ANALYSIS AND SIMULATION OF THE LEG OF AN HEXAPOD ROBOT FO REMOTE EXPLORATION.

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KEYWORDS
Hexapod robot, walknig machines, rover, remote exploration, simulation.

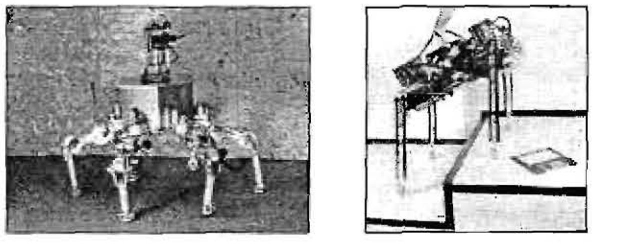
ABSTRACT

The locomotion system is determined by the terrain conditions. The aim of this paper is to introduce the characteristics and simulation of a hexapod legged robot that can be easily used for exploration of abrupt and harsh terrains, like the Rio Tinto environment.

A walking robot seems like the best option for this kind of terrain. Some of the advantages are that they do not need a continuous terrain, they have less problems with sliding and they also have greater capacity to overcome obstacles as they produce less harm to the environment that the scientist wants to explore on the contrary when faced with mechanical design they present a design challenge, also in the static and dynamic analysis problem of a legged robot, there is a high complexity that has to be taken into account.
This paper shows how to easily cope with the analysis of a hexapod robot movement based on a design developed by the Center of Astrobiology INTA-CSIC for operation in Rio Tinto (Huelva - Spain).

WALKING MACHINES

Walking robots (fig. 1) are well suited for unstructured environments and abrupt terrains having some drawbacks like movement coordination, speed and power consumption.

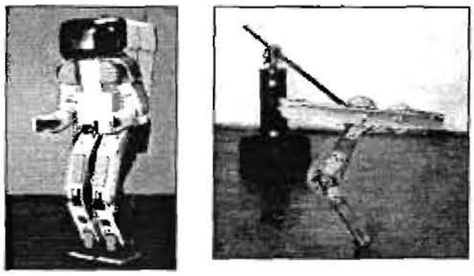


a) b)

Figure 1. a). Katharina (Fraunhoffer Inst.), b). Scout 1 (MIT).

In order to choose the best configuration the state of the art in walking machines has to be reviewed. Walking machines are usually found classified by their number of legs ranging from eight to one. Walking robots with six legs and four legs are the more frequently built, there exists multiple designs based on the choice of actuators, dimensions and design implementations like articulated bodies giving high nu of active degrees of freedom (Song and Waldron 1989)

With new technologies advancing an increasing mark begun with microrobots, alone or in communities th work cooperating between each other are appearing, thi of robots have the disadvantage that they perform p tasks that do not deal with high payload capacity. Last b least bipeds and one legged machines are reachin markets specially bipeds which simulate and perform h actions as shown in the following figures.



a) b)

Figure 2. a). Honda human robot, b). Olie Vrije Univers

As it has mentioned before walking machines look li good option when it deals with harsh terrains, they can a better to abrupt terrains and be less harmful to environment they are in, rover wheels usually damage terrain we want to analyze or explore. Some of the wal machines summarized before are feasible for re exploration of harsh terrains. But the design had to a "mechanical complexity" which means low reliability, power consumption and large control problems (Song Waldron 1989).

When dealing with a robot design of this complexity, design will be based on the design requirements, These depend on the type of scientific missions goals and these have to be clearly specified by the scientific group for design engineers to begin. When a design of this type star will vary depending on the scientific payload that needs to carried, the type of environment that wants to be explo and the range of area that needs to be covered. These affect the design materials, type of actuators, mechanics power consumption that needs to be used. These will give estimate dimensions of our robot that will also help us the decision of the robot configuration.

The Center of astrobiology having in mind all the des specifications and mission requirements involved and tak into account the number of different instruments that will like to be placed in the robot has designed a six legged robot having in mind the abrupt terrain that it will work in *'Rio Tinto'*, (Huelva, SouthWest of Spain) (Bruhn 1992). The Tinto River has shown a large scientific interest due to its special characteristics from a biological and geological point of view. The study of such environment is characterized by its hard conditions, beside the need of performing some of the experimentation in situ. This forces some exceptional exploration methods, like the use of robots.The robot will develop its activities in a rocky terrain with dry and wet areas, like those shown in the following figure.

Figure 3. 'Rio Tinto' terrain.

This rover must be designed having in mind that will transport a scientific payload and it should be able to achieve as much location as possible in order to collect information of different river zone. One of the elements more sensible to the terrain conditions is the locomotion system because since it should make feasible any displacement along the river. The locomotion system is determined by the terrain conditions. The aim of this article is to introduce a six legged robotwith low power consumption and maximum payload capacity. The following paragraphs will summarize the first trade off calculations of the design and its first analysis and simulations.

HEXAPOD DESIGN

Based on a design requirement of 40 kilograms of payload, and in order to minimize mechanical complexity the final design chosen after analyzing several configurations, concluded in a hexapod shaped rover powered by linear DC actuators (Torres and Pomares 2002, Barrientos and Peñin 1997). These type of actuators were chosen for its high force outputs as we are dealing with an approximate 80 kilograms robot. The robot has a design configuration like the one shown in figure 3 (Waldron et al. 1984). The main function of the robot hexapod box is to carry the payload. It has to be large enough to fit all of the payload and robust to withstand the forces and moments due to the walking motion and possible collisions with objects. The hexagonal design is to allow more space between the legs when they perform the rowing motion (Bruhn 1992). The number of legs were chosen as a compromise between complexity and stability (Song and Waldron 1989), and six seemed like a good compromise.

With these six leg configuration the walking motion could be performed as follows: the robot can stand in three legs in a triangular configuration meanwhile the other three legs are in the air. The three legs on the floor can perform a rowing motion forward and when they reached the maximum motion, the legs in the air can come down and the same procedure will follow, with these movements we can avoid having the 18 actuators acting at the same time (Torres and Pomares 2002).

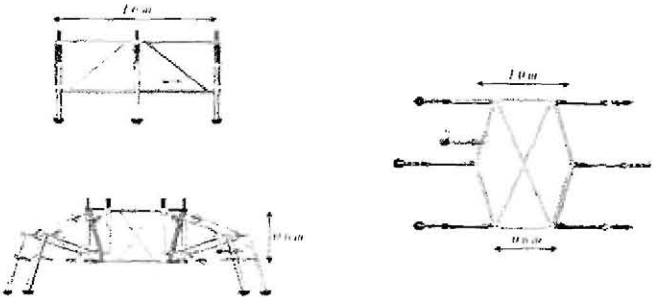


Figure 4. Dimensions of the prototype design.

LEG DESIGN

When dealing with any design the desired result from a mechanical point of view is its simplicity in manufacturing, also simplicity during mounting and with repair, this design was thought primary to be highly robust (Gere and Timoshenko 1990). The linear DC motors chosen will allow large movements of the legs but will act as part of structural members of the mechanical design (McGuee and Orin 1976).

Each of the legs has three independent degrees of freedom, the linear actuators controls two degrees of freedom The third degree of freedom is controlled by a DC gear motor. Below is a detailed sketch of the leg and the minimum and maximum positions of all the actuators involved. The maximum angles and positions that it can move on will depend on collisions, large force or moments acting and unstable positions.

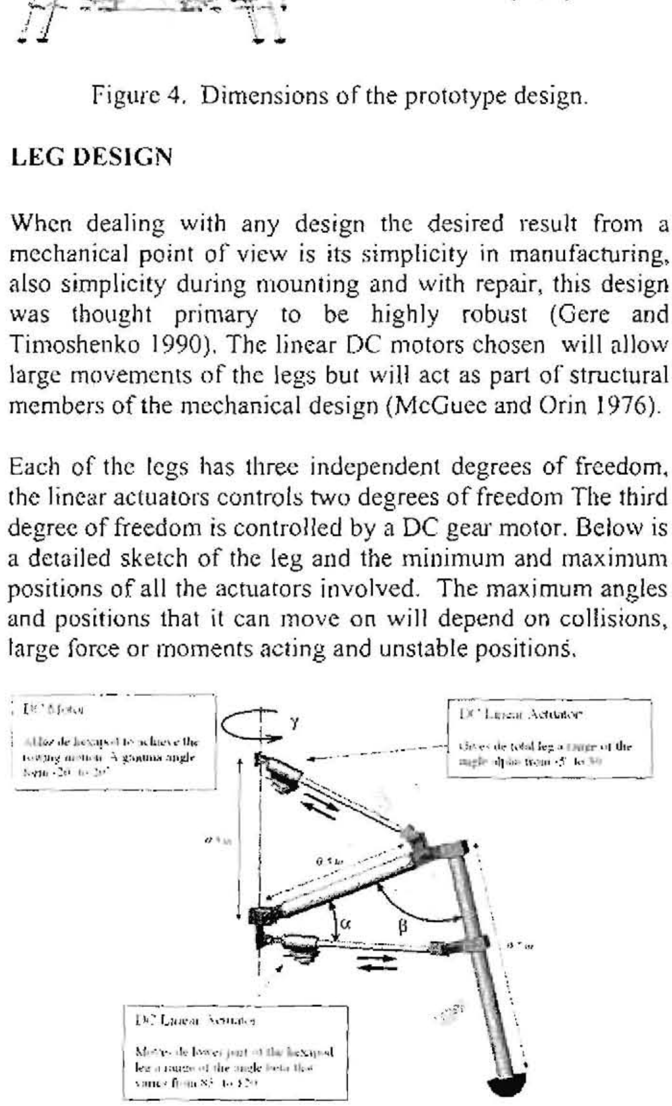


Figure 5. Attachment and function of the actuators.

The materials will be aluminum hollow bars, which are light but have high mechanical strength and to assure smooth movements they will pivot in bearings.

REACTIONS

After analyzing the robot mechanical design, the first trade off calculations that will improve and change the design have to be made. The first step to start the calculations is to find out what are the reactions 'R' in each of the individual legs taking into consideration all of the weights the structure and actuators are going to withstand at all of the possible leg configurations. The procedure is to find the moments and forces about a point in the hexapod leaving a system of three equations and three unknowns, these equations will be listed here, and solved using *Matlab*©. The reactions are found in the worst case assuming that the hexapod is standing in three legs, which are performing the rowing motion. The other three legs do not have a ground load reaction but contribute with their weight and displacement configuration. The following figure explains graphically the loads involved. Weight loads are shown only at one leg labeled '6'. Each leg is suffering the same represented weights as leg '6', but different R_2, R_4 and R_6 will be obtained depending on the configurations.

For the verification of ground reactions a static *Nastran*© force analysis will be performed to validate the results obtained from *Matlab*©.

Also from these *Nastran*© analysis, materials and different design configurations will also be analyzed, but this will not be dealt in this article and from the program the reactions will be taken to compare our theoretical results, these is later shown below in results.

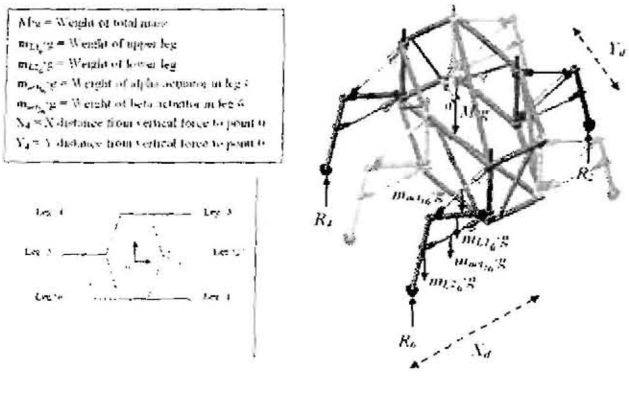


Figure 6. Ground reactions.

The resulting equations are reduced to three due to the addition of forces and moments at point '0'. Due to the direction of the vertical forces acting, 'z' distances do not appear in the equations. This three resulting equations are a function of the next shown variables which are calculated under a loop so all possible configurations are taken into consideration. Legs '1', '3' and '5' are kept at fixed positions so the program has enough memory to iterate the different configurations of the three legs which have ground reactions.

$$\alpha_{2,4,6} = -5^\circ : 30^\circ \quad (1)$$

$$\beta_{2,4,6} = 85^\circ : 120^\circ \quad (2)$$

As the three legs are rowing at the same time it can be assumed that:

$$\gamma_2 = \gamma_4 = \gamma_6 = -20^\circ : 20^\circ \quad (3)$$

The resulting equations can be summarized to the foll[...] system of equations:

$$\begin{bmatrix} 1 & 1 & 1 \\ Y_2 & Y_4 & Y_6 \\ X_2 & X_4 & X_6 \end{bmatrix} \cdot \begin{bmatrix} R_2 \\ R_4 \\ R_6 \end{bmatrix} = \begin{bmatrix} -W_T \\ M_x \\ M_y \end{bmatrix} \quad (4)$$

Equations I. Reaction equations.

, where

W_T = Addition of all weights, box + legs +actuators ('F_z' equation)

M_x = All the independent terms in the moment 'i' equation for a[...] legs acting : All vertical weight forces times their 'Y' distance to p[...]

M_y = All the independent term in the moment 'j' equation for all [...] legs acting : All vertical weight forces times their 'X' distance to poi[...]

X_n = 'X' distance from the reaction force 'R_n' to point '0'.

Y_n = 'Y' distance from the load reaction 'R_n' to point '0'.

LEG FORCE ANALYSIS

Due to the number of unknowns the analysis of each o[...] robot legs has to be broken into separate sections in ord[...] be able to calculate these unknowns.

The calculations will be performed for leg '2' which a[...] illustrated in figure 6 withstands the greatest gro[...] reactions, varying 'α_2', 'β_2' and 'γ_2'.

The following figure will illustrate the first cut section [...] will be calculated.

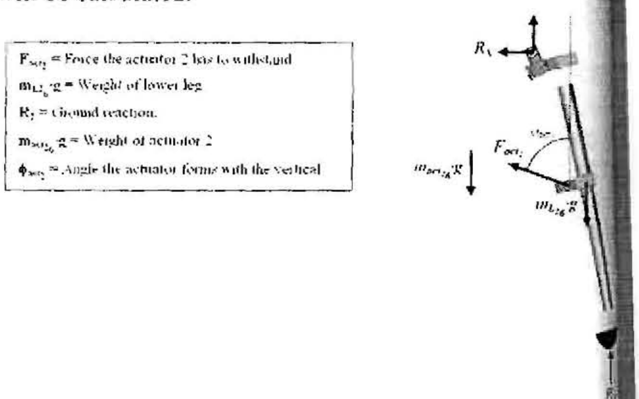


Figure 7. First section analysis.

In figure 6, we have reduced the number of equations a[...] unknowns to three unknowns and three equations, with th[...] we can begin to calculate the first reaction forces.

The three equations involved are the summation of forces [...] 'x' and 'z' directions and taking moments about point '[...] which is located where 'R_x' and 'R_z' are acting.

$$\sum F_z = R_z + R_2 - m_{L_2} \cdot g + F_{act_2} \cdot \cos(\phi_{act_2}) - m_{act_2} \cdot g \quad (5)$$

$$\sum F_x = R_x + F_{act_2} \cdot \sin(\phi_{act_2}) \quad (6)$$

$$\sum M = R_2 \cdot X_{d_{R_2}} - m_{L_2} \cdot g \cdot X_{d_{m_{L_2} g}} - F_{act_2} \cdot \cos(\phi_{act_2}) \cdot X_{d_{F_{act_2}}} + F_{act_2} \cdot \sin(\phi_{act_2}) \cdot Z_{d_{F_{act_2}}} + m_{act_2} \cdot g \cdot X_{d_{m_{act_2} g}} \quad (7)$$

$$\downarrow$$

$$\begin{bmatrix} 1 & 0 & \sin(\phi_{act_2}) \\ 0 & 1 & \cos(\phi_{act_2}) \\ 0 & 0 & \sin(\phi_{act_2}) - \cos(\phi_{act_2}) \end{bmatrix} \cdot \begin{bmatrix} R_x \\ R_z \\ F_{act_2} \end{bmatrix} = \begin{bmatrix} 0 \\ m_{L_2} \cdot g - R_2 + m_{act_2} \cdot g \\ m_{L_2} \cdot g \cdot X_{d_{m_{L_2} g}} - R_2 \cdot X_{d_{R_2}} + m_{act_2} \cdot g \cdot X_{d_{m_{act_2} g}} \end{bmatrix} \quad (8)$$

Equations II. Force equations in first section analysis.

We can continue with the second section cut, with the value of the reactions in the hinge we start solving for the next unknowns shown which can also be reduced to three equations and three unknowns that can easily be solved.

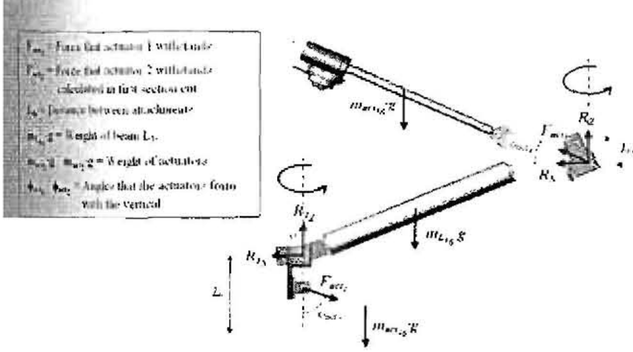


Figure 8. Second section analysis.

The equations involved are the summation of forces in 'x' and 'z' directions and taking moments about point '0' which is located where 'R_{1_x}' and 'R_{1_z}' are acting (eqs. III).

$$\sum F_z = R_{1_z} + R_z - m_{L_1} \cdot g + F_{act_1} \cdot \sin(\phi_{act_1}) - F_{act_2} \cdot \cos(\phi_{act_2}) - m_{act_2} \cdot g \quad (9)$$

$$\sum F_x = R_x + R_{1_x} + F_{act_1} \cdot \cos(\phi_{act_1}) - F_{act_2} \cdot \sin(\phi_{act_2}) \quad (10)$$

$$\begin{aligned} \sum M = & -m_{L_1} \cdot g \cdot \frac{L_1}{2} \cdot \cos(\alpha) + F_{act_1} \cdot \cos(\phi_{act_1}) \cdot L_1 \cdot \sin(\alpha) - \\ & - F_{act_1} \cdot \sin(\phi_{act_1}) \cdot L_1 \cdot \cos(\alpha) + R_z \cdot L_1 \cdot \cos(\alpha) + \\ & + R_x \cdot L_1 \cdot \sin(\alpha) + F_{act_2} \cdot \sin(\phi_{act_2}) \cdot L_h - m_{act_2} \cdot g \cdot X_{d_{m_{act_2} g}} \end{aligned} \quad (11)$$

Equations III.a. Force equations in second section analysis.

$$\begin{bmatrix} 1 & 0 & \cos(\phi_{act_1}) \\ 0 & 1 & \sin(\phi_{act_1}) \\ 0 & 0 & \cos(\phi_{act_1}) \cdot L_1 \cdot \sin(\alpha) - F_{act_1} \cdot \sin(\phi_{act_1}) \cdot L_1 \cdot \cos(\alpha) \end{bmatrix} \cdot \begin{bmatrix} R_x \\ R_z \\ F_{act_1} \end{bmatrix} = \begin{bmatrix} -R_x + F_{act_2} \cdot \sin \cdot (\phi_{act_2}) \\ m_{L_1} \cdot g - R_z + F_{act_2} \cdot \cos \cdot (\phi_{act_2}) \\ m_{L_1} \cdot g \cdot \frac{L_1}{2} \cdot \cos \cdot (\alpha) \\ -R_z \cdot L_1 \cdot \cos \cdot (\alpha) \\ -R_x \cdot L_1 \cdot \sin \cdot (\alpha) \\ +F_{act_2} \cdot \sin \cdot (\phi_{act_2}) \\ +m_{act_2} \cdot g \cdot X_{d_{m_{act_2} g}} \end{bmatrix} \quad (12)$$

Equations III.b. Matrix force's equations in second section analysis.

In the last section cut, shown in figure 9, the vertical bar is attached with bearings so it can be assumed that is simply supported withstanding the forces shown, due to the resultant number of unknowns and equations it has to be reduced to an easily solved case.

Each of the acting forces can be reduced to a force and a moment acting at the ends of the vertical bar. The moment force appears because the attachments have an offset in the 'x' and 'z' direction.

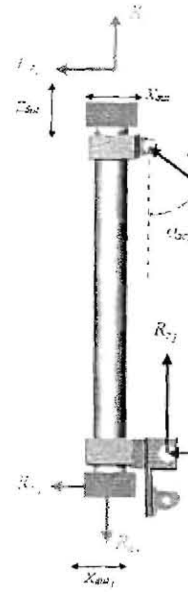


Figure 9 . Third section analysis.

In this section, we have more unknowns than equations so we have to apply a simple method in which we can reduce it to three unknowns, for these we can assume that every force that acts in the bar is equal to the sum of a force plus a moment, from the *Roark's* book of formulas for stress and strain (Young and Budynas 2001) we find the following:

In figure 10 we have the four unknows *(R_{2_x}, R_{2_z}, R_{3_x} and R_{3_z})* and four known forces acting *($F_{act_{1_x}}$, $F_{act_{1_z}}$, R_{1_z} and R_{1_x})*, that we can apply to them the above reduction case. The distance at which the force is acting is important. We have forces acting in two points at which a from figure 10, will be equal to *'0'* and *'L_3'*.

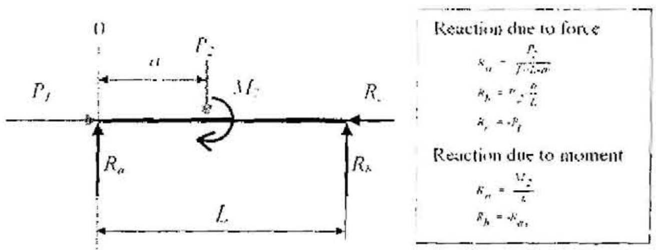


Figure 10. Reduction to known cases.

For *'a=0'* , the force acting is from actuator *'1'*, the force *'F_{act_1}'* in the *'x'* and *'y'* direction is equal to:

$$F_{act_{1_x}} = F_{act_1} \cdot sin(\phi_{act_1}) \tag{13}$$

$$F_{act_{1_z}} = F_{act_1} \cdot cos(\phi_{act_1}) \tag{14}$$

Applying the equations of figure 10 at *'a=0'* and *'L=L_3'*, we obtain the following values for point *'1'*.

$$R_{a1} = \frac{P_2}{L} \cdot (L-0) = P_2 = F_{act_{1_x}} \tag{15}$$

$$R_{b1} = P_2 \cdot \frac{0}{L} = 0 \tag{16}$$

$$R_{x_1} = -F_{act_{1_z}} \tag{17}$$

$$R_{a_{M_1}} = \frac{F_{act_{1_z}} \cdot x_{dist}}{L_3} \tag{18}$$

$$R_{a_{M_1}} = \frac{F_{act_{1_x}} \cdot z_{dist}}{L_3} \tag{19}$$

$$R_{b_{M_1}} = -R_{a_1} \tag{20}$$

Applying the equations for the reaction forces 'R_{x_1}' and obtained in earlier calculations we obtain:

$$R_{a_2} = \frac{P_2}{L_3} \cdot (L_3 - L_3) = 0 \tag{21}$$

$$R_{b_2} = P_2 \cdot \frac{L_3}{L_3} = P_2 = R_{x_1} \tag{22}$$

$$R_{a_{M_2}} = \frac{R_{x_1} \cdot z_{dist_1}}{L_3} \tag{23}$$

$$R_{a_{M_2}} = \frac{R_{z_1} \cdot x_{dist_1}}{L_3} \tag{24}$$

$$R_{b_1} = -R_{a_2} \tag{25}$$

$$R_{c_2} = -R_{z_1} \tag{26}$$

By adding the following forces we can find the rea forces in the vertical bar:

$$R_{z_2} = R_{c_1} + R_{c_2} \tag{27}$$

$$R_{z_3} = R_{c_1} + R_{c_2} \tag{28}$$

$$R_{x_1} = R_{a_1} + R_{a_{M_1}} + R_{a_{M_2}} + R_{a_2} + R_{a_{M_2}} + R_{a_{M_2}} \tag{29}$$

$$R_{x_2} = R_{b_1} + R_{b_2} + R_{b_1} \tag{30}$$

Equations IV. Vertical reaction forces.

RESULTS

The equations here presented were programmed in *Ma* and validated with *Nastran©*, a finite element prog *Nastran©* took the design a step further by taking into acc real dimensions and materials that were going to be (Song et al. 1985).

In this way it can be verified that the previous calcula were the reaction force in the legs from the weight of payload and the different geometrical configurations tha robot will have to encounter matched our calculations.

Also it is a way to check that the materials and compo selected are able to resist these reaction loads that will ap during the walking motion and irregular configurations.

The steps followed are clear through the article.

1.- The fist step was to analyze the ground reactions; this a first approach in order to know the magnitude of the that each leg will be carrying. By breaking in sections we easily find the reactions and forces acting in all Knowing the forces that are going to act in our robot legs can now choose the right actuator that suits our applic and the materials that will resist these loads.

A closer look at the forces and moment of each leg for a value in each section, the equations are programmed in *Matlab*© for the different configurations that the robot will encounter and a second review of the actuators and material has to be performed.

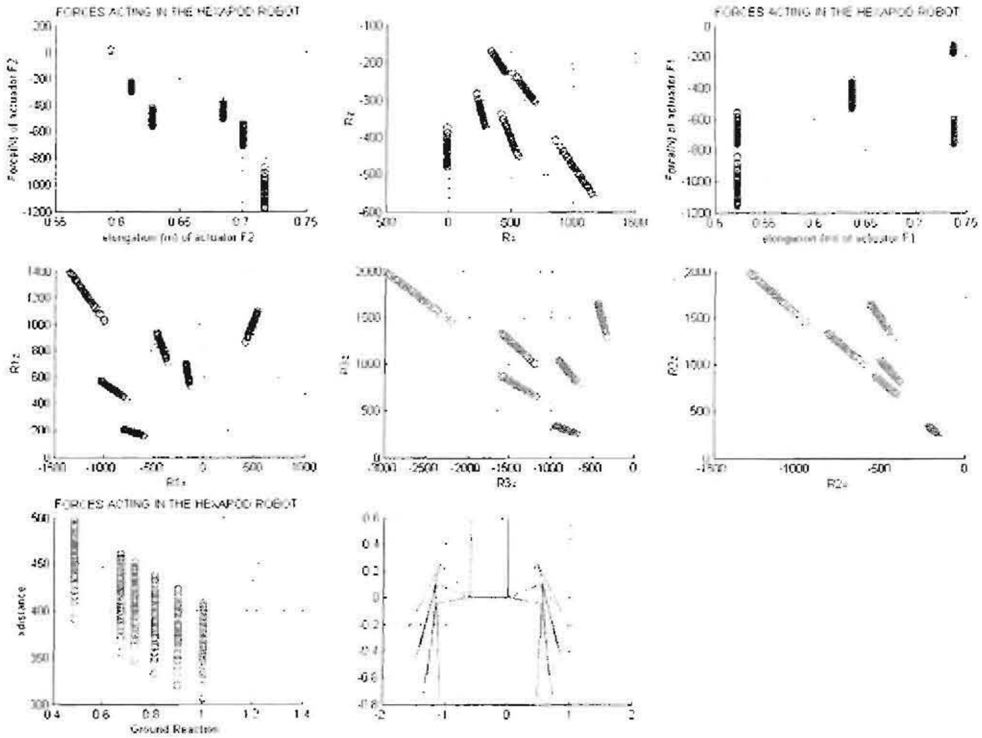


Figure 11. Reactions *Matlab*© results.

	Maximum Force (N)
F_{act_2}	*1200*
F_{act_1}	*1200*
R_y	*1300*
R_z	*600*
R_{1_x}	*1300*
R_{1_z}	*1400*
R_{2_x}	*1400*
R_{2_z}	*2000*
R_{3_x}	*600*
R_{3_z}	*2000*

Table I. Maximum force values for each reaction.

Knowing the ground reactions we can proceed to the section cuts, were we obtain the rest of the desired forces, they are shown in the above plots and are summarized in the table. The forces will depend on the elongation of the actuators, with the desired elongation required in the design and the maximum limit force that we want to have we can have a trade off of the actuators as the force will constraint the size of th actuators. Very heavy actuators are not desired as they are part of the structure and will have to be redesigned according to the new weight and dimensions.

2.- Validation of the results a structural program like *Nastran*© and conclusion of the design and components involved.

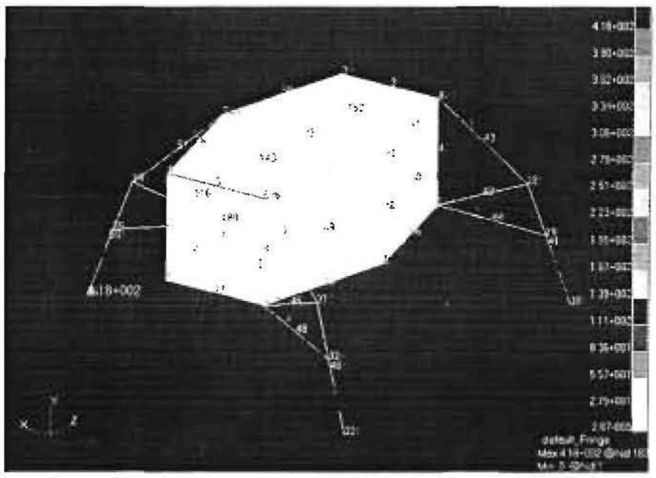


Figure 12. Reaction *Nastran*© analysis for one configuration.

Here a static subcase is shown of our robot it shows a configuration that we had found previously as of high acting forces, we can see that the point were the leg has the weight on its own shows the maximum value of *418 N.* If we take a look at figure 11, *ground reactions* versus *'X' distance* , we find a maximum value for the leg standing in its own with a maximum value of *500 N.*, this value is when the leg is in a position nearest to the center body.

This is consistent with the results found theoretically also this involves materials and real geometry which gives a more closer value to the one we are going to encounter in reality. This model was also simulated for all of the theoretical cases analysed, here only one static case is shown.

CONCLUSIONS

The analysis of a complex design such as this, has to be taken with a lot of care and having very clear in the design what your goals are. Start off information as what your design is meant for, what load do you want to carry and what environment has the design to face will limit the development and analysis of the robot.

This paper was meant to explain the equations around a hexapod robot configuration but also to clarify and teach a person facing with a similar design problem how to cope with the analysis by approaching the problem by section and steps. These calculations will probably have to be done cyclical every time new actuators or new payload is selected in order to achieve a trade off between weight, characteristics and budget.

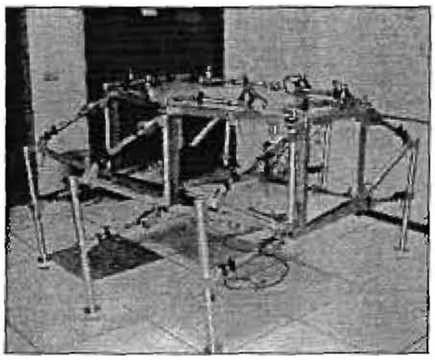


Figure 13. Hexapod robot design developed by the Center of Astrobiology INTA-CSIC.

An important issue in this design will be validation with the real model, right now the first prototype is in the Robotics lab of the Center of Astrobiologia (fig. 13) and before starting any field work the fist tests of mobility based in this paper have to be performed. Also dynamic movement and pre programmed trajectories will be a task to be performed in the following months and will be dealt in future articles.

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BIOGRAPHY

JOSEFINA TORRES received her BS engineering c in 1998 and her master degree in Aerospace engineer 2000 from Parks College (USA). She has worked assistant professor at Parks College from 1998 to 2000 Mechanical engineering department. She is curr working at the Robotics and Planetary Exploration gro the Center of Astrobiology in Madrid were she wor structural analisys and dynamic modelling in res projects together with ESA and NASA. Currently she is working in her Mechanical engineering PhD at the Tech University of Madrid in Spain(UPM). She has publi more than 10 technical papers and has been actively invo in over 10 research projects.

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