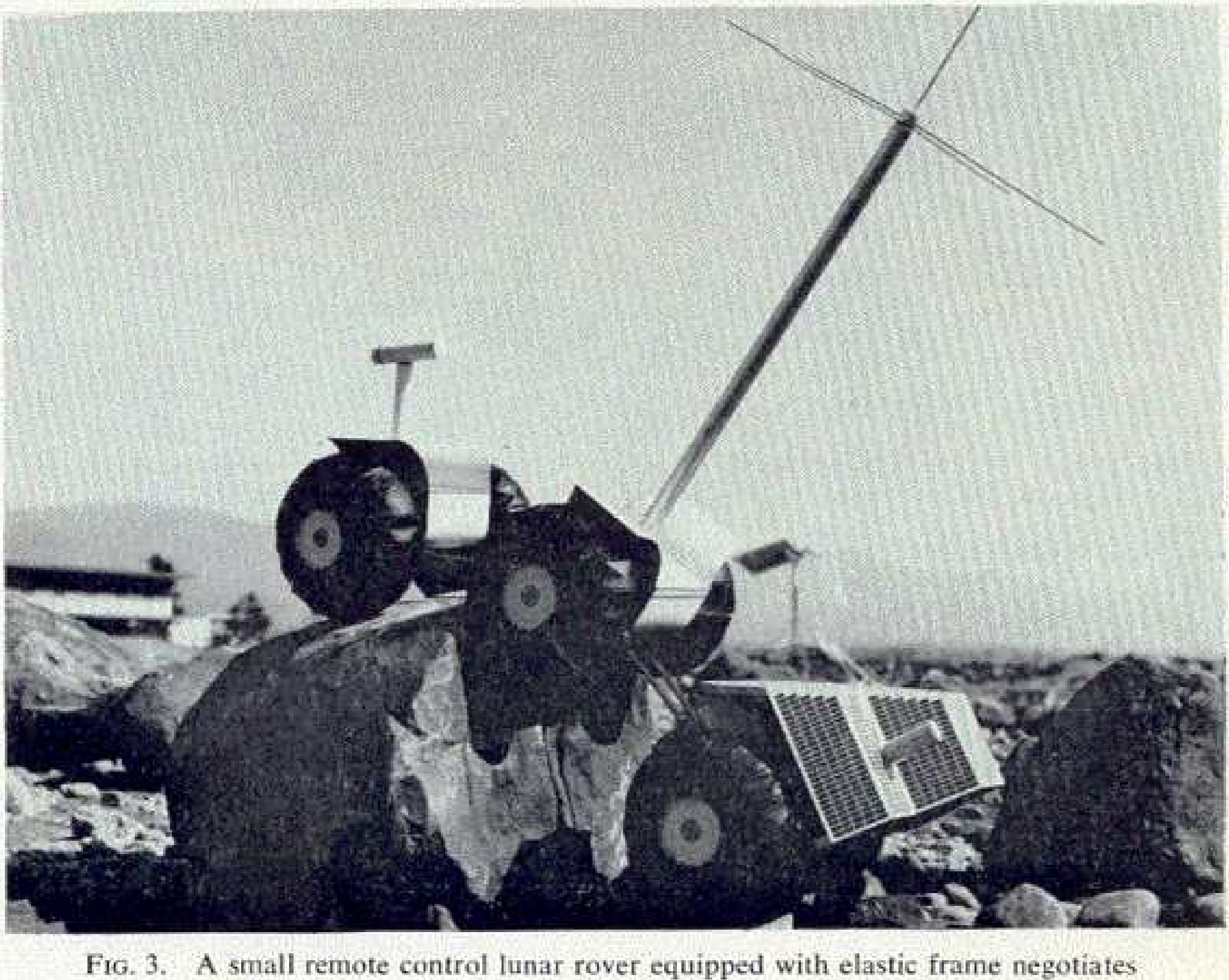

FIG. 3. A small remote control lunar rover equipped with elastic frame negotiates an obstacle.

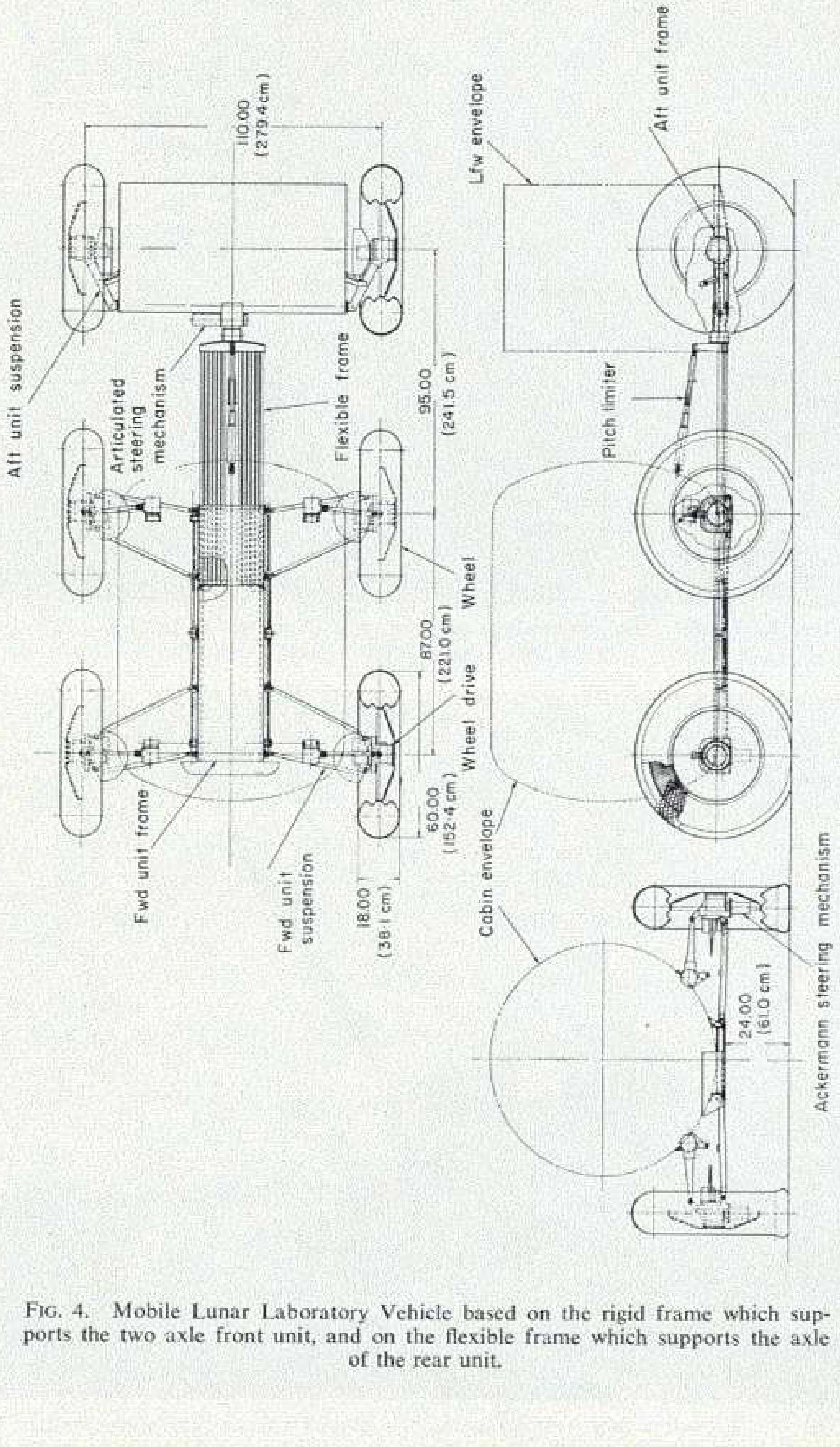

FIG. 4. Mobile Lunar Laboratory Vehicle based on the rigid frame which supports the two axle front unit, and on the flexible frame which supports the axle of the rear unit.

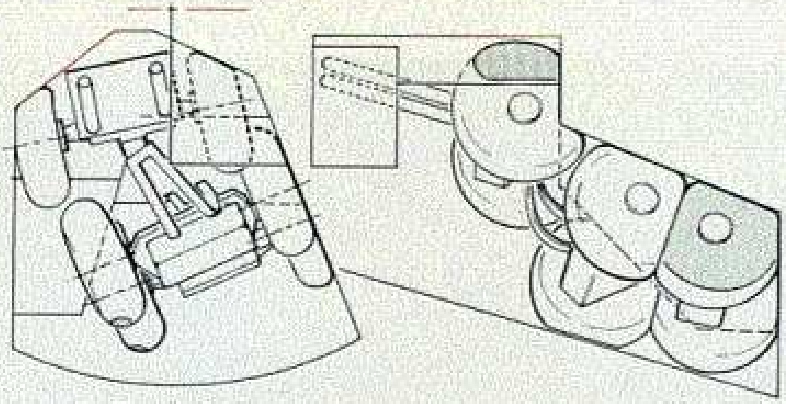

FIG. 5. The small unmanned lunar rover stowed in the available space of the carrier. Note the folded elastic frame and collapsed wheels.

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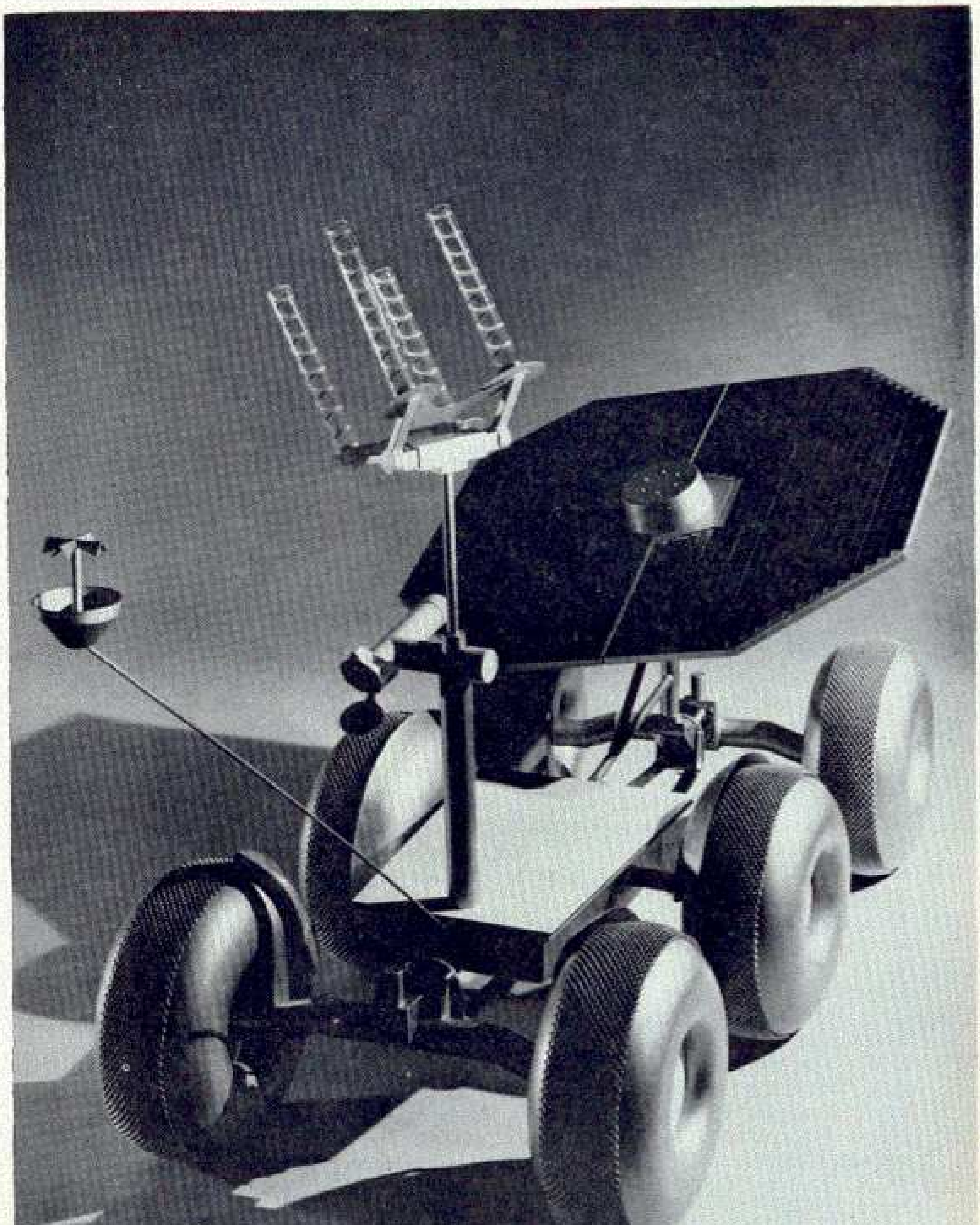

FIG. 6. Unmanned lunar rover for exploration of the surface of the moon.

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