Effect of Friction Models on Snake Robot Performance

Hadi Kalani and Alireza Akbarzadeh

Abstract—**In this paper, performance of a 16 link snake robot in serpentine locomotion using two friction models is investigated. Both Coulomb and viscous friction models are considered. Snake performance as defined by ratio of energy consumption to distance travelled is used as optimization goal. Key kinematics and dynamics parameters are identified. Dynamics and kinematics equations of snake robot are used to perform simulation and obtain results. Taguchi method is utilized and orthogonal array table is constructed. ANOVA technique is used to analyze the statistical significance of kinematic and dynamic parameters. Using Taguchi method optimum parameter settings effecting performance of snake robot are determined. The snake robot is also modeled in WEBOTS software. It is shown forward motion is obtained.**

Index Terms—**Snake-like robots; Taguchi method; DOE; Energy consumption; Serpentine gait; Kinematics; Dynamics.**

I. Introduction

The environmental conditions in search and rescue operations are not known in advance. Therefore, robots that allow better navigation in such environments are advantages. Snake locomotion provides several advantages over traditional forms of locomotion used by both animals and machines. Due to their elongated form and lack of legs, snakes have compact cross-sections and thus can move through very thin holes and gaps. Snake robots were first introduced by Hirose [1]. Since then many snake robots are designed. Snake robots may be designed to move in water and land [2]. Serpentine movement is one of the quickest and most common locomotion used by real snakes. Locomotion is accomplished by propagating a wave in the form of the serpenoid curve throughout the snake robot. In other words, locomotion is only accomplished through shape changing, like a real snake. Hirose understood that main basis for forward propulsion, using the serpentine gait, is anisotropy in the friction coefficients between the lateral and tangential frictions. Therefore, he used small wheels in direction of links which are placed on the bottom of them. Bayraktaroglu [3] presented a new way for producing body shape of snake robot which uses circles with constant radius and polynomial functions. Conkur [4] considered the trajectory of snake robot. Lio [5] optimized the serpenoid curve by using Genetic Algorithm (GA) and presented a new trajectory for snake robot. Ma et al [6] proposed serpentine curve and showed that this curve is very similar to serpenoid curve.

Hasanzadeh and Akbarzadeh [7] presented a novel gait, forward head serpentine (FHS), for a two dimensional snake robot. In their work, GA was used to find FHS gait parameters and results were validated using experiments. Hasanzadeh and A. Akbarzadeh [8] applied GA to optimize CPG-network parameters of a snake robot in order to achieve maximum robot speed. Next, they found relations between optimal CPG-network parameters and environmental conditions for snake robot with different numbers of links. Next, they proposed a new method that can be used with a controller to provide instantaneous changes in environmental conditions. They also generated a novel gait, FHS gait, for snake robot [9]. By using the proposed gait, the head of snake robot always remains in the general direction of motion. The friction models presented in literature on snake robots are based on a Coulomb or viscous-like friction model and such models are explained [11, 12 13]. Hopkins [14] investigated the relationship between snake-inspired robot dimensions, performance and velocity. He found that snake robots share many common characteristics which allow them to be easily grouped under general classification.

This paper is organized as follows: first kinematics and dynamics of a snake robot using both Coulomb and viscous models are obtained. WEBOTS software is used to simulate the kinematic model. To find the optimum kinematics and dynamics parameters of a 16 link snake robot, Taguchi method is applied. Effects of parameters and optimum levels using both friction models are determined. Finally, confirmation runs are performed using the dynamic model.

II. Snake Robot Model

The serpenoid curve is used for generating serpentine locomotion. The curvature function is defined as follows

$$\rho(s) = -\frac{2K_n\pi}{L}\sin\left(\frac{2K_n\pi s}{L}\right) \tag{1}$$

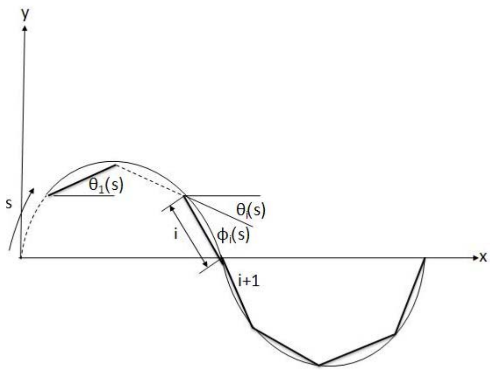

Figure 1. Scheme for fitting the serpenoid curve

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Where L is the total length of snake robot, K_n is the number of undulation, α is the initial winding angle and s is the body length along the body curve, as shown in Fig. 1.

Since $s = \frac{1}{\rho}\varphi$, so we have

$$d\varphi = \rho\, ds = \int_{s+(i-1)l}^{s+il} \frac{-2K_n\pi\alpha}{L}\sin\left(\frac{2K_n\pi u}{L}\right)du \quad (2)$$

After simplifying, the relative angles are obtained as follows:

$$\varphi_i(s) = -2\alpha\sin\left(\frac{k_n\pi}{L}\right)\times\sin\left(\frac{2k_n\pi s}{L} + \frac{2k_n\pi i}{n} - \frac{k_n\pi}{n}\right) \quad (3)$$

Where n is the number of links and l is the unit length of link.

Next, it is demonstrate that serpentine gait is realized when a snake robot is equipped with wheels and serpenoid curve, (3), is used to derive the motors. To show this, Webots software is used. Webots is a professional mobile robot simulation software package. Wheels are also placed at the bottom of each link of snake robot. Fig. 2 shows the simulation of snake robot with 16 links. When K_n=1, 2. As shown in this figure, forward progression is achieved.

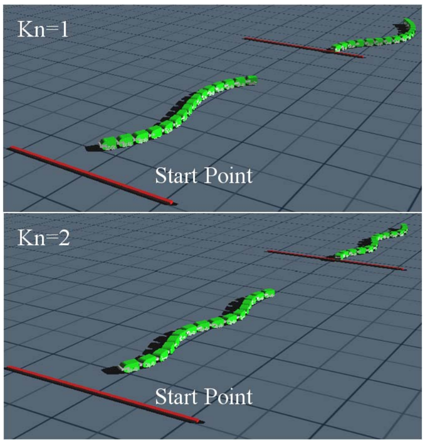

Figure 2. Simulation of snake robot in Webots

Relative value of angle velocities and angle accelerations can be obtained by differentiating (3),

$$\dot{\varphi}_i(s) = \frac{-4\alpha k_n\pi}{L}\sin\left(\frac{k_n\pi}{L}\right)\times\sin\left(\frac{2k_n\pi s}{L} + \frac{2k_n\pi i}{n} - \frac{k_n\pi}{n}\right)\dot{s} \quad (4)$$

$$\ddot{\varphi}_i(s) = \frac{-4\alpha k_n\pi}{L}\sin\left(\frac{k_n\pi}{L}\right)\times\sin\left(\frac{2k_n\pi s}{L} + \frac{2k_n\pi i}{n} - \frac{k_n\pi}{n}\right)\ddot{s}$$
$$\frac{-8\alpha\, k^2 n\pi^2}{L^2}\sin\left(\frac{k_n\pi}{L}\right)\times\sin\left(\frac{2k_n\pi s}{L} + \frac{2k_n\pi i}{n} - \frac{k_n\pi}{n}\right)\dot{s}^2 \quad (5)$$

From Fig. 2, the relation between relative angle and absolute angle is obtained as,

$$\theta_i = \theta_1 + \sum_{k=1}^{i-1}\varphi_k \quad (6)$$

$$\dot{\theta}_i = \dot{\theta}_1 + \sum_{k=1}^{i-1}\dot{\varphi}_k \quad (7)$$

$$\ddot{\theta}_i = \ddot{\theta}_1 + \sum_{k=1}^{i-1}\ddot{\varphi}_k \quad (8)$$

Where θ_i, $\dot{\theta}_i$ and $\ddot{\theta}_i$ are the absolute value of joint angle, angle velocity, and angle acceleration of i^{th} link with respect to the x-axis, respectively. Obviously, by consider Fig. 3, the kinematic of snake robot can be easily obtained. Also position, velocity and acceleration for center of gravity of each link can be calculated as follows,

$$x_{ci} = x_b + \sum_{j=1}^{i-1} l_j\cos\theta_j + d_i\cos\theta_i \quad (9)$$

$$y_{ci} = y_b + \sum_{j=1}^{i-1} l_j\sin\theta_j + d_i\sin\theta_i \quad (10)$$

Where (x_b, y_b) is coordinate of the end of tail link. It should be mentioned that, by knowing position and absolute angle of the tail link, the framework of snake robot can be determined. The generalized coordinates are selected as follows,

$$q_j = [\theta_1, \theta_2, ..., \theta_n, x_b, y_b] \quad (11)$$

The equation of motion can be written as,

$$\frac{d}{dt}\left(\frac{\partial K}{\partial \dot{q}_i}\right) - \frac{\partial K}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i^{nc} \quad (i = 1,2,..n+2) \quad (12)$$

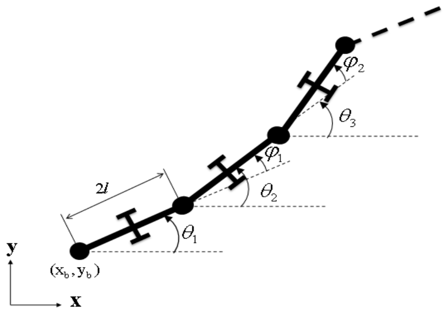

Figure 3. Schematic of snake robot

where K is kinematic energy, Q_i^{nc} is non-conservative forces and V is potential energy. Actuators torques and friction forces are non conservative forces. During locomotion, the center of gravity of each link remains on the ground. Therefore, the potential energy will be zero. By solving the Lagrangian formulation [7, 10], the dynamic model for snake robot can be derived as,

$$B\tau = M(\theta)\ddot{q} + H(\theta,\dot{\theta}) + F(\theta) \quad (13)$$

where M(θ) is the (n+2)×(n+2) positive definite and symmetric inertia matrix, $H(\theta,\dot{\theta})$ is the (n+2)×1 matrix related to centrifugal and Coriolis terms, F(θ) is an (n+2)×1 matrix related to frictional forces, B is an (n+2)×(n-1) constant matrix. τ, is (n-1)×1 matrix, represent input torques and $q, \dot{q}, \ddot{q}$ are (n-1)×1 matrix of generalized coordinates and their derivatives. $\theta, \dot{\theta}$ and $\ddot{\theta}$ are n×1 matrix of links absolute angles and their derivatives.

The average power consumption per unit distance (E) can be calculated as,

$$E = \frac{\sum_{i=1}^{n} \int_{0}^{T} \tau_i \omega_i}{L_{dis}} \tag{14}$$

where T is simulation time, τ_i and ω_i represent the torques and the absolute velocity angle of the i^{th} link, respectively. In order to generate significantly different friction coefficients in normal and tangential directions a fixed wheel axis or a blade is attached to each link [1]. Two different friction models are considered; simple Coulomb and viscous friction models. Friction forces used in Coulomb and viscous friction models are formulated using (15) and (16), respectively. Fig. 4 shows the free body diagram of n-link snake robot in a snapshot.

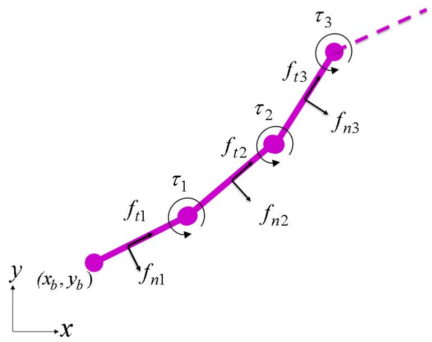

Figure 4. Free body diagram of n-link snake robot

$$f_{ei} = \begin{cases} -m_i g \mu_e sign(v_i^e) & v_i^e \geq v_c^e \\ -v_i^e \dfrac{m_i g \mu_e}{v_c^e} & v_i^e < v_c^e \end{cases} \tag{15}$$

$$f_{ei} = -m_i C_e v_i^e \tag{16}$$

where $e = t, n$ (t and n represent tangential and normal directions). v_c is the maximum value of the velocity at the friction point which changes static friction to dynamic friction. g is the gravity constant. μ_t and μ_n are normal and tangential coulomb friction coefficients. C_t and C_n are normal and tangential viscus friction coefficients. Suffix i corresponds to the i-th link, f_{ti} and f_{ni} are friction forces in tangential and normal direction, respectively. v_i^t and v_i^n are tangential and normal velocities of the center of mass of i-th link, respectively. In this paper, values of μ_t=0.01and μ_n=0.55 as well as C_t=1 and C_n=5.5 are used. Fig. 5 shows the torque of joint#9 using the two friction models.

Also it should be mention that joint torques are periodic and amount of maximum joint toques for joints 3, 7 and 9 are in increasing order while joint 13 is lower. This is because joint 9 is the nearest joint to the gravity center of the snake robot. In other words, as joints get closer to the center of gravity, the required maximum torque increases.

The changes in joint torques for joints 3, 6, 9, 12 using Coulomb friction model is shown in Fig. 6.

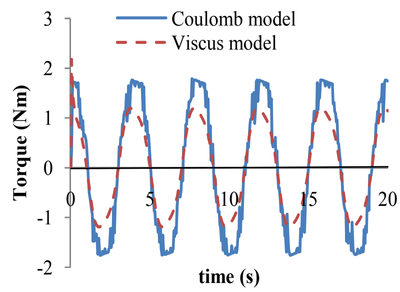

Figure 5. Torque of joint #9 using both frictional models

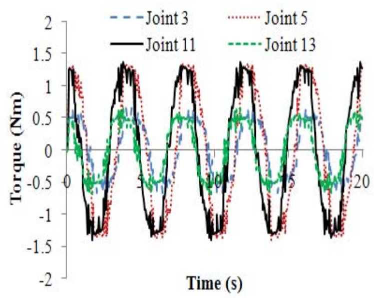

Figure 6. Joint torques for different joints

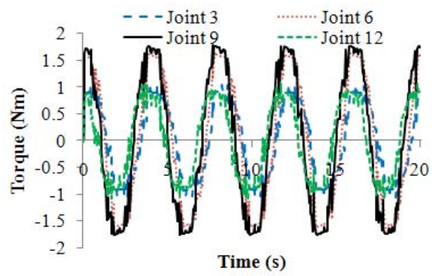

Figure7. Symmetrical joint torques

Also consider the symmetrical joints 3 and 13 as well as joints 5 and 11. These joints have the same distance from the gravity centre. As expected, the amplitude and variations of torques for these joints are the same.

In order to achieve optimum performance of the robot, it is important to properly set the kinematics and dynamics parameters. The selected input parameters in this study and their levels of the snake-like robot are shown in Table 1. The selected response is the ratio of energy to the total distance traveled.

III. TAGUCHI METHOD

Dr. Genichi Taguchi has developed a method based on orthogonal array experiments that has much less needed experiments to reach an optimum setting of process control parameters. Thus, the Taguchi Method achieves the integration of design of experiments (DOE) with the parametric optimization of the process, resulting in the desired results. The orthogonal array (OA) provides a set of minimum experimental runs. In OA any two columns of an array form all combinations the same number of times. In order to evaluate optimal parameter settings, the Taguchi Method uses a statistical measure of performance called signal-to-noise ratio (S/N) which is logarithmic function of desired output.

Taguchi's signal-to-noise ratios take both the mean and the variability into account. The S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The standard S/ N ratios generally used are Nominal is best (NB), lower the better (LB) and higher the better (HB). Since in the paper the lower value for Energy/Distance is better, therefore, the formula for lower the better is (17) and (18) are used.

$$LB = \frac{1}{n}(\sum (y_i)^2) \quad (17)$$

$$\eta_{ij} = -10Log(L_{ij}) \quad (18)$$

The optimal setting is always the parameter combination which has the highest S/ N ratio regardless of the used type. The L_{32} Taguchi design and the calculated S/N ratios using Coulomb and viscous friction models are shown in Tables 2 and 3, respectively. The corresponding ANOVA results are shown in Tables 4 and 5. As shown in these tables, all single factors are significant. Although all single factors are statistically significant, due to higher F-value, K_n is the most effective parameter while m is the least effective.

TABLE 1. INPUT FACTORS AND THEIR LEVELS

Factor	Symbol	1st level	2nd level	3rd level	4th level
length	l	0.08	0.1	0.12	0.14
angle	α_0 (rad)	0.4	0.5	0.6	0.7
mass	m (kg)	0.1	0.12	0.14	0.16
undulation	K_n	1	2	-	-

TABLE 2. THE L32 TAGUCHI DESIGN & CALCULATED S/N RATIOS - COULOMB FRICTION

No. Exp.	K_n	l	m	α	Energy/distance	SNR
1	1	0.08	0.1	0.4	5.44	-14.71
2	1	0.08	0.12	0.5	6.15	-15.78
3	1	0.08	0.14	0.6	7.44	-17.43
4	1	0.08	0.16	0.7	10.96	-20.79
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29	2	0.14	0.1	0.6	24.06	-27.62
30	2	0.14	0.12	0.7	42.47	-32.56
31	2	0.14	0.14	0.4	25.17	-28.02
32	2	0.14	0.16	0.5	27.62	-28.82

TABLE 3. THE L32 TAGUCHI DESIGN & CALCULATED S/N RATIOS- VISCOUS FRICTION

No. Exp.	K_n	l	m	α	Energy/distance	SNR
1	1	0.08	0.1	0.4	2.7557	-8.8047
2	1	0.08	0.12	0.5	4.8252	-13.6703
3	1	0.08	0.14	0.6	8.1872	-18.2627
4	1	0.08	0.16	0.7	13.4639	-22.5834
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
29	2	0.14	0.1	0.6	29.6463	-29.4394
30	2	0.14	0.12	0.7	56.5999	-35.0563
31	2	0.14	0.14	0.4	15.2302	-23.6541
32	2	0.14	0.16	0.5	29.1857	-29.3034

TABLE 4. ANOVA FOR SN RATIOS - COULOMB FRICTION

Source	DF	SS	MS	F	P
K_n	1	2387.84	2387.84	8282.32	0
l	3	110.58	36.86	127.85	0
m	3	27.21	9.07	31.46	0
α	3	98.25	32.75	113.59	0
Residual Error	18	5.19	0.29		
Total	31	2629.43			

TABLE 5. ANOVA FOR SN RATIOS - VISCOUS FRICTION

Source	DF	SS	MS	F	P
K_n	1	2723.25	2723.25	26086.36	0
l	3	107.90	35.97	344.53	0
m	3	39.08	13.03	124.79	0
α	3	556.32	185.44	1776.35	0
Residual Error	18	2.19	0.1		
Total	31	3428.74			

The graphical representation of the S/N ratios is shown in Figs 8 and 9. As shown in these two figures, in order to get the minimum Energy/distance, lower level of K_n and m, while higher level of l should be used. The winding angle however requires slightly different setting. The 2nd level of α and 1st level are selected for Coulomb and viscous models, respectively. The final optimum settings using Coulomb and viscous models are, $K_{n1}l_4m_1\alpha_2$ and $K_{n1}l_4m_1\alpha_1$, respectively.

For confirmation test the optimal values l=0.14, K_n=1, m=0.1, α=0.5 and the coulomb model are used in Matlab simulation program. The value of 2.58 for Energy/distance is obtained. Results are summarized in Table 6. The value for Distance/energy is improved from initial level of 5.4443 to 2.5817. This represents 52% improvement in robot performance.

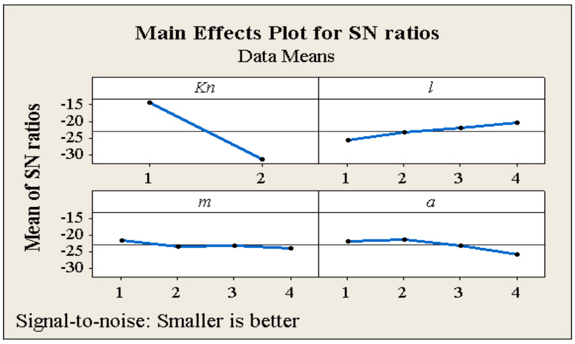

Figure 8. Main effect plot for SN ratios - Coulomb friction

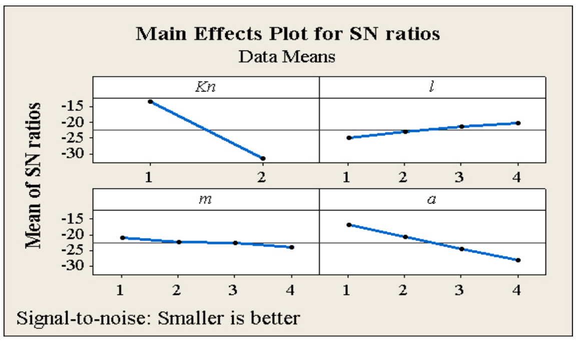

Figure 9. Main effect plot for SN ratios - viscous friction

TABLE 6. TAGUCHI CONFIRMATION RESULTS - COULOMB FRICTION

	Starting condition $l_1m_1K_{n1}\alpha_1$	***Predicted value (ANOVA model)*** $l_4m_1K_{n1}\alpha_2$	***Predicted value (Dynamics model)*** $l_4m_1K_{n1}\alpha_2$
S/N ratio	-14.7189	-8.71014	-8.2381
Energy/Distance	5.4443	2.7259	2.5817

Improvement S/N ratio for Energy/Distance = 6.48 (dB)

TABLE 7. TAGUCHI CONFIRMATION RESULTS - VISCOUS FRICTION

	Starting condition $l_1m_1K_{n1}\alpha_1$	***Predicted value (ANOVA model)*** $l_4m_1K_{n1}\alpha_1$	***Predicted value (Dynamics model)*** $l_4m_1K_{n1}\alpha_1$
S/N ratio	-8.80463	-4.67616	-3.92352
Energy/Distance	2.7557	1.7132	1.5710

Improvement S/N ratio for Energy/Distance = 4.13 (dB)

Next, viscous friction is considered and confirmation test using the optimal values l=0.14, K_n=1, m=0.1 and α=0.4 are again used in Matlab simulation program. The value of 1.57 for Energy/distance is obtained. Results are summarized in Table 7. The value for Distance/energy is improved from initial level of 2.7557 to 1.710. This also represents 38% improvement in robot performance.

IV. CONCLUSIONS

In this paper, effects of parameters settings on performance of a snake robot in serpentine locomotion are investigated. Two friction models, Coulomb and viscous, are used. Dynamic and kinematics of snake robots are used in simulation. The snake robot is further modeled in WEBOTS software to demonstrate forward progression. To obtain the performance results. Taguchi Method is utilized to find the optimum levels of l, α, m and K_n for a 16 link snake robot. Results indicate that regardless of the friction model, minimum energy/distance is obtained when lower level of K_n and m, while higher level of l should are selected. The winding angle however requires slightly different setting. The 2nd and 1st level of α are required to maximize performance for Coulomb and viscous models, respectively. ANOVA results also show that K_n is the most important and m is the least important factor for both friction models. Using the optimum settings results in 52% and 38% improvement in robot performance using Coulomb and viscous models, respectively. Finally, these results can be utilized by a designer as guidelines for mechanical design of the snake robot. For future works, effects of number of the links on the performance of the snake robot will be investigated.

REFERENCES

[1] S. Hirose, Biologically Inspired Robots: Snake-Like Locomotors and Manipulators. *Oxford University Press, 1993.*

[2] J.S. Gray, “The Mechanism of Locomotion in Snakes”. *Journal of Experimental Biology*, vol. 23, 1946.

[3] Z. Y. Bayraktaroglu, Fa. Butel, Pi. Blazevic, Vi. Pasqui, “A Geometrical Approach to the Trajectory Planning of a Snake-like Mechanism”, *In the Proceedings of the 1999 IEEE;RSJ International Conference on Intelligent Robots and Systerns.*

[4] E.S. Conkur, “Path Planning Algorithm For Snake-Like Robots”, *Information Tecnology and Control*, Vol.37, No.2, 2008.

[5] Jinguo. Liu, Yuechao. Wang, Bin. li, Shugen. Ma, “Path Planning of a Snake-like Robot Based on Serpenoid Curve and Genetic Algorithms”, *Proceedings of the in World Congress on Intelligent Control and Automation, June 15-19, 2004, Hangzhou, P.R. China.*

[6] Shugen. MA, “Analysis of Snake Movement Forms for Realization of Snake like Robots”, *Proceedings of the 1999 EEE International Conference on Robotics & Automation Detroit, Michigan May 1999.*

[7] Sh. Hasanzadeh, A. Akbarzadeh Tootoonchi, “Ground adaptive and optimized locomotion of snake robot moving with a novel gait”, *Auton Robot 28 (2010) 457–470.*

[8] Sh. Hasanzadeh, A. Akbarzadeh Tootoonchi , “Adaptive Optimal Locomotion of Snake Robot Based on CPG-Network Using Fuzzy Logic Tuner”, *IEEE - CIS RAM2008 , 2008-09-22.*

[9] Sh. Hasanzadeh, A. Akbarzadeh Tootoonchi, “Obstacle Avoidance of Snake Robot Moving with A Novel Gait Using Two-Level PID Controller”, *IEEE - CIS RAM2008 , 2008-09-22.*

[10] Sh. Hasanzadeh, A. Akbarzadeh Tootoonchi, “Dynamic and Multi-Modal Locomotion Analysis of Snake Robot Using Central Pattern Generator”, *Submitted to Advance robotics, unpublished.*

[11] P. Liljeb¨ack, Ø. Stavdahl and K. Y. Pettersen, “Modular Pneumatic Snake Robot: 3D Modelling, Implementation and Control,” *Proceedings of 16th IFAC World Congress, Prague, Czech Republic (Jul. 2005).*

[12] O. Egeland and J. T. Gravdahl, “Modeling and Simulation for Automatic Control,” (MarineCybernetics, Trondheim,Norway, 2002).

[13] Aksel Andreas Transeth, Kristin Ytterstad Pettersen, Pal Liljeb¨ack, “A survey on snake robot modeling and locomotion,” *Robotica. 27, 999–1015 (2009).*

[14] J.K. Hopkins, B.W. Spranklin, and S.K. Gupta. “A survey of snake-inspired robot designs,” *Bionispiration and Biomimetics. 4, (2009).*

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