International Journal of Automation, Mechatronics & Robotics– IJAMR
Volume 1 : Issue 2 [ISSN 2374 – 1546]
Publication Date : 25 June 2014

Study on Motion Characteristics for a Novel Quadruped Robot with Hydraulic Actuator

[Jing Wang , Xiaolei Han, Feng Gao]

***Abstract*—A novel quadruped robot with special hybrid mechanism and hydraulic actuator is proposed in this paper. The feature of the robot is high power density and high reliability. It promotes the possibility of practical application of robots. The advantage of the hybrid mechanism is that it makes hydraulic actuators mounted on the torso intensively. This is benefit for adopting protective measures to prevent robots from nuclear, water and fire. The aim of this paper is to analyze the motion characteristics of the hybrid mechanism and to find out the inherent law of actuator designation with robot mechanism. The analysis results indicate that in a certain range the changes of step length have nothing to do with the maximum flow rate of actuators as long as the travel speed of robot remains constant, but the stroke of actuator changes with the step length. The Swing angle of actuator is very small, which is useful for extending hydraulic hose service life and improving robot reliability and safety.**

***Keywords*—hydraulic, actuator, quadruped robot**

I. Introduction

Walking robots have the ability to cross obstacles and walk through special surfaces as sand and swamp, thus their wide application prospects in military transportation, disaster rescue and nuclear power plant maintenance are forecasted. The basic requirements for power drive system of walking robots are heavy duty, light weight and low energy consumption. The developed motor-driven walking robots [1-3] always have the problems of insufficient carrying capacity. Walking robots with hydraulic drive systems can carry heavy load, but their drive systems are complicated and expensive[4-6].

A novel quadruped robot named 'Baby Elephant' is developed by Shanghai Jiao Tong University recently, as shown in Figure 1. Its leg adopts special hybrid mechanism with features of high stiffness and high load capacity. This hybrid mechanism especially makes the hydraulic actuators focus on the torso, which is benefit for robots to prevent nuclear, water and fire. Its power drive system adopts a kind of independent developed actuator called 'Hy-Mo' for the first time. 'Hy-Mo' is a novel hydraulic actuator controlled by a mirco-motor. The advantage of 'Hy-Mo' is to simplify hydraulic system, as well as to reduce leakage, to improve reliability and anti-pollution capacity. The 'Baby Elephant' shown in Figure 1, weighs 130 kg and can carry loads of 60 kg.

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Figure 1. A Quadruped Robot Named 'Baby Elephant'

Its power drive system consists of one battery, one motor, one pump, twelve 'Hy-Mo' actuators and several pipes, while the system dispenses with hydraulic accessories such as filters, coolers, accumulators and oil tanks.

In this paper, the motion characteristics and hydraulic drive performance will be investigated based on the novel quadruped robot with hybrid mechanism legs. The aim of this paper is to provide theoretical basis for design of hydraulic drive system and 'Hy-Mo' actuator of 'Baby Elephant'. In section 2, there is the brief description of mechanism model of the hybrid mechanism leg. In section 3, through kinematic analysis, the relationship between toe trajectory and actuator movement is established. In section 4, based on polynomial fitting method, the toe trajectory planning of trot gait is carried out. In section 5, actuator performance is deduced with the results of kinematic analysis and toe trajectory planning.

II. Mechanism Model

The structure model of hybrid mechanism leg is shown in Figure 2. Define the coordinate system of leg as O(X, Y, Z). If the movement of side leg swing is omitted, then there is Y=0.

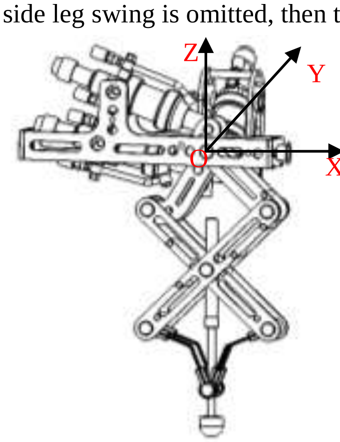
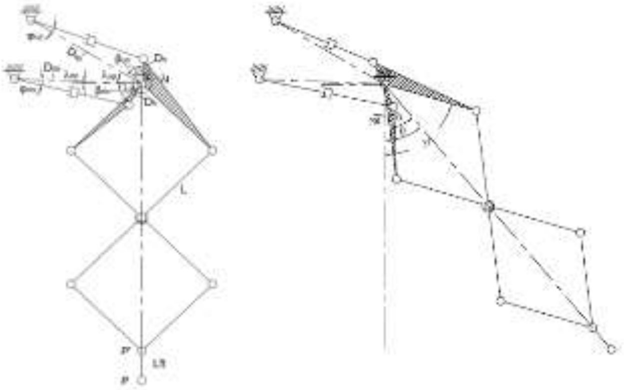


Figure 2. Leg Structure Model

The schematic diagram of leg mechanism is shown in Figure 3. The dimension parameters defined in Figure 3 are rod length L, toe length L_{ft}, fixed edge length D_h, D_{up}, D_{dn}, drive angle of upper actuator β_{up}, drive angle of lower actuator β_{dn}, swing angle of upper actuator φ_{up}, swing angle of lower actuator φ_{dn}, swing angle of leg γ_s, θ, γ_l, half angle of diamond mechanism α, fixed angle λ_l, λ_s, λ_{up}, λ_{dn}.



(a) upright (b) inclined

Figure 3. Schematic Diagram of Leg Mechanism

III. Kinematic Analysis

A. *Inverse Kinematics*

Assuming the toe trajectory $P(x, z)$ is known, compute the movement of actuators.

From the diagram in Figure 3, geometric relations are as follows:

Distance between the toe and the fixed hinge point (O, origin of coordinates) is,

$$L_p = \sqrt{x^2 + z^2} \tag{1}$$

Distance between the two vertices of the diamond mechanism is,

$$L_{P'} = L_P - L_{ft} \tag{2}$$

Half angle of the diamond mechanism is,

$$\alpha = \arccos\left(\frac{L_{P'}}{4L}\right) \tag{3}$$

Swing angle of the leg mechanism is,

$$\theta = -\arctan\left(\frac{x}{z}\right) \tag{4}$$

$$\gamma_l = \theta + \alpha \tag{5}$$

$$\gamma_s = \theta - \alpha \tag{6}$$

Drive angle of the upper actuator is,

$$\beta_{up} = \frac{3}{2}\pi - (\lambda_l + \gamma_l) - \lambda_{up} \tag{7}$$

Drive angle of the lower actuator is,

$$\beta_{dn} = \frac{\pi}{2} + \lambda_s + \gamma_s + \lambda_{dn} \tag{8}$$

Length of actuators is,

$$\begin{cases} Cy_{up} = \sqrt{D_{up}{}^2 + D_h{}^2 - 2D_{up}D_h \cos\beta_{up}} \\ Cy_{dn} = \sqrt{D_{dn}{}^2 + D_h{}^2 - 2D_{dn}D_h \cos\beta_{dn}} \end{cases} \tag{9}$$

B. *Forward Kinematics*

Assuming the length of actuators Cy_{up} and Cy_{dn} is known, compute the toe trajectory.

From the diagram in Figure 3, geometric relations are as follows:

Drive angle of the upper actuator is,

$$\beta_{up} = \arccos\left(\frac{D_{up}^2 + D_h^2 - Cy_{up}^2}{2D_{up}D_h}\right) \tag{10}$$

Drive angle of the lower actuator is,

$$\beta_{dn} = \arccos\left(\frac{D_{dn}^2 + D_h^2 - Cy_{dn}^2}{2D_{dn}D_h}\right) \tag{11}$$

Swing angle of the leg mechanism is,

$$\gamma_l = \frac{3}{2}\pi - \lambda_{up} - \lambda_l - \beta_{up} \tag{12}$$

$$\gamma_s = -\frac{\pi}{2} - \lambda_{dn} - \lambda_s + \beta_{dn} \tag{13}$$

$$\theta = \frac{\gamma_l + \gamma_s}{2} \tag{14}$$

$$\alpha=\frac{\gamma_l-\gamma_s}{2} \tag{15}$$

Distance between the toe and the fixed hinge point (*O*, origin of coordinates) is,

$$L_p=4L\cos\alpha+L_{ft} \tag{16}$$

Toe trajectory can be expressed as:

$$\begin{cases}x=L_p\sin\theta\\ z=-L_p\cos\theta\end{cases} \tag{17}$$

C. Relationship between Velocity of Toe and Actuators

Combine equation (9) with equation (7) and (8). The derivation is as follows:

$$\begin{bmatrix}\dot{C}y_{up}\\ \dot{C}y_{dn}\end{bmatrix}=\begin{bmatrix}-\dfrac{D_{up}D_h\sin\beta_{up}}{Cy_{up}}\dot{\gamma}_l\\ \dfrac{D_{dn}D_h\sin\beta_{dn}}{Cy_{cn}}\dot{\gamma}_s\end{bmatrix} \tag{18}$$

Combine equation (17) with equation (14), (15) and (16). The derivation is as follows:

$$\begin{cases}v_x=\dot{x}=\left[\left(4L\cos\alpha+L_{ft}\right)\sin\theta\right]'\\ v_z=\dot{z}=\left[-\left(4L\cos\alpha+L_{ft}\right)\cos\theta\right]'\end{cases} \tag{19}$$

Set $A=2L\cos\alpha+\frac{L_{ft}}{2}$, $B=2L\sin\alpha$, then equation (20) can be deduced from equation (19).

$$\begin{bmatrix}v_x\\ v_z\end{bmatrix}=\begin{bmatrix}A\cos\theta-B\sin\theta & A\cos\theta+B\sin\theta\\ A\sin\theta+B\cos\theta & A\sin\theta-B\cos\theta\end{bmatrix}\begin{bmatrix}\dot{\gamma}_l\\ \dot{\gamma}_s\end{bmatrix} \tag{20}$$

Convert equation (20) to equation (21).

$$\begin{bmatrix}\dot{\gamma}_l\\ \dot{\gamma}_s\end{bmatrix}=\begin{bmatrix}\dfrac{\cos\theta}{2A}-\dfrac{\sin\theta}{2B} & \dfrac{\sin\theta}{2A}+\dfrac{\cos\theta}{2B}\\ \dfrac{\cos\theta}{2A}+\dfrac{\sin\theta}{2B} & \dfrac{\sin\theta}{2A}-\dfrac{\cos\theta}{2B}\end{bmatrix}\begin{bmatrix}v_x\\ v_z\end{bmatrix} \tag{21}$$

Combine equation (21) with equation (18), the relationship of velocity of toe and actuators can be obtained:

$$\begin{bmatrix}\dot{C}y_{up}\\ \dot{C}y_{dn}\end{bmatrix}=\left[D\right]\begin{bmatrix}\dfrac{\cos\theta}{2A}-\dfrac{\sin\theta}{2B} & \dfrac{\sin\theta}{2A}+\dfrac{\cos\theta}{2B}\\ \dfrac{\cos\theta}{2A}+\dfrac{\sin\theta}{2B} & \dfrac{\sin\theta}{2A}-\dfrac{\cos\theta}{2B}\end{bmatrix}\begin{bmatrix}v_x\\ v_z\end{bmatrix} \tag{22}$$

Where, $\left[D\right]=\begin{bmatrix}-\dfrac{D_{up}D_h\sin\left(\beta_{up}\right)}{Cy_{up}} & 0\\ 0 & \dfrac{D_{dn}D_h\sin\left(\beta_{dn}\right)}{Cy_{dn}}\end{bmatrix}$

IV. Toe Trajectory Planning

Take the trot gait into accounted. The toe trajectory consists of two parts: step and support. When the leg steps, it moves forward relative to torso coordinate system. When the leg supports, it moves backward relative to torso coordinate system. The abridged general view of leg movement is shown in Figure 4.

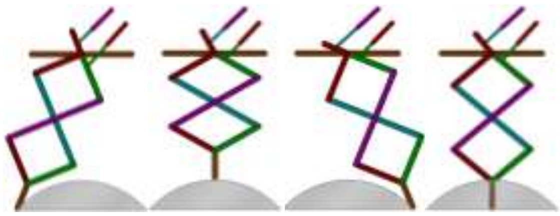


Figure 4. Abridged general view of Leg Movement

A. Step Process

Given that step period is T_1, step length is X_1, lift height is Z_1, and the boundary conditions can be expressed as follows:

$$\begin{cases}t=0, x=-\dfrac{X_1}{2}, \dot{x}=0, \ddot{x}=0, z=Z_0, \dot{z}=0, \ddot{z}=0\\ t=\dfrac{T_1}{2}, z=Z_0+Z_1, \dot{z}=0\\ t=T_1, x=\dfrac{X_1}{2}, \dot{x}=0, \ddot{x}=0, z=Z_0, \dot{z}=0, \ddot{z}=0\end{cases}$$

In order to get a smooth trajectory, polynomial fitting method is to be used for trajectory planning.

Suppose the motion in *X* direction can be described as a quintic polynomial equation,

$$x=C_{x0}+C_{x1}t+C_{x2}t^2+C_{x3}t^3+C_{x4}t^4+C_{x5}t^5 \tag{23}$$

Where, $C_{x0},C_{x1},C_{x2},C_{x3},C_{x4},C_{x5}$ are coefficients.

Take the above boundary conditions into equation (23), the motion in *X* direction is to be obtained.

$$\begin{cases} x = -\dfrac{X_1}{2} + \dfrac{10X_1}{T_1^3}t^3 - \dfrac{15X_1}{T_1^4}t^4 + \dfrac{6X_1}{T_1^5}t^5 \\ \dot{x} = \dfrac{30X_1}{T_1^3}t^2 - \dfrac{60X_1}{T_1^4}t^3 + \dfrac{30X_1}{T_1^5}t^4 \\ \ddot{x} = \dfrac{60X_1}{T_1^3}t - \dfrac{180X_1}{T_1^4}t^2 + \dfrac{120X_1}{T_1^5}t^3 \end{cases} \quad (24)$$

Suppose the motion in Z direction can be described as a septic polynomial equation,

$$z = C_{z0} + C_{z1}t + C_{z2}t^2 + C_{z3}t^3 + C_{z4}t^4 + C_{z5}t^5 + C_{z6}t^6 + C_{z7}t^7 \quad (25)$$

Where, $C_{z0}, C_{z1}, C_{z2}, C_{z3}, C_{z4}, C_{z5}, C_{z6}, C_{z7}$ are coefficients.

Take the above boundary conditions into equation (25), the motion in Z direction is to be obtained.

$$\begin{cases} z = Z_0 + \dfrac{64Z_1}{T_1^3}t^3 - \dfrac{192Z_1}{T_1^4}t^4 + \dfrac{192Z_1}{T_1^5}t^5 - \dfrac{64Z_1}{T_1^6}t^6 \\ \dot{z} = \dfrac{192Z_1}{T_1^3}\left(t^2 - \dfrac{4}{T_1}t^3 + \dfrac{5}{T_1^2}t^4 - \dfrac{2}{T_1^3}t^5\right) \\ \ddot{z} = \dfrac{384Z_1}{T_1^3}\left(t - \dfrac{6}{T_1}t^2 + \dfrac{10}{T_1^2}t^3 - \dfrac{5}{T_1^3}t^4\right) \end{cases} \quad (26)$$

B. *Support Process*

Given that support period is T_2, toe backward distance (relative to torso coordinate system) is X_1, lift height is 0, and the boundary conditions can be expressed as follows:

$$\begin{cases} t = 0, x = \dfrac{X_1}{2}, \dot{x} = 0, \ddot{x} = 0, z = Z_0, \dot{z} = 0, \ddot{z} = 0 \\ t = T_2, x = -\dfrac{X_1}{2}, \dot{x} = 0, \ddot{x} = 0, z = Z_0, \dot{z} = 0, \ddot{z} = 0 \end{cases}$$

In order to get a smooth trajectory, polynomial fitting method is to be used for trajectory planning.

Suppose the motion in X direction can be described as a quintic polynomial equation as equation (23).

Take the above boundary conditions into equation (23), the motion in X direction is to be obtained.

$$\begin{cases} x = \dfrac{X_1}{2} - \dfrac{10X_1}{T_2^3}t^3 + \dfrac{15X_1}{T_2^4}t^4 - \dfrac{6X_1}{T_2^5}t^5 \\ \dot{x} = -\dfrac{30X_1}{T_2^3}t^2 + \dfrac{60X_1}{T_2^4}t^3 - \dfrac{30X_1}{T_2^5}t^4 \\ \ddot{x} = -\dfrac{60X_1}{T_2^3}t + \dfrac{180X_1}{T_2^4}t^2 - \dfrac{120X_1}{T_2^5}t^3 \end{cases} \quad (27)$$

According to the toe trajectory planning results, given that gait period T=0.6 s, step period T_1=0.4T=0.24 s, step length X_1=400 mm, lift height Z_1=80 mm, and original leg length Z_0=-722.3 mm, the specified toe trajectory is the curve shown in Figure 5. Figure 6 illustrates the toe movement in X direction and in Z direction separately. The mentioned parameters are derived from trot gait time sequence diagram displayed in Figure 7. From equation (28), the travel speed of robot is 4 km/h.

$$V = \frac{X_1}{\beta \cdot T} \quad (28)$$

Where, β is duty cycle, β=0.6.

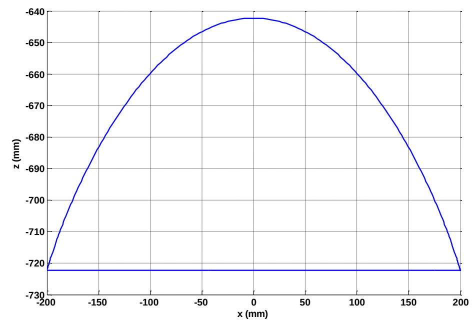


Figure 5. Toe Trajectory Curve

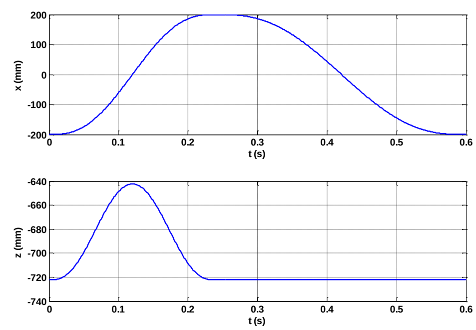


Figure 6. Toe Movement in X Direction and Z Direction

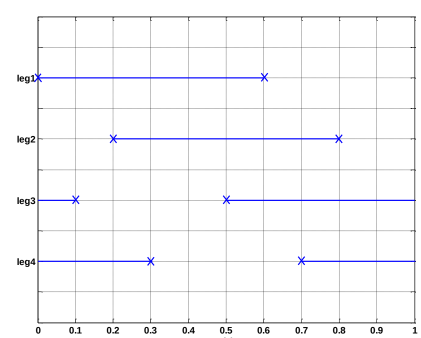


Figure 7. Trot Gait Time Sequence Diagram

V. Actuator Performance Analysis

According to section 3.1 and 3.3, the motion characteristics of actuators can be deduced from the toe trajectory. A set of dimension parameters of mechanism is given in Table Ⅰ. From the toe trajectory curve displayed in Figure 5, the displacement and velocity of actuators can be calculated with equations in section 3.1 and 3.3, and the results are shown in Figure 8 and Figure 9.

TABLE I. MECHANISM DIMENSION PARAMETERS

Name	D_{up}	D_{dn}	D_h	L	L_{ft}
Unit(mm)	235.92	235.17	46	180	95
Name	λ_{up}	λ_{dn}	λ_l	λ_s	
Unit(°)	30.15	2.19	133	15.3	

A. Actuator Displacement

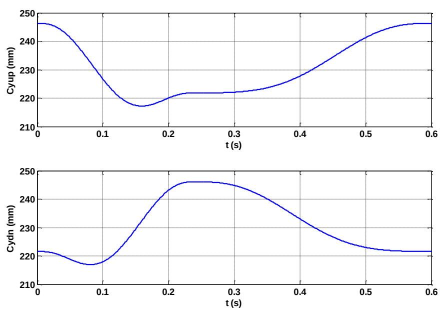


Figure 8. Displacement of Actuators

Figure 8 shows that the maximum length of the upper actuator is 246 mm, the minimum length of the upper actuator is 217 mm, and the stroke of the upper actuator is 29 mm; the maximum length of the lower actuator is 246 mm, the minimum length of the lower actuator is 217 mm, and the stroke of the lower actuator is 29 mm. The upper actuator and the lower actuator are symmetric.

B. Actuator Velocity

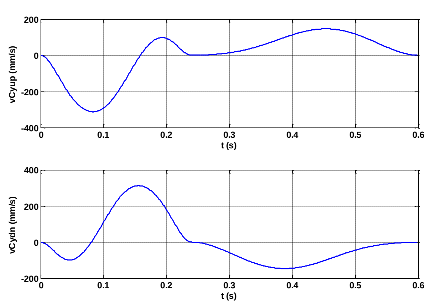


Figure 9. Velocity of Actuators

Figure 9 shows that the maximum stretching velocity of the upper actuator is 146 mm/s, and the maximum retracting velocity of the upper actuator is 312 mm/s; the maximum stretching velocity of the lower actuator is 146 mm/s, and the maximum retracting velocity of the lower actuator is 312 mm/s.

C. Actuator Swing Angle

The curves of swing angle of upper actuator φ_{up} and swing angle of lower actuator φ_{dn} are shown in Figure 10. In the process of robot movement, the swing angle of actuator is very small, just 0.6°. This is useful for extending hydraulic hose service life and improving robot reliability and safety.

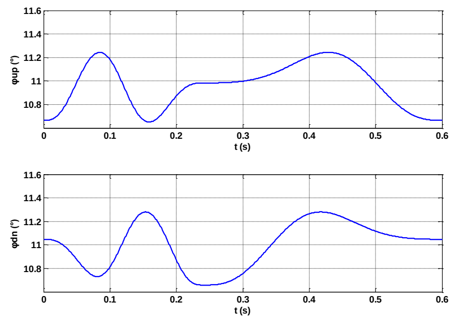


Figure 10. Swing angle of actuators

D. Requirement for Flow Rate

From the velocity of actuators, the requirement for flow rate of hydraulic power supply can be obtained. Suppose that the areas of double acting actuator are equal, so in one gait period the flow of one leg can be calculated by equation (28), here the movement of side leg swing is omitted.

$$Q = A \cdot \left(\left| vCy_{up} \right| + \left| vCy_{dn} \right| \right) \qquad (29)$$

Given that step length X_1=400 mm, lift height Z_1=80 mm, the flow rate curve of one leg is displayed in Figure 11. The total flow rate curve of quadruped robot is shown in Figure 12, corresponding to the trot gait time sequence diagram shown in Figure 7.

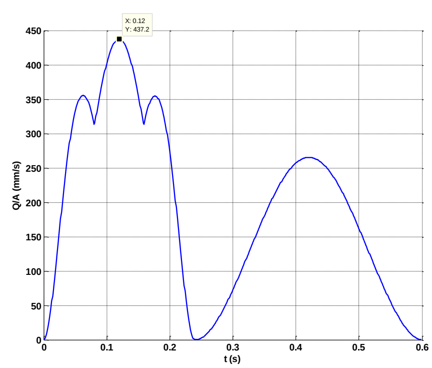


Figure 11. Flow rate Curve of One Leg

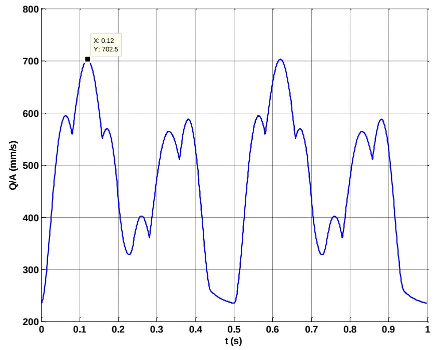


Figure 12. Total Flow rate Curve of Quadruped Robot

E. Relationship between Flow rate, Stroke and Step Length

By changing the step length X_1 and keeping the lift height Z_1=80 mm, the curve of maximum flow rate and actuator stroke versus step length is shown in Figure 13. When the step length increases from 200 mm to 300 mm, the maximum flow rate is decreasing rapidly. When the step length is over 300 mm, the maximum flow rate maintains a constant value. On the other hand, with the increase of step length, the stroke of actuator is increasing continuously.

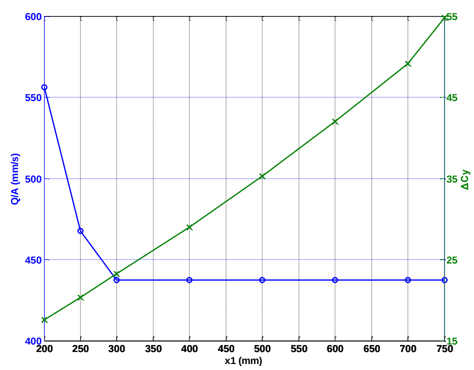


Figure 13. Maximum Flow rate, Stroke versus Step Length

VI. Conclusions

This work presents a novel quadruped robot with special hybrid mechanism and hydraulic actuator. The toe trajectory planning of trot gait is obtained by polynomial fitting method. According to the toe trajectory curve, the actuator movements are identified based on the kinematic analysis results. Through the analysis results of actuator movements we can find that:

(1) In a certain range, the changes of step length have nothing to do with the maximum flow rate of actuators as long as the travel speed of robot remains constant, but the stroke of actuator changes with the step length.

(2) The swing angle of actuator is very small, which is useful for extending hydraulic hose service life and improving robot reliability and safety.

The results provide a theoretical basis for design of hydraulic actuators and system of the novel quadruped robot.

Acknowledgment

This research was supported by Major State Basic Research Development Program of China (973 Program, Grant No.2013CB035501) and Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20120073120053).

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