

## DESIGN OF A HEXAPOD ROBOTIC SYSTEM

J. P. Flores Fernandes  
Mech. Engineering Depart.  
School of Engineering  
University of Minho  
Campus de Azurém  
4800-058 Guimarães  
Portugal  
pflores@eng.uminho.pt

J. C. Pimenta Claro  
Mech. Engineering Depart.  
School of Engineering  
University of Minho  
Campus de Azurém  
4800-058 Guimarães  
Portugal  
jcpclaro@dem.uminho.pt

Fernando Ribeiro  
Industrial Electronic Depart.  
School of Engineering  
University of Minho  
Campus de Azurém  
4800-058 Guimarães  
Portugal  
fernando@dei.uminho.pt

### ABSTRACT

The main purpose of this work was to design 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, using a motion analysis software. This 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 demonstrated. The mobility of the geometric model presented in this paper is a trade-off between natural idea and technical feasibility. Some results of the virtual simulation of the movement of this hexapod robotic system are presented.

### INTRODUCTION

The main purpose of the work presented in this paper was to design a prototype of a hexapod robotic system. 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). Nevertheless, 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.

The analytical 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. Their major limitation is related to the dynamic equilibrium control, for reasonable operating speeds.

Two main groups of robotic systems that are currently under study can be identified: 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 was 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.

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 virtual simulation are presented in section four. Finally, in the last section the main conclusions from this study are drawn and the perspectives for future research are outlined.

## COMPUTATIONAL PROGRAMS

In recent years a number of computer-based aids for engineering have emerged, due not only to the development on hardware but also 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.

These software packages present several advantages, such as the possibility of simulating and visualizing the global motion produced by the creation of virtual models, the opportunity of testing, evaluating and correcting different configurations in real conditions, the capability of observing the functionality of the system, the flexibility and easiness to process the information and, above all, the economy of time, materials and money spent on its development (14-17).

In a general way, mechanical simulation requires data inputs on components geometry (which can be created via a CAD<sup>1</sup> 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 generated and solved for every component, using numerical methods approach, and displacements, velocities, accelerations and reaction forces are computed.

The computational programs use numerical methods to allow the solution of the motion of mechanical systems, which are governed, in general, by a set of algebraic-differential equations arising from mechanics principles. 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 and the time step. The time step is a critical parameter in fixed numerical integrators, because it affects the speed and accuracy of the result significantly. In general, a small time 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.

These 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 these 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 joints (allowing 0-6 degrees of freedom, DOF). The connections provided by these programs are called ideal or perfect connections, that is, clearance, mass and friction of joints is 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 MBS when a computational program specially dedicated to mechanical systems analysis is used (14).

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.

---

<sup>1</sup> 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 (14,16,17).

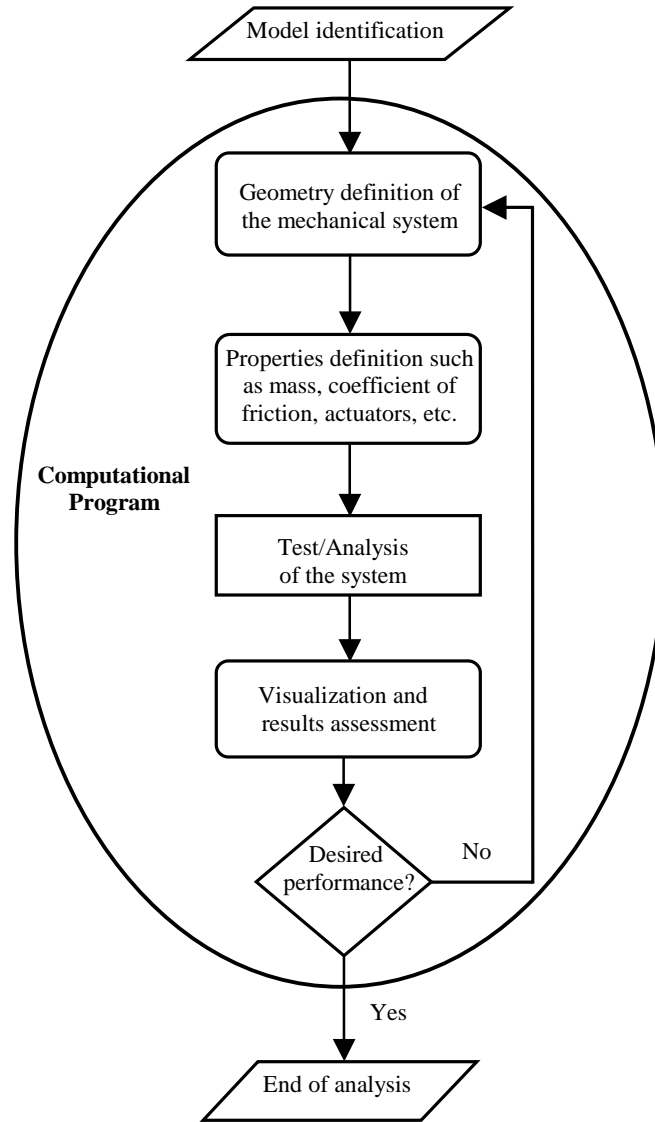


Figure 1 – Working steps with computational programs dedicated to mechanical systems analysis.

### MODEL GEOMETRY

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 mechanical structure of the hexapod robot consists of one rigid, 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 dimensions of the model are length  $\approx 750$  mm, width  $\approx 500$  mm and height  $\approx 500$  mm, being the total weight estimated as 18 Kg. This model is 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

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

This mathematical expression, usually called the Grüebler-Kützbach equation, can be used to determine the mobility of the hexapod robotic model (16-18).

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.

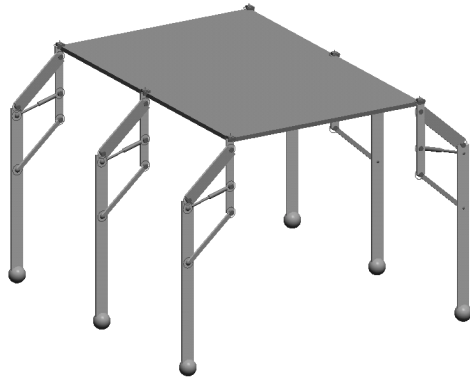


Figure 2 – Mechanical structure of the hexapod robot.

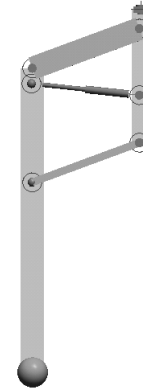


Figure 3 – Kinematic configuration of a leg.

### SIMULATION AND RESULTS

In this section, two representative virtual simulations are presented in order to study the behaviour of the movement characteristics of the proposed 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  $\approx 170$  mm, deep  $\approx 280$  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 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 friction and restitution coefficient between ground and feet is 0.9. At the start model is assumed to be in contact with the ground, and in an horizontal position.

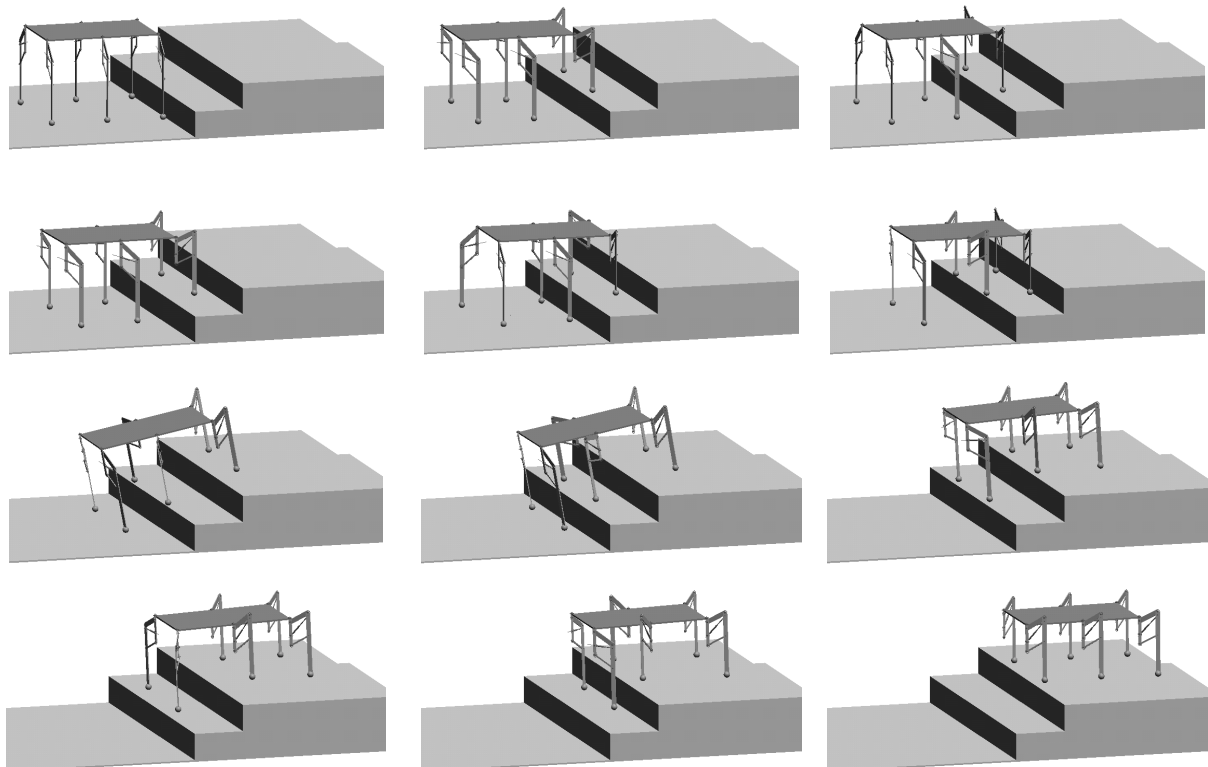


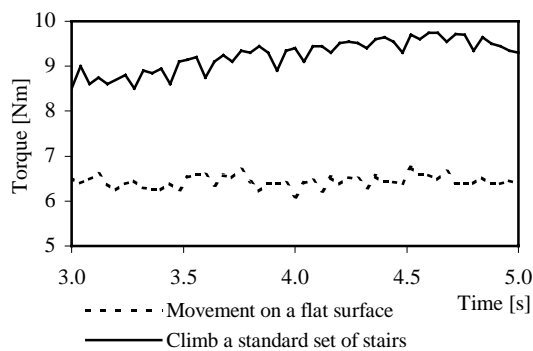
Figure 4 – Animation sequence of a virtual simulation of a standard set of stairs climbing.

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.

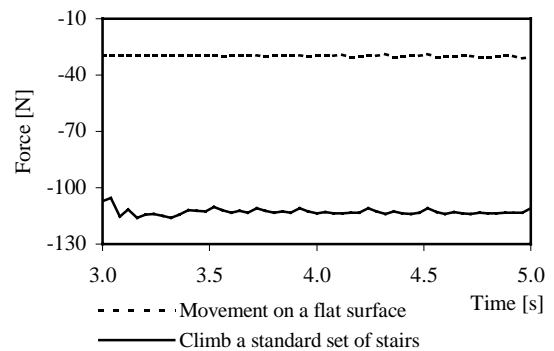
For each leg, the software computes forces and torques that act in all bodies. During the traction movement the applied torque on motor and the force that acts on linear actuators were calculated for a front leg. Figures 5 and 6 illustrate some of these results. As it was expected, the worst situation 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).

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.



**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.**

## CONCLUSION

In this work, a virtual prototype of a hexapod robotic system was designed. The merits of this hexapod configuration consist of walking control of a hexapod being easier than that of a biped robot, and the model can adjust its gait and leg movements to compensate for changes due to load and obstacles on the surface.

A computer aided analysis software was used to study kinematic and dynamic characteristics of motion. 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 study of these systems involves several areas of the knowledge, such as mechanical, electronic, computer science, and, eventually, biomechanics engineering.

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.

## REFERENCES

1. Suzuki, M., Masamune, K., Ji, L., Dohi, T., Yano, H., Development of a robot arm controlled by force sensors as a walking aid for elderly, Robotica, 1998, 16, pp 537-542.
2. Kirchner, F., Hertzberg, J., A Prototype Study of an Autonomous Robot Platform for Sewerage System Maintenance, Autonomous Robots, 1997, 4, pp 319-331.
3. Fujita, M., Kitano, H., Development of an Autonomous Quadruped Robot for Robot Entertainment, Autonomous Robots, 1998, 5, pp 7-18.
4. Machado, J. A. T., Rodrigues, C. M. B., Sistemas Robóticos de Locomoção Quadrúpede e Hexápode: Perspectiva Histórica e Aspectos Gerais de Funcionamento, Robótica e Automatização, 30, 1998, pp 20-23.
5. Rodrigues, C. M. B., Machado, J. A. T., Silva, F. M., Sistemas Robóticos de Locomoção Quadrúpede e Hexápode: Coordenação de Movimentos e Síntese de Sistemas, Robótica e Automatização, 31, 1998, pp 27-32.
6. Silva, F. M. Machado, J. A. T., Dynamic Performance of Biped Locomotion Systems, AMC'98 5<sup>th</sup> International Workshop on Advanced Motion Control, Coimbra 1998, pp 451-456.
7. Abba, G. Chaillet, N., Robot Dynamic Modeling Using a Power Flow Approach with Application to Biped Locomotion, Autonomous Robots, 1999, 6, pp 39-52.
8. Barreto, J. P., Trigo, A., Menezes, P., Dias, J. Almeida, A. T., FBD – The Free Body Diagram Method. Kinematic and Dynamic Modeling of a Six Leg Robot, AMC'98 5<sup>th</sup> International Workshop on Advanced Motion Control, Coimbra 1998, pp 423-428.
9. Berns, K., Ilg, W., Deck, M., Dillmann, R., The Mammalian-Like Quadrupedal Walking Machine BISAM, AMC'98 5<sup>th</sup> International Workshop on Advanced Motion Control, Coimbra 1998, pp 429-433.
10. Velimirovic, A., Velimirovic, M., Hugel, V., Iles, A., Blazevic, P., A New Architecture of Robot with “Wheels-With-Legs” (WWL), AMC'98 5<sup>th</sup> International Workshop on Advanced Motion Control, Coimbra 1998, pp 434-439.
11. Pires, J. N., Costa, J. M. G. S., Modelização e Controlo Posição/Força de Robôs Manipuladores Industriais, Robótica e Automatização, 28, 1997, pp 16-20.
12. Koren, Y., Robotics for Engineers, McGraw-Hill, New York 1985.
13. Craig, J. J., Introduction to Robotics: Mechanics and Control, Second Edition, Addison-Wesley Publishing Company, New York 1989.
14. Fernandes, J. P. F., Análise Cinemática e Dinâmica de Mecanismos com Recurso a Meios Computacionais, Universidade do Minho, Guimarães 2000.
15. MSC/Working Model User's Manual, 1999.
16. Nikravesh, P. E., Computer Aided Design of Mechanical Systems, Prentice Hall, New Jersey 1988.
17. Shabana, A. A., Dynamics of Multibody Systems, John Willey & Sons, New York 1989.
18. Paul, B., Kinematics and Dynamics of Planar Machinery, Prentice-Hall, New Jersey, 1979.
19. Rahnejat, H., Multi-body dynamics: historical evolution and application, Proceedings Institution of Mechanical Engineers, part C, Journal of Mechanical Engineering Science, 2000, 214(1), pp 149-173.
20. Shigley, J. E. and Uicker, J. J., Theory of Machines and Mechanisms, McGraw-Hill, New York, 1981.