SnakeSIM: a Snake Robot Simulation Framework for Perception-Driven Obstacle-Aided Locomotion

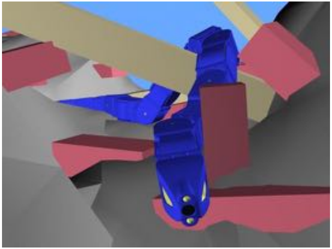
Filippo Sanfilippo[1], **Øyvind Stavdahl**[1] **and Pål Liljebäck**[1]

[1]Dept. of Engineering Cybernetics, Norwegian University of Science and Technology, 7491 Trondheim, Norway
Email: filippo.sanfilippo@ntnu.no

The 2nd International Symposium on Swarm Behavior and Bio-Inspired Robotics (SWARM),
Kyoto, Japan, 2017

NTNU

Bio-inspired robotic snakes



Building a robotic snake with such agility:

- different applications in challenging real-life operations, pipe inspection for oil and gas industry, fire-fighting operations and search-and-rescue.

***Obstacle-aided locomotion (OAL)*:**

- snake robot locomotion in a cluttered environment where the snake robot utilises walls or external objects, other than the flat ground, for means of propulsion.

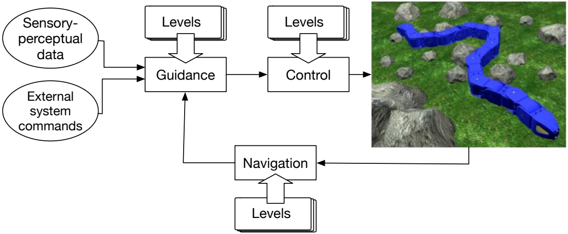
[2,3]

[2] A.A. Transeth et al. "Snake Robot Obstacle-Aided Locomotion: Modeling, Simulations, and Experiments". In: *IEEE Transactions on Robotics* 24.1 (2008), pp. 88–104. ISSN: 1552-3098. DOI: 10.1109/TRO.2007.914849.

[3] Christian Holden, Øyvind Stavdahl, and Jan Tommy Gravdahl. "Optimal dynamic force mapping for obstacle-aided locomotion in 2D snake robots". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Chicago, Illinois, United States*. 2014, pp. 321–328.

NTNU

Perception-driven obstacle-aided locomotion



Perception-driven obstacle-aided locomotion (POAL):

- locomotion where the snake robot utilises a sensory-perceptual system to perceive the surrounding operational environment, for means of propulsion.

[4–6]

[4] Filippo Sanfilippo et al. "A review on perception-driven obstacle-aided locomotion for snake robots". In: *Proc. of the 14th International Conference on Control, Automation, Robotics and Vision (ICARCV), Phuket, Thailand.* 2016, pp. 1–7.

[5] Filippo Sanfilippo et al. "Virtual functional segmentation of snake robots for perception-driven obstacle-aided locomotion". In: *Proc. of the IEEE Conference on Robotics and Biomimetics (ROBIO), Qingdao, China.* 2016, pp. 1845–1851.

[6] Filippo Sanfilippo et al. "Perception-driven obstacle-aided locomotion for snake robots: the state of the art, challenges and possibilities". In: *Applied Sciences* 7.4 (2017), p. 336.

Perception-driven obstacle-aided locomotion

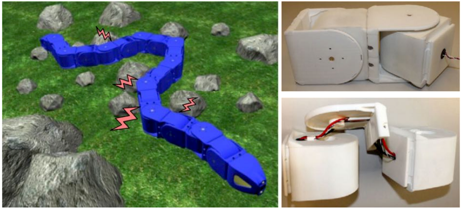
Perception-driven obstacle-aided locomotion challenges:

- snake robots are kinematically hyper-redundant systems. A high number of degrees of freedom is required to be controlled.

Existing literature considers motion across smooth, usually flat, surfaces[7].

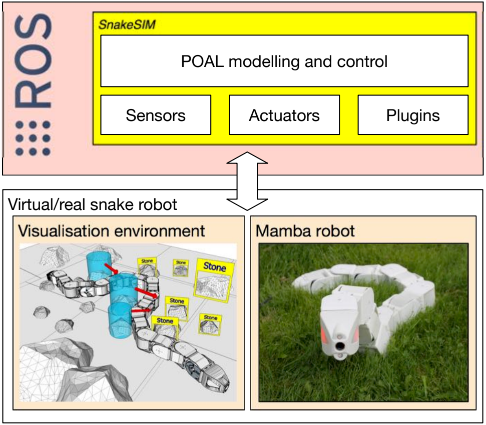
Testing new control methods for POAL in a physical environment is challenging:

- challenging requirements on both the robot and the test environment in terms of robustness and predictability.



[7] G. S. Chirikjian and J. W. Burdick. "Hyper-redundant robot mechanisms and their applications". In: *Proc. of the IEEE/RSJ International Workshop on Intelligent Robots and Systems (IROS), Osaka, Japan.* Nov. 1991, 185–190 vol.1. DOI: 10.1109/IROS.1991.174447.

Underlying idea: *SnakeSIM*



[8]

SnakeSIM:

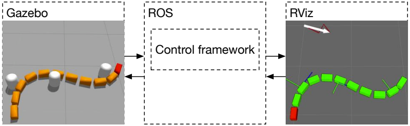
- simulate the snake robot model in a virtual environment cluttered with obstacles
- different sensors can be added to the robot (tactile and visual perception)
- transparently integrated with a real robot
- large variety of robotics sensors that are supported by the Robot Operating System (ROS).

[8] Morgan Quigley et al. "ROS: an open-source Robot Operating System". In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA), workshop on open source software*. Vol. 3. 3.2. 2009, p. 5.

SnakeSIM design guidelines

Design guidelines:

- flexibility: collecting different sensor information
- reliability: easy to maintain, modify and expand by adding new components and features
- integrability: transparent integration with real robots in the future



[8–10]

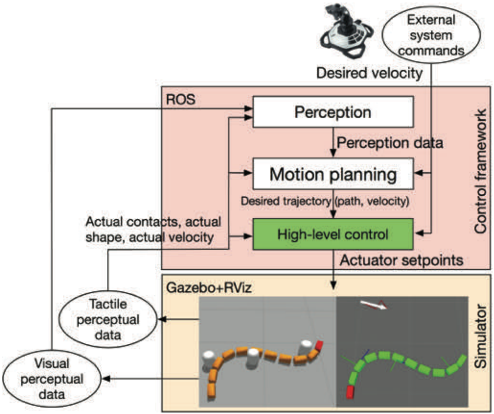
ROS + Gazebo 3D + RViz:

- ROS as a common platform for implementing the rapid-prototyping framework and as the interface for the snake robot model
- The Gazebo 3D simulator for seamless simulations
- The RViz (ROS visualisation) visualisation tool for visualisation and monitoring of sensor information retrieved in real-time from the simulated scenario

[9] Nathan Koenig and Andrew Howard. "Design and use paradigms for gazebo, an open-source multi-robot simulator". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. vol. 3. 2004, pp. 2149–2154.

[10] Hyeong Ryeol Kam et al. "RViz: a toolkit for real domain data visualization". In: *Telecommunication Systems* 60.2 (2015), pp. 337–345.

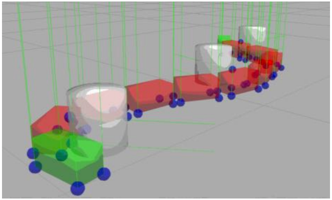
SnakeSIM framework architecture

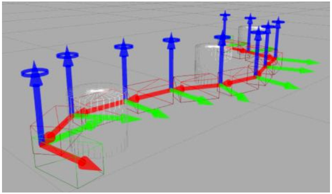


Low-level control:

- Perception: responsible for achieving the functions of sensing, mapping and localisation
- Motion planning: responsible for decision making in terms of where, when and how the robot should ideally move
- High-level control: enables researchers to develop their own alternative control method for POAL

SnakeSIM scenario, snake robot model and sensors





[11]

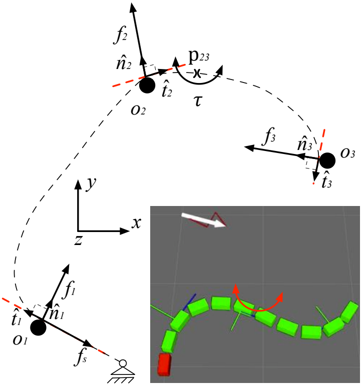
SnakeSIM:

- Simulated scenario: built in Gazebo reproducing a cluttered environment
- Snake robot model: implemented with the Universal Robotic Description Format (URDF)
- Snake robot sensors: forces, torques, contact positions and normals can be retrieved for tactile perception. A depth camera can be attached for visual perception.

[11] Open Source Robotics Foundation. *Tutorial: Using a URDF in Gazebo*. 2016. URL: http://gazebosim.org/tutorials/?tut=ros_urdf.

NTNU

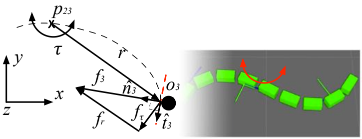
The obstacle triplet model



Based on the foundations proposed in [12]. The aim is to reduce the problem from a multi-dimensional problem to a two-dimensional problem (along the path, across the path).

1. a path, $S(s)$ is known. The obstacle locations, o_1, o_2, o_3, are also known;
2. the snake is always on the path $S(s)$;
3. the snake is planar and discrete;
4. there is no ground or obstacle friction;
5. the snake is at rest;
6. the snake tail is tethered to the ground. The tether is unactuated. No tangential movements are allowed. A tensile force, f_s, acts along the tangent at o_1;
7. the snake is perfectly rigid except at the point where an internal torque can be applied. The obstacles are perfectly rigid and fixed to the ground surface;
8. we choose to apply an internal torque, τ, at a known point, p_{23}, on the path between o_2 and o_3.

The obstacle triplet model



$$f_3 \cdot \hat{t}_3 = 0, \quad (1)$$

$$f_3 = f_\tau + f_r, \quad (2)$$

$$f_\tau = r \times \tau, \quad (3)$$

where f_r is the force component parallel to the torque radius, r, and by definition can be expressed as:

$$f_r \triangleq |f_r| \frac{r}{|r|}. \quad (4)$$

By combining (2), (3) and (4):

$$f_3 = r \times \tau + |f_r| \frac{r}{|r|}, \quad (5)$$

which, because of (1), can be rewritten as:

$$(r \times \tau + |f_r| \frac{r}{|r|}) \cdot \hat{t}_3 = 0. \quad (6)$$

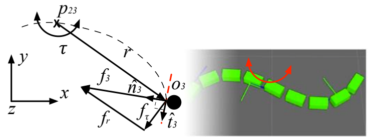
Distributive prop. of $\cdot$ and the anticommutative prop. of the $\times$:

$$|f_r| \frac{r}{|r|} \cdot \hat{t}_3 = (\tau \times r) \cdot \hat{t}_3, \quad (7)$$

$$|f_r| = \frac{(\tau \times r) \cdot \hat{t}_3}{\frac{r}{|r|} \cdot \hat{t}_3}. \quad (8)$$

NTNU

The obstacle triplet model



Consequently, because of (5) and (8), f_3 can be rewritten as:

$$f_3 = r \times \tau + \left[\frac{(\tau \times r) \cdot \hat{t}_3}{\frac{r}{|r|} \cdot \hat{t}_3} \right] \frac{r}{|r|}. \quad (9)$$

Because of assumption 6 (static conditions):

$$f_s + f_1 + f_2 + f_3 = 0, \quad (10)$$

where, f_s is the tensile force that need to be counterbalanced, f_3 is given by (9), while f_1, f_2 are unknown variables.

The torques exerted on the robot about the global origin by the external forces is:

$$o_1 \times (f_s + f_1) + o_2 \times f_2 + o_3 \times f_3 = 0. \quad (11)$$

Given any point, s, on the path, it is possible to uniquely express τ as follows:

$$\tau(s) = f(f_s, f_1, f_2, f_3). \quad (12)$$

Equivalently, f_s, can be obtained as:

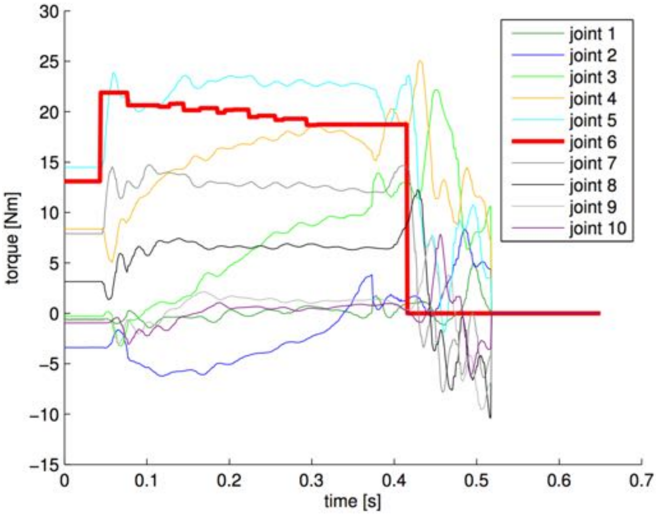
$$f_s = g(\tau(s), f_1, f_2, f_3). \quad (13)$$

Remark:

For an obstacle triplet model, only one control variable, $\tau(s)$, is needed to achieve obstacle-aided locomotion. The torque, $\tau(s)$, can be applied at any point and it can be seen as a thruster for the snake robot.

SnakeSIM and the obstacle triplet model

SnakeSIM and the obstacle triplet model



Conclusion

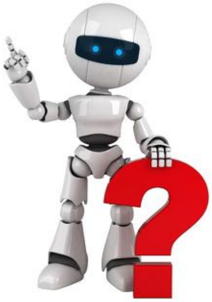
Contribution:

- *SnakeSIM*, a virtual rapid-prototyping framework that allows for the design and simulation of control algorithms for POAL
- The framework is integrated with ROS
- This integration makes the development of POAL algorithms more safe, rapid and efficient
- Different sensors can be simulated both for tactile as well as visual perception purposes
- The integration with a real snake robot is possible

[13]

[13] P. Liljebäck et al. "Mamba - A waterproof snake robot with tactile sensing". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Sept. 2014, pp. 294–301. DOI: 10.1109/IROS.2014.6942575.

Thank you for your attention



Contact:

- F. Sanfilippo, Department of Engineering Cybernetics, Norwegian University of Science and Technology, 7491 Trondheim, Norway, filippo.sanfilippo@ntnu.no.

References

[1] Shigeo Hirose and Hiroya Yamada. "Snake-like robots [tutorial]". In: *IEEE Robotics & Automation Magazine* 16.1 (2009), pp. 88–98.

[2] A.A. Transeth et al. "Snake Robot Obstacle-Aided Locomotion: Modeling, Simulations, and Experiments". In: *IEEE Transactions on Robotics* 24.1 (2008), pp. 88–104. ISSN: 1552-3098. DOI: 10.1109/TRO.2007.914849.

[3] Christian Holden, Øyvind Stavdahl, and Jan Tommy Gravdahl. "Optimal dynamic force mapping for obstacle-aided locomotion in 2D snake robots". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Chicago, Illinois, United States*. 2014, pp. 321–328.

[4] Filippo Sanfilippo et al. "A review on perception-driven obstacle-aided locomotion for snake robots". In: *Proc. of the 14th International Conference on Control, Automation, Robotics and Vision (ICARCV), Phuket, Thailand*. 2016, pp. 1–7.

[5] Filippo Sanfilippo et al. "Virtual functional segmentation of snake robots for perception-driven obstacle-aided locomotion". In: *Proc. of the IEEE Conference on Robotics and Biomimetics (ROBIO), Qingdao, China*. 2016, pp. 1845–1851.

References (contd.)

[6] Filippo Sanfilippo et al. “Perception-driven obstacle-aided locomotion for snake robots: the state of the art, challenges and possibilities”. In: *Applied Sciences* 7.4 (2017), p. 336.

[7] G. S. Chirikjian and J. W. Burdick. “Hyper-redundant robot mechanisms and their applications”. In: *Proc. of the IEEE/RSJ International Workshop on Intelligent Robots and Systems (IROS), Osaka, Japan*. Nov. 1991, 185–190 vol.1. DOI: 10.1109/IROS.1991.174447.

[8] Morgan Quigley et al. “ROS: an open-source Robot Operating System”. In: *Proc. of the IEEE International Conference on Robotics and Automation (ICRA), workshop on open source software*. Vol. 3. 3.2. 2009, p. 5.

[9] Nathan Koenig and Andrew Howard. “Design and use paradigms for gazebo, an open-source multi-robot simulator”. In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Vol. 3. 2004, pp. 2149–2154.

[10] Hyeong Ryeol Kam et al. “RViz: a toolkit for real domain data visualization”. In: *Telecommunication Systems* 60.2 (2015), pp. 337–345.

[11] Open Source Robotics Foundation. *Tutorial: Using a URDF in Gazebo*. 2016. URL: http://gazebosim.org/tutorials/?tut=ros_urdf.

References (contd.)

[12] Christian Holden and Øyvind Stavdahl. "Optimal static propulsive force for obstacle-aided locomotion in snake robots". In: *Proc. of the IEEE International Conference on Robotics and Biomimetics (ROBIO), Shenzhen, China*. 2013, pp. 1125–1130.

[13] P. Liljebäck et al. "Mamba - A waterproof snake robot with tactile sensing". In: *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Sept. 2014, pp. 294–301. DOI: 10.1109/IROS.2014.6942575.

NTNU