Journal of Theoretical and Applied Mechanics, Sofia, 2014, vol. 44, No. 3, pp. 21–30

WALKING ROBOT LOCOMOTION SYSTEM CONCEPTION*

D. Ignatova, E. Abadjieva, V. Abadjiev, Al. Vatzkitchev
Institute of Mechanics, Bulgarian Academy of Sciences,
Acad. G. Bonchev St., Bl. 4, Sofia 1113, Bulgaria,
e-mails: `ignatova@imbm.bas.bg`, `abadjiev@imbm.bas.bg`, `alex@imbm.bas.bg`

[Received 28 March 2014. Accepted 02 June 2014]

Abstract. This work is a brief analysis on the application and perspective of using the walking robots in different areas in practice. The most common characteristics of walking four legs robots are presented here. The specific features of the applied actuators in walking mechanisms are also shown in the article. The experience of Institute of Mechanics – BAS is illustrated in creation of Spiroid and Helicon[1] gears and their assembly in actuation of studied robots. Loading on joints reductors of robot legs is modelled, when the geometrical and the walking parameters of the studied robot are preliminary defined. The obtained results are purposed for designing the control of the loading of reductor type Helicon in the legs of the robot, when it is experimentally tested.

Key words: Rescue walking robots, four legs robots, high reduction gears, hyperboloid gear type Helicon.

1. Introduction

Walking machines have been attempted since the beginning of the technology of transportation machinery with the aim to overpass the limits of wheeled systems by looking at legged solutions in nature. Only since the last part of the 20-th century very efficient walking machines have been designed and built with good performances that are suitable for practical applications carrying significant payload with relevant flexibility and versatility. A natural outdoor environment is the typical scenario for using legged robots [1]. In such scenarios, these mobile machines exhibit many theoretical advantages over conventional vehicles that use wheels or tracks [2]. There are various applications

---

[*] Corresponding author e-mail: `ignatova@imbm.bas.bg`

[1] Spiroid and Helicon are registered marks of Illinois Tool Works, Chicago, Illinois.

for legged robots in outdoor environments including inspection of nuclear power plants [3], volcano exploration [4], forestry related tasks [5] and humanitarian de-mining [6]. The location of the robot must be known in order to achieve efficient exploration whether these projects are carried out by autonomous or teleoperated robots.

A walking robot, which is engaged in practical works can not be developed with ease. This is because: 1) Designing of light weight and high output mechanism which is equipped with multi-degree of freedom driving system and allows independent free movement is difficult; 2) Sufficiently rugged and high performance tactile sensors and force sensors of distribution type which are required for realization of intelligent terrain adaptive walking, or 3D visual sensors have not reached practical application level, yet; 3) Control system which combines mechanism motion with sensor information to generate rational leg motion has not been discussed sufficiently, yet. [7]

However, a walking robot has many practical advantages resulting from motion function peculiar to it. For example: 1) This robot can walk on uneven land in a stable manner and can clear obstacles on the ground in a non-contact manner; 2) Movement in any direction is possible on uneven land without damaging the ground; 3) Generation of stable footing even on uneven land is possible, and freedom of the leg for movement can be utilized for works, too [8].

2. Construction of four – legs robots applicable actuators

Most four legged robots use dynamic stable walking (like nearly all four legged animals), because static stable walking requires at least three points of ground contact. The type of walking robot actuation is chosen according to its purpose, i.e. of pre-defined exploitation characteristics of the leg.

For transmissions of the walking robot legs are used reductors, coupled with (direct current) DC or asynchronous motor. The high frequency of rotation of DC motors and the need to ensure maximum torques values of the actuators under the minimum speed require the application of reductors with high ratios (more than 250–300 to 6000). The application of high reduction gears is associated with creation of the mechanical joint actuators with optimal structural configuration, when the input angular velocity vector is perpendicular to the output angular velocity vector.

The idea of high gear ratio of the electromechanical driving of robot's leg to be split in two by the plane (planetary or harmonic) gear and the high reduction hyperboloid gear of type Helicon, that are coupled, is suggested by V. Abadjiev and is partially realized in the researched project between Institute of Mechanics – Bulgarian Academy of Sciences and Institute of Applied

Mathematics – Russian Academy of Sciences in 1995. The result of the study is the synthesized and developed technological model of hyperboloid gear of type Helicon possessing 105 gear ratio. This gear is designed to be integrated in the actuating of an insect-type robot with six legs [8].

Similar solution of the actuating of joint of mobile robot with four legs is presented in reference [7]. There, the enclosed hyperboloid gear is from the same group spatial face transmissions, known in the specialized literature as Spiroid gears [9, 10, 11].

Spiroid and Helicon gears occupy one essential place among progressive combinations of spatial gears. These spatial gear transmissions are characterized by following geometrical and technological features [8, 9]:

- The mesh region of the two gears is displaced with respect to the offset line O_1O_2 along the axes of both gears. The shape of every additional surface that bounds the gear teeth is conical. Those features are typical of hypoid gear geometry. When a small gear has a cylindrical form, then the large gear becomes a disc and that gear pair is known as Helicon.
- A second group of features is related to the method of generating the toothed surfaces. The small gear, called a Spiroid pinion, has threads whose active flanks are conical helical surfaces with straight-line generatrices and with a constant axial parameter (a constant axial module). The teeth of the larger gear, called a Spiroid gear, are spiral and are generated according to Olivier's second principle. The small gear of the Helicon gear set, called a Helicon pinion, has threads whose flanks are cylindrical helical surfaces. The teeth of the larger gear of the Helicon gear set (Helicon gear) are spiral and are generated according to Olivier's second principle. Those features are typical for the technology of worm gears manufacture.
- Because of the technological similarity of the worm and Spiroid (Helicon) gears, the Spiroid and Helicon pinion, respectively play a determining role in the synthesis and design of those gears. The geometrical resemblance between the Spiroid pinion (and essentially the Helicon pinion) and a classical cylindrical worm, determines the pinion manufacture technology. Thus, technology limits the thread numbers, usually not greater than 6, and the possible gear design ratios, i.e. their basic kinematics characteristics - the angular velocity ratios. A possible interval of reduction concerning these spatial transmissions is $i_{12} \in [10, 200]$. This fact, does not limit the possibility of obtaining gear sets with angular velocity ratios not belonging to this interval. From an exploitation point of view, Spiroid and Helicon gears have the following characteristics. The research in references [9] to [12] shows that the Spiroid gear sets have higher loading capacity than the cylindrical worm gears. This fact

is explained by more favourable position of contact lines in the mesh region and by larger values of the contacting surfaces curvature radii. A large number of simultaneously contacting teeth is the typical characteristic of the Spiroid gears. It is known [9], that for ratios in the interval [10, 60] the number of simultaneously contacting teeth of Spiroid and Helicon gears is 3–4 times larger than for the wormgears.

- One essential characteristic of the considered class of spatial gears is the simplicity of backlash control. This is related to the constant axial pitch of a Spiroid pinion and the conical form of a Spiroid pinion reference surface. Thus, the backlash control between the tooth flanks is obtained by the pinion displacement along its axis. The backlash regulation in this case is performed by the gear displacement along its axis, since the Helicon gear form is a disk. This is why, these gear pairs are successfully applied, when the accurate work of the mechanism requires a without backlash meshing.

3. Structural-constructive, kinematics and force characteristics of the studied model

Graphic model of insect-type three-link leg. The graphic model is based on the constructive characteristics of the mobile robot's leg, which is an object of study in [7]. As it is shown in Fig. 1, the leg obtains three-link open structure, containing three rotational joints R_1, R_2 and R_3. The joints R_2 and R_3, connecting the links L_1, L_2 and L_3, respectively are with parallel axes of rotation. The kinematics joint R_1, which is formed between the robot corpus and the link L_1, has axis of rotation perpendicular to the axes of R_2 and R_3. During the model design, its construction elements are developed as a 3D object in Auto Cad, as it is given their mass characteristics. The elements, included in the drives (including the encoder) are presented as compact bodies with mass equal to the same one cited in the catalogue. The displacement of the mass center is determined by the external geometry of the assembled units.

Kinematics and force characteristics of the joint drives. The kinematics and force characteristics of the leg actuator of the studied mobile robot are shown in Fig. 1. They are chosen analogically to those in publication [7]. Their special feature is using the two-stage motor-reductor with external stage – spatial gear type Helicon (see Fig. 2).

This type assembly construction ensures partially or fully limitation of the movement of robot's legs, under the external forces (forces reactions in the robot foot), without applying additional brake efforts. This circumstances is important for construction of the hardware and software of the control on the walking of the mechanical system

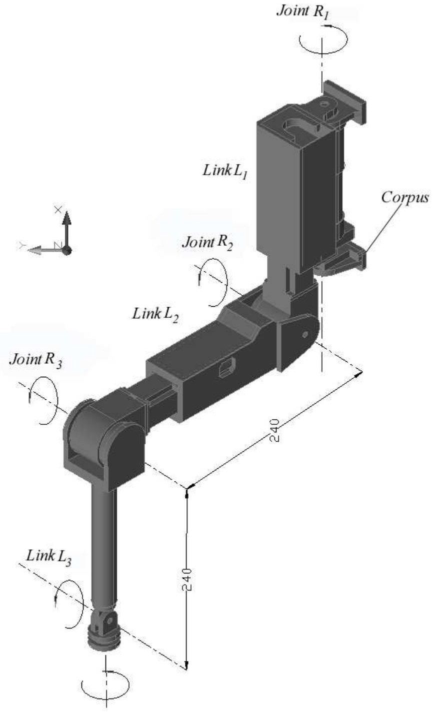


Fig. 1. Insect legs model of insect-type robot: joint R_1 – motor power (W) 14, motor no load speed (rpm) 4800, motor stall torque (mNm) 105, Planetary reductors gear possessing ratio 246:1, joint angle (degrees) ±80; joint R_2 – motor power (W) 72, motor no load speed (rpm) 5300, motor stall torque (mNm) 510, Planetary reductors gear ratio 14:1, Spiroid reduction 20.5: 1, joint angle (degrees) $+45{:}\ -90$; joint R_3- motor power (W) 26, motor no load speed (rpm) 5500, motor stall torque (mNm) 177, Planetary reductors gear ratio 14:1, Spiroid reduction 20.5: 1, joint angle (degrees) $+10{:}\ -135$

Fig. 2. Helicon gear pair: gear ratio 1:20.5; offset – 17 mm

4. Choosing the locomotion of the walking robot

The mentioned specific characteristics of the studied types of robots are in relation with the ensured possibility for realization of definite type locomotion. The force loading in joints reductors depends on the following parameters of the chosen locomotion:

– *Configuration and dimensions of the translocation zone (reachable area) of one leg.* The translocation zone is a plane figure – a locus of the geometrical center of the foot, when it forms new foot/ground interaction point of the robot, when its mass center is static.

– *Character of the velocity function, when the robot moves.* This function is important for inertial loadings of the elements, forming the robot construction, and for the loading of the drive's joints, respectively.

The aim of the article is a study of the locomotion of the walking robot with maximal long step, when the velocity for the moving of corpus mass center is maximal for reaching the given in Fig. 1 boundary values for the joints' coordinates.

As it was mentioned, the four legs robot keeps its statical stability, with three or four foot-ground interaction legs. In both cases, the projection of robot's mass center has to lie on the supporting triangle or quadrangle. When the foot-ground interaction legs are three, the opportunity for moving is limited by the line between the two diagonally displaced supporting legs. If it is accepted that every leg performs equal movement, dephasing in time in relation to other legs, hence that the zone of moving of the corpus with three foot-ground interaction legs is two times smaller then for the four legs.

In this concrete case, it is accepted the locomotion with four foot-ground interaction legs. The corpus of the robot is moved forward, when every leg is moved and positioned, is shown in Fig. 3.

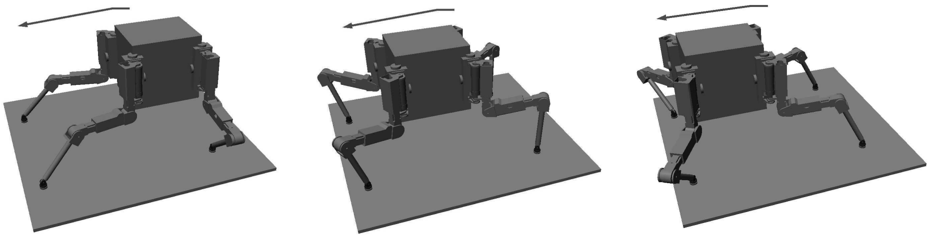
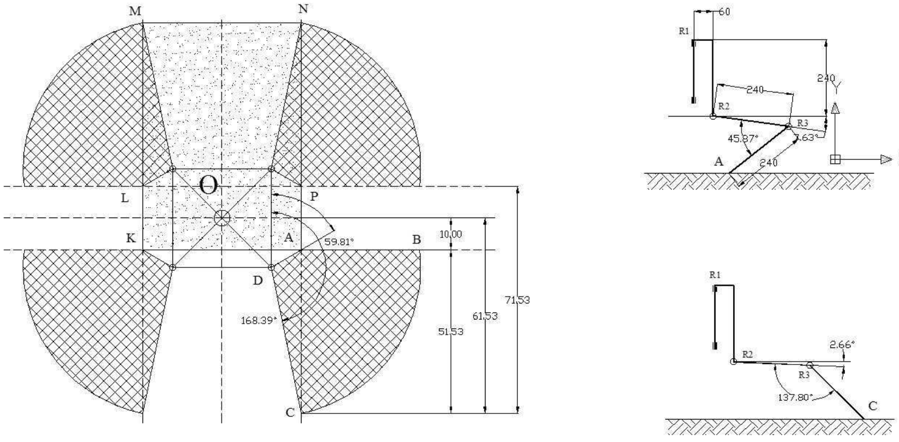


Fig. 3. Locomotion (gait) with four supporting legs

As it is shown in Fig. 4, the front legs are always placed in front of the mass center of the robot (the zone between the lines MN and LP), and the back legs-behind the mass center. The center is the zone between lines

AK and RC. The hatched zones in Fig. 4 are the achievability zones for every leg, with fixed ground clearance – 0.15 m. The step with length 0.515 m is realized by movement of the legs, closed to the corpus (segments ML, NP, KR and AC), when the joints' limitation are taken into account. At least half of the achievability zone for every leg (hatched areas) is used in order to keep the static stability.



(a) (b)

Fig. 4. Geometric parameters of locomotion: (a) achievability areas for the foot of every leg, for chosen gait with length 0.515 m and ground clearance 0.15 m; (b) configuration $R_1R_2R_3$ of the legs in two final positions

The reserve of the static stability is 0.10 m, i. e. the corpus mass center always remains in the zone with the following dimensions: $0.20 \times X$ m (X is distance between the two parallel lines MR and NC of the fulcrums of the feet).

5. Modelling of the joints' loading

The used approach. Determination the loading in joints of the mobile robot's legs is related to analysis of the realized by them translocations, velocities and accelerations. The present software products simplify considerably solution of the reverse task of robotics – finding the joints coordinates, when there are given the same generalized coordinates. In this study, the following approach is used for analysis of the joints' loadings:

– It is accepted that the branched structure of four-legs robot is statically defined;

– The robot feet are fixed to the terrain;

– A law of moving is applied on the mass center of the corpus and then it reaches its maximal velocity of 1.5 m/min, accordingly [7].

– The virtual horizontal moving is designed using the software 4D Visual Nastran, when one step with 0.515 m length is performed and then, the variation of the joints coordinates of the legs is determined, as a function of time t.

– The determined joints functions are entered as a task for the motors in the legs.

– The realized law for moving of the body is verified and it is compared its correspondence with the same one initially entered, when the legs are active.

– The corresponding mass characteristics are entered for every robot element; the material type and according to the type – the density and strength characteristics.

– The loading on the active joints of the legs is read, by which the corpus of the robot is moved.

Analysis of the movement in the joints, when the moving of the corpus is given. On the mass center of the robot's corpus is applied a law of moving according to the upper described study approach, which realizes the velocities and accelerations, shown in Fig. 5.

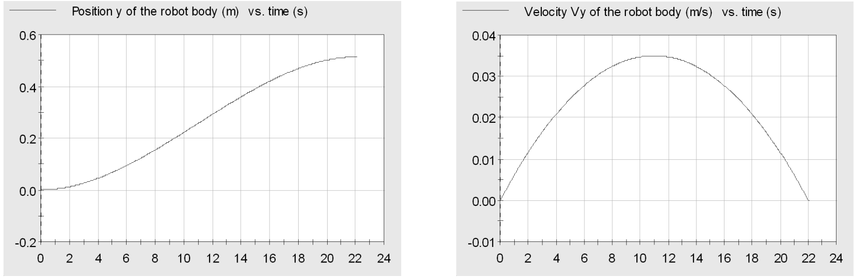
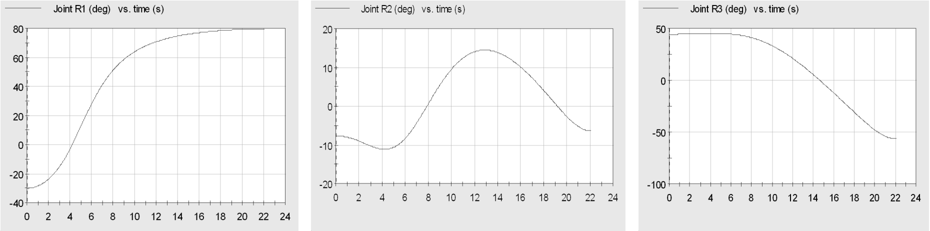


Fig. 5. Variation of the position and velocity of the mass center of the corpus

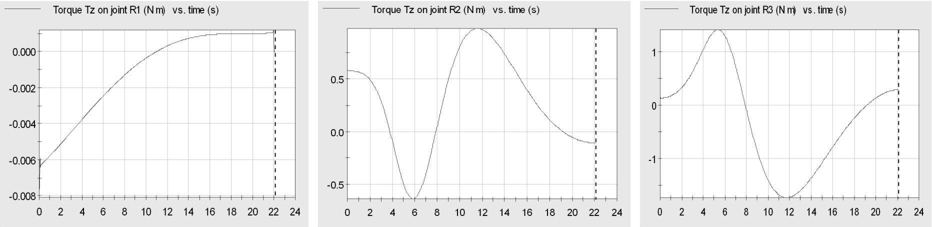
The shown in Fig. 6 variations of joints' coordinates of the rotation joints R_1, R_2 and R_3 corresponds to the upper mentioned law.

The functions presented in Fig. 6 are given as a task for the motors in active robot's legs. The control for correspondence between the given and realized moving of the body ***does not exceed*** the positional exactness from



(a) (b) (c)

Fig. 6. Variation of joints coordinates: (a) in joint R_1; (b) in joint R_2; (c) in joint R_3



(a) (b) (c)

Fig. 7. Necessary motor moments: (a) in joint R_1; (b) in joint R_2; (c) in joint R_3

0.0001 m of the calculated in 4D Visual Nastran model.

Analysis of the loadings in joints. The loading in the joints of the legs depends on the mass and the inertial characteristics and also from that part from the mass of the corpus, which loads the given leg. In borders of one step, the corpus is moved away and loads the different foot-ground interaction legs with variable forces and moments. For the chosen and described locomotion of four supporting foot-ground interaction legs, the variable weight of the corpus on every leg is described with the following dependency:

$$F = G(L - X)L^{-1},$$

where F is the loading mass force, G is the weight of the corpus; L is the distance between one sight placed supporting legs; X is the moving of the corpus $X = [0.1\ \mathrm{m}, 0.615\ \mathrm{m}]$.

The used software takes into account inertial loadings on all elements in robot's structure. The necessary motor moments in joints R_1, R_2 and R_3 are presented in graphics in Fig. 7.

6. Conclusion

The received values of the driving moments in each joint are transformed in power for the corresponding driving joints. The calculated values of the power are applied in control of driving in the process of experimental study.

REFERENCES

[1] Cobano, J. A., J. Estremera, P. Gonzalez de Santos. Location of Legged Robots in Outdoor Environment. *J. of Robotics and Autonomous Systems*, **56** (2008), 751–756.

[2] Todd, D. J. Walking Machines: An Introduction to Legged Robots, Kogan Page Ltd., 1985.

[3] Russell, M. ODEX I: The First Functionoid. *Robotics Age,* **5** (1983), No. 5, 12–18.

[4] Bares, J. , D. Wettergreen. Dante II: Technical Description, Results, and Lessons Learned. *International Journal of Robotics Research*, **18** (1999), No. 7, 621–649.

[5] Timberjack. Available: `www.timberjack.com/development/conceptdevelopment.htm`, 2004.

[6] Huang, Q. J., K. Nonami. Humanitarian Mine Detecting Six-legged Walking Robot and Hybrid Neuro-walking Control with Position/force Control. *Mechatronics*, **13** (2003), 773–790.

[7] Santos, P., J. Galvez, J. Estremara, E. Gracia. SILO4. A True Walking Robot for the Comparative Study of Walking Machine Techniques. *Robotics & Automation Magazine*, **10** (2003), No. 4, 23–32.

[8] Abadjiev, V., D. Okhotsimsky, A. Platonov. Research on the Spatial Gears and Applications, Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Preprint No. 89, Moscow, 1997, 25 pp.

[9] Bohle, F. Spiroid Gears. A New Development in Gears of the Skew-Axis Type. *Machinary*, **62** (1955), No. 2, 155–161.

[10] Dudley, D. Gear Handbook. The Design, Manufacture, and Application of the Gears, New York-Toronto, London, McGRAW-HILL BOOK COMPANY INC., 1962, 24–35.

[11] Nelson, W. Spiroid Gearing. Part 1 – Basic Design Practices. Mashine Design, 16 Febr. 1961, 136–144.