CAD DESIGN AND ANALYTICAL MODEL OF A TWELVE BAR WALKING MECHANISM

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Această lucrare prezintă o abordare generală privind proiectarea unui robot mobil păşitor bazată pe aspecte specifice mediului mecatronic cum ar fi proiectarea de tip CAD. Modelul analitic şi simularea mecanismului păşitor utilizat pentru construcţia unei structuri de robot păşitor sunt de asemenea descrise. Metoda conturului vectorial şi metoda geometrică simplă sunt utilizate pentru studiul cinematic direct.

This paper presents a general approach to design of walking robot based upon aspects regarding mechatronic environment such as CAD design. The analytic model and simulation of the walking mechanism that is used for building a walking robot structure is also described. The vector loop and simple geometric method are used for studying forward kinematics.

Keywords: Mechatronics, CAD design, Walking robot, Kinematics, Vector loop.

1. Introduction

The concept of mechatronic includes many types of research fields due to the fact its goal is to study and develop different useful applications including modern machines such as walking robots. Mechatronics is a complex area that combines with success mechanical field with electronics, control systems and embedded software fields. A general overview regarding the main components of a mechatronic system is presented in figure 1[1].

This area of research aims to study and develop several kinds of robots with different useful applications including both mechanical designs and control algorithm, such as quadruped walking robot, personal robot, wall climbing robot, inpipe robot and robot hand [2], [3].

The goal of most researchers in studying walking robots it consists in obtaining energy efficient structures with improved performances in traversing challenging terrains using optimized leg configuration. For this purpose new types of leg designs are studied and optimized for obtaining capabilities comparable to biological walkers [4].

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A new type of walking mechanism design introduced by Dutch physicist and kinetic sculptor Theo Jansen it consists of a twelve bar linkage powered by the wind that walks similar to a crab and it appears in studies of few researchers [5], [6] and [7].

The present paper is structured around four parts. The first part consists in a short introduction; the second part describes how a walking robot can be a part of a mechatronic system and presents the main characteristics of a mechatronic system. The third part deals with the methods used for studying a new type of walking mechanism and highlight the design of the leg structure based upon the CAD design and forward kinematics and finally the fourth part consists in conclusions.
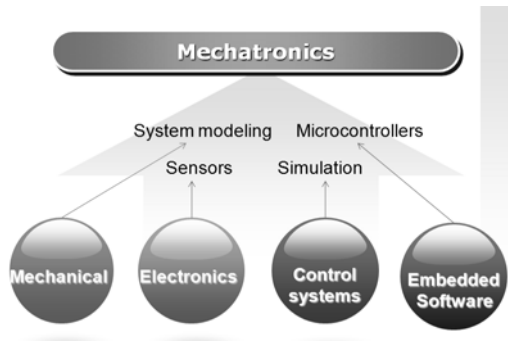

Fig. 1. The main components of a mechatronic system

2. Walking robot as part of mechatronic system

2.1 Classification

Walking robots developed in the field of robotics research that are using legs for traveling have few advantages instead wheel locomotion: less energy consumption, no need for roads, capable to cross obstacles, the contact with soil is minimized at a discrete point, don't destroy surfaces of the ground, climbing abilities and maintaining the body at a specific height during walking. A short classification of walking robots is presented in figure 2 after three main criteria:
- number of legs,
- type of environment,
- purpose.

Generally, people use two types of sensors for dealing with the environment challenges (internal and external type of sensors) and in analogy,

walking robots do the same, especially bipeds. A parallel between the two types of sensors meet both for human and robot behavior is shown in figure 3.
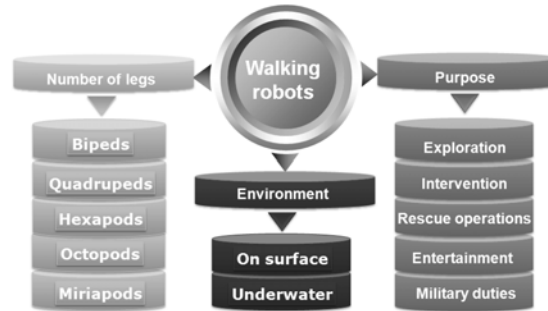

Fig. 2. Classification of walking robots

Another classification regarding walking robots is presented in figure 4, depending on scope that walking robots are build for and on the type of application that it is achieved.

The system of walking robots can be considered as an integrated part of mechatronic systems due to fact that bring together the three major component subsystems: information, mechanical and electronically. In figure 5 is presented an example of functions hierarchy for a walking robot system which consists in three major functions such as mobility, information and protection function that are related to the three subsystems mentioned before. This is done in order to achieve new ideas for design concept. For every function described there are components that sustain it. As an example for the mobility function in case of a walking robot, the main components consists in source of energy, the type of motor and the type of walking mechanism considered for obtaining a good mobility [8].

Also the walking robot system needs a controller for coordinating the movement, a data acquisition system for collecting all the information received from sensors that accomplish the protection function of the system.
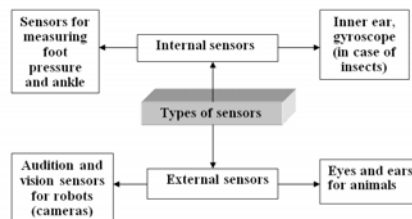

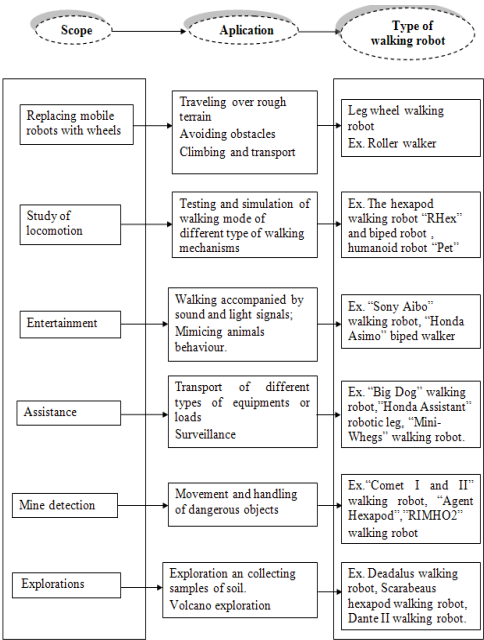Fig. 3. The basic parameters used for studying walking robots

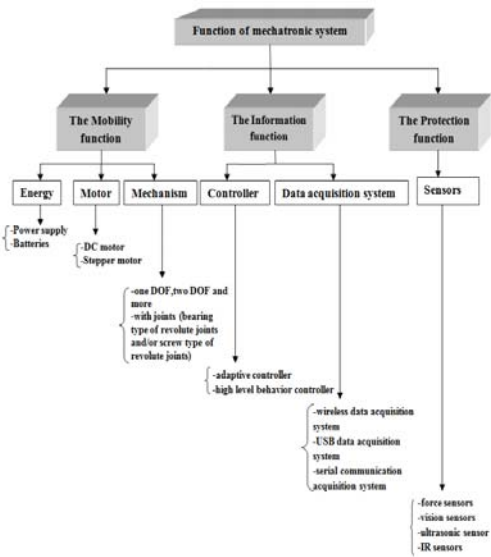Fig. 4. Walking robots classification based on purpose

Fig. 5. An example of functions hierarchy for a walking robot

2.2 The basic parameters in the study of walking robots

In a similar way it can be obtained the other values for the position angles and the coordinates for each point that belongs to the corresponding element.

Among the basic parameters in the study of walking robots the most important is the type of walking which determine other parameters such as: stability, number of legs, leg configuration and method of control. In figure 6 is presented a chart that illustrates the main parameters for studying walking robot. This chart emphasizes the most important parameter without showing the link between it and the rest of parameters.

The investigated mechanism presents:

- a bio inspired leg configuration;
- at least six legs which offer a great stability during walking;
- optimized leg proportions achieved and tested by the inventor;
- a low value of the moment of inertia and torque due to the slow motion;
- articulated legs that help overcome obstacles of certain size.

The walking mechanisms used as reliance for obtaining a specific mobility of the robots are the primary aims of the optimum constructive analysis and offer different advantages regarding manoeuvrability, stability and dynamics. For this reason, researchers are seeking for solution in real world and study the locomotion and behaviour process, the control methods and leg configuration of living creatures which achieved great performances during the evolution [9], [10].
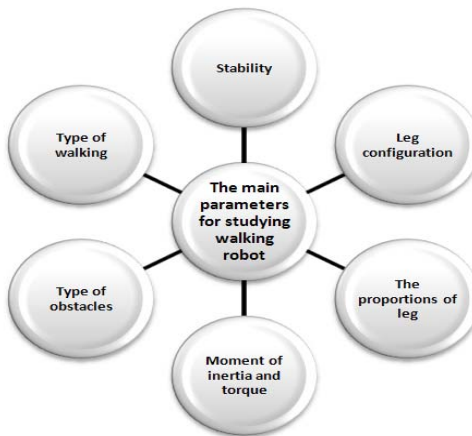

Fig. 6. Walking robots classification based on purpose

3. Study of the walking robot proposed

The present investigated mechanism studied here in order to design and build a new type of walking robot was introduced around 90's by Dutch physicist and kinetic sculptor Theo Jansen similar to the one presented in figure 7, which is designed for analyzing the possibility of using this type of leg configuration in building a walking robot. The proportions of the leg were established with help of evolutionary algorithms which perform well approximating solutions based upon an evolution process similar to natural one. It is necessary to initially identify the objective functions of the investigated system and then to apply an optimization method for obtaining the best solution before building a real model [11], [12].

There are few major steps that should be accomplish during the research stage for building a new model of walking robot based on Theo Jansen walking mechanism:

- kinematic analysis of the mechanism;
- kinetostatic and dynamic analysis;
- optimal synthesis;
- structural analysis;
- simulation of the new optimal structure obtained;
- the design of the prototype.

3.1 CAD design

In the first stage of research it has been chosen a specific method for analyzing the mechanism from a kinematic point of view among different types of methods. A short evaluation and comparative study of methods of kinematic analysis is described in figure 7 [13].

The advantage consists in the fact that a walking robot structure which will be based on this type of leg mechanism will achieve a smooth and stable walk with a reduced number of actuators and energy consumption.

For studying the structure of Jansen type of walking mechanism it was designed in CAD, using two different programs (Solid Works and Pro Engineer), two types of prototypes that are shown in figure 8 together with the 2D sketches for the basic walking mechanism. The first prototype is situated on the top of the image and the second, is located at the bottom of the image. Between the first and the second type of design there is a difference regarding the ending part of the leg mechanism.

For comparison it was used another CAD program for kinematic analysis of the walking mechanism such as Working Model 2D. The graphical results

obtained for velocity and acceleration of the foot during walking are shown in figure 9. The proportions of the mechanism are the same with the one used for obtaining the results presented in this figure. It can be seen that the acceleration of the end point of the foot at the contact with ground has a low value which adds an advantage for using this type of mechanism.

In order to understand better the construction of the leg mechanism and the way it works it should be built an analytical model first for studying and comparing the results between the theoretical part and simulation procedure.

A mathematical model is suposed to be use for determing the position of each element from the closed loop chain mechanism. By knowing the positions of each point of the mechanism it could be obtain the velocities and acceleration values for that points and in particular for the end point of the leg.

Graphical methods

• Advantages:
-Determining kinematic parameters directly through the graphical construction, without using computing relations.
• Disadvantages:
- Smaller precision, the estimation error of 2% for paths, 5% and 10% for speed acceleration.

Graphic-analytical method (method of vector equations)

• Advantages:
- Sufficient accuracy;
-Simple analytical calculations are based on Euler's equations;
-Allow analysis of all points of a moving mechanism
-Develop intuition.
• Disadvantages:
-Heavy workload;
-Not may be used for all mechanisms.
• Disadvantages:
-require accurate data entries that are often obtained from classical methods.

CAD method

• Advantages:
-Allow real time simulation and follow the trajectory described by mobile points.
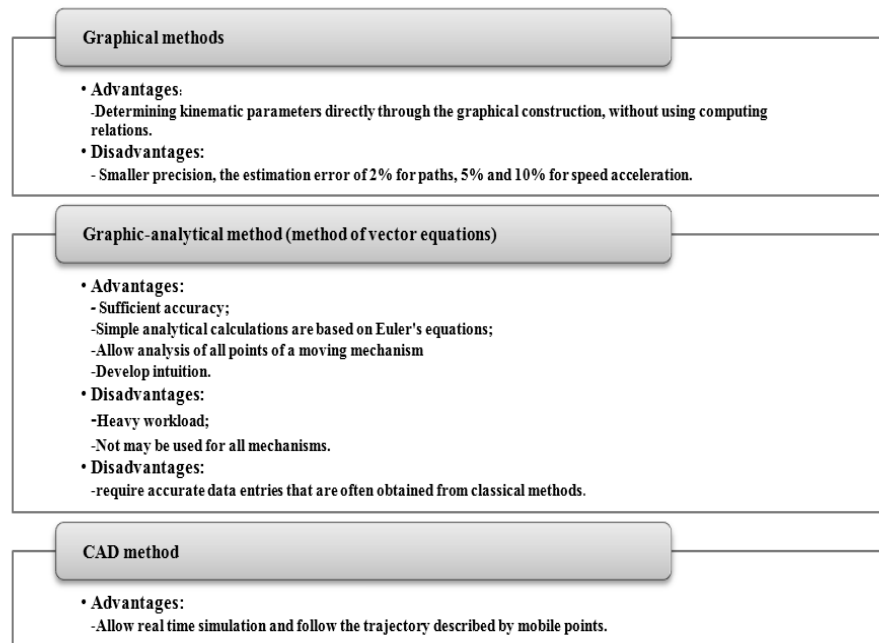
Fig. 7. The comparison between three kinematic analyzing methods

3.2 Forward kinematic analysis based on analytical model

For studying the leg of the mechanism from an analytical point of view it has been chosen as configuration for the leg the kinematic sketch view, as shown in figure 10. An important advantage of using this type of leg design for building new structures it results from the mobility of the mechanism. It has one input

motion at the crank measured by φ [deg] angle, twelve bar elements (including the fix element O_1O_2) and two fix points. The position of centre of the coordinate system is considered in the fix point O_2.
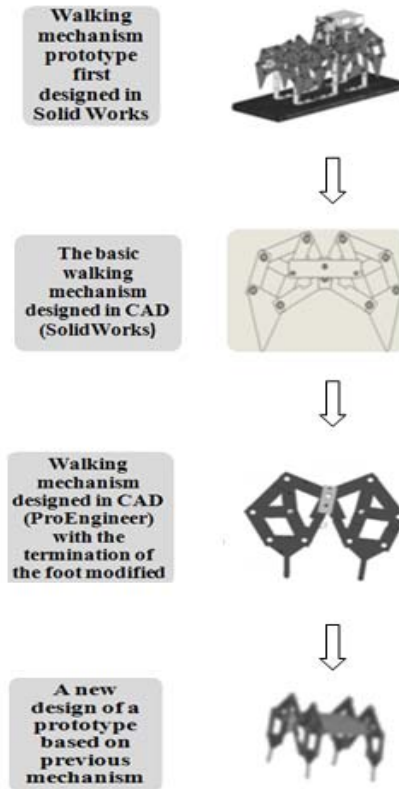

Fig. 8. The prototypes of the walking mechanism built in CAD- the structure with legs and the basic mechanism.

To determine each element position towards coordinate system is used the forward kinematic analysis based upon vector loop method and simple geometric method [13].

The entire structure of the leg mechanism shown in figure 10 is decomposed into four vector loops coresponding to each group of elements analysed in particular.The „φ_i"angles corresponding to each element, with "i" taking values from 1 to 12 are all presented on the sketch.
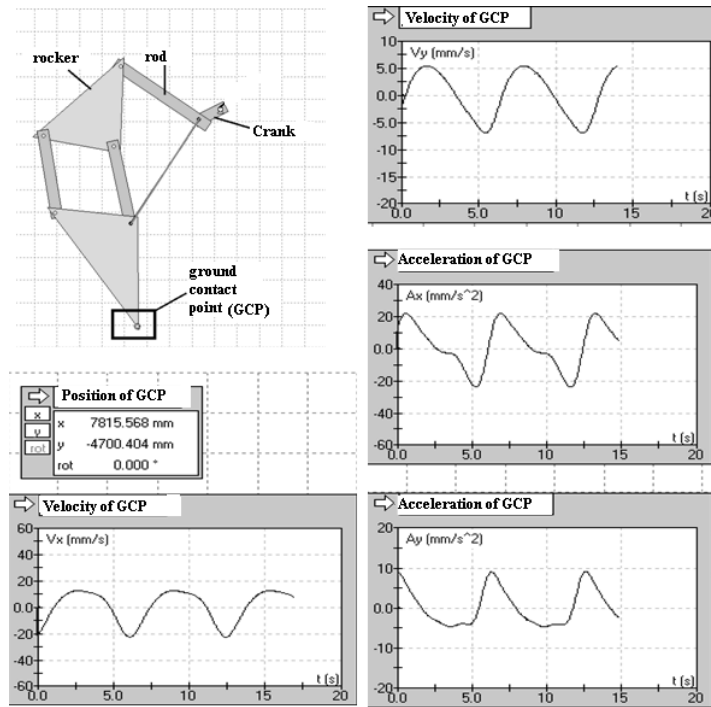
Fig. 9. The results of kinematic analysis, for the end point of the foot of the investigated mechanism, obtained using Working Model 2D software.
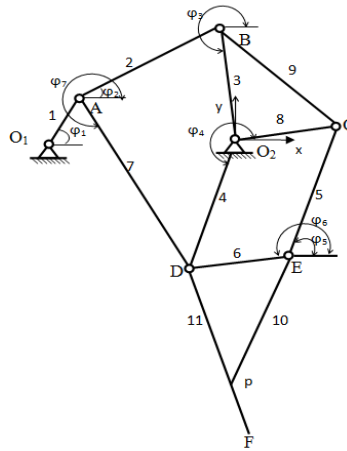

Fig. 10. The kinematic sketch view of one leg of the mechanism.

The entire mechanism structure consists in only one DOF and revolute joints.

In Table 1 are described the contour vector loops for the leg mechanism. As input values for the analytical model we have the lenghts of the elements that are all known and constant, the crank angle φ_1 and as output values are the other position angles for every element and the position of the end point of the leg.

Table 1

Contour loop vector

Contour loop vector	The kinematic sketch view
The first contour loop vector O_1ABO_2 is a four bar mechanism in which φ_1 angle has a know constant input value. For an easier determination for the next contour elements it has been consider O_2 the centre of the coordinate system	
The second contour loop vector O_1ADO_2 represents a reverse four bar mechanism	
The third contour loop vector O_2CED represents an irregular parallelogram. α' represents the angle between O_2C and x axis..	

For the first vector loop contour the equations for determination of position of element AB and BO_2 it can be written as in (1):

$$\bar{l}_1 + \bar{l}_2 = \bar{l}_3 + \bar{l}_0 \tag{1}$$

$$l_1 \cdot \cos \varphi_1 + l_2 \cdot \cos \varphi_2 = l_3 \cdot \cos \varphi_3 + l_0$$
$$l_1 \cdot \sin \varphi_1 + l_2 \cdot \sin \varphi_2 = l_3 \cdot \sin \varphi_3$$
(2)

If will eliminate φ_3 from (2) will obatin:

$$\sin \varphi_3 = \frac{l_1 \sin \varphi_1 + l_2 \sin \varphi_2}{l_3}$$

$$\cos \varphi_3 = \frac{l_1 \cos \varphi_1 + l_2 \cos \varphi_2 - l_0}{l_3}$$
(3)

And if we consider the equations that follow in (5) it can be obtained φ_2 as in (4).

$$\sin \varphi_2 = \frac{-A_1 \cdot A_3 \pm A_2 \cdot \sqrt{A_1^2 - A_3^2 + A_2^2}}{A_1^2 + A_2^2}$$
(4)

$$A_1 = 2l_1 l_2 \sin \varphi_1$$
$$A_2 = -2l_1 l_2 \cos \varphi_1 + 2l_2 l_0$$
$$A_3 = l_1^2 + l_2^2 + l_0^2 - l_3^2 - 2l_1 l_0 \cos \varphi_1$$
(5)

By knowing φ_2 it can be determined the position of point B as in (6).

$$x_B = x_{O_1} + x_A + l_2 \cos \varphi_2$$
$$y_B = y_{O_1} + y_A + l_2 \sin \varphi_2$$
(6)

In a similar way it can be obtained the other values for the position angles and the coordinates for each point that belongs to the corresponding element of the second and the third contour loop vector as in (7) and (8).

$$\bar{l}_3 + \bar{l}_5 = \bar{l}_4 + \bar{l}_6$$
$$l_3 \cos \varphi_3 + l_5 \cos \varphi_5 = l_4 \cos \varphi_4 + l_6 \cos \varphi_6$$
$$l_3 \sin \varphi_3 + l_5 \sin \varphi_5 = l_4 \sin \varphi_4 + l_6 \sin \varphi_6$$
(7)

$$\bar{l}_1 + \bar{l}_7 = \bar{l}_0 + \bar{l}_4$$
$$l_1 \cos \varphi_1 + l_7 \cos \varphi_7 = l_0 \cos \varphi_0 + l_4 \cos \varphi_4$$
$$l_1 \sin \varphi_1 + l_7 \sin \varphi_7 = l_0 \sin \varphi_0 + l_4 \sin \varphi_4$$
(8)

The position of point D is computed in (9) as:

$$x_D = x_{O_2} + l_4 \cos \varphi_4$$
$$y_D = y_{O_2} + l_4 \sin \varphi_4$$
(9)

Where:

$$\varphi_4 = a \cos(\frac{x_D}{l_4}) + x_{O_2}$$
(10)

In a similar manner can be computed the coordinates for point C. Knowing the positions of the C and D points it can be determine the position of point E as in (11):

$$\sqrt{(x_E - x_C)^2 + (y_E - y_C)^2} = CE$$
$$\sqrt{(x_E - x_D)^2 + (y_E - y_D)^2} = DE$$

(11)

Similar, if we know the position of point D and E it can be computed the position for points p and F as in (12):

$$\sqrt{(x_F - x_E)^2 + (y_F - y_E)^2} = EF$$
$$\sqrt{(x_F - x_D)^2 + (y_F - y_D)^2} = DF$$

(12)

The position analysis ends when the coordinates for the end point of the leg F are known.

Locomotion systems such as walking robots are capable to maintain their own energy systems during the equilibrium phase and can be considered as a conservative system defined by a constant total mechanical energy [14].

Considering the twelve bar walking mechanism analyzed in this paper as a conservative mechanical system and characterized by conservative forces, the law of conservation of energy is:

$$\overline{l_i} = F_i / m_i$$
$$F_i = -\frac{\partial E_p}{\partial l_i}, i = \overline{1,12}$$

(13)

Where $\overline{l_i}$ represents the vector of lengths for each element, F_i the forces that act on each element, m_i the masses and E_p the potential energy of the system.

The *Lagrangian* function, *L*, for a system consists in the difference between the kinetic (E_c) and potential energies expressed as a function of positions and velocities described in (14). An important property of the Lagrangian formulation is that it can be used to obtain the equations of motion of a system in any set of coordinates, not just the standard Cartesian coordinates, through the Euler-Lagrange equation as in (15) [14]:

$$\dot{l_i} = \dot{l_1}, ..., \dot{l_{12}}$$
$$L(l_i, \dot{l_i}) = E_c - E_p = \sum_{j=1}^{i} \frac{1}{2} m_i \dot{l_i}^2 - E_p(l_i)$$

(14)

$$\frac{d}{dt}(\frac{\partial L}{\partial l_i}) - \frac{\partial L}{\partial l_i} = m_i \overline{l}_i - F_i = 0 \tag{15}$$

For validating the results obtained from the mathematical model for the leg mechanism was designed and simulated in Matlab environment the kinematic sketch view of the leg.

The graphic that resulted after the simulation is presented in figure 11. It is also presented the trajectory path described by the end point of the leg during a walking cycle. From the graphic it can be obtained the minimum and maximum value of the shape of the trajectory corresponding to the height and length of a step.
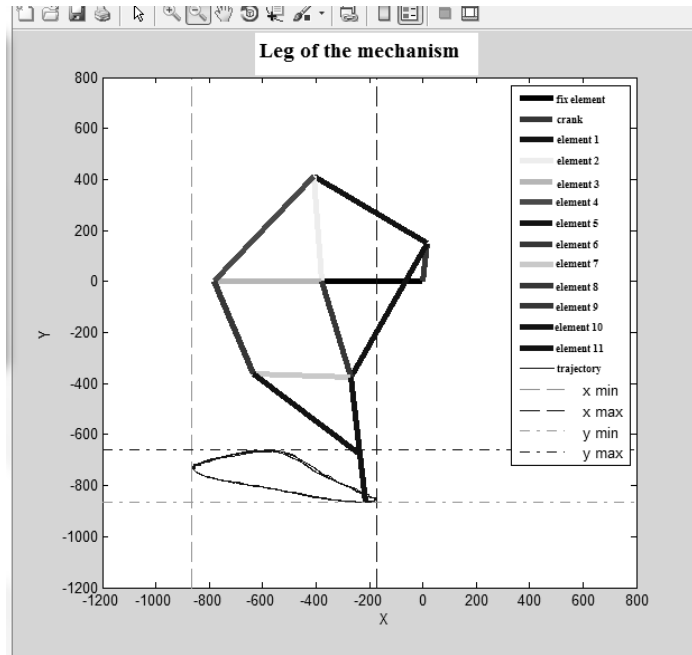

Fig. 11. The kinematic sketch view of the leg of the mechanism

4. Conclusions

The simulation results from CAD and Matlab for the investigated mechanism can be compared with the analytical model presented regarding the forward kinematics. By measuring the step height and length it could be determined the size and type of obstacle that it can be overcome by the leg of the mechanism that it will be implemented in a walking robot structure.

Inverse kinematics and dynamics of the mechanism it will be analyzed further. Also, it is necessary, as a future research, to optimise the structure of the leg in order to achieve a reduced level of energy consumption during walking and of the impact at the contact with the ground.

R E F E R E N C E S

[1]. *Valer Dolga,* Proiectarea sistemelor mecatronice (Mechatronic systems design) 244-263.Politehnica, Timisoara, 2007.
[2]. *I.Maniu, C. Rădulescu, I. Bogdanov, Ş.Varga,V. Dolga, V.Ciupe*, Robotică. Aplicaţii robotizate (Robotics. Robotical applications),Editura Politehnica, Timişoara, 2009.
[3]. *I. Popescu*, Mecanisme-Noi algoritmi şi programe (Mechanisms-New algorithms and programs) , 317- 338, Editura Sitech, Craiova, 1997.
[4]. *M.Buehler , A. Cocosco and Other*, Stable Open Loop Walking in Quadruped Robots with Stick Legs , IEEE Int. Conf. Robotics and Automation , 2348-2353, 1999.
[5]. *D.Giesbrecht, C. Qiong Wu*, Dynamics of Legged Walking Mechanism "Wind Beast", Department of Mechanical and Manufacturing Engineering, University of Manitoba, California, 2010.
[6]. *A.J. Ingram*, A new type of walking machine. thesis*,* University of Johannesburg, 2006. Available at: http://152.106.6.200:8080dspace/handle/10210/598. Accessed 2010-03-10.
[7]. *F. Moldovan, V. Dolga*, Analysis of Jansen walking mechanism using CAD. Solid State Phenomena (Volumes), Robotics and Automation Systems (166 - 167), 297-302,2010.
[8]. *D.Shetty, , R. Kolk,* Mechatronics System Design,2nd Edition,. Cenage Learning, Stamford USA, 2011.
[9]. *J.C. Spagna, D.I. Goldman, P.C. Lin, Koditschek and R. J. Full*, Distributed mechanical feedback in arthropods and robots simplifies control of rapid running on challenging terrain. *Institute of Physics Publishing,* Bioinsp. Biomim.*,* (2), 9–18, 2007.
[10]. *S. Vatău*, Optimizarea constructiv-functionala a robotilor mobili patrupezi (Functional constructive optimization of quadruped mobile robots) ,thesis, Editura Politehnica, Timişoara, 2008
[11]. *T.Jansen* , http://www.strandbeest.com/. Accessed:2011- 03-01.
[12]. *L.Tudose, D. Pop*, Proiectarea optimala cu algoritmi genetici (Optimal design using genetic algorithms), 19-25. Mediamira, Cluj-Napoca, 2002.
[13]. *C. Duca, F. Buium, G. Paraoaru*, Mecanisme (Mechanisms), 106. Gh. Asachi, Iasi, 2003.
[14] *L.N. Hand, J.D. Finch*, Analytical Mechanics, Cambridge University Press, Cambridge, UK, 1998.