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Adaptive head stabilisation system for a snake-like robot

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Abstract

Central Pattern Generators (CPGs) have become a popular solution for robot's locomotion control, in particular for snake-like robots. CPGs based on coupled nonlinear oscillators can be integrated with a sensory feedback to adapt the robot's locomotion to the environment or to achieve the desired dynamic characteristics of the movement. In this paper we present an adaptive head stabilisation system for a robotic snake that can adjust parameters of the oscillators to achieve minimal angular and linear motions of the robot's head. This allows to stabilise a video flow that comes from the camera attached to the head. Two head stabilisation systems are designed and the simulation results of the head movement are presented. It is shown that the linear displacement can be minimised by the proposed three oscillator method.

1 Introduction

Snake-like robots have a unique locomotion ability that allows them to move through a confined cluttered environment compared with their wheel robots counterparts. The potential market for this types of robots is 'search and rescue' missions, including exploration and surveillance applications. To ensure compliance of the search operation and provide a navigation in an unknown environment, the robot's head is normally equipped with a camera. This is especially relevant to underwater applications where the robot is controlled autonomously.

The most efficient way to propel a robotic snake forward is a serpentine locomotion [Hirose, 1993]. As a result of this movement, the robot's body forms a S-shaped wave and the trajectory of the motion can be represented as a serpenoid curve [Hirose, 1993]. Therefore, the head's motion of the robot has an oscillatory character, or, in other words, the robot changes its head direction constantly as shown in Fig. 1. Consequently, the robot's head must be stabilised to obtain readable videos from the camera. Head stabilisation can be performed in two stages: (i) compensation of an angular motion; and (ii) compensation of an angular motion and a linear displacement.

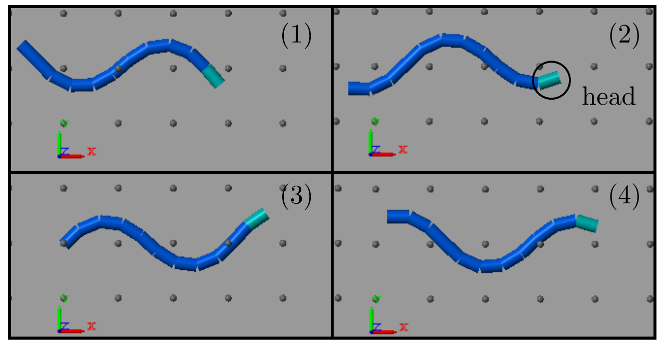

Figure 1: Locomotion of the snake robot without head stabilisation

The problem of a gaze stabilisation is not new and has been partially [Wu and Ma, 2010] or completely addressed for the snake robots. Yamada et al. [2007] offered to use a continuous model of a planar snake robot called "Active Cord Mechanism" that is based on the kinematics of the system. The time-varying curvature of the body is used as an input of the control system to compute reference joint angles. A robot is divided onto three parts such as 'head', 'neck' and 'body'; and a curvature for each part is calculated to satisfy a zero yaw angle and a zero lateral speed of the head. This approach requires prior knowledge of robot's kinematics and does not take into account dynamics of the motion and environmental disturbance. Furthermore, discretisation and linearisation of the continuous model bring inevitable inaccuracies in this method that lead to the residual errors of the head orientation and position.

Another approach is to consider the head stabilisation as an optimisation problem [Hasanzadeh and Tootoonchi, 2008], where genetic algorithm is applied to find optimal parameters, such as an amplitude and a phase lag, of the first joint angle. The orientation of the head link is introduced as a fitness function. This method provides the stabilisation of the head direction only, not compensating linear displacement. Furthermore, the set of optimal parameters that are found using genetic algorithm suit only one particular locomotion mode and can not be adjusted to different motion patterns in real time.

Wu and Ma [2010] applied the concept of central pattern generators (CPGs) based on Matsuoka's oscillators to control the snake robot and navigate its head. The dependence between joint angles before and after compensation of the head angular motion is found experimentally. Therefore, one virtual oscillator is added to the chain of CPGs to calculate parameters of the head joint angle to keep the direction of the head constant.

The dynamics of the snake-like robot can be described as for an under-actuated redundant floating-base mechanism. Consequently, the control of the head position can be calculated using the inverse dynamics algorithms setting the desired acceleration and velocity of the head link [Yamakita *et al.*, 2003]. Their approach requires the knowledge of an accurate dynamic model and is computationally time-consuming.

There are other types of head stabilisation systems developed for different types of robots. Gay et al. [2012] developed such a system based on adaptive frequency oscillators for the legged robot. Optical flow is used as a feedback signal to compensate periodic motion of the head during locomotion. Moreover, this approach was tested on the salamander robot that experiences the same type of locomotion as a snake mechanism. However, a camera has a separate actuator from the head section motor and a gaze stabilisation does not affect the robot's motion and can not be applied to the cases when a camera is rigidly attached to the head.

In this paper we propose an adaptive head stabilisation system that uses data from a vestibular sensor to compensate the rhythmic motion of the head. Two methods are offered: (i) stabilisation of the head's direction involving one joint; (ii) stabilisation of the direction and position of the head involving two or three joints. First, we present the generic structure of the robot's 2-D locomotion control with a chain of coupled Hopf oscillators. Then we demonstrate the mathematical model of the adaptive oscillators that compensates an angular and linear motions of the head. Simulation results of the proposed control methods are presented as well.

2 Methodology

In this section we present the basic motion control model of the snake robot, followed by the description of two head stabilisation systems.

2.1 CPGs Structure

The proposed control system of the robot is an integration of CPGs with a lower level controller as shown in Fig. 2, where $\tilde{\varphi}_i, \dot{\tilde{\varphi}}_i$ are angles and angular velocities between joints measured by the rotary encoders, φ_i are reference joint angles generated by CPGs and τ_i are control torques applied to servomotors.

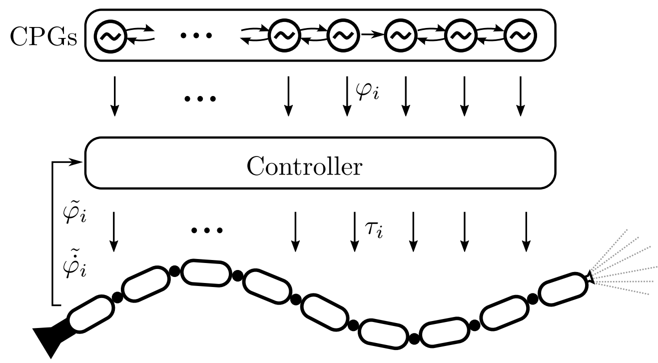

Figure 2: Architecture of the control system.

Each CPG controls one joint angle and is designed as a modified Hopf oscillator with the following equations [Degallier *et al.*, 2011]:

$$\dot{x} = (m - r^2)x - \omega y = f_x(x, y, \omega), \tag{1}$$

$$\dot{y} = (m - r^2)y + \omega x = f_y(x, y, \omega), \tag{2}$$

$$\dot{m} = C(\mu - m), \tag{3}$$

where x, y are the state variables of the oscillator, $r = \sqrt{x^2 + y^2}$, μ and ω are the amplitude and the frequency of the oscillation, m is an auxiliary variable and a constant C controls the convergence speed. Fig. 3 demonstrates the convergence of the Hopf oscillator with different initial conditions, when $x(0)$ and $y(0)$ vary from -2 to 2.

We use y as an output of the oscillator that represents a joint angle $\varphi = y = r\sin(\theta)$, where $\theta = \mathrm{sgn}(x)\arccos(-y/r)$ is the phase of the oscillator. This choice is caused by more gradual convergence to steady angles after the system initialisation.

Oscillators in the CPGs chain can have different phase delays and amplitudes, therefore, the coupling scheme is implemented in the following way [Chung and Slotine, 2010]:

$$\dot{x}_i = f_{xi} - \tau \sum_j \left(x_i - \frac{\mu_i}{\mu_j} \left(x_j \cos\phi_{ij} - y_j \sin\phi_{ij} \right) \right), \tag{4}$$

$$\dot{y}_i = f_{yi} - \tau \sum_j \left(y_i - \frac{\mu_i}{\mu_j} \left(x_j \sin\phi_{ij} + y_j \cos\phi_{ij} \right) \right), \tag{5}$$

where f_{xi} and f_{yi} are defined in (1) and (2) respectively, τ is a coupling constant, j represents adjacent neighbors

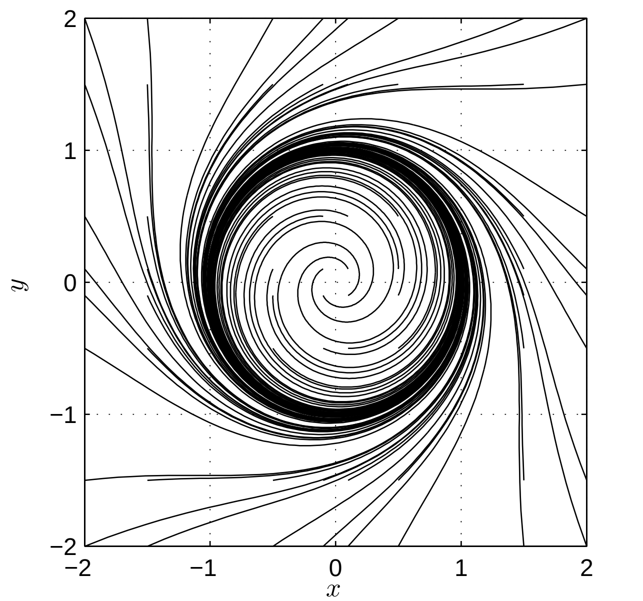

Figure 3: Limit cycle behavior of the Hopf oscillator with different initial conditions

for the i-th oscillator, ϕ_{ij} is a phase difference between adjacent oscillators.

2.2 Stabilisation of Direction

During locomotion a snake's head with other parts of the body is involved in the propulsion process; therefore, the head's motion is oscillatory with respect to the environment. Stabilisation of the head direction (a compensation of the yaw movement) can be achieved by adjusting an amplitude and a phase lag of the first joint angle. The oscillation frequency of the head is the same as the motion of the rest of the body and equals to the frequency of the Hopf oscillators in the CPGs chain. Therefore, we use an approach that is similar to Gay's [Gay *et al.*, 2012] with the following modifications:

- we assume that the oscillation frequency of the body is known, as our system combines the motion control and the head stabilisation control together;
- angular speed of the head around a vertical axis (ω_z) is used as an external forcing signal.

The modified structure of the CPGs is demonstrated in Fig. 4. The first oscillator that controls the head movement is adaptable and takes an angular speed of the head as an input signal to change the amplitude and the phase lag of the oscillation.

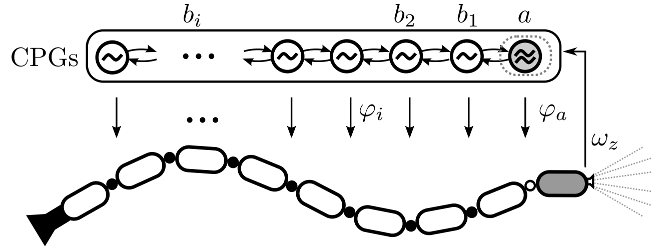

Figure 4: CPGs structure for the direction stabilisation

The equations of the first oscillator become:

$$\dot{x}_a = (\mu_a - r_a^2)x_a - \omega y_a - \tau\left(x_a - \frac{\mu_a}{\mu_{b_1}}\left(x_{b_1}\cos\phi_a - y_{b1}\sin\phi_a\right)\right), \tag{6}$$

$$\dot{y}_a = (\mu_a - r_a^2)y_a + \omega x_a - \tau\left(y_a - \frac{\mu_a}{\mu_{b_1}}\left(x_{b_1}\sin\phi_a + y_{b_1}\cos\phi_a\right)\right), \tag{7}$$

$$\dot{\alpha}_a = -\eta_a\omega_z\frac{y_a}{r_a}, \tag{8}$$

$$\dot{\phi}_a = \beta_a\omega_z\frac{x_a}{r_a}, \tag{9}$$

$$\varphi_1 = \varphi_a = \alpha_a y_a, \tag{10}$$

where a subscript a means that an oscillator is dependent on an angular motion, and b_1 relates to the first oscillator of the body part (in this case it is the second one in a chain). Equations (6)-(7) describe a Hopf oscillator that is coupled to b_1 with a phase difference of ϕ_a and has an amplitude μ_a. The phase lag ϕ_a is determined by (8) and is responsible for synchronisation of signals ω_z and y_a. When the phases of the two processes coincide, the amplitude scale factor α_a will start increasing until ω_z becomes zero. η_a and β_a characterise the convergence rate.

2.3 Stabilisation of Direction and Position

The serpentine locomotion of the snake robot leads not only to the angular rotation of the head but also to its lateral displacement that also needs to be compensated. Therefore, a certain body part must perform the role of the neck and at least one additional joint should be involved to solve this problem. The minimum amount of required joints to execute the task of the neck depends on the length of each link and the total number of links in the body. We introduce two variations of this system: (i) one joint for the head and one joint for the neck; (ii) one joint for the head and two joints for the neck. Fig. 5 demonstrates the head stabilisation system that is based on three oscillators. An angular (ω_z) and a linear (v_y) velocity of the head measured in its axes provide the input signals to the adaptive oscillators.

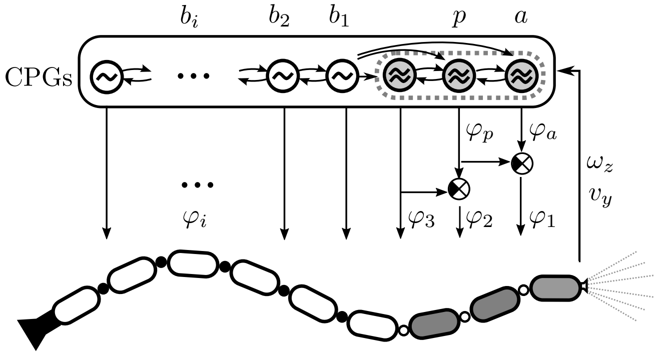

Figure 5: CPGs structure for the direction and position stabilisation based on three oscillators

Compensation of Angular Movement

All oscillators included in the head stabilisation system take part in the compensation of angular movement. Therefore, the sum of the 'head' and 'neck' angles $(\varphi_h + \varphi_n)$ should be such as to compensate for the angular displacement of the rest of the robot's body and should satisfy the requirement:

$$\varphi_h + \varphi_n = \varphi_a, \tag{11}$$

where φ_a is calculated using equations (6)-(9), φ_h and φ_n are

(i) for the system with two oscillators $\varphi_h = \varphi_1$ and $\varphi_n = \varphi_2$;

(ii) for the system with three oscillators $\varphi_h = \varphi_1$ and $\varphi_n = \varphi_2 + \varphi_3$.

Compensation of Position

The task of 'neck' joints is to eliminate a lateral movement of the head; therefore, we use the projection v_y of the linear speed on the lateral axis of the head as an external forcing signal into the adaptive oscillator:

$$\begin{aligned}\dot{x}_p &= (\mu_p - r_p^2)x_p - \omega y_a \\ &\quad - \tau\left(x_p - \frac{\mu_p}{\mu_{b1}}\left(x_{b1}\cos\phi_p - y_{b1}\sin\phi_p\right)\right), \quad (12)\\ \dot{y}_p &= (\mu_p - r_p^2)y_p + \omega x_p \\ &\quad - \tau\left(y_p - \frac{\mu_p}{\mu_{b1}}\left(x_{b1}\sin\phi_p + y_{b1}\cos\phi_p\right)\right), \quad (13)\\ \dot{\alpha}_p &= -\eta_p v_y \frac{y_p}{r_p}, \quad (14)\\ \dot{\phi}_p &= \beta_p v_y \frac{x_p}{r_p}, \quad (15)\\ \varphi_p &= \alpha_p y_p, \quad (16)\end{aligned}$$

where a subscript p means that oscillator is dependent on the head position. The sum of 'neck' angles should satisfy the requirement:

$$\varphi_n = \varphi_p. \tag{17}$$

It should be noted, that equations (6)-(9) and (12)-(15) hold when only the forcing signals have the same frequency as the adaptive Hopf oscillators. A signal of an angular speed ω_z has one frequency component ω and the direction stabilisation system is convergence. However, the signal of linear velocity v_y has multiple frequency components with the fundamental harmonics as ω. As a result, an adaptive oscillator p due to the presence of other frequencies will not be able to converge completely and an additional condition is needed to stop its adaptation. For this purpose we use the time moment when the bottom value of the longitudinal speed approaches to zero, i.e. if $(v_x \leq 0)$ then $t_{a(stop)}$.

In a case when 'neck' includes two joints ($\varphi_n = \varphi_2 + \varphi_3$), there are numerous combinations of φ_2 and φ_3 to satisfy equation (17). Therefore, additional requirements can be set depending on the preferences, such as the maximum angle of the servo or preferred form of the arch of the neck.

3 Simulation Results

In this section we present the simulation results of the proposed head stabilisation system. The model of a snake-like robot is developed in SimMechanics$^{\text{TM}}$ and contains 11 links each with a length of 0.1 m. The snake's locomotion is constrained by the horizontal plane; ground friction forces are applied to the center of mass of each link with coefficients of friction $c_t = 1$ and $c_n = 10$. Data of the angular and linear speed are provided by 'Transform sensor' attached to the head link. Parameters used for the CPGs are as follows:

- $\mu_i = \mu = 0.2742$ (joint angles amplitudes are 30 deg);
- a phase lag $\phi_{ij} = \phi = 0.6283$ rad (36 deg) if $i > j$ or $\phi_{ij} = -\phi$ if $i < j$;
- the frequency of the oscillation $\omega = 0.6981$ rad/sec (40 deg/sec);
- $C = 1$;
- $\tau = 0.5$.

3.1 Stabilisation of Direction

Fig. 6 shows a case of tuning of the system parameters during the stabilisation of the head direction ($\eta_a = 1$; $\beta_a = 1$). After adaptation, when the amplitude of the first joint angle increases by 1.8 times (α_a) and the phase shift reaches the level of –62 deg, the angular velocity goes down from ±36 deg to ±0.3 deg (a yaw angle from ±53 deg to ±0.5 deg), that indicates the effectiveness of the proposed system.

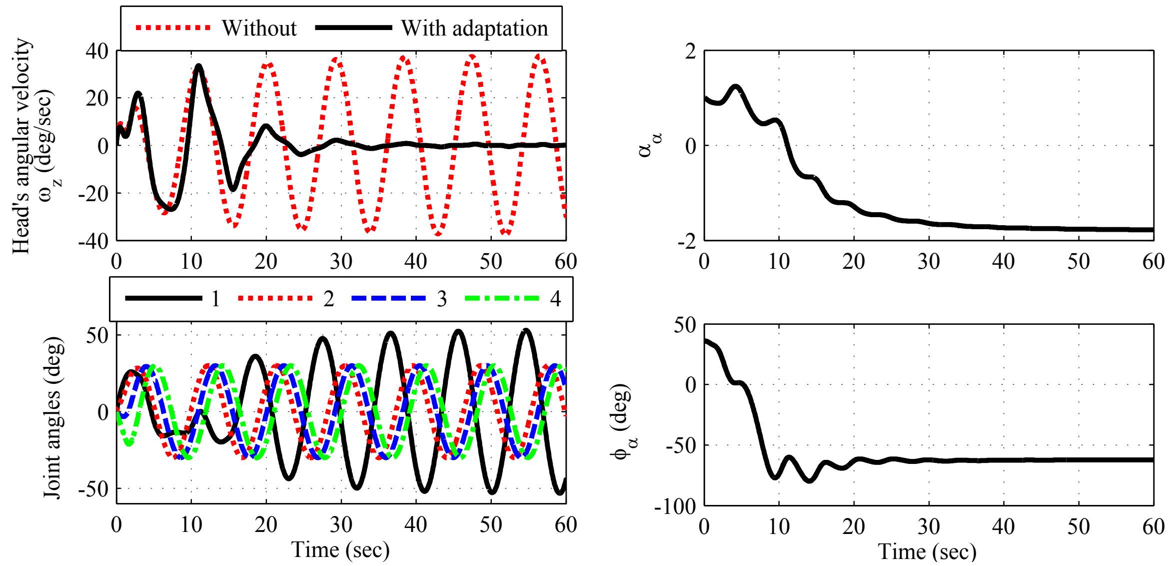

Figure 6: The result of the joint angles and the direction stabilisation

3.2 Stabilisation of Direction and Position

The stabilisation of direction and position is simulated for two cases: (i) when system includes two oscillators; and (ii) for the system with three oscillators. Fig. 7 demonstrates changes in the angular speed (ω_z), a lateral speed (v_y) and a lateral displacement as well as the evolution of the adaptive oscillators parameters. The head's angular speed goes down to the level of ± 1 deg after 40 sec, while the linear speed and displacement decrease only 2.5 times and the latter remains within a

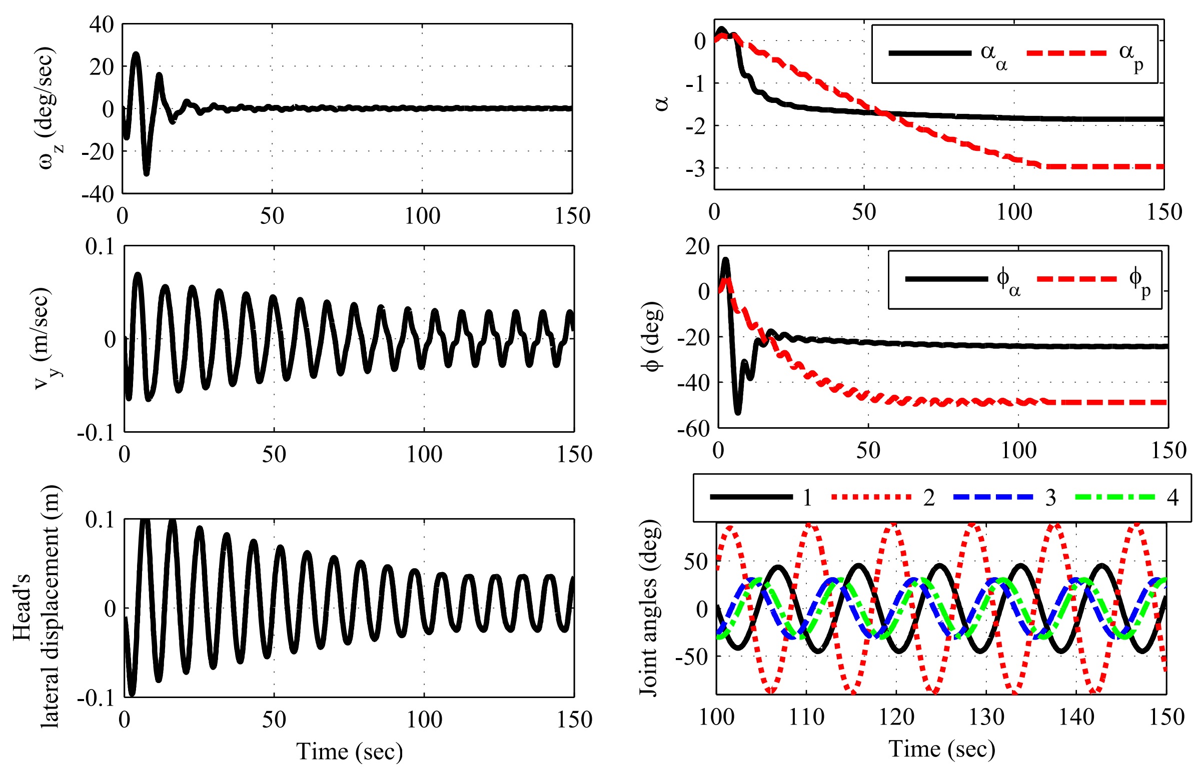

Figure 7: The result of the direction and position stabilisation (case with two oscillators)

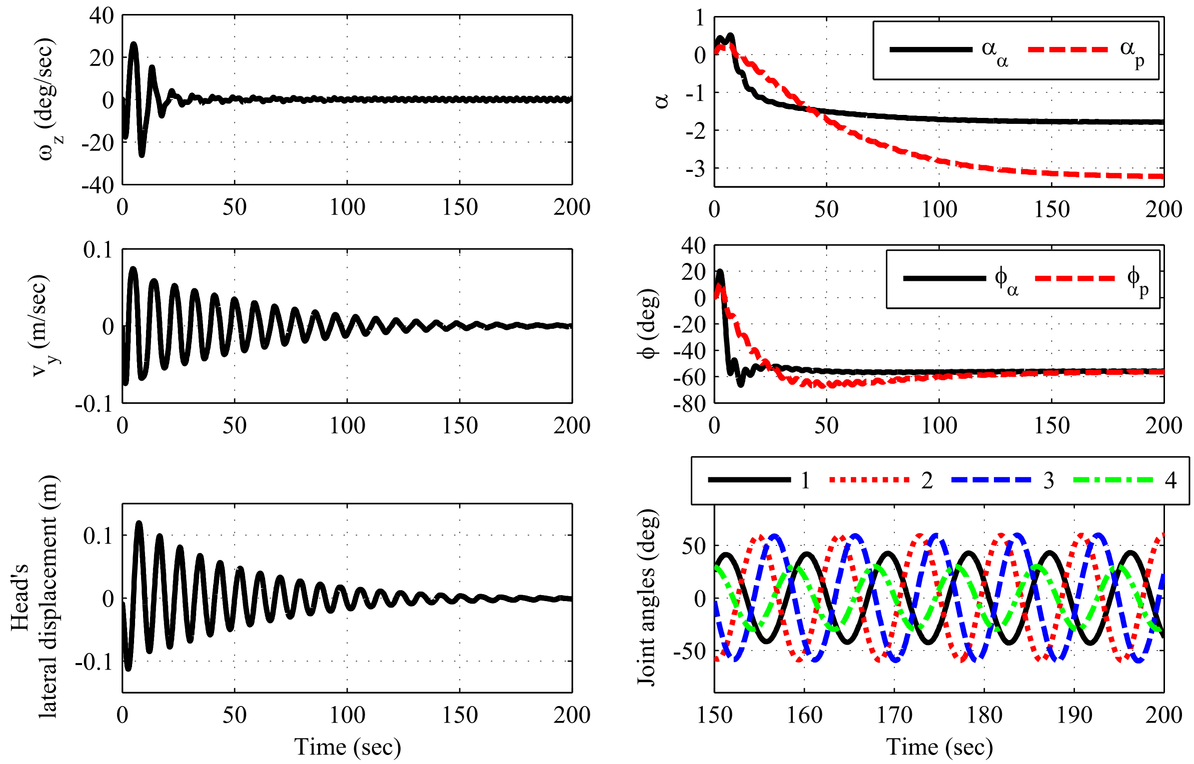

Figure 8: The result of the direction and position stabilisation (case with three oscillators)

range of ± 3 cm while the amplitude of the whole body movement is ± 10 cm. The presence of residual errors can be explained by higher frequency components in a linear velocity and it is simply impossible to completely eliminate the errors by using one frequency periodic signal in a system with two joints involved. It is clear that the second joint angle reaches ± 80 deg, that may cause difficulty in practical application to the real robots due to the physical limitations of their servomotors.

Fig. 8 shows the same set of results but for the system with three oscillators involved in the stabilisation. The system achieves complete convergence after 150 sec and the residual error is in a range of ± 0.3 cm for the linear displacement and ± 1.5 deg for the orientation angle. The convergence time depends on the oscillation frequency of the Hopf oscillator and adaptive oscillators' parameters; therefore, it can vary from case to case.

3.3 Head stabilisation during turning motions

The robot's movement is not constrained by the straight line motion; therefore, turns to the right/left and on

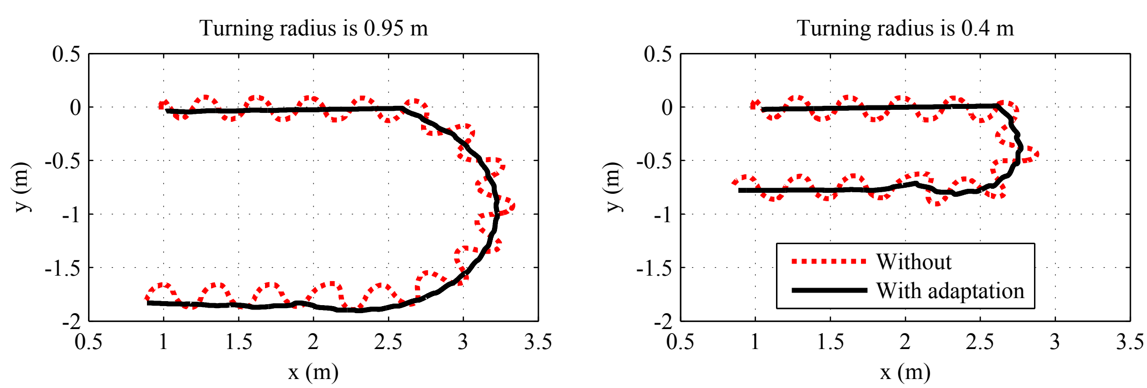

Figure 9: The path followed by the head link during turning motions

the spot should be considered. These locomotion modes provide an additional angular velocity about a vertical axis. Fig. 9 demonstrates the trajectory of the head link while the robot is performing 360 degree turns with different radii (0.95 m and 0.4 m). It is shown that the proposed stabilisation system with three oscillators prevents swinging motion of the head while the robot is turning.

4 Conclusion

The described head stabilisation system can be applied to the snake robots when the dynamic model is unknown. Simulation results prove that the insufficient number of joints involved in the stabilisation process cannot guarantee the full elimination of the linear displacement, but in all cases the angular motion is compensated. This system demonstrates the great benefit of the adaptive oscillators. Fig. 10 demonstrates the body shape of the snake robot when the head stabilisation system is activated.

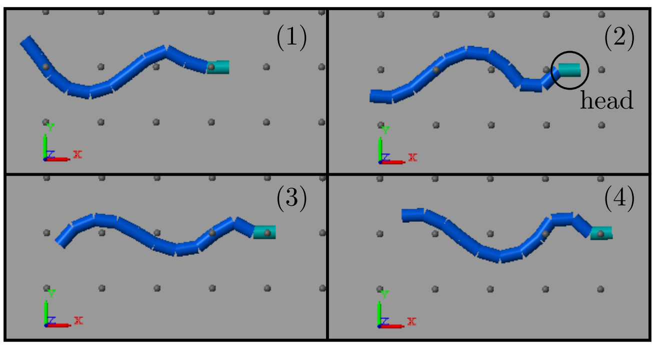

Figure 10: Locomotion of the snake robot with head stabilisation

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