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Movement Planning and Control of an Overhead Power Transmission Line Inspection Bionic-Robot*

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***Abstract*— Inspection robotics is attracting much attention on overhead power transmission lines to replace manual inspection tour. In this paper, based on a benchmark of underactuated Acrobot, we mainly focus on movements and control of a two-link bionic-robot for online inspection by adding grippers at the end of connecting links. Firstly, a movement planning is proposed for brachiating suspended on high-voltage aerial lines. Considering motion efficiency and some obstacles on the lines, two movements consisting of line-walking and obstacle-navigation are analyzed in details. Then, according to the Lyapunov-based analysis and the theory of energy conservation, an energy-based controller is presented for obstacle-navigation to track and stabilize the planned movement. Finally, Simulation results show that the bionic-robot can realize obstacle-navigation motion and proves the valid of the controller.**

I. Introduction

High-voltage overhead power transmission lines are to support long-distance power transmission and to provide electric insulation between a steel tower and electrical conductors at different potentials, which are essential for transmission networks without any interruption [1]. With the development of mechanical, thermal, and environmental stresses, some defects or severe deterioration in aerial lines could lead to a power outage. To ensure power supply reliability, aerial lines inspection is a must for most maintenance operations [2], [3]. Traditional aerial lines inspection work for linemen is foot patrol, *i.e.*, walking over the mountains or wading across rivers, with the help of binoculars and sometimes with corona detection cameras. This inspection type is in contact with high-strength labor and low inspection accuracy, which represents risk of poor efficiency and reliability.

As in many fields of application, robotics are making their mark on aerial lines maintenance [4]. During the past decades, many theoretical and experimental studies have been made in order to develop live-line inspection robots to travel along aerial lines to perform inspection. Among them, wheel-assisted and gripper-assisted manipulators are the two most common types in the hot research area. Wheels are the simplest way for walking along aerial lines and wheel-assisted robots are also becoming well-applied for live-line inspection [5]–[8]. Wu *et al.* [9] proposed a dual-wheel driving suspended robot on high voltage transmission lines, which could surmount the obstacles along the wire such as clamps and vibration dampers. Not only that, they designed the robot system had complex dimensions by using the additional grippers to access online inductive power supplies. From the optimized viewpoint, few design reviews on the proposed robot were key to implementing configuration optimization between wheels and additional grippers [10].

Based on gripper-assisted manipulators, another type is the brachiating or legged locomotion. Brachiation resembles the motion of an arboreal animal, which moves expanding its own arms/legs and climbing branches, and presents step walking in the trees. For the legged robot's obstacle-navigation, meticulously manipulator mechanisms can maintain good behavior when obstacles are placed at equal intervals. Toward this end, some brachiating robots and their controllers are presented [11], [12]. For example, Tsujimura *et al.* [13] proposed the suspended "legged robot" walking on aerial cables, whose walking locomotion resembles the motion of a Folivora. Wang *et al.* [14] developed a biped robot for inspection of power transmission lines, which can realize legged locomotion. More precisely, its one foot hangs from the line and the other foot swings from the rear to the front to overcome obstacles on the line. Spong *et al.* [15] considered the underactuated "Acrobot" and researched its swing-up problem which is connected with the requirement of an oscillatory exchange of kinetic energy and potential energy in the gravitational field. Additionally, the landmark success in Acrobot's brachiating locomotion [16] represents the most important influence on the present work.

This paper mainly focuses on a two-link bionic-robot for online inspection by adding grippers at the end of connecting links based on a benchmark of underactuated Acrobot. Specifically, a novel motion planning is proposed for brachiating suspended on high-voltage aerial lines. Two movements consisting of line-walking and obstacle-navigation are analyzed in details with onsideration of motion efficiency and some obstacles on the lines, Then, according to the Lyapunov-based analysis and the theory of energy conservation, an energy-based controller is presented for obstacle-navigation to track and stabilize the planned movement. At last, simulations results are conducted to confirm the effectiveness of motion planning and controller we proposed.

II. System Framework and Dynamics

As shown in Fig. 1, we propose a two-link brachiating robot system, which could walk on high-voltage aerial lines for inspection. The robot system described here has a body and two gripper mechanisms. The mechanical body of the bionic-robot is basically made up of two parts, *i.e.*, an

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actuated shoulder joint and two nonactuated arms (fore-arm and rear-arm) which are identical and connected to the lines via their grippers. Note that the grippers cannot impose torque on the handhold, the mechanical body of the bionic-robot is one benchmark of underactuated system [17], [18], $i.e.$, it has fewer actuators than degrees of freedom.

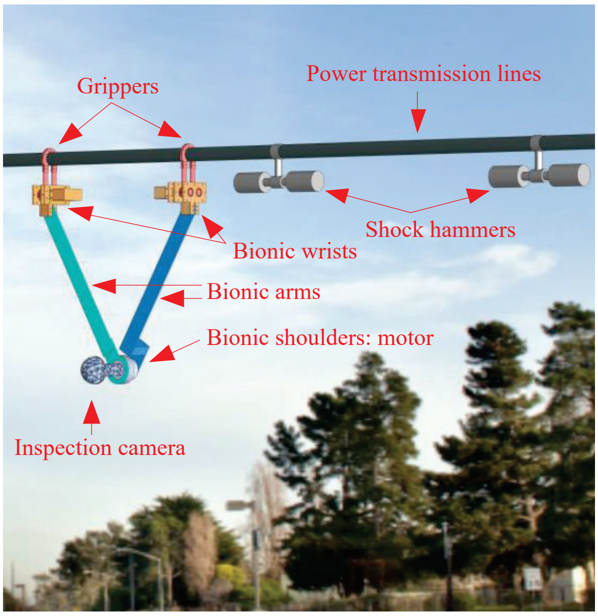

Fig. 1. A two-link brachiating bio-robot system.

The dynamics of the two-link brachiating robot system is analyzed in the previous work [15] and could be shown schematically in Fig. 2, which can be mathematically described as follows

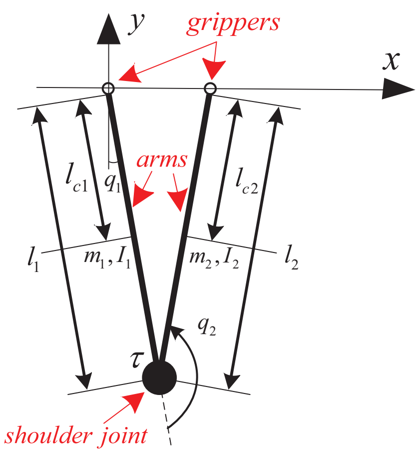

Fig. 2. Mechanical body of the bionic-robot.

$$D\left(q\right)\ddot{q}+C\left(q,\dot{q}\right)\dot{q}+G\left(q\right)=\tau \tag{1}$$

The dynamics of matrix form (1) could be written as

$$d_{11}\ddot{q}_1+d_{12}\ddot{q}_2+h_1+\phi_1+N_1=0 \tag{2}$$

$$d_{21}\ddot{q}_1+d_{22}\ddot{q}_2+h_2+\phi_2+N_2=\tau_2 \tag{3}$$

where

$$\begin{aligned}
d_{11}&=\theta_1+\theta_2+2\theta_3\cos q_2\\
d_{12}&=d_{21}=\theta_2+\theta_3\cos q_2\\
d_{22}&=\theta_2\\
h_1&=-\theta_3\dot{q}_2\sin\left(2\dot{q}_1+\dot{q}_2\right)\\
h_2&=\theta_3\dot{q}_1^2\sin q_2\\
\phi_1&=\theta_4 g\cos q_1+\theta_5 g\cos\left(q_1+q_2\right)\\
\phi_2&=\theta_5 g\cos\left(q_1+q_2\right)\\
\theta_1&=m_1l_{c1}^2+m_2l_1^2+I_1\\
\theta_2&=m_2l_{c2}^2+I_2\\
\theta_3&=m_2l_1l_{c2}\\
\theta_4&=m_1l_{c1}+m_2l_1\\
\theta_5&=m_2l_{c2}
\end{aligned}$$

where q_i, $\dot{q}_i$ and $\ddot{q}_i$ represent the ith vector, velocity and acceleration of generalized coordinates, respectively; d_{ij} represents the each element of positive definite inertia matrix $D\left(q\right)$; h_i represents the ith element of centripetal and Coriolis matrix $C\left(q,\dot{q}\right)$; ϕ_i represents the ith element of gravitational torques matrix $G\left(q\right)$; τ_2 represents applied joint torque; represents the nominal value of the gravity constant; m_i and l_i represent the ith mass of arm and length, respectively; I_i represents the moment of inertia; N_i denotes the ith friction; $l_i=2l_{ci}$ and $i=1,2,j=1,2$.

The passivity of the bionic-robot [15] can be written as

$$\dot{E}=\sum_{i=1}^{2}\tau_i\dot{q}_i\equiv 0 \tag{4}$$

where E represents the total energy of the robot, restricted by the physical control torques. Note that under the actuation of the shoulder joint, the arms can brachiate in turns to the next handhold.

III. Movement Planning and Control

A. *Movement Planning*

As shown in Fig. 3, we mainly focus on two kinds of movement types on high-voltage aerial lines, which are line-walking and obstacle-navigation.

The movement process of line-walking is shown in Fig. 3. Resembling the athletes brachiating under the parallel ladder, the bionic-robots line-walking dynamically reaches to the fore-handhold by the left arm and leaves form the rear-handhold by the right arm.

- When the right gripper fastens the original handhold on the line, the left gripper will release while the left arm is driven to the desired handhold.
- Reaching to the next desired handhold, the left gripper will fasten the line instantaneously; at the same time, the right gripper should release the original handhold and also reach to the next desired handhold.
- Periodically, the bionic-robot can walk forward step by step all the time by the left arm and its gripper.

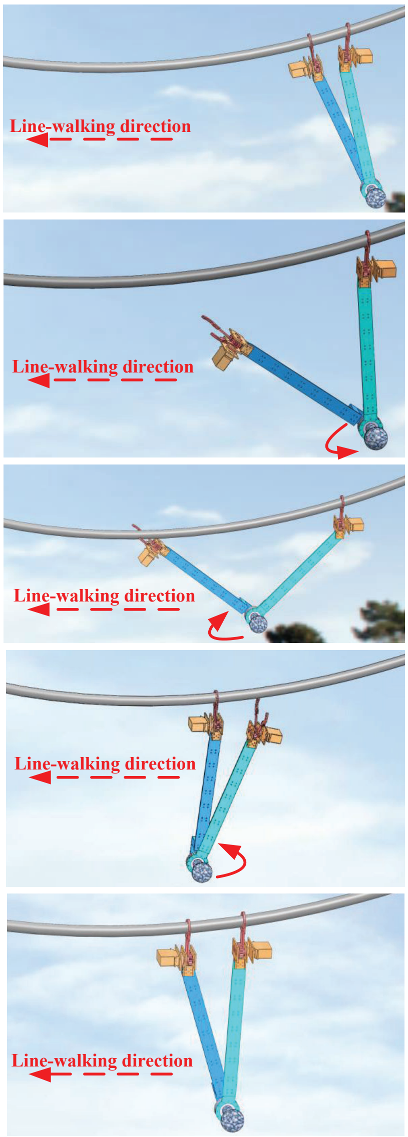

Fig. 3. Movement planning: Line-walking.

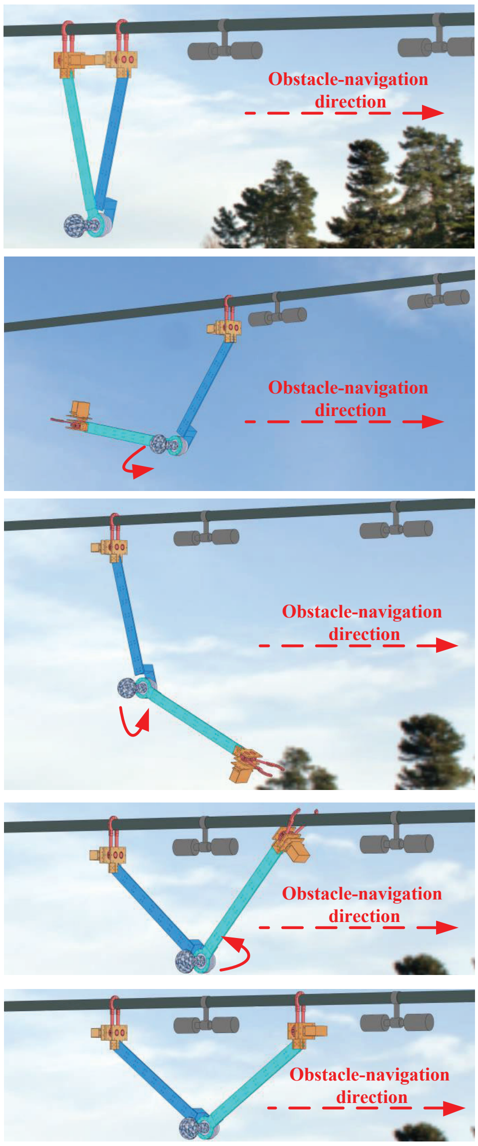

Fig. 4. Movement planning: Obstacle-navigation.

Line-walking is an easy way for the bionic-robot to walk along the lines. While, note that line-walking can hardly be used in the case that the size of obstacles is larger than the stride, such as counterweights. For the field power line inspection application, the bionic-robot must have the ability to overcome obstacles so that it can work on several segments of high-voltage aerial lines continuously. Hence, a larger stride should be achieved by bionic-robots brachiating.

Expanding the arms and climbing the next handhold, the bionic-robots obstacle-navigation dynamically reaches to the latter handhold by the brachiating cycle, which is a periodic orbit achieved by the arm far from the obstacle and inspired by a gibbon swinging through the trees, as shown in Fig. 4.

The bionic-robot could navigate obstacles by exchanging the two arms and repeating by the following steps.

- Before the obstacle, the left gripper will release the original handhold and the left arm is driven to fall and extents till the left gripper reaches the line with the right side of the obstacle.
- When the previous left gripper (now is new right gripper in this step) fastens the new handhold, the previous right gripper (now is new left gripper in this step) will release its handhold.
- By the rotating of the new left arm, the left arm is driven to fall and extents till the left gripper reaches the line with the right side of the obstacle.

B. *Control Design*

Based on the movement planning, the control design about mechanical body of the bionic-robot is presented as follows.

Aiming to drive the arm to a desired generic state instantaneously, stabilizing of generic handholds is impossible and a possible way is to stabilize periodic orbits passing through the desired handholds. Different from the stabilization control or tracking control, the control objective of bionic-robot is state points, but a certain periodic orbit is achieved in practice, which is dynamical servo control.

Definition 1: For system $\dot{x} = f(x,u)$, $x(t_0) = x_{\mathbf{0}}$, given one reference orbit $\beta_d(t)$ and tracking error δ, suppose there exists a control law $u(t)$. If $\exists T_0$ when $t > T_0$, $|q(t) - \beta_d(t)| < \delta$ holds, then it is called servo control; if $\exists T_0$ when $t_i > T_0$, $i = 1, 2, \cdots$, $|q(t_i) - \beta_d(t_i)| < \delta$ holds, then it is called dynamical servo control.

For the bionic-robot, the dynamical servo control means that its arms could arrive at the given orbits. Now, supposing we have chosen one reference orbit β_{id}, denotes the ith vector of the robot will be controlled to satisfy

$$\begin{cases} q_i = \beta_{id} \\ \dot{q}_i = \dot{\beta}_{id} \end{cases} \tag{5}$$

According to (5), the matrix for dynamics (1) is taken as

$$\begin{aligned} &D(\beta_{1d}\cdots\beta_{md}, q_n)\ddot{q}_n + G(\beta_{1d}\cdots\beta_{md}, q_n) \\ &\quad + C\left(\beta_{1d}\cdots\beta_{md}, \dot{\beta}_{1d}\cdots\dot{\beta}_{md}, q_n, \dot{q}_n\right)\dot{q}_n \ = \tau \end{aligned} \tag{6}$$

where $i \leqslant m < n$. Notice that q_i and $\dot{q}_i$ ($i \leqslant m$) are driven to steer the reference orbits by the control input τ. Let the reference orbits be constants, then, taking the integration of (5) with respect to time and the dynamic orbits of q_i ($m < i \leqslant n$) can be achieved. Additionally, if the reference orbits are chosen as zeroes, $i.e.$, $\beta_{id} = 0$ or $\dot{\beta}_{id} = 0$.

Based on (4), the control input τ will not do any work and the bionic-robot will keep the energy conservation. For (6), note that $D(\beta_{1d}\cdots\beta_{md}, q_n) = d_{nn}$. Let q_c denote the system equilibrium and can be obtained from

$$G(\beta_{1d}\cdots\beta_{md}, q_c) = 0 \tag{7}$$

Further, taking the derivative of the total potential energy of the bionic-robot (except for the grippers gravitational potential energy) with respect to q_n and making some mathematical arrangements yields

$$\frac{\partial P}{\partial q_n} = G(\beta_{1d}\cdots\beta_{md}, q_n) \tag{8}$$

where the curvature of the total potential energy curve of the system is bounded at the minimal point, that is

$$\frac{\partial G(\beta_{1d}\cdots\beta_{md}, q_n)}{\partial q_n} > 0 \tag{9}$$

For the movement of obstacle-navigation, the brachiating arm is actuated, we can get

$$q_2 = q_{2d} \tag{10}$$

where the total energy of the bionic-robot is only composed of its total potential energy, we can get

$$E_d = m_1 g l_{c1}\sin q_1 + m_2 g l_{c2}\sin(q_2 - q_1) \tag{11}$$

the orbits $q_d = [q_{1d}, q_{2d}, 0, 0]$ is ensured by (10) and (11).

Based on the total energy of the bionic-robot, the periodic orbits can be written as

$$\begin{cases} q_2 = q_{2d} \\ E = E_d \end{cases} \tag{12}$$

Let $e_E = E - E_d$ and $e_{q_2} = q_2 - q_{2d}$, (12) can be written as

$$\begin{cases} e_{q_2} = 0 \\ e_E = 0 \end{cases} \tag{13}$$

Obviously, one input is in the bionic-robot and two output is needed to controlled. To let e_E and e_{q_2}, both converge to zero, following nonnegative storage function is constructed

$$V = 0.5k_E e_E^2 + 0.5k_D\dot{q}_2^2 + 0.5k_P e_{q_2}^2 \tag{14}$$

where $k_E > 0$, $k_D > 0$, $k_P > 0$. Defining $\Delta = d_{11}d_{22} - d_{12}d_{21} \geqslant 0$ and $\rho = d_{11}/\Delta > 0$, we can get

$$\rho^* = \min\left[\frac{\theta_1 + \theta_2 + 2\theta_3\cos q_2}{\theta_1\theta_2 - (\theta_3\cos q_2)^2}\right] > 0 \tag{15}$$

For the dynamics (2) and (3), if the following inequalities are true

$$k_D > \frac{2k_E E_{Top}}{\rho^*} \tag{16}$$

we can get the controller as

$$\tau_2 = \frac{k_V\dot{q}_2 + k_P e_{q_2} + \frac{k_D}{\Delta}\left[d_{21}(h_1 + \phi_1) - d_{11}(h_2 + \phi_2)\right]}{-k_E e_E - \frac{k_D d_{11}}{\Delta}} \tag{17}$$

where the control Lyapunov function (14) converges to zero, and $e_E \to 0$, $e_{q_2} \to 0$.

IV. Simulation Results

The inspection bionic-robot platform is shown in Fig. 5. The simulations are based on the physical parameters listed in TABLE I. The parameters of the controller τ_2 are tuned as $k_V = 25, k_P = 5, k_E = 5, k_D = 2$. The orbits q_d are tuned as $[q_{1d}, q_{2d}, 0, 0] = [0, 1, 0, 0]$. The initial orbits are tuned as $[q_1, q_2, 0, 0] = [0, 0, 0, 0]$.

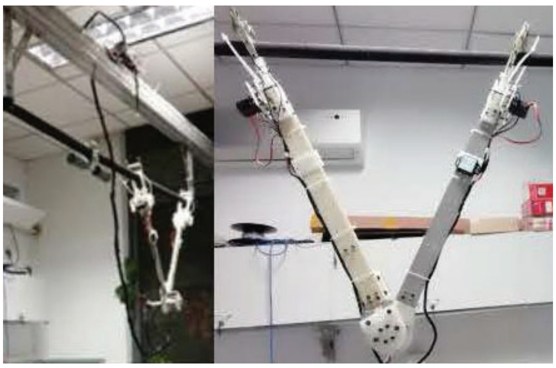

Fig. 5. The inspection bionic-robot platform.

For the given condition, to apply the proposed controller, the simulation results are plotted in Fig. 6. From the simulation results, we can see that the total energy E dynamically stabilizes at the stable value after 10 s. Meanwhile, q_2 gradually converges to the desired orbit within 10 s, and q_1 gradually realizes periodical variation, which means the brachiating arm of the bionic-robot periodically reaches the target position. Note that the value of physical control input

TABLE I

PARAMETERS BASED ON INSPECTION BIONIC-ROBOT PLATFORM

Notations	Values	Units
m_1, m_2	1.0, 1.0	kg
l_1, l_2	0.5, 0.5	m
l_{c1}, l_{c2}	0.25, 0.25	m
I_1, I_2	0.021, 0.021	$kg \cdot m^2$
g	9.81	m/s^2
τ	-	$N \cdot m$

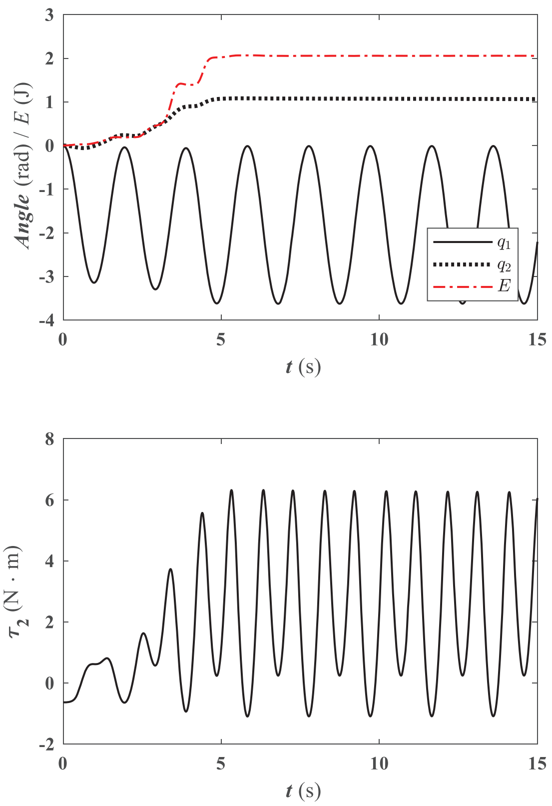

Fig. 6. The simulation results on the obstacle-navigation controller.

torque τ_2 is not more than 6 N·m, which is needed to input with time varying for overcoming the influence of the gravity. Combining with the grasp control of the grippers, the simulations on inspection bionic-robot system by using the proposed controller could realize obstacle-navigation movement. Furthermore, the experiments on inspection bionic-robot platform by using the proposed controller is in progress.

V. CONCLUSION

In this paper, based on an underactuated Acrobot, after suitable extensions, steering a brachiating bionic-robot on aerial lines for obstacle-navigation is studied. A movement planning is designed for brachiating suspended on high-voltage aerial lines. Two movements consisting of line-walking and obstacle-navigation are analyzed in details, with consideration of the motion efficiency and some obstacles on the lines. After that, an energy-based controller is presented for obstacle-navigation to track and stabilize the planned movement. Simulation results show that the proposed control design can steer the brachiating bionic-robot to the planned movements successfully.

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