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KINEMATICS AND DYNAMICS STUDY OF A HEXAPOD ROBOTIC SYSTEM USING COMPUTATIONAL PACKAGES' CAPABILITIES

ABSTRACT

The main purpose of this work was to perform kinematics and dynamics analysis of a prototype of an autonomous hexapod robot. This paper reports on an initial phase, where the basic geometry of the system was specified and improved through a kinematics and dynamic study by using a motion analysis software. This study also allowed the design of all mechanical components and the definition of motion generation needs. In this paper the importance of legged robots on mobile research is emphasised. The capabilities of the computational programs specially dedicated to the analysis of mechanical systems are also discussed. The mobility of the geometric model presented in this paper is a trade-off between natural idea and technical feasibility. Some results of the computational simulations of the movement of the proposed hexapod robotic system are presented and discussed under the premises and assumptions adopted in this work.

1. INTRODUCTION

The main purpose of the work presented in this paper was to present a kinematic and dynamic study of a prototype of a hexapod robotic system.

It is well known that, nowadays tasks in which human presence may be avoided are increasing, such as rote and boring activities, work which imply a great danger and, consequently, very strict security rules (e.g. some of the work carried out in nuclear power-plants), and activities which occur in places where the human being can hardly get (e.g. spatial and underwater exploration). Robotic systems can be used in other fields as well. In order to reduce or avoid the human element it is essential to design and develop mobile robotic systems, which are able to undertake tasks that imply a great deal of danger. Therefore, alternative systems to deal with these tasks must be explored.

Over the last decades, the computational simulation of Multi-Body Systems (MBS) is getting an increasing weight in mechanical design, as developments in control software demand higher mobility, flexibility and dexterity of moving structures, from simple manipulators to autonomous robots. In this field, the legged locomotion systems find several applications, such as walking aid of handicap and elderly people [1], operations in hostile environments or inaccessible locals, as it was shown by Kirchner [2], and even in entertainment applications as, for example the well-known pet robot presented by Fujita et al. [3]. An important advantage of these robotic systems is the ability to walking on rough and irregular surfaces, overcoming obstacles with a high degree of softness. However, one of the major limitations is related to the dynamic equilibrium control, for reasonable operating speeds.

There are two main groups of robotic systems that are currently under study and can be classified as: wheels' robots and legs' robots [4-13]. The former undertake more rapid and soft movements in planar surfaces. However, they are very sensitive to natural obstacles or on surfaces whose contact is not continuous. The USA army estimates that the wheel can only reach 50% of the places on earth. The later, also known as 'walking machines', are able to overcome the problems presented by the wheels' robots as they have a greater mobility and adaptability to irregular surfaces, with obstacles, such as climbing and down the stairs. Nevertheless, it should be noted that the process of modelling and controlling these systems entails much more difficulties. Velimirovic et al. [10] studied a hybrid system which presents the advantages of both wheels and legs robots.

Over the last decade, a number of legged mobile robot prototypes has been developed, from biped to four and six legged robots [3-10]. The first designs tried to imitate animal movements, while later developments had a more realistic and simpler configuration. Several published research works relate to the control and modelling process of the movement, but only a few studies report quantitative results of the system motion characteristics, namely in what concerns to the analysis of the mechanical efforts developed during the movement.

The reasons stated above justify the growing motivation for the study of locomotion robots. It is within this context that the present work was undertaken aimed at designing and developing a hexapod robotic system. In this research a computational program was used, enabling the kinematic and dynamic study of the mechanical systems.

The mechanical complexity of legged locomotion systems is one of the characteristics that make their study both interesting and difficult. Overall, the mobile robotic systems are mechanisms capable of being analysed according to the Classic Mechanic (e.g. Newton-Euler method, Lagrange-D'Alembert formulation, Denavit Hartenberg method, among others) [6,7,11]. Furthermore, a kinematic and dynamic study of mechanical systems is intended to analyse the movement in terms of displacement, velocity, acceleration, coupled with the forces and torques generated and transmitted. This enables the determination of the more critical situations and, consequently, the design of the components. Nevertheless, the expressions resulting from this kind of analysis can make the study of motion characteristics hard. Therefore, computing packages related to the mechanical systems in general become a powerful alternative to the classic approach [15,16].

The use of computers in mechanical design is becoming widespread and leads to the development of general purpose computer aided mechanical design, such as Mechanica Motion, Simpack, Adams, Working Model, and so on. These dedicated computer applications have been widely used to simulate the dynamic loads acting on the parts of a machine or machine system.

In this paper a six-legged walking machine is presented which is biologically inspired according to the kinematic construction. The remainder of the paper is organized as follows. In section two the capabilities of the computational programs are presented. A short description of model geometry is given in

section three. Some results of the computational simulation are presented and discussed in section four. Finally, in the last section the main conclusions from this study are drawn and the perspectives for future research are outlined and analyzed.

2. COMPUTER-AIDED PACKAGE'S CAPABILITIES
In recent years a number of computer-based aids for engineering has emerged, due not only to the development on hardware, but also owing to the improvements on software and mathematical tools. In this context, the computational programs specially dedicated to the kinematic and dynamic analysis of mechanical systems became a powerful alternative to the classic methods. Simulation software allows testing design performance and predicting component's behaviour, prior to building a physical prototype [14,15]. These software packages present several advantages, such as (*i*) the possibility of simulating and visualizing the global motion produced by the creation of virtual models, (*ii*) the opportunity of testing, (*iii*) evaluating and correcting different configurations in real conditions, (*iv*) the capability of observing the functionality of the system, (*v*) the flexibility and easiness to process the information and, above all, (*vi*) the economy of time, materials and money spent on its development [14-17].

By and large, mechanical simulation requires data inputs on components geometry (which can be created via a CAD[1] system) and mass properties, connections between the elements (i.e., degrees of freedom or restrictions/constraints) and external forces acting on the system (springs, dampers, revolute and linear actuators, etc.). From these inputs, the equations of motion are automatically generated and solved for every component, using numerical methods approach, and displacements, velocities, accelerations and reaction forces are computed [16].

In general, the computational programs use numerical methods to allow the solution of the equations of motion of mechanical systems, which are governed, in general, by a set of algebraic differential equations arising from mechanics principles [16]. The main numerical methods used by these computational programs are Newton Raphson's method, Euler's method (the simplest and the fastest method) and Runge-Kutta's method, among others [14-18]. The accuracy of results depends on the choice of integration method as well as on the time step selected. The choice of the time step is a critical parameter in fixed numerical integrators, because it affects significantly the speed and accuracy of the result. In general, a small time step produces more accurate simulation results, but requires more computational effort per given time period than a larger integration time step [15-17].

Additionally, these software packages have automatic collision detection, which is used to simulate body's surface interaction. Results are presented to the designer either in graphic or digital form and the computed data can also be exported to other applications such as spreadsheets or Finite Element Analysis (FEA) programs, where additional analysis, evaluation and post processing can be performed.

Computer-Aided programs, usually, offer a complete array of 3D joints and constraints, from motors, actuators, etc. enabling the user to model all types of complex 3D mechanisms. In commercial programs the moving components (part and assemblies) of the mechanical systems are modelled as rigid bodies that are connected to each other in accordance with realistic connections between components with various types of joints (allowing 0-6 degrees of freedom, DOF). The connections provided by these programs

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[1] The abbreviation CAD is commonly used for both Computer-Aided Drafting and Computer Aided Design. Most of the CAD systems available today are intelligent computerized drafting with limited design capability.

are called ideal or perfect connections, that is, the effects of clearance, mass and friction of joints are neglected. Another limitation of the commercial packages is related to the non consideration of the flexibility/deformability of bodies [16,17].

Figure 1 depicts the working steps during the analysis of mechanisms when a computational program especially dedicated to perform kinematic and dynamic analysis of mechanical systems is used [14].

In short, according to the above mentioned issue, computational packages related to the mechanical systems, in general, become a powerful and user-friendly alternative to the classic methods, mainly in complex systems, such as robots, where the traditional approach is very problematic, if not impossible in some cases.
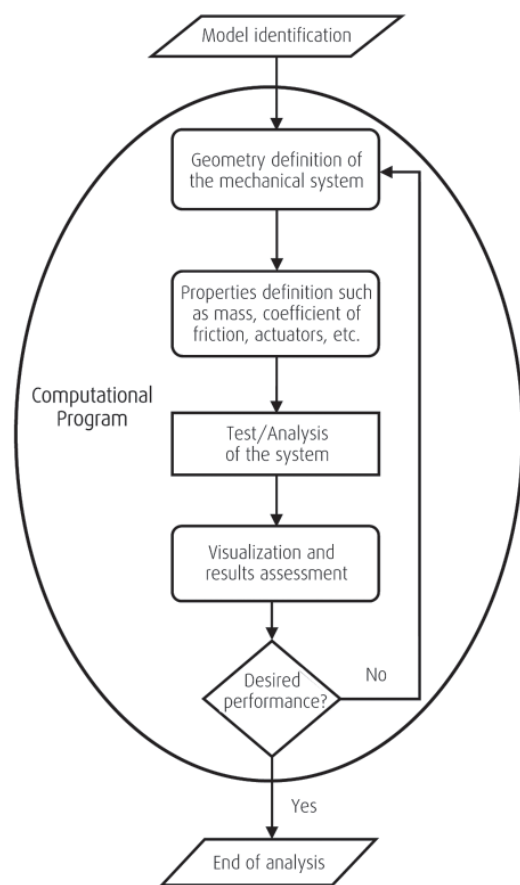

Figure 1 · Working steps with computational programs dedicated to perform kinematic and dynamic analysis of mechanical systems.

3. COMPUTATIONAL MODEL OF THE HEXAPOD ROBOT
The hexapod robotic system presented in this paper was developed bearing in mind several abilities such as, moving on irregular paths, overcoming obstacles, climbing and going down stairs, without compromising its stability and keeping a low overall weigh. After several iterations, a geometric model was achieved, as it is shown in the figure 2. The motors and actuators are not shown in the figure in order to keep the model simple and for illustrative purpose.

The mechanical structure of the hexapod robot consists of one rigid body, load carrying mainframe with six legs, similar and symmetrically distributed. Each leg is composed by four links, interconnected by four revolute joints and attached to the main body by means of a fifth revolute joint. Revolute

motors and linear actuators accomplish traction movement and elevation, respectively. The figure 3 illustrates the kinematic configuration of one leg. The foot of each leg is rigidly attached.

The main specifications imposed in the present phase of this research work were geometric, since it was intended to perform some computational simulations in order to help in the selection of the best suitable values for the main physical parameters used in this model. The model would be able to move in a flat surface and to climb standard stairs. Thus, the main dimensions of the model are length ≈ 750 mm, width ≈ 500 mm and height ≈ 500 mm, being the total weight estimated as 18 Kg. This model was used to generate elementary locomotion behaviour.

For an n_b rigid body system with n_c independent constraint equations, the mobility or the number of degrees of freedom (DOF) is given by,

$$DOF = 6 \times n_b - n_c \qquad (1)$$

This mathematical expression, usually called as Grüebler-Kützback equation, can be used to determine the mobility of the hexapod robotic model [16-18].

Thus, using equation (1) each leg has 2 DOF. Considering six legs the system has a total of 12 DOF. So it is necessary 6 generators of motion (motors) and 6 linear actuators for producing the global motion.

Figure 2 · Mechanical structure of the hexapod robot.

Figure 3 · Kinematic configuration of a leg.

4. SIMULATION AND RESULTS

In this section, two representative computational simulations are presented in order to study the behaviour of the movement characteristics of the pro-

posed legged robot model. In the first simulation, a straight path on a planar, horizontal and non rough surface is considered. The second one deals with climbing a standard set of stairs (height ≈ 170 mm, deep ≈ 280 mm). In the former simulation it was considered both static and dynamic stability, while in the later only static stability was used to simulate the motion. Figure 4 shows an animation sequence of the virtual simulation that corresponds to the second situation.

Static stability implies that, at least, three legs support the structure at any instant, and when in a top view the centre of mass falls into a polygonal region drawn through ground point contacts. In situations where less than three legs support the system, the polygonal region is reduced to a line or a point. In these circumstances the system is considered to be dynamically stable if it maintains the equilibrium. The static stability is limited in terms of speed and manoeuvre ability. On the other hand, the dynamic stability demands constant and complex control system in order to maintain the stability [4,5].

The contact-impact model used for modelling the interaction between foot and ground was based on the nonlinear Hertz contact law together with a dissipative term that accounts for the energy loss during the contact-impact process [21]. Furthermore, the Coulomb's friction law was included to model the friction action between foot and ground [22]. A dynamic term is included in the friction model to account for the stiction and slip phenomena.

The main parameters used in these simulations are height of the legs 500 mm; total weight about 18 kg (including equivalent weight for motors, actuators, batteries, and hardware), the restitution coefficient between ground and feet used during the simulations was equal to 0.9. On the other hand, the friction used to represent the feet and ground assumed different values, namely between 0.01 and 0.90, representing different types of ground and feet interaction. At the start model is assumed to be in contact with the ground, and in an horizontal position.

Working Model Motion, a commercial simulation software, was used to create and analyse the virtual model. This computing package is based on the Classic Mechanic, so-called Newtonian, in which the solutions are obtained by successive approaches [15]. For each situation mentioned above, kinematic and dynamic motion characteristics were performed.

For each leg, the software computes forces and torques that act in all bodies. During the traction movement the applied torque on motor and the force that acts on linear actuators were calculated for a front leg. Figures 5 and 6 illustrate some of these results. As it was expected, the worst situation in terms of mechanical efforts on the components occurs in stairs climbing case. Therefore, these results were used to design the components and to access motion generation requirements. The design was carried out using basic stress/strain concepts.

As pictured in figure 5 the necessary torque to drive each leg is about 10 Nm. The range rotation speed for motors is 10-15 rad/s. These results were corroborated by several published results on physical experiments in this field, namely in what concerns the average values of speed achieved on planar motion, and driving torque needed for motors [9]. These values will be used as base of selection of the motors and actuators needed for actuate the real hexapod robot proposed in this work.

For the straight path movement on planar and horizontal surface the average speed is 0.2 and 2.0 Km/h, respectively, for static and dynamic stability during the motion. This model needs about 50 s to climb the two stairs, as it was shown in figure 4.
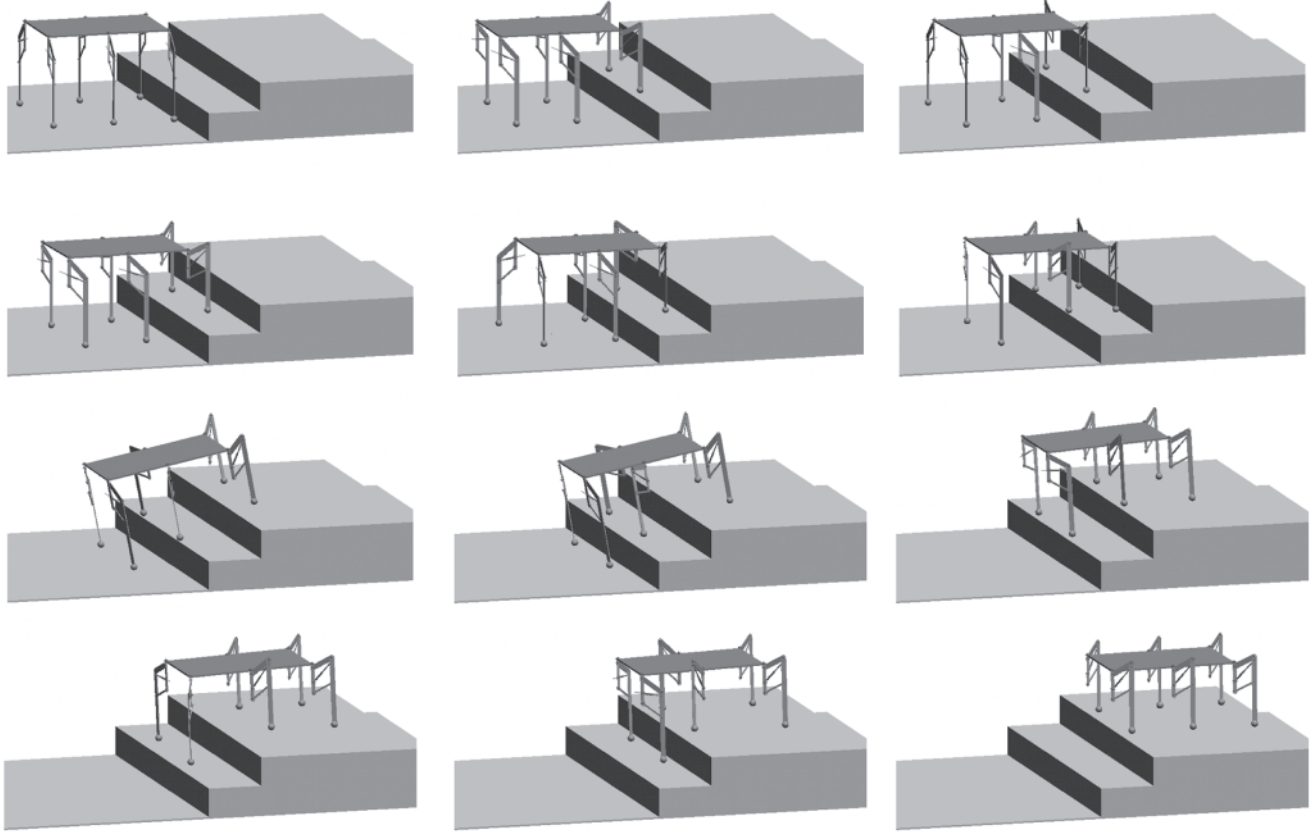
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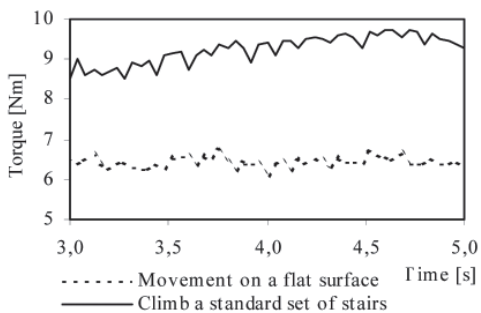**Figure 4** · Animation sequence of a virtual simulation of a standard set of stairs climbing.

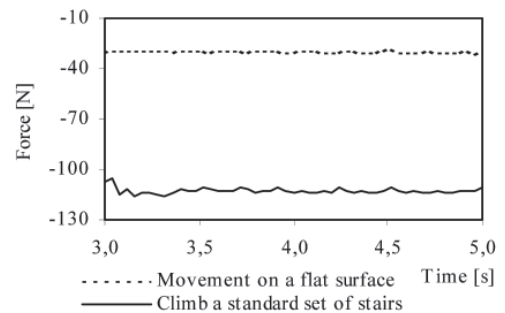**Figure 5** · Torque applied on motor during the traction movement in the front leg.

Figure 6 · Force on linear actuator during the traction movement in the front leg.

5. CONCLUDING REMARKS

In this work, a computational prototype of a hexapod robotic system was studied by using a commercial software especially dedicated to perform kinematic and dynamic analysis of mechanical systems. The merits of this hexapod configuration consist of walking control of a hexapod being easier than that of a biped robot. Furthermore, and the model can adjust its gait and leg movements to compensate for changes due to load and obstacles on the surface. The study of these systems involves several areas of the knowledge, such as mechanical, electronic, computer science, and, eventually, biomechanics engineering.

A computer aided analysis software was used to perform the kinematic and dynamic study of the characteristics of motion of the proposed hexapod robot. Design software simulation allows testing design performance and simulating the behaviour of components prior to building a physical prototype. This enables the determination of the most critical situation and, hence, the design of the

components and motion generators needs.

As it was pointed out in the second section, the computational programs dedicated to the kinematic and dynamic analysis of the mechanical systems are a powerful tool for designers. Indeed, these programs present several capabilities such as real-time simulation. Also, they allow designers to answer questions such as "Does it work as intended?", "Is it strong enough?" and "Is it over or under designed?" without a large investment of preparation and without the underlying technologies.

The study of robotic systems, in general, and legged walking machines, in particular, is recognised as being a very important problem in modern science and technology, because robots have great mobility and flexibility from control software and high degrees of freedom, compared with other automatic machines. Besides, the robotic systems find numerous applications in the most varied sectors of activity. On the other hand, entertainment

application is also an important target at this stage of both scientific and industrial development. It is expected that various kinds of entertainment applications will create a completely new market in the near future.

The main focus of this paper has been on mechanical specifications in order to determine the more critical situations and, consequently, the design of the components.

As further work, new gaits of locomotion for the hexapod will be studied, as well as other legged robotic systems. The gaits should be as similar as possible to the biological locomotion gaits of animals. Therefore, in the near future, this simulation is intended to be used as a 'virtual test rig' for the development of the motion control system, prior to its implementation on the physical model. In addition, the selection of the mechanical and electronic components will be based on the kinematic and dynamic results obtained in the simulations performed in several computational simulations inferred from this work.

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