Snake Robots
(Part 2)

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Mobile robots (MICRO-454) - EPFL

Chapter 10 Snake robots (Part 2)

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Further reading:
http://km-robota.com
http://biorobotics.ri.cmu.edu/index.html
Snake Robots, Liljeback, P. - Springer 2013
Biologically Inspired Robots Hirose, S. - Oxford 1993
Objectives of Part 2

- Identify the challenge of representing 3D motion in due to lack of static frames of reference
- Use existing models to estimate motion
- Recognize the types of compliant actuation that might be present in a snake robot

My personal objective:

Propose some future avenues for snake robot research
Outline

1. Representing snake robots in 3D
2. Motion estimation
3. Compliant actuation
4. Snake robot new avenues
1. Representing snake Robots in 3D

The lack of a static point in the snake robot's body make the locomotion difficult to be captured

The challenge increases as a single snake robot can perform different gaits that differ in shape and direction

Selecting head or robot's center as body frames might not be the best way to represent the motion

There are different approaches.
(i) External motion capture systems (good for 2D)
(ii) Virtual chassis (good for first approaches)
(iii) Floating Frame of Reference (Real time, gait dependent, no require optimization)
1. Representing snake robots in 3D

Simple MoCap based representation in 2D

When the system or the experiment allows it, represent the robot is rather simple

In 2D locomotion in flat surfaces, if a motion capture system is available, tracking head modules configuration (position (x,y) and orientation(\theta)) can be possible

Then, by solving direct kinematics, the positions and orientations of all the links in the robot are obtained straightforward

EPFL-Biorob's Amphibot uses this method for tracking its position and orientation while swimming in the lab pool
1. Representing snake robots in 3D

Extension to 3D motion?

Whereas motion capture still can work in 3D snakes, the markers are not symbolizing only one “point”

Position can be estimated but orientation is definitely unattainable

The experimental set up requires more complexity as an IMU (inertial measurement unit) need to be incorporated

Most important, data can not be captured, nor processed in a small on-board computer
1. Representing snake robots in 3D

Virtual Chassis

\[ P_i = [x_i - \bar{x} \quad y_i - \bar{y} \quad z_i - \bar{z}] \]

\[ P = \begin{bmatrix} p_1 \\ \vdots \\ p_s \end{bmatrix} \]

\[ U S V^T = P. \]

\[ T = \begin{bmatrix} V & \bar{p} \\ 0 & 1 \end{bmatrix} \]


The “Virtual chassis” method is a fast, on-line method for calculating the orientation of a connected shape in the space. By extracting the principal components of the mass distribution, an orthogonal vector basis (i.e. a frame of reference) is formed. This frame can be used to represent the orientation of the shape in space.

The snake robot is represented as connected masses with positions of each mass related to the center of mass is given by vector \( P \).

Singular value decomposition of \( P \), provide the matrix \( V \) that contains the eigenvectors (principal components) of \( P^TP \).

\( V \) thus, represents the rotation matrix used to re-orient the shape in the space.
1. Representing snake robots in 3D

Representations of virtual chassis (VC) for side-winding and rolling gaits

Side-winding has a shape symmetry that makes the VC to capture it well

Lateral rolling gait shape present an unique shape that barely changes in time, making it easier for VC to capture it

However, challenges arise if

(i) Side-winding uses non integer number of wavelengths along the robot's body
(ii) Helix rolling is ambiguous in 2\textsuperscript{nd} and 3\textsuperscript{rd} principal components
Complementing the VC formulation, dealing with the challenges:

(I) Side-winding uses non integer number of wavelengths along the robot's body
(ii) Helix rolling is ambiguous in 2\textsuperscript{nd} and 3\textsuperscript{rd} principal components

The FFR arises as on-line, real-time method, based only in the same gait programming parameters. Fast and no optimization is used to address challenges

However, it is only a very good approximation. It is gait oriented, thus is less flexible than VC

It is calculated geometrically by defining the director vector “dir”
1. Representing snake robots in 3D

Floating Frame of Reference (FFR).
Gait decomposition

With the purpose of understanding how the algorithm works, each “core” gait will be decomposed in simple motions

Rolling gait, decomposed as a rotating elongated wheel

Side-winding, decomposed as 2 waves or an horizontal wave and a ellipsoidal rolling tread

Linear progression decomposed as a simple propagating wave
The whole algorithm for rolling gaits is explained.

After the definition of the director vector, an orthogonal basis is extracted using this vector and the closest line from the center of mass. Then the third vector is found by cross product.

Then, consecutive rotations about:
(i) the director vector (now z) by an angle (rho) defines direction
(ii) the new x axis by an angle (alpha)
(iii) the new y axis by an angle (beta)
(iv) the new z axis by an angle (gamma), defines the whole orientation of the body shape in the space.
Angles (rho, alpha, beta, gamma) changes according to the gait. For more info consult


Then, the final orientation is used as rotation matrix (similarly than for the VC) to represent the transformation matrix from any module local frame to the floating frame of reference
2. Motion Estimation

Based on VC

\[ \Delta a_i^t = a_i^t - a_{i-1}^t \]

\[ r_i^t = (R_i^t)^{-1} \begin{bmatrix} 0 \\ 0 \\ -d/2 \end{bmatrix} \]

\[ \Omega_i^t = (R_{i-1}^t)^{-1}R_i^t \]

\[ \Delta b_i^t = R_i^t \Omega_i^t r_i^t - (\Omega_i^t)^{-1} r_i^t \]

\[ \Delta p_i^t = \Delta a_i^t + \Delta b_i^t \]


Using the VC, calculating the position and orientation of each module in a snake robot it is possible every time step.

Two motions can be captured. Translation motion (a) and rotation motion (b).

With this and a ground interaction motion, that defines contact thresholds within the ground, the speed of the robot can be estimated.
2. Motion Estimation

Based on FFR (rolling)

\[
V_{\text{wheel}} = \omega_{o,e} R_R
\]

\[
\rho_{\text{wheel}} = \tan^{-1}\left(\frac{\sqrt{\theta_2^2 + \theta_h^2}}{\lambda_{o,e}}\right) = \tan^{-1}\left(\frac{\lambda_{o,e} A_{h,p}}{2}\right)
\]

Using the FFR representation, by means of a decomposition of the gaits, the speed and heading of each gait can be easily described in real time using the same parameters that generate the gait.

For rolling gaits, estimation is done by replacing the robot by a cross section of it and using its radius and the frequency of the gait. Then the speed is calculated as a normal wheel.

In the case of helix rolling gaits, the (rho) angle deviates the robot around the locomotion surface. Then, the use of this angle decomposes the progress motion into two components.
2. Motion Estimation

Based on FFR (side-winding)

\[ V_{\text{wave}} = V_{\text{wheel}} \cos(\rho_n) \]
\[ V_{\text{net}} = V_{\text{wheel}} \sin(\rho_n) \]
\[ \rho_n = M_m - \tan^{-1}\left(\frac{\lambda^2 M_m}{2}\right) \]
\[ V_{\text{wave}} = \omega \lambda L \]

\[ V = V_{\text{net}} = \omega \lambda L \tan(\rho_n) \]

In the case of side-winding, the speed is calculated using the speed of propagation of the wave along its body. However, this speed is a mere component of the net locomotion speed that depends on the orientation of the body frame. Also defined by (rho)

Imagine a wheel pushed from one side in a diagonal. As it moves sideways it is also pushed forward. This is the essence of the gait estimation
3. Compliant Actuation
3. Compliant Actuation

Different kinds of compliance in snakes

There are 4 types of compliance in a snake robot body

Series elastic compliance in the joints

Elastic structure

Variable stiffness actuators

External compliance (contact compliance)
3. Compliant Actuation

These are examples of our research with compliant snake robots.

Grid search for locomotion parameters that optimize the use of compliance.

Use of compliance to adapt a rigid gait into a uneven terrain.
Take home message
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Possible Questions

• Discuss about the clever use of compliance in snake robots
• Identify the challenges of using virtual chassis representations for a given gait
• For a given unstructured terrain, discuss which motion estimation method will you use
• Formulate a “linear regression” based approach to capture orientation in planar robots