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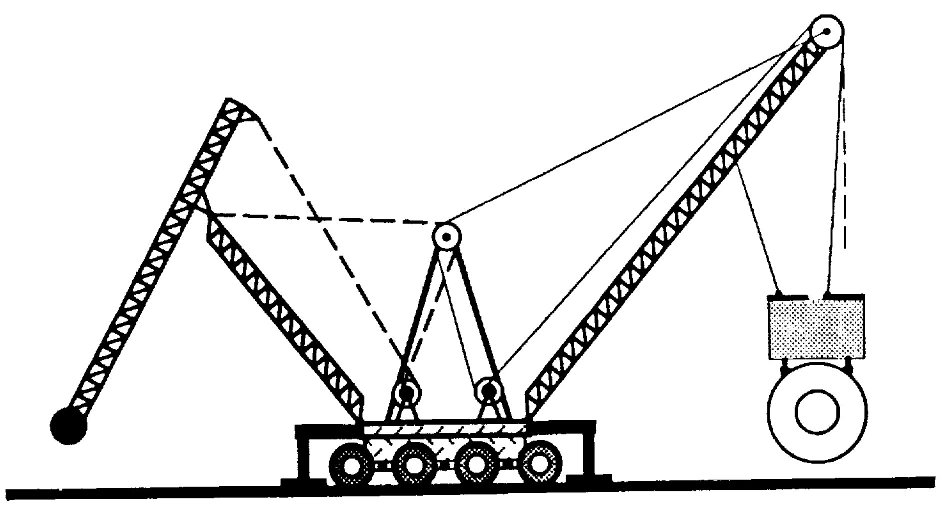

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CONCEPTUAL DESIGN OF A MULTIPLE CABLE CRANE FOR PLANETARY SURFACE OPERATIONS

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INTRODUCTION

Future Lunar Base or Mars Base missions will likely involve off-loading large massive modules from a landing site and moving them to designated areas for construction into an operational base. Because of the remoteness of the bases there will be very little if any involvement of astronauts in these operations. Thus the machinery for conducting these operations must be capable of highly stable and automated operations. In reference 1 a crane concept is presented for automated and precision operations in the zero gravitational field of space. For a zero-g environment an efficient crane takes the form of a long slender beam. In the presence of a gravitational field such as on the surface of a planet there is a large steady static load component for which the crane must be designed to carry in an efficient fashion. The most efficient structural form for carrying large steady loads is a set of tension members and compression members configured to hold the load with the lowest possible load in each member. In earth based construction operations, large cranes with a single vertical support cable are commonly used and the design methodology for such cranes is well documented (see reference 2). With such a crane, only a single degree of freedom is positively controlled. The other 5 payload degrees-of-freedom are precision positioned by several workers holding onto the payload with guy lines. In reference 3 a study is conducted of a large crane suitable for automated operations in the heavy construction industry and in the ship building industry. The particular crane concept presented in reference 3 has 6 cables attached to the payload so that all 6 degrees-of-freedom can be positively controlled much like the Stewart platform of reference 4. Although a 6 cable crane does provide positive control for all degrees-of-freedom, it also requires that all 6 cables be controlled.

In this paper an alternate crane concept with 3 cables is presented. For the three cable crane, 3 degrees-of-freedom are positively controlled while the other three derive their stiffness from the nonlinear stiffness of the cable crane system. To provide a basic insight into the behavior of such a crane, a 2-D version of the crane with only two cables was analyzed. An exact solution was obtained for the lowest natural frequency of the system, and results are presented in parametric form to demonstrate dynamic characteristics of the multiple cable suspension system.

FIGURE 1

The two major type of cranes used for earth applications are shown in figure 1. The mobile crane is used in the majority of construction projects because of their mobility and versatility. On the other hand, stationary cranes are used for very high-rise applications or other applications which have sufficient localized operations to justify a fixed, dedicated crane. In the present paper it is assumed that Lunar or Mars construction operations will be of a varied enough nature that a mobile crane will be required. However, the cable suspension system considered in this paper could readily be adapted to a stationary tower type crane.

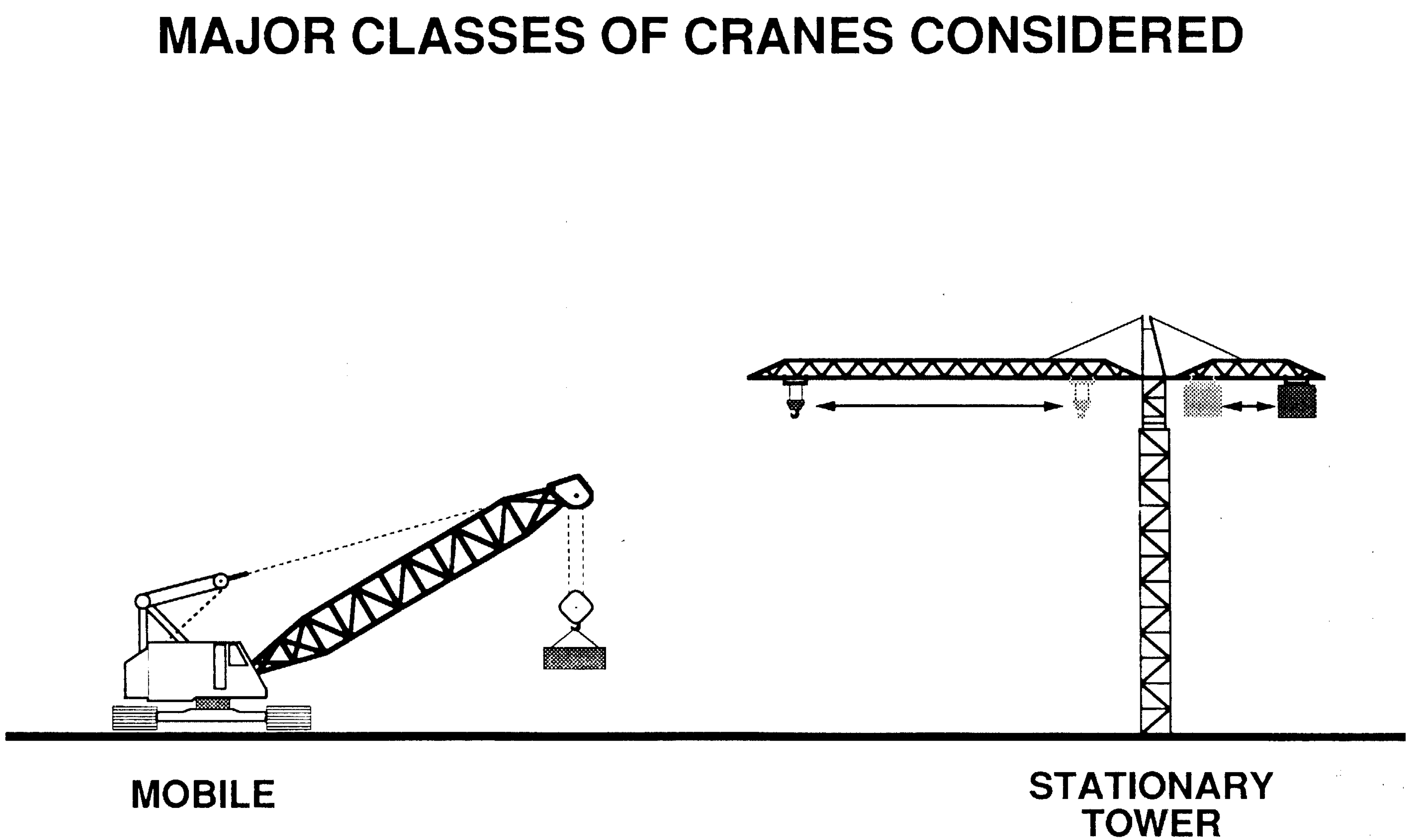
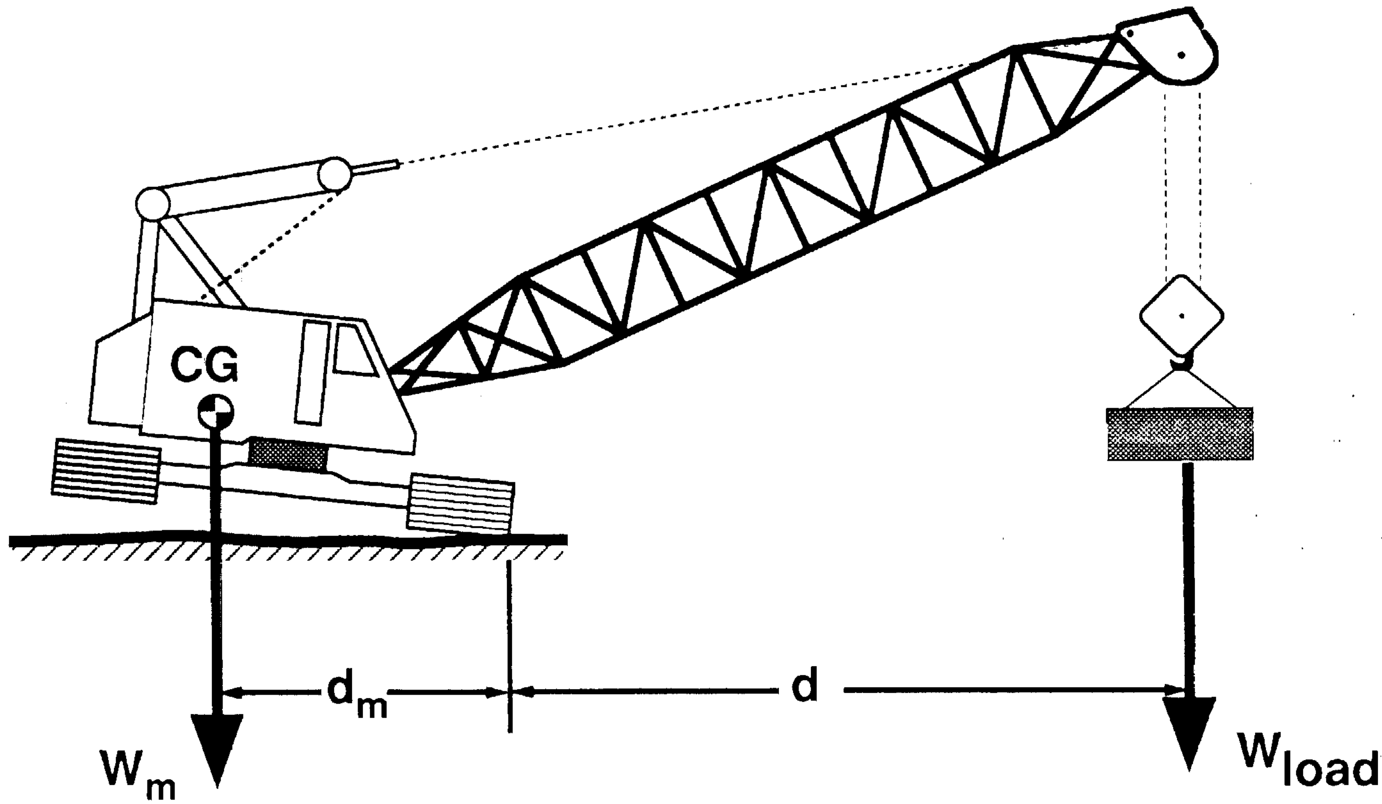


Figure 1.- Two major classes of cranes considered in design study.

FIGURE 2

The major design consideration for a mobile crane is the weight required to offset the overturning moment generated by picking up the payload as indicated in figure 2. The equation governing the machine weight Wm required to pick up a payload weight Wload at a distance d from the crane outermost fulcrum point is shown in the lower left of the figure. A cursory study of typical earth cranes revealed that the ratio of payload operational distance d to machine c.g. to fulcrum distance dm is typically on the order of 3 or 4 to 1. The numerical example in the lower right hand of figure 2 shows that a crane designed to lift a payload of 60,000 lb with a machine d/dm ratio of 4 would weigh 240,000 lb. Such machine weight to payload weight ratios are practical for earth applications where machine weight is not a major cost factor. For planetary missions where launch costs are a major portion of the mission costs, crane weight to payload weight ratios must be reduced to the absolute minimum possible.

MOBILE CRANE MAJOR DESIGN CONSIDERATION IS MASS REQUIRED TO OFFSET OVERTURNING MOMENT



$$W_m \times d_m = W_{load} \times d$$

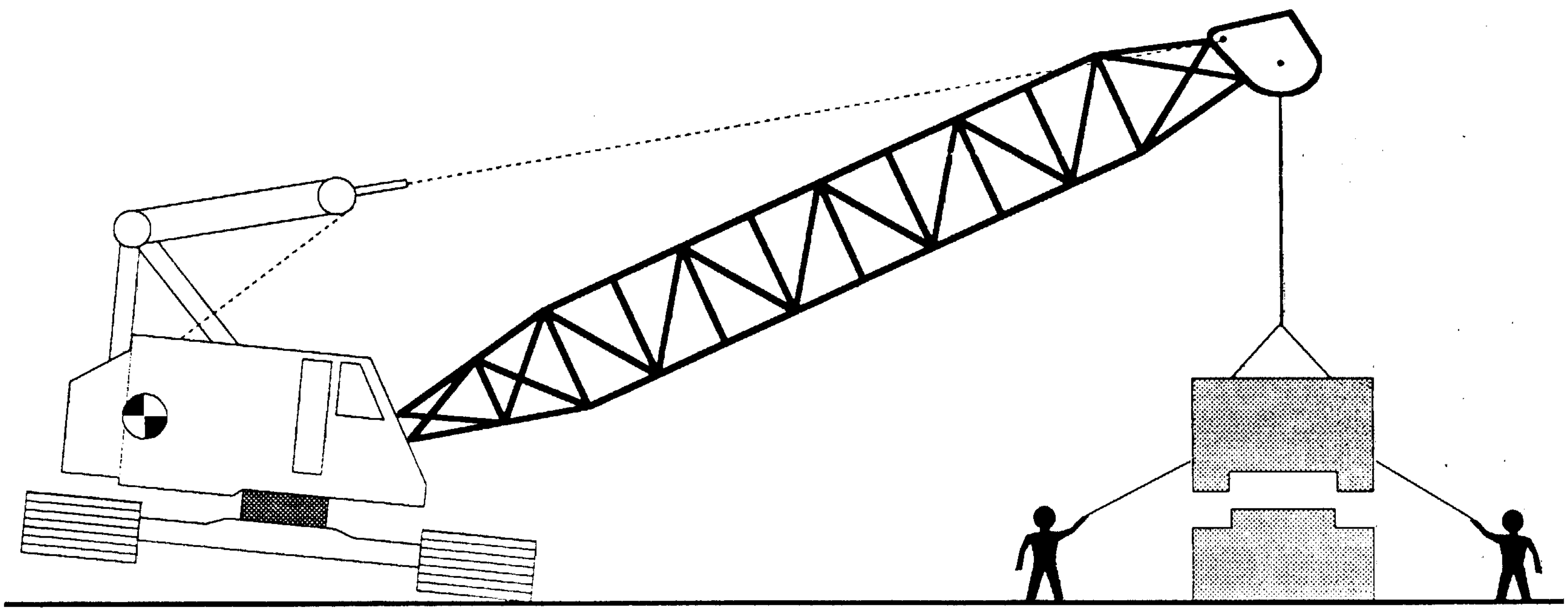
$$W_m = \frac{80}{20} \times 60{,}000 = 240{,}000 \text{ Lbs}$$

Figure 2.- Example of crane machine weight required to lift 60,000 lb payload at a distance of 80 feet.

FIGURE 3

The two major shortcomings of an earth based type crane for planetary operations are shown in figure 3. The first shortcoming is the large machine weight required to offset the overturning moment provided by lifting a payload as discussed in figure 2. The other major shortcoming of a typical cable crane is shown on the right hand side of figure 3. Since the payload is picked up by a single cable, only one of the six degrees of freedom of the payload is positively controlled. The other 5 payload degrees-of-freedom are typically precision positioned by several workers holding onto the payload with guy lines. For planetary operations it would be highly desirable for the crane to perform precision operations without the use of astronauts because of cost and safety reasons. To accomplish autonomous operations with a crane is necessary to self-stabilize the payload with respect to the crane to provide a positive positioning capability. One approach for establishing a stabilized payload is to lift the payload with multiple cables. In the next figure different cable attachment schemes are discussed.

TYPICAL MOBILE CRANE HAS TWO MAJOR SHORTCOMINGS FOR LUNAR BASE APPLICATION



1) Very large mass required to resist tipping

2) Human guidance required for accurate positioning

Figure 3.- Operational considerations of an earth based type mobile crane.

FIGURE 4

In figure 4, four candidate cable suspension schemes for a crane are shown. The objective of the current study was to develop and study a cable suspension system that provides complete control of the payload with the minimum number of cables. As was mentioned previously the single cable system only provides control for one of the six possible degrees of freedom, and thus is unsatisfactory from an automated operations point of view. The six cable suspension system as shown on the right hand side of the figure provides control for all six degrees of freedom, and is studied in depth in reference 3. In the present paper attention is focused on a 3 cable suspension system to determine if a fewer number of cables can be used to provide a stable operations platform. Two possibilities for a 3-cable crane are shown in the center of figure 4. The 3-cable suspension system with parallel cables provides positive control for 2 rotations and the vertical displacement. The parallel cables also provide a small value of geometric nonlinear stiffness for the other 3 degrees of freedom. A study of the non parallel, 3-cable suspension system where the cables are arranged such that they point towards the center of gravity (c.g.) of the payload was found to have significantly higher values of geometric nonlinear stiffness. In this paper a study is made of applying the non parallel 3-cable suspension system to a Lunar or planetary crane which requires complete control of the payload to achieve autonomous precision operations.

CANDIDATE CRANE CABLE SUSPENSION SYSTEMS

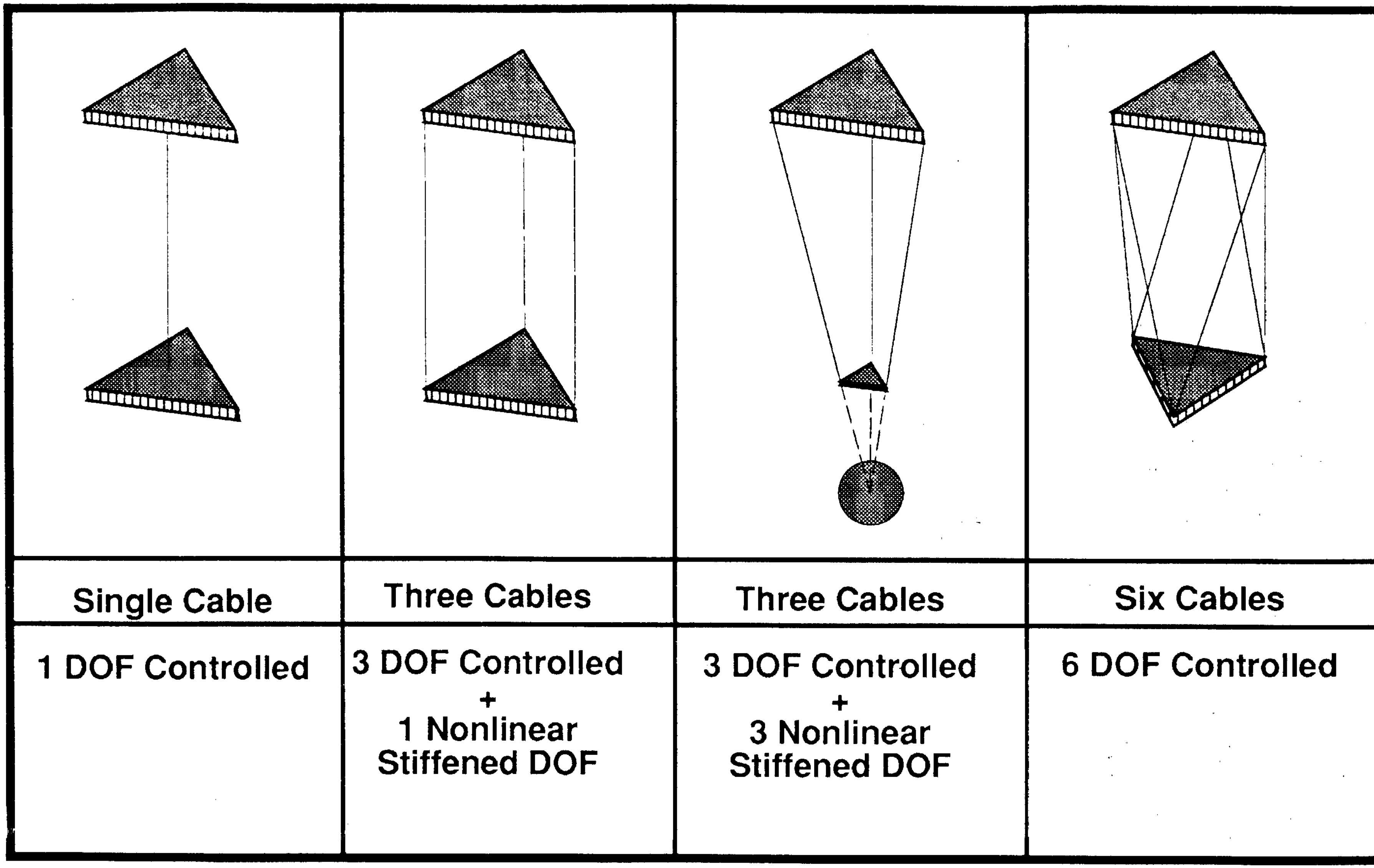


Figure 4.- Potential cable suspension systems for payload support.

FIGURE 5

This figure is a sketch of a Lunar crane concept designed specifically to overcome the shortcomings discussed in figure 3. On the left of the mobile crane is an actively controlled counterweight. To achieve the lightest weight overall crane design it would be necessary to use the minimum magnitude counterweight required to offset the overturning moment produced by lifting the payload weight. If the weight of the central portion of the crane were small compared with the payload weight and the counterweight , it would be necessary to continually balance the crane in an active fashion. Such an active control scenario is certainly within the state-of-the-art of modern electronics and would result in the minimum weight design for a Lunar crane. On the right hand side of the mobile crane is shown a 3-cable payload suspension system with a smart end effector for capturing and controlling the payload. The 3 dimensional aspects of the crane boom are shown in figure 6, and the dynamic control of the payload is discussed in figure 7.

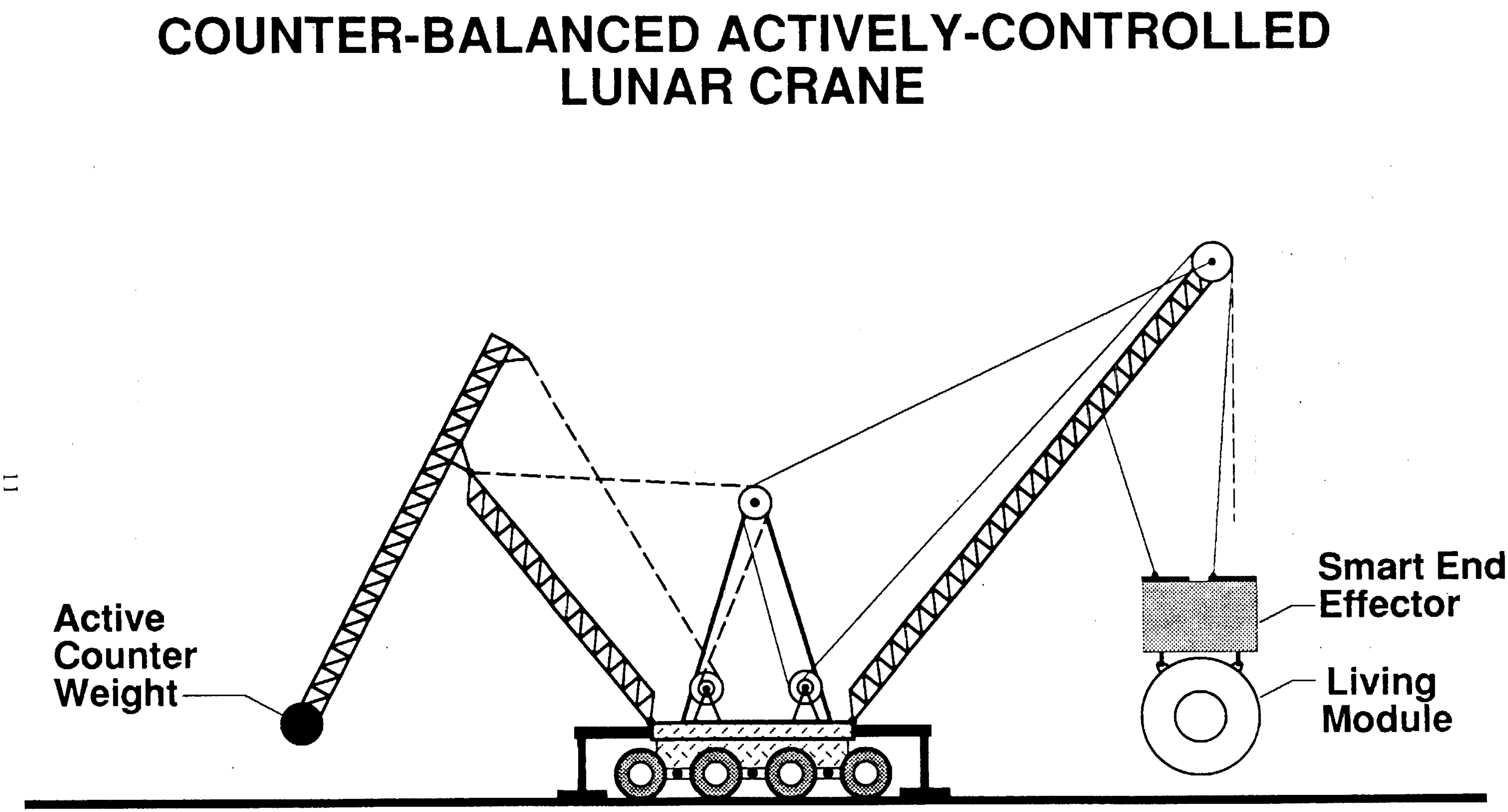


Figure 5.- Schematic of Lunar crane concept showing multiple cable payload support system as well as active controlled counter balance system.

FIGURE 6

This figure shows a perspective sketch of the 3-cable Lunar crane boom with the cables attached to an interim structural framework which in turn is attached to the payload which in this case is a module. As will be discussed later the three cables are arranged in such a fashion that their theoretical point of intersection coincides with the center of gravity of the payload. It was determined that such an arrangement resulted in the highest natural frequency of the cable/payload system, and it is assumed that this arrangement would be the most desirable from a payload control point-of-view. Further studies will have to be conducted to understand the cable attachment schemes from a control perspective. In the next figure the active control of the cables relative to the payload is discussed.

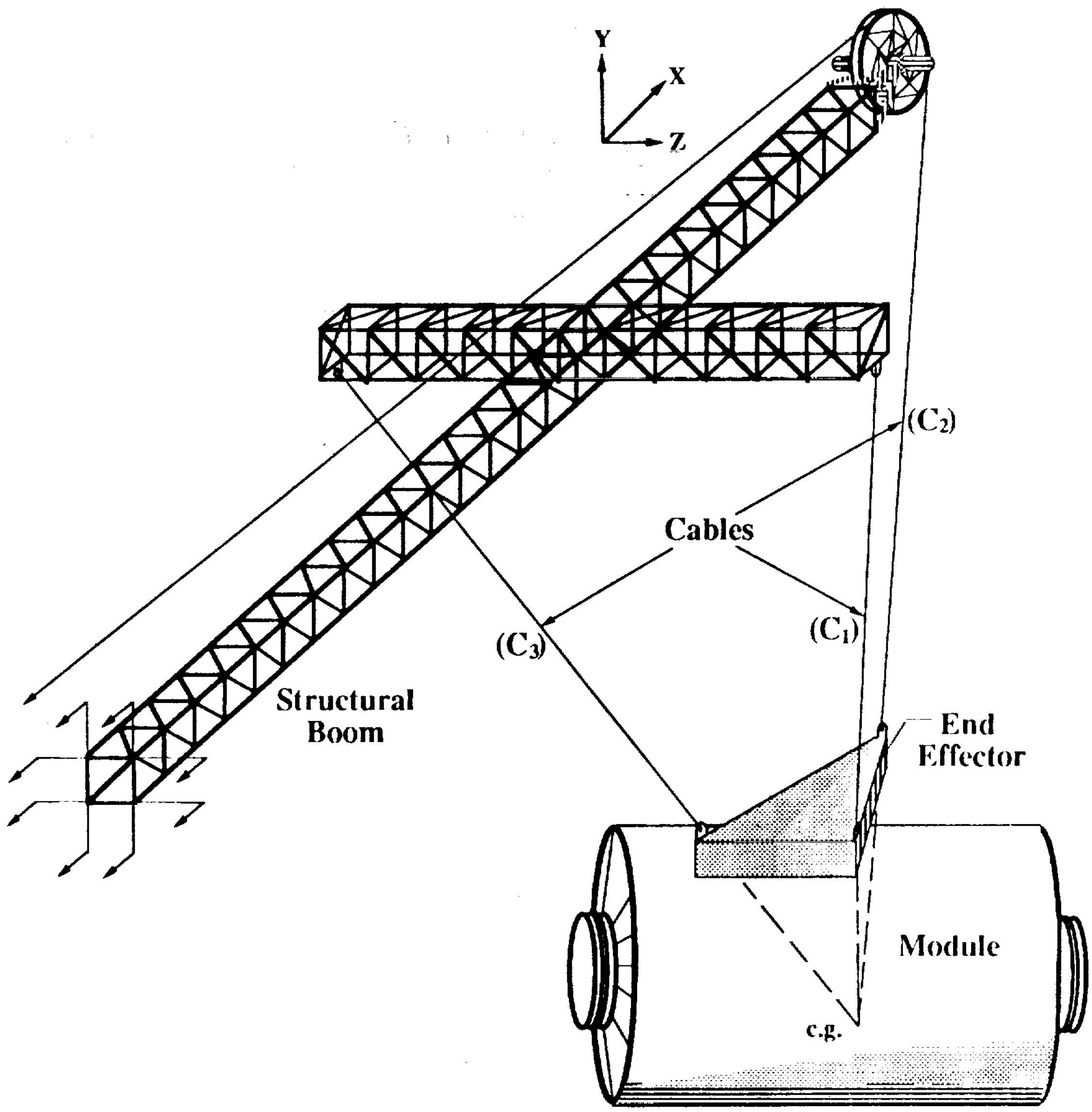


Figure 6.- Perspective of boom/cable suspension system.

FIGURE 7

This figure shows a concept for attaching the 3-cable suspension system to the payload. The lightweight end effector is intentionally designed "deep" to provide a separation of the cable attachment points thus providing a large control moment. As indicated in the sketch, there are active cable positioners at the top of the end effector to provide for active control of the payload. At the bottom of the end effector there would be attachment fixtures for grasping and firmly holding the payload. It is assumed that there would be a number of different end effectors to handle different size and types of payloads. It is also assumed that a robot could be attached to the end effector so that the crane could provide a mobile-remote stable platform for robotic operations. As was mentioned earlier, it was determined that attachment of the cables in such a fashion that their intersection point coincided with the c.g. of the payload, results in the highest natural frequency of the cable/payload combination. To study this quantitatively a 2-D model was analyzed and the results are shown in the next figure.

LUNAR CRANE PENDULUM MECHANICS

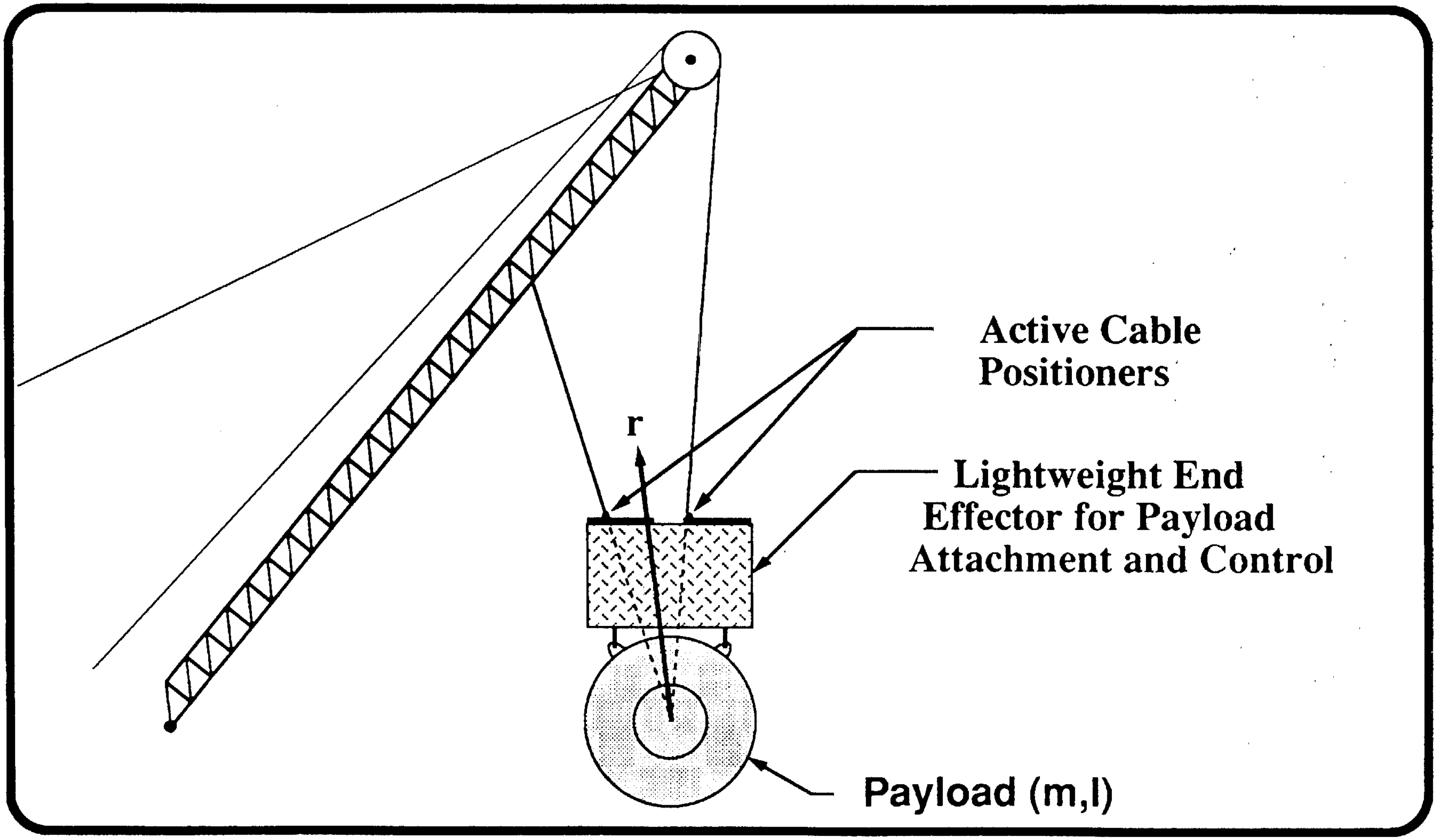


Figure 7.- Schematic showing payload attachment end effector.

FIGURE 8

To study the effect of the position of the payload c.g. relative to the theoretical intersection point of the cables on system dynamics, a 2-D model was considered as shown in this figure. The closed form equation for the natural frequency of the one-degree-of-freedom cable/payload system is shown at the top of the figure. The numerical results shown are for a 60,000 lb payload suspended by cables that are 50 feet long. As can be seen in the figure, the natural frequency peaks for a value of epsilon close to zero. This corresponds to the payload c.g. coinciding with the theoretical intersection point of the cables. Also, as can been seen from the figure, the mass moment of inertia of payload has a large effect on the natural frequency as would be expected. For a zero value of mass moment of inertia, there would be a singularity in the frequency for epsilon equal to zero.

NATURAL FREQUENCY OF SINGLE-DEGREE-OF-FREEDOM RIGID BODY PENDULUM

$$f = \frac{1}{2\pi}\sqrt{\frac{mg\left[\frac{b}{\cos(\alpha)} + \frac{2b^2\sin^3(\alpha)}{d\cos(\alpha)} + e\left(\frac{2b\sin(\alpha)}{a-2b\sin(\alpha)}\right)^2\right]}{m\left[b\cos(\alpha) - e\left(\frac{2b\sin(\alpha)}{a-2b\sin(\alpha)}\right)\right]^2 + I\left[\frac{2b\sin(\alpha)}{a-2b\sin(\alpha)}\right]^2}}$$

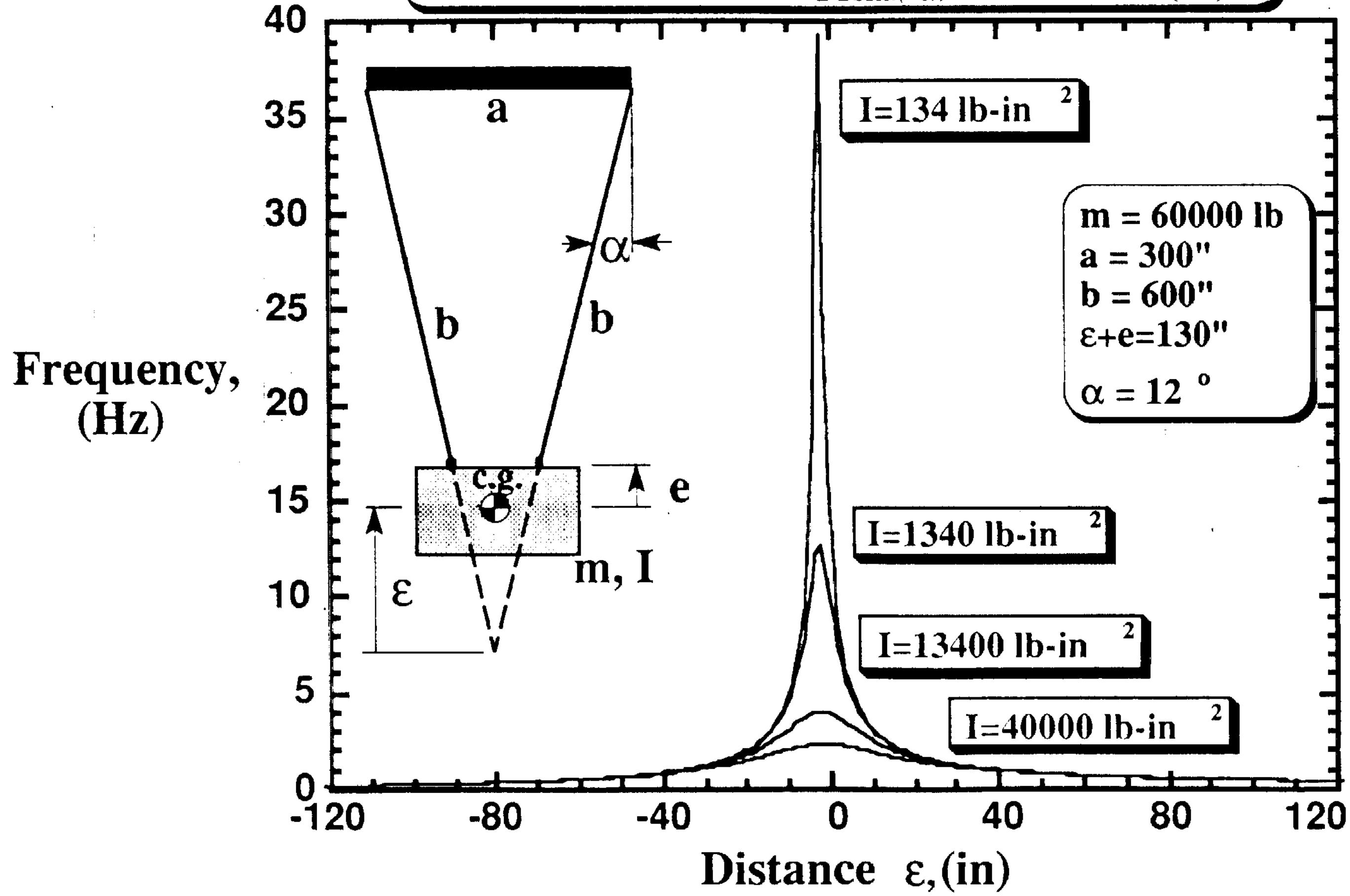


Figure 8.- Natural frequency of a 2-cable pendulum as a function of c.g. distance from the intersection of the cables.

FIGURE 9

This figure shows a comparison of the weight of an earth based type mobile crane with the weight of a mobile crane which is counter balanced. As shown on the upper left of the figure, the weight of a standard mobile crane increases dramatically for large payload distances. However, because of the counter weight the Lunar crane weight increases much more slowly with payload distance and in fact its weight is significantly less for all values of payload distance. Considering the fact that the counter balance weight could be mainly local material from the planet surface, the machine weight of an actively controlled, counter balanced crane is an order of magnitude less than a standard earth based type mobile crane. This type of a decrease in machine weight is necessary to make such pieces of construction equipment practical because of launch costs. The concept presented herein is preliminary in nature, and considerable work needs to be done on the machine to ensure its practicability.

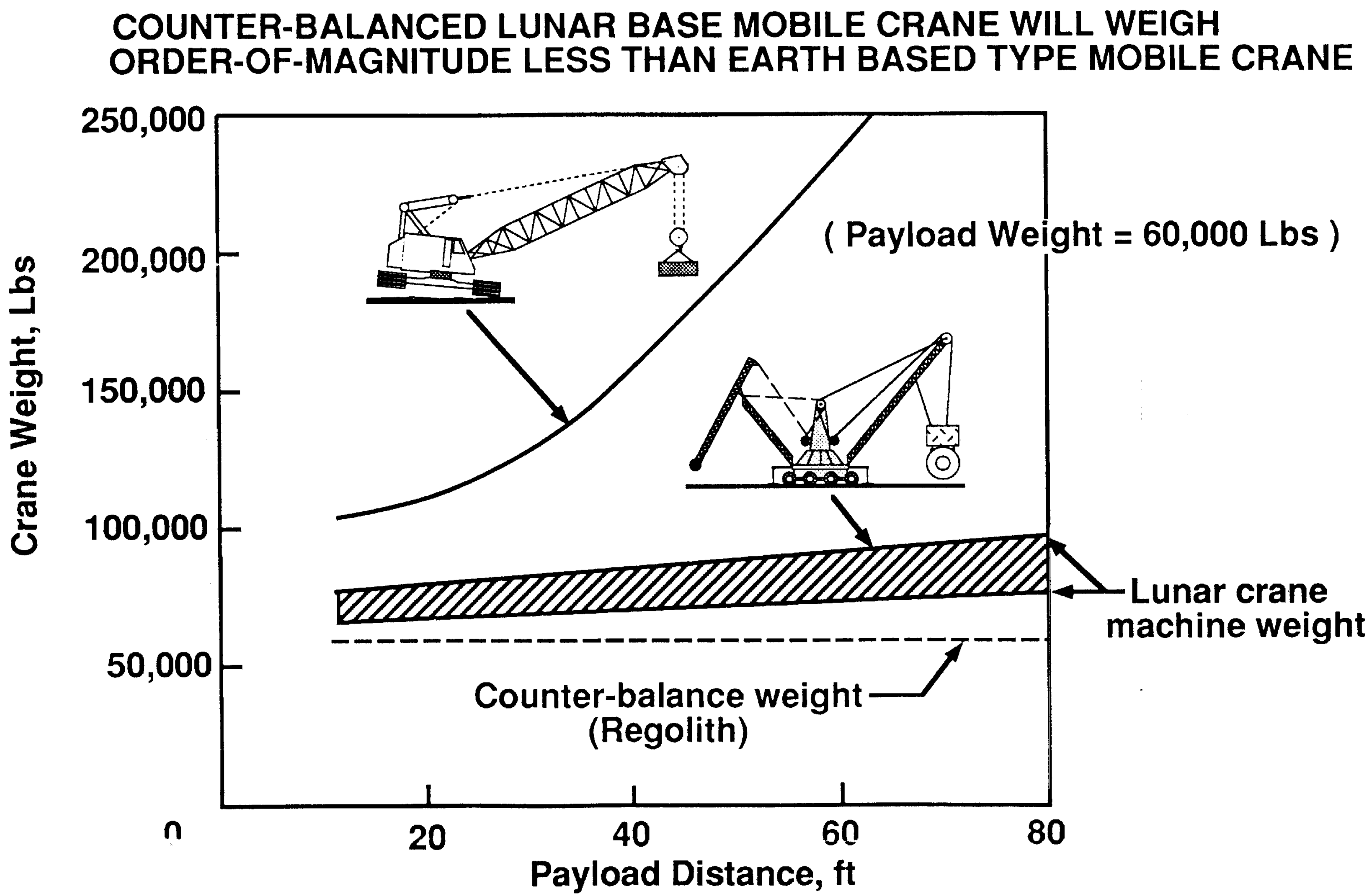


Figure 9.- Comparison of standard earth based type mobile crane weight with counter balanced mobile crane weight.

CONCLUDING REMARKS

A preliminary design study has been conducted of a mobile crane suitable for conducting remote, automated construction operations on planetary surfaces. A cursory study was made of earth based mobile cranes and the need for major improvements were identified. One improvement identified was that the weight of earth based type cranes would have reduced significantly before launch costs would be practical. Furthermore it was observed that the only way to make a major reduction in weight is to develop an actively controlled, counter balanced crane. The other improvement to an earth based type crane identified was the need to provide payload stability for precision positioning operations. Current earth based cranes have a single cable supporting the payload, and precision positioning is accomplished by the use of construction workers controlling the payload by the use of tethers. For remote, autonomous operations on planetary surfaces it will be necessary to perform the precision operations with out the use of humans. To accomplish this the payload must be stabilized relative to the crane. One approach for accomplishing this is to suspend the payload on multiple cable. In the present paper a 3-cable suspension system crane concept is developed. An analysis of the natural frequency of the system is presented which verifies the legitimacy of the concept. However, significantly more research is required to establish active control systems for both the counter weight and for the cable/payload system.

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16. Abstract

A preliminary design study is presented of a mobile crane suitable for conducting remote, automated construction operations on planetary surfaces. A cursory study was made of earth based mobile cranes and the need for major improvements were identified. One improvement identified was that the weight of earth based type cranes would have reduced significantly before launch costs would be practical. Furthermore it was observed that the only way to make a major reduction in weight is to develop an actively controlled, counter balanced crane. The other improvement to an earth based type crane identified was the need to provide payload stability for precision positioning operations. Current earth based cranes have a single cable supporting the payload, and precision positioning is accomplished by the use of construction workers controlling the payload by the use of tethers. For remote, autonomous operations on planetary surfaces it will be necessary to perform the precision operations without the use of humans. To accomplish this the payload must be stabilized relative to the crane. One approach for accomplishing this is to suspend the payload on multiple cable. In the present paper a 3-cable suspension system crane concept is developed. An analysis of the natural frequency of the system is presented which verifies the legitimacy of the concept.

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