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Hexapod Robot Kinematics Modeling and Tripod Gait Design Based on the Foot End Trajectory

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***Abstract*—Hexapod robots have strong crawling abilities and complex gaits. Referring the configuration of ants, a hexapod robot is designed. Based on the DH parameters and the homogeneous transformation matrix, the direct and inverse kinematic models are built, and the workspace of the foot end is analyzed. For the tripod gait, the relationship between the rotation angle of the leg with respect to body and the foot movement is built. The foot end trajectories of the swing phase are designed by adopting sine and cosine functions, the stance phase by horizontal straight line function. The angle joint trajectories are obtained by evaluating the inverse kinematic equations. Finally, the tripod gaits, including straight, transvers and swivel gaits, are designed. The experimental results illustrate the effectiveness of the robot gait planning algorithms. The design method in this paper is easy to understand and calculate.**

Keywords—Gait Planning;Hexapod Robot;Workspace Analysis; Tripod Gait

I. INTRODUCTION

Compared to wheeled robots, legged robots have stronger ability to adapt in the unstructured ground. Hexapod robots are rich in gait forms for the different terrain environment and application scenarios with better stability and load capacity.

Saranli, U. et al. [1] design a hexapod robot named RHex with C shape legs. The six legs of RHex are divided into two groups. Three legs in each group make up a stance triangle making RHex move stably. Inpired by RHex, endorfer, R.et al.[2] add the spring inversion pendulum model into RHex stability analysis, providing the mathematical explanation for hexapod robot movement analysis. In order to make it clear that the effect of passive and mechanical design on RHex performance improvement, Huang, KJ, et al. [3] design a hexagonal spring loaded inverted pendulum runner, proposed a more detailed dynamic model, named R2-SLIP, for describing critical non-linear features of the legs. Napora, J. K., et al. [4] propose a comprehensive design method for hexapod robot design, analysis and simulation. The model can be used to get various motion parameters, such as displacement, speed, acceleration and trajectory.

The structure design of the bionic robot should refer to the structure of the creature. Chen, J.et al. [5] design a leg mechanism HITCR-II based on the abstract structure of the insect leg with a spring on its end to provide buffer. Robots that use the motor as the driver most often require multiple PWM control signals. Pa, P. S., et al. [6] use the CPLD to generate PWM, reducing the CPU workload. But the CPLD requires an independent programming language to implement the algorithm.

To prevent the entire robot movement failure, robots need to avoid the collision between the legs. It is necessary to determine the constraint range of the movement of each leg. Simulation can not only plan the effective working range of the robot, but also verify the feasibility of the control algorithm [7][8][9]. Arcía-López, M.C .et al. [10] use C ++ and OpenGL program to carry out the kinematic simulation of the hexapod robot.

Duan, X.[11] analyze the single leg workspace of hexapod robot, design the obstacle avoidance rotation gait. In his experiment, hexapod robot can effectively avoid obstacles in its forward route. At present, hexapod robots are difficult to perform mammalian dynamic gait, such as trot gait, running gait [12]. Hexapod robots commonly use static gait, such as tripod gait, quadruped gait and one-by-one types of gait [13] and some other free gait [14,15].

In this paper, we design a hexapod robot prototype, establish a coordinate frame and give DH parameters to establish a kinematic model. Then, we analyze the workspace of foot end, plan the foot end trajectories of straight gait, transverse gait and swivel gait on account of tripod gait. We get each joint angles of corresponding leg by evaluating the inverse kinematics with MATLAB. This data was recorded by the Arduino and sent to servo motors. Finally, the accuracy of the above analysis and design is illustrated by experiments.

II. MODEL AND KINEMITICS

A. Model of Hexapod Robot

For the hexapod robot's leg structure design, we refer to the African red ant body structure as shown in Fig. 1 (a). The coordinate frame is shown in Fig. 1(b).

Respectively, L_1, L_2, L_3 represent the length of coxa, femur, and tibia ; θ_1, θ_2, θ_3 represent the angle of hip joint, knee joint and ankle joint. Σ_c is the mass center coordinate frame of hexapod robot. Positive direction of z_c perpendicular to the ground up. Positive direction of x_c along the body transverse direction to the right. Positive direction of y_c is determined by right-hand rule, and is also the direction of hexapod robot's

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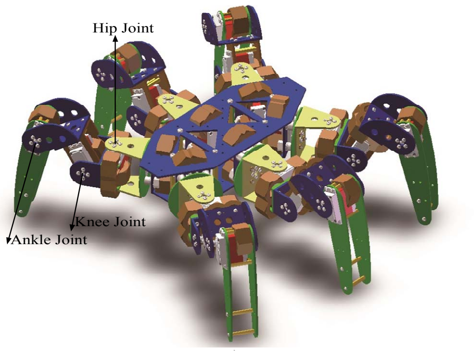
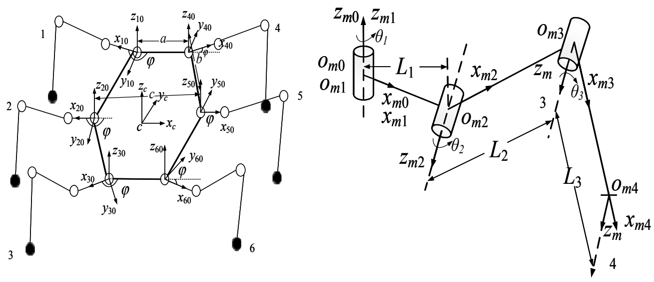
head. The base coordinate frame of each leg is obtained by translating and rotating the mass center coordinate frame with the rotation angle φ. Each leg of hexapod robot is numbered. Respectively, index 1,2,…,6 represent left front leg, left middle leg, left hind leg, Right front leg, right middle leg, right hind leg. Σo_{m0} is the leg base coordinate frame of hexapod robot.Σo_{mi} is the coordinate frame of i^{th} joint of m^{th} leg. m=1, 2…6 is the number of legs, i=1, 2, 3 is the number of joints on leg, representing hip joint, knee joint, ankle joint. When i=4, it presents the coordinate frame of the foot end. Axes z_{mi} is the rotation axis of the joint, axes x_{mi} is chosen along the common normal to axes $z_{m(i-1)}$ and axes $z_{m(i-1)}$ with the direction from former to latter, y_m is determined by right-hand rule.



(a) Model of hexapod robot



(b) Hexapod robot configuration

Fig. 1. Hexapod robot model and configuration.

B. Hexapod Robot Kinematics

1) Forward Kinematics

According to the coordinate frames established in Fig. 1 (b) and taking leg on the right as example, the right leg D-H parameters are shown in Table I.

TABLE I. D-H PARAMETERS OF RIGHT LEGS OF HEXAPOD ROBOT

Link	b_i	θ_i	a_i	α_i
1	0	$\theta_1 \in [-\pi/4, \pi/4]$	0	0
2	0	$\theta_2 \in [-\pi/2, \pi/2]$	L_1	$\pi/2$
3	0	$\theta_3 \in [-\pi, 0]$	L_2	0
4	0	0	L_3	0

The homogeneous transformation matrix ${}^{o_{m0}}T_{o_{m4}}$ represents the transformation matrix from the foot end coordinate frame Σ_{om4} to the leg basis coordinate frame Σ_{om0}, and can be obtained by

$$
{}^{o_{m0}}T_{o_{m4}} = {}^{o_{m0}}T_{o_{m1}} \cdot {}^{o_{m1}}T_{o_{m2}} \cdot {}^{o_{m2}}T_{o_{m3}} \cdot {}^{o_{m3}}T_{o_{m4}} = \begin{bmatrix} c_1c_{23} & -c_1s_{23} & s_1 & L_1c_1 + L_2c_1c_2 + L_3c_1c_{23} \\ s_1c_{23} & -s_1s_{23} & -c_1 & L_1s_1 + L_2s_1c_2 + L_3s_1c_{23} \\ s_{23} & c_{23} & 0 & L_2s_2 + L_3s_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)
$$

where $c \equiv cos$; $s \equiv sin$; $c_{23} \equiv \cos(\theta_2+\theta_3)$; $s_{23} \equiv \sin(\theta_2+\theta_3)$.

If we take mass center coordinate frame Σc as the reference coordinate frame system, by translating and rotating, the homogeneous transformation matrix ${}^{c}T_{o_{mo}}$ from leg base coordinate frame Σo_{m0} to mass center coordinate frame can be deprived as Eq. (2)

$$
{}^{c}T_{o_{mo}} = Trans(x_{o_{m0}}, y_{o_{m0}}, z_{o_{m0}}) \cdot Rot(z, \varphi) = \begin{bmatrix} c\varphi & -s\varphi & 0 & x_{o_{m0}} \\ s\varphi & c\varphi & 0 & y_{o_{m0}} \\ 0 & 0 & 1 & z_{o_{m0}} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)
$$

where $(x_{o_{m0}}, y_{o_{m0}}, z_{o_{m0}})$ is the coordinate frame value of m^{th} leg's base coordinate frame original point in mass center coordinate frame. Correspondingly, φ is the rotation angle of the leg base coordinate frame relative to the mass center coordinate frame along the z-axis.

2) Inverse Kinematics

Taking the legs on the right hand as example, let the inverse matrix of ${}^{o_{m0}}T_{o_{m1}}$ post multiply by ${}^{o_{m0}}T_{o_{m4}}$, then get Eq.(3)

$$
{}^{o_{m0}}T_{o_{m1}}^{-1} \cdot {}^{o_{m0}}T_{o_{m4}} = {}^{o_{m1}}T_{o_{m2}} \cdot {}^{o_{m2}}T_{o_{m3}} \cdot {}^{o_{m3}}T_{o_{m4}} \quad (3)
$$

that is

$$
\begin{bmatrix} c_1n_x + s_1n_y & c_1o_x + s_1o_y & c_1a_x + s_1a_y & c_1x_o + s_1y_o \\ -s_1n_x + c_1n_y & -s_1n_x + c_1o_y & -s_1n_x + c_1a_y & -s_1x_o + c_1y_o \\ n_z & o_z & a_z & z_o \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_{23} & -s_{23} & 0 & L_3c_{23} + L_2c_2 + L_1 \\ 0 & 0 & -1 & 0 \\ s_{23} & c_{23} & 0 & L_3s_{23} + L_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)
$$

Let the corresponding elements of the fourth column of the matrixes on both sides of equal sign be equal, and by evaluating the equation, the inverse kinematics of the right leg in leg base coordinate frames is as follow

$$
\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} \arctan(y_o / x_o) \\ \arcsin(z_o / \sqrt{(L_3c_3 + L_2)^2 + (L_3s_3)^2}) - \gamma \\ \arcsin(((c_1x_o + s_1y_o - L_1)^2 + z_o^2 - L_3^2 - L_2^2)/(2L_2L_3)) - \pi/2 \end{bmatrix} \quad (5)
$$

where $\gamma \equiv \arctan(L_3s_3 / (L_3c_3 + L_2))$.

C. Workspace of Foot End

In the gait plan, the foot trajectory must be in the foot end workspace, and the overlap of adjacent legs workspace should be considered that is, the interference problem.

Taking leg1 and leg2 as example, analyze the workspace of them The maximum angular range for each joint is as follows, $\theta_1\in[-\pi/4,\ \pi/4]$,$\theta_2\in[-\pi/2,\ \pi/2]$, $\theta_3\in[0,\ \pi]$.For the left leg, the rotation angle φ is equal to π. The physical parameters of the hexapod robot are shown in Table II.

TABLE II. DESIGN PARAMETERS OF HEXAPOD ROBOT

Parameter	Value
Size(L×W×H)(m)	0.298×0.12×0.065
Mass(kg)	5.64
Coxa L_1(m)	0.041
Femur L_2(m)	0.081
Tibia L_3(m)	0.15
a(m)	0.19
b(m)	0.19
c(m)	0.285

As the coordinate of mass center is (0,0,0) and the z_c value of foot end is less than zero, select the discrete point whose z_c value less than zero and plot the three-dimensional point graph as shown Fig.2(a). Respectively, figure2 (b)、(c)、(d) are top views of foot end workspace along x-axis, y-axis, z-axis.

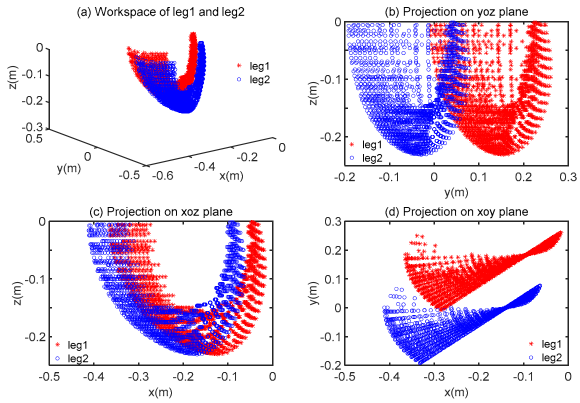


Fig. 2. Workspace of foot end of right legs

As shown in Fig. 2, the foot end workspace of a single leg is an irregular space, with a middle depression and both ends raised. From the xoz plane view, the movement of the leg is U-shaped and there is a middle area that the foot can not reach. From the xoy plane view, the working space of the leg is fan-shaped.

III. GAIT PLANING FOR TRIPOD GAIT

During the hexapod robot tripod gait, also known as triangular gait, there are always three feet in stance gait and the other three feet in the swing state. To achieve robot's walk, the two groups of legs switch alternately, as shown in Fig. 3.

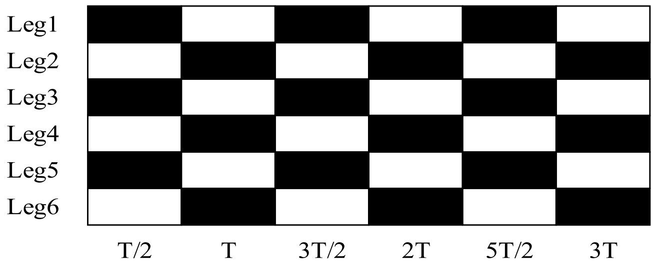


Fig. 3. Diagram of stance and swing phase of tripod gait.

White box indicates the stance phase, and black box indicates the swing phase. Legs {1,3,5} are in the same phase, legs {2,4,6} are in the same phase. The phase difference between the two group is π.

The relationship among the foot end, the base of leg and the center of mass is shown in Fig. 4.

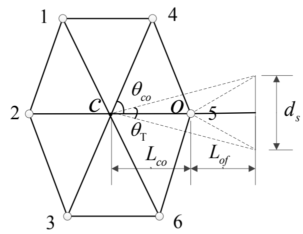


Fig. 4. Relationship of rotation angle and foot end displacement

L_{co} represents the distance from the mass center to the origin point of the leg base coordinate frame, and L_{of} represents the distance of mass center to foot end on the ground projection in the initial state, namely, the span of a leg.

A. Straight Gait

Straight gait refers to the robot walking along the y-axis, as shown in Fig. 5.

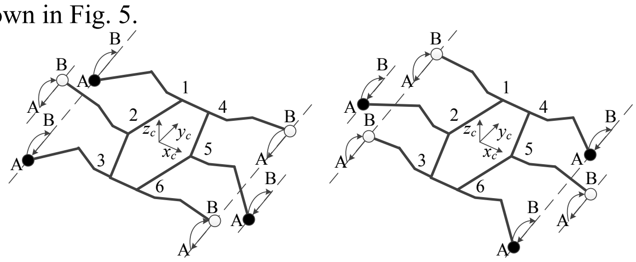


Fig. 5. Two states of the straight gait planning

The trajectory of the robot's straight gait swing phase is a half-cycle sinusoidal curve

$$\begin{cases} x_c = x_{om0} + L_{of}\cos(\varphi) \\ y_c = y_{om0} + L_{of}\sin(\varphi) + 0.002k - 0.06 \qquad k = 0,1\cdots\cdots N \\ z_c = z_{om0} - 0.15 + 0.05\cos(\pi(y_c - y_{om0} - L_{of}\sin(\varphi))/0.12) \end{cases} \tag{6}$$

The trajectory of the robot's straight gait stance phase is a horizontal line

$$
\begin{cases}
x_c = x_{om0} + L_{of}\cos(\varphi) \\
y_c = y_{om0} + L_{of}\sin(\varphi) + 0.06 - 0.002k \qquad k = 0,1\cdots\cdots N \\
z_c = z_{om0} - 0.15
\end{cases} \tag{7}
$$

where x_c, y_c, z_c represents the configure of the foot end in the mass center coordinate frame. N indicates the number of sampling points, and is equal to 60. The sampling frequency is 30Hz. k represents a discrete value.

In straight gait, rotation angle of leg1, leg 2, leg3 is equal to π and rotation angle of leg 4, leg 5, leg 6, is equal to zero.

The joint angle trajectory is obtained by substituting the foot end trajectory of Eq. (6) and Eq. (7) in Eq. (5).

Joint angles of right leg and foot end trajectory curve of straight gait is shown in Fig. 6. Joint angles of leg on the left hand are the opposite of the right hand. The foot end trajectories of the legs on left and right hand are symmetrical about the y-axis of mass center coordinate frame.

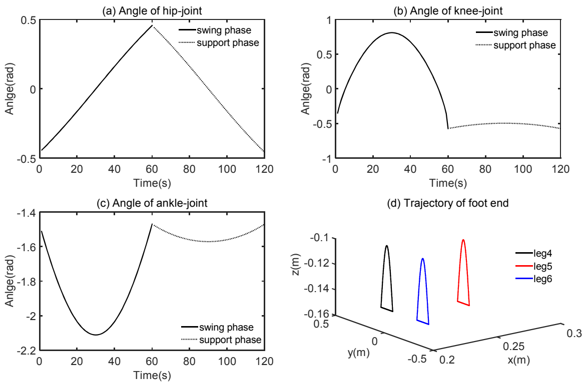


Fig. 6. Joint angles and foot end trajectories of right legs of straight gait

B. Transverse Gait

The transverse gait is similar to the crab walking gait, and the robot walks along the x-axis in the positive or negative direction, as shown in Fig 7.

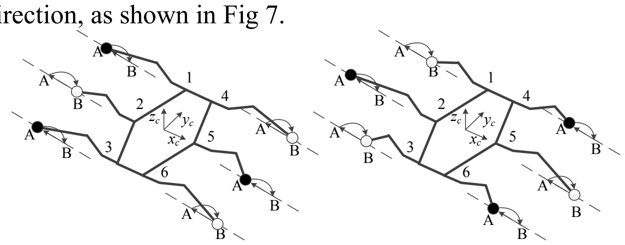


Fig. 7. Two states of the transverse gait planning

Respectively, the trajectory of swing phase and stance phase is given as Eq. (8) and Eq. (9).

$$
\begin{cases}
x_c = x_{om0} + L_{of}\cos(\varphi) + 0.002k - 0.06 \\
y_c = y_{om0} + L_{of}\sin(\varphi) \qquad k = 0,1\cdots\cdots N \\
z_c = z_{om0} - 0.15 + 0.05\cos(\pi(x_c - x_{om0} - L_{of}\cos(\varphi))/0.12)
\end{cases} \tag{8}
$$

$$
\begin{cases}
x_c = x_{om0} + L_{of}\cos(\varphi) + 0.06 - 0.002k \\
y_c = y_{om0} + L_{of}\sin(\varphi) \qquad k = 0,1\cdots\cdots N \\
z_c = z_{om0} - 0.15
\end{cases} \tag{9}
$$

The joint angle trajectory is obtained by substituting the foot end trajectory of Eq. (8) and Eq. (9) into Eq. (5).

Joint angles of leg on the right hand and foot end trajectory curve of transverse gait is shown in Fig. 8. In straight gait, hip-joints keep constant, knee-joints and ankle-joints keep moving. Legs on both right and left hand have the same foot end trajectory shape and are parallel to the yoz plane. In swing phase, foot end swing along curve AB; in stance phase, foot end move along straight line AB.

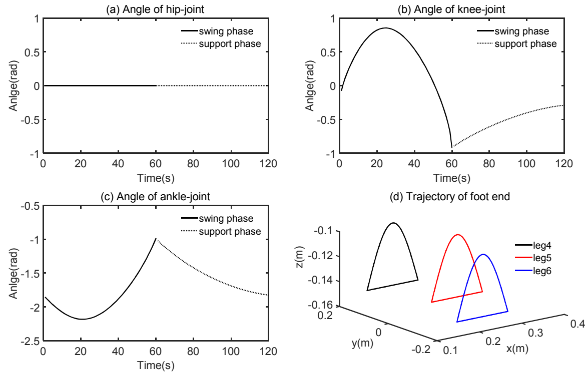


Fig. 8. Joint angles and foot end trajectories of right legs of transvers gait

C. Swivel Gait

Swivel gait refers to the robot swivel counterclockwise or clockwise as shown in Fig. 9.

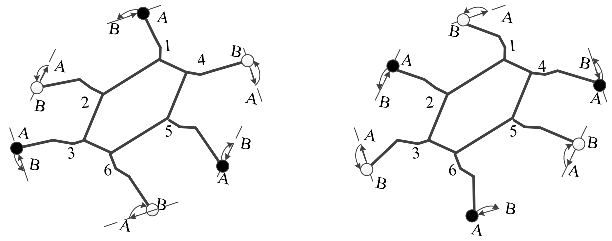


Fig. 9. Two states of swivel gait planning

In swivel gait, legs are no longer parallel to each other. Each leg distributes along the direction from mass center to original point of the base coordinate frame. The swivel gait of the robot is divided into two states. First, legs {1,3,5} are in the swing phase and legs {2,4,6} are in the stance phase. After switching to the next state, legs{1,3,5} become in stance phase and legs{2,4,6} become in swing phase. The legs in swing phase move along the arc AB, and the legs in the stance phase move along the straight line BA.

In a movement cycle, the relationship between the foot strip and the rotation angle is given as Eq. (10).

$$
\theta_T = 2\arctan(d_s / 2(L_{co} + L_{of})) \tag{10}
$$

In one cycle of the swivel gait, the rotation angle of the six legs relative to the mass center should be the same. Otherwise the relative position between each leg will be changed and the robot cannot swivel cyclically.

Because of the L_{co} value of the front legs and hind legs which is equal to 0.207m is greater than the L_{co} value of the middle legs, it's necessary to change foot end trip distance to ensure that each leg turns the same angle. For this purpose, the L_{of} value of front legs and hind legs should be greater than the L_{of} value of middle legs with the former is equal to 0.15m and the later is equal to 0.12m. For all of the legs, L_{of} is equal to 0.122m. By substituting these values to Eq. (10), the swivel angle is got and equal to 0.51 rad.

Food end trajectory is designed as Eq. (11) and Eq. (12).

$$\begin{cases} x_c = \cos(\varphi)(L_{co}+L_{of}) - \sin(\varphi)(d_s k / N - d_s / 2) \\ y_c = \sin(\varphi)(L_{co}+L_{of}) + \cos(\varphi)(d_s k / N - d_s / 2) \quad k = 0,1\cdots\cdots N \\ z_c = -0.15 + 0.05\cos(\pi(d_s k / N - d_s / 2) / d_s) \end{cases} \tag{11}$$

$$\begin{cases} x_c = \cos(\varphi)(L_{co}+L_{of}) - \sin(\varphi)(d_s k / N - d_s / 2) \\ y_c = \sin(\varphi)(L_{co}+L_{of}) + \cos(\varphi)(d_s k / N - d_s / 2) \quad k = 0,1\cdots\cdots N \\ z_c = -0.15 \end{cases} \tag{12}$$

The foot end trip distance of middle legs and the distance of the front and back legs is different, so the amplitude of the joint angles will be different. Taking leg4 as an example, ,each joint angle and foot end trajectory are shown in Fig. 10.

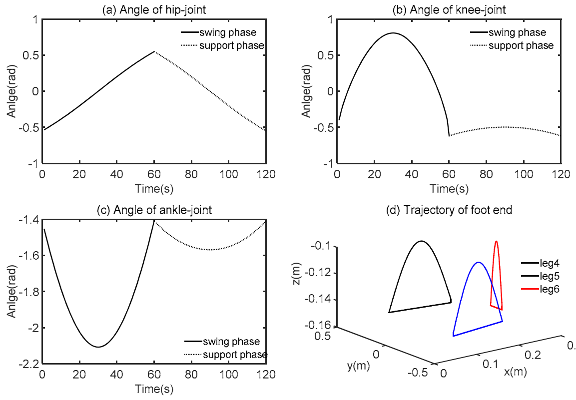


Fig. 10. Joint angles and foot end trajectories of right legs of swivel gait

The foot trajectory of the right leg is centrally symmetric along mass center. There is an angle between the planes of foot end trajectories. The foot end trip distance of legs{1,3,4,6} is greater than the distance of legs{2,5}.In this way, rotation angles of all legs around mass center could be equal.

IV. Experiment

A. System Design of Hexapod Robot

MCU used in this paper is Arduino Mega 2560.Besides, a servo control module, a display module, a wireless serial communication module are also included in this system, as shown in Table III detailly.

TABLE III. Hexapod Robot Hardware System Model

Name	Model	Parameters
Controller	Arduino	Mega 2560
Servo Driver	V3.2	INPUT DC-8.4V 16M Flash 32 outputs
Servo	KST X20-8.4-50	
Display Module	LCD 12864	Serial Port

B. Expriment of Tripod Gait

1) Straight Gait

According to the gait planning scheme, the step length of the straight gait is 0.12m. The host computer calculates the foot trajectory in Matlab, and uses the inverse kinematics equation to get the angles of each joint. The angles data was performed by steering engine to achieve the straight gait in tripod gait, which is shown in Fig. 11.

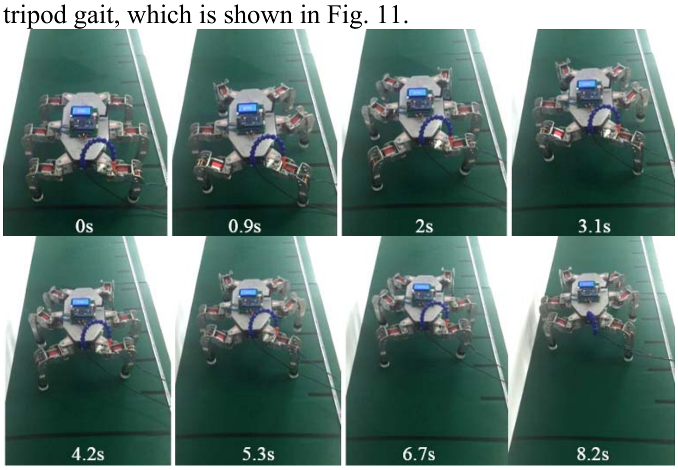
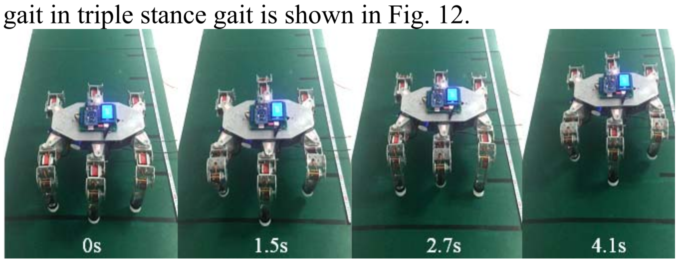


Fig. 11. Straight gait

The robot starts at a black line. 0s, the robot is initialized and the six legs are in the stance state. Then, the legs {1,3,5} become the swing phase, the foot ends swing from back to front, and the legs {2,4,6} become stance phase. 0.9s, the legs {1,3,5} have completed the swing phase movement, automatically switch to stance phase. Legs {2,4,6} switch into the swing phase, synchronically, and foot end leave off the ground and begin to swing. 2s, legs {2,4,6} have completed the swing phase, switch into stance phase, foot end move on the ground from front to back, so the robot mass center move forward. The phase difference between the two groups of legs is stable and no collision happens. Phases between legs meet the planning requirements. During walking, the robot can walk normally without tilting. The actual displacement in the 20s is 1.02m with average step is 0.1m and the average velocity 0.051m/s.

2) Transverse Gait

The step length of transvers gait is set to 0.12m. Transvers gait in triple stance gait is shown in Fig. 12.



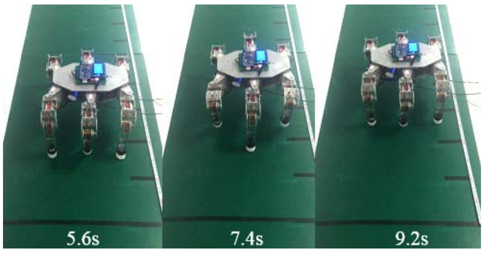


Fig. 12. Transvers gait

In transvers gait, foot end trajectories of all legs are parallel to each other. Two groups of legs alternately, constantly stance and swing, to achieve a stable and coordinate frame walking. The actual displacement in the 20s is 0.92m with average step length 0.12m and average velocity 0.054m/s.

3) Swivel Gait

The theoretical rotation angle of tripod swivel gait in one gait cycle one is of 0.51rad. Tripod swivel gait experiment is shown in Fig. 13.

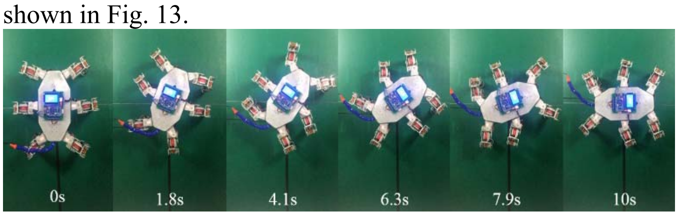


Fig. 13. Swivel gait

In swivel gait, foot end trip distance of middle legs is 0.12m and foot end trip distance of forelegs and hind legs is 0.15m. The swivel angle in on cycle could be changed by adjusting foot end trip distance. Robot can swivel to any direction. The experimental results show that the control signal from the controller can make the robot rotate steady. The phase difference between the legs is stable. Legs do not interfere with each other. In summary, the trajectory planning is reasonable. The hexapod robot leg acts 12 swing motions in one cycle.

V. Conclusion and Future Work

A. Conclusion

1) The foot end workspace of a single leg is irregular, depressed in the middle, and raised at both ends.

2) According to the rotation angle of the leg base coordinate frame rotating along the z-axis and the leg's span, foot end trajectories of different move distance can be designed.

3) The foot end trajectory in swing phase is designed as a half-cycle sinusoidal curve and stance phase as a straight line. This algorithm is easy for gait plan and can be applied to the motion of straight, transvers and swivel gait.

B. Future Work

The method of evaluating inverse kinematic equation of designed foot end trajectory to get joint angles cannot adjust the speed and gait of the hexapod robot flexibly. However, CPG is a kind of biological control scheme which can make robot move stably even in disturbing environment. In future work, CPG will be introduced to the hexapod gait plan.

Acknowledgment

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