NTNU AMOS

Centre for Autonomous Marine Operations and Systems

SNAKE ROBOTS

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DKNVS Akademiet, 17. September, 2018.

Part I:

BIO-INSPIRATION

THE INSPIRATION: BIOLOGICAL SNAKES

THE INSPIRATION: BIOLOGICAL SNAKES

Part II:

RESEARCH

BACKGROUND / MODELING / ANALYSIS / CONTROL

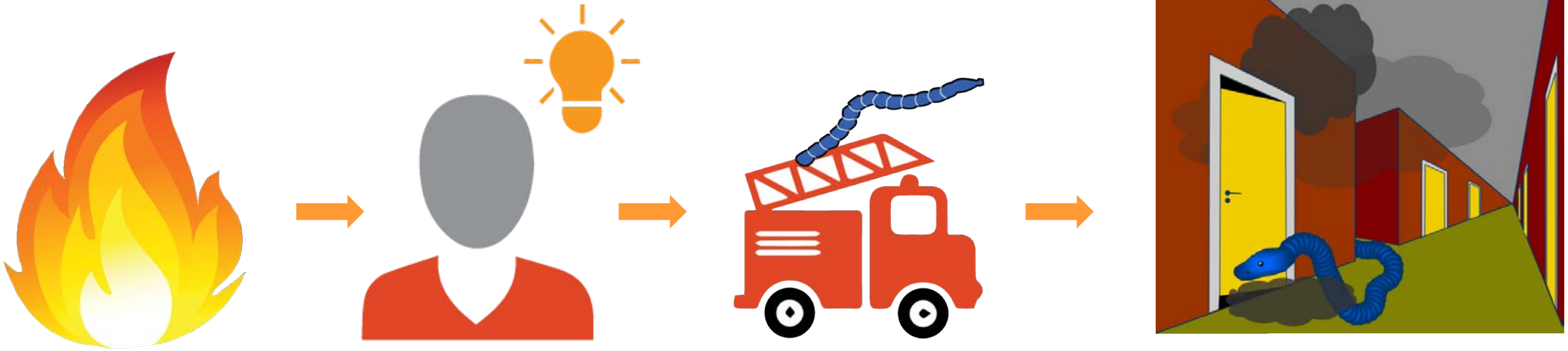
BACKGROUND OF OUR RESEARCH ON SNAKE ROBOTS

Several major city fires in Trondheim, Norway 2002 – 2004.

BACKGROUND OF OUR RESEARCH ON SNAKE ROBOTS

A **self-propelled fire hose** where water is used as:

- A **hydraulic** medium (for enabling the hose to move).
- A **fire extinguishing** medium (for fighting the fire).
- A **cooling** medium (in environments with extreme temperatures).



SINTEF

ANNA KONDA

- **Length:** 3 m
- **Weight:** 75 kg
- **Num joints:** 20
- The first **water-hydraulic** snake robot in the world.
- The biggest and strongest snake robot in the world (at time of development).

Slashdot: Anna Konda, the Robotic Firefighter,

Engadget: Anna Konda: the firefighting snakebot,

Technovelgy: Robotic Fire Hose Anna Konda,

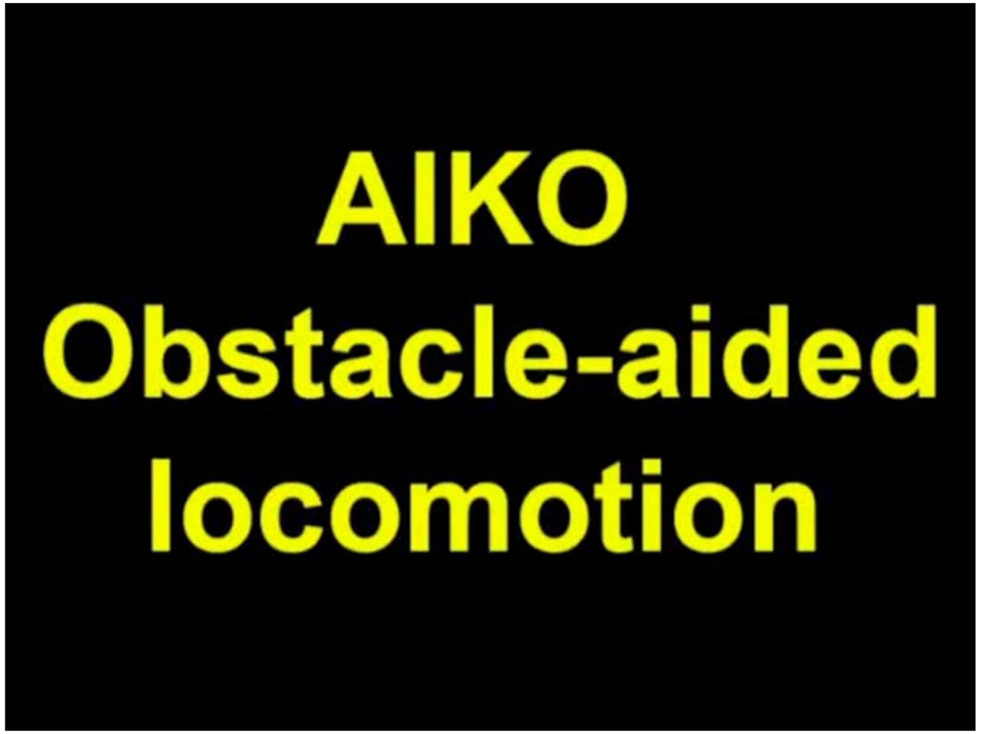
Innovations report: Snake robot to the rescue.

Dagbladet 15.02.2005: Verdens mest avanserte brannslange.

AIKO

Snake robot with electric motors

- DC motor actuation
- Length: 1.5 m
- Weight: 7 kg
- 20 DOF



KULKO

A snake robot with tactile sensors

- A smooth gliding surface
- Contact force sensors

WHEEKO

A snake robot with passive wheels

Developed to study snake robot locomotion across flat surfaces

WheeKo

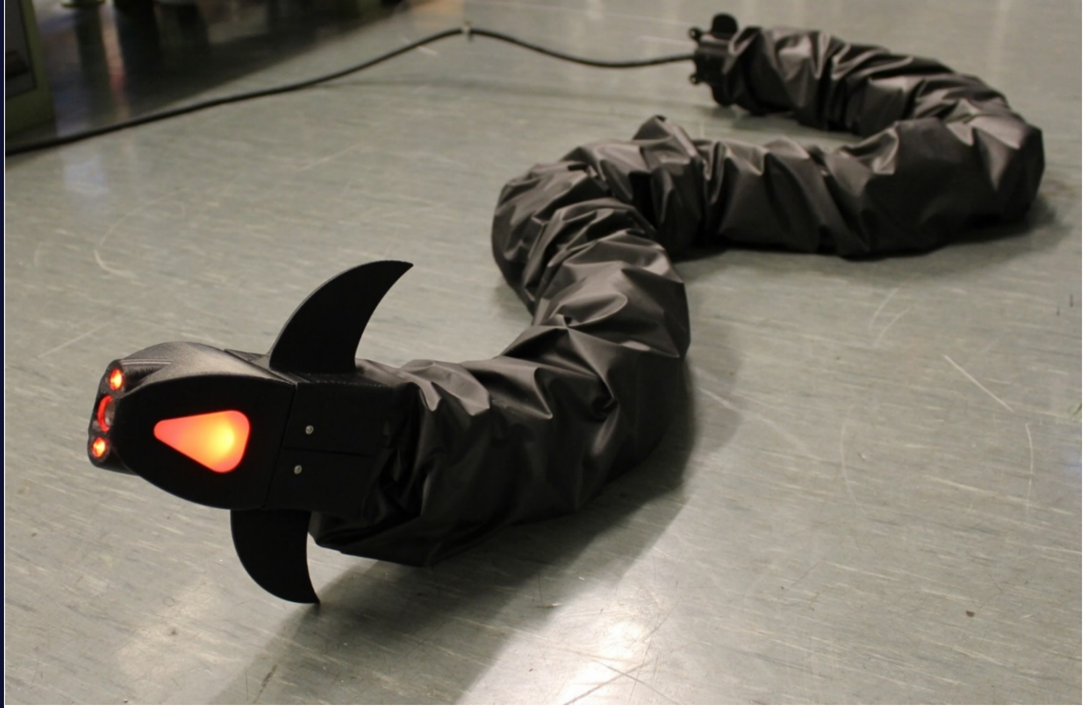
SINTEF

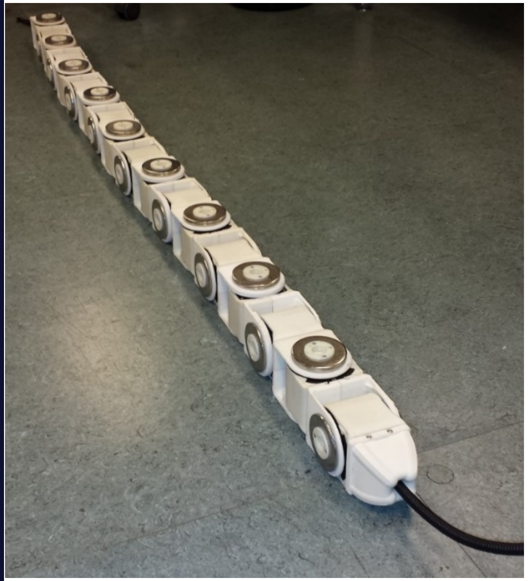
NTNU

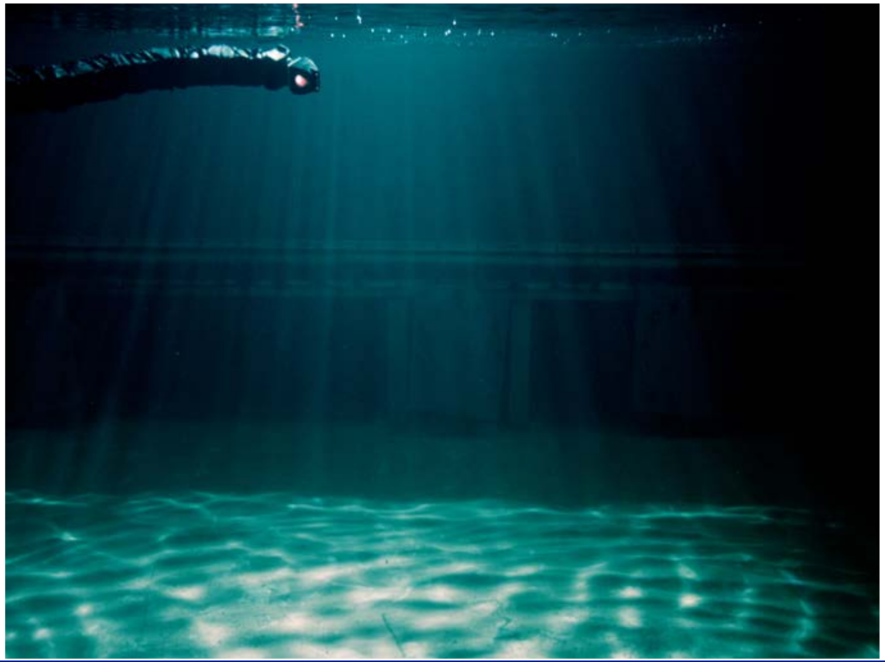
MAMBA

A water-proof snake robot

Designed to move both on land and in water (amphibious)







MODELING

MODELING

Kelasidi, Pettersen and Gravdahl (2014). Modeling of underwater snake robots moving in a vertical plane in 3D, in *Proc. of International Conference on Intelligent Robots and Systems (IROS),* Chicago, Illinois.
Kelasidi, Pettersen, Gravdahl, Strømsøyen and Sørensen (2017). Modeling and propulsion methods of underwater snake robots, in *Proc. IEEE Conference on Control Technology and Applications (CCTA),* Hawaii.

We have developed a model for underwater snake robots, which is in closed form, and thus is particularly well suited for model-based analysis and control design.

$$\mathbf{M}_\theta \ddot{\boldsymbol{\theta}} + \mathbf{W}_\theta \dot{\boldsymbol{\theta}}^2 + \mathbf{V}_{\theta,\dot\theta} \dot{\boldsymbol{\theta}} + \mathbf{N}_{\theta,\dot\theta}(\mathbf{e}\dot{p}_x - \mathbf{V_x}) + \mathbf{P}_{\theta,\dot\theta}(\mathbf{e}\dot{p}_y - \mathbf{V_y}) + \mathbf{K_x f_{Dx}} + \mathbf{K_y f_{Dy}} = \mathbf{D}^T \mathbf{u}$$

$$\begin{bmatrix} \ddot{p}_x \\ \ddot{p}_y \end{bmatrix} = -\mathbf{M_p N_p} \begin{bmatrix} \mathrm{diag}(\dot{\boldsymbol{\theta}}) & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}(\dot{\boldsymbol{\theta}}) \end{bmatrix} \mathbf{E} \begin{bmatrix} \dot{p}_x \\ \dot{p}_y \end{bmatrix}$$
$$- \mathbf{M_p N_p} \begin{bmatrix} \mathrm{diag}(\dot{\boldsymbol{\theta}}) & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}(\dot{\boldsymbol{\theta}}) \end{bmatrix} \begin{bmatrix} l\mathbf{K}^T \mathbf{S}_\theta \dot{\boldsymbol{\theta}} - \mathbf{V_x} \\ -l\mathbf{K}^T \mathbf{C}_\theta \dot{\boldsymbol{\theta}} - \mathbf{V_y} \end{bmatrix}$$
$$- \mathbf{M_p L_p} \begin{bmatrix} l\mathbf{K}^T(\mathbf{C}_\theta \dot{\boldsymbol{\theta}}^2 + \mathbf{S}_\theta \ddot{\boldsymbol{\theta}}) \\ l\mathbf{K}^T(\mathbf{S}_\theta \dot{\boldsymbol{\theta}}^2 - \mathbf{C}_\theta \ddot{\boldsymbol{\theta}}) \end{bmatrix} + \mathbf{M_p E}^T \begin{bmatrix} \mathbf{f_{Dx}} \\ \mathbf{f_{Dy}} \end{bmatrix}$$

where

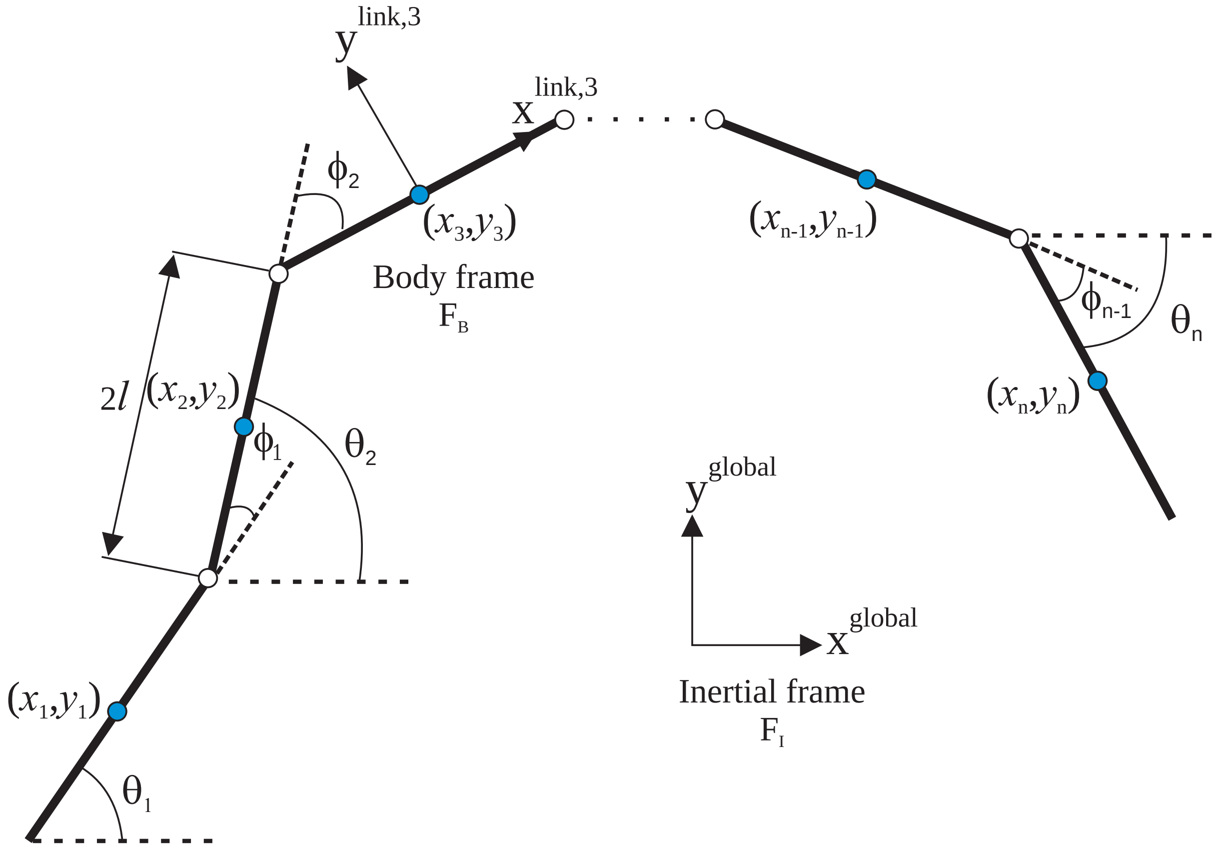
$$\mathbf{M}_p = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} nm + \mathbf{e}^T \mu_n \mathbf{S}_\theta^2 \mathbf{e} & -\mathbf{e}^T \mu_n \mathbf{S}_\theta \mathbf{C}_\theta \mathbf{e} \\ -\mathbf{e}^T \mu_n \mathbf{S}_\theta \mathbf{C}_\theta \mathbf{e} & nm + \mathbf{e}^T \mu_n \mathbf{C}_\theta^2 \mathbf{e} \end{bmatrix}^{-1}$$

and $\mathbf{f_{Dx}} = \mathbf{f}_{\mathbf{D_x}}^{\mathrm{I}} + \mathbf{f}_{\mathbf{D_x}}^{\mathrm{II}}$ and $\mathbf{f_{Dy}} = \mathbf{f}_{\mathbf{D_y}}^{\mathrm{I}} + \mathbf{f}_{\mathbf{D_y}}^{\mathrm{II}}$ are the drag forces in x and y directions.

MODELING

Kelasidi, Pettersen and Gravdahl (2014). Modeling of underwater snake robots moving in a vertical plane in 3D, in *Proc. of International Conference on Intelligent Robots and Systems (IROS),* Chicago, Illinois.
Kelasidi, Pettersen, Gravdahl, Strømsøyen and Sørensen (2017). Modeling and propulsion methods of underwater snake robots, in *Proc. IEEE Conference on Control Technology and Applications (CCTA),* Hawaii.

KINEMATICS OF THE ROBOT



JOINT ANGLE

$$\phi_i = \theta_i - \theta_{i+1}.$$

HEADING-ORIENTATION

$$\bar{\theta} = \frac{1}{n}\sum_{i=1}^{n}\theta_i.$$

POSITION OF CM

$$\mathbf{p}_{\mathrm{CM}} = \begin{bmatrix} p_x \\ p_y \end{bmatrix} = \begin{bmatrix} \frac{1}{nm}\sum_{i=1}^{n} m x_i \\ \frac{1}{nm}\sum_{i=1}^{n} m y_i \end{bmatrix}.$$

MODELING

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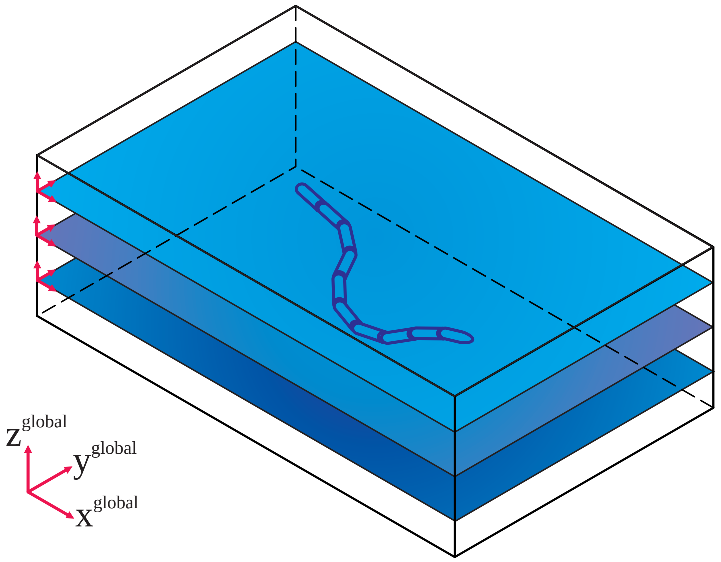
Kelasidi, Pettersen, Gravdahl, Strømsøyen and Sørensen (2017). Modeling and propulsion methods of underwater snake robots, in *Proc. IEEE Conference on Control Technology and Applications (CCTA),* Hawaii.

The resulting model is in closed form.



$$\mathbf{M}_\theta \ddot{\boldsymbol{\theta}} + \mathbf{W}_\theta \dot{\boldsymbol{\theta}}^2 + \mathbf{V}_{\theta,\dot\theta}\dot{\boldsymbol{\theta}} + \mathbf{N}_{\theta,\dot\theta}(\mathbf{e}\dot{p}_x - \mathbf{V}_\mathbf{x}) + \mathbf{P}_{\theta,\dot\theta}(\mathbf{e}\dot{p}_y - \mathbf{V}_\mathbf{y}) + \mathbf{K}_\mathbf{x}\mathbf{f}_\mathbf{Dx} + \mathbf{K}_\mathbf{y}\mathbf{f}_\mathbf{Dy} = \mathbf{D}^T\mathbf{u}$$

$$\begin{bmatrix} \ddot{p}_x \\ \ddot{p}_y \end{bmatrix} = -\mathbf{M}_\mathbf{p}\mathbf{N}_\mathbf{p} \begin{bmatrix} \mathrm{diag}(\dot{\boldsymbol{\theta}}) & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}(\dot{\boldsymbol{\theta}}) \end{bmatrix} \mathbf{E} \begin{bmatrix} \dot{p}_x \\ \dot{p}_y \end{bmatrix} - \mathbf{M}_\mathbf{p}\mathbf{N}_\mathbf{p} \begin{bmatrix} \mathrm{diag}(\dot{\boldsymbol{\theta}}) & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}(\dot{\boldsymbol{\theta}}) \end{bmatrix} \begin{bmatrix} l\mathbf{K}^T\mathbf{S}_\theta\dot{\boldsymbol{\theta}} - \mathbf{V}_\mathbf{x} \\ -l\mathbf{K}^T\mathbf{C}_\theta\dot{\boldsymbol{\theta}} - \mathbf{V}_\mathbf{y} \end{bmatrix}$$
$$-\mathbf{M}_\mathbf{p}\mathbf{L}_\mathbf{p} \begin{bmatrix} l\mathbf{K}^T(\mathbf{C}_\theta\dot{\boldsymbol{\theta}}^2 + \mathbf{S}_\theta\ddot{\boldsymbol{\theta}}) \\ l\mathbf{K}^T(\mathbf{S}_\theta\dot{\boldsymbol{\theta}}^2 - \mathbf{C}_\theta\ddot{\boldsymbol{\theta}}) \end{bmatrix} + \mathbf{M}_\mathbf{p}\mathbf{E}^T \begin{bmatrix} \mathbf{f}_\mathbf{Dx} \\ \mathbf{f}_\mathbf{Dy} \end{bmatrix}$$

$$\mathbf{M}_\theta = \mathbf{J} + ml^2\mathbf{S}_\theta\mathbf{V}\mathbf{S}_\theta + ml^2\mathbf{C}_\theta\mathbf{V}\mathbf{C}_\theta - l\mathbf{S}_\theta\mathbf{K}\mathbf{A}_1 + l\mathbf{C}_\theta\mathbf{K}\mathbf{A}_4 + l\mathbf{K}_5\mathbf{K}_1\mathbf{K}^T\mathbf{S}_\theta$$
$$- l\mathbf{K}_5\mathbf{K}_2\mathbf{K}^T\mathbf{C}_\theta + l\mathbf{K}_6\mathbf{K}_3\mathbf{K}^T\mathbf{S}_\theta + l\mathbf{K}_6\mathbf{K}_4\mathbf{K}^T\mathbf{C}_\theta + \boldsymbol{\Lambda}_1$$

$$\mathbf{W}_\theta = -ml^2\mathbf{S}_\theta\mathbf{V}\mathbf{C}_\theta + ml^2\mathbf{C}_\theta\mathbf{V}\mathbf{S}_\theta - l\mathbf{S}_\theta\mathbf{K}\mathbf{A}_2 + l\mathbf{C}_\theta\mathbf{K}\mathbf{A}_5 + l\mathbf{K}_5\mathbf{K}_1\mathbf{K}^T\mathbf{C}_\theta$$
$$+ l\mathbf{K}_5\mathbf{K}_2\mathbf{K}^T\mathbf{S}_\theta + l\mathbf{K}_6\mathbf{K}_3\mathbf{K}^T\mathbf{C}_\theta - l\mathbf{K}_6\mathbf{K}_4\mathbf{K}^T\mathbf{S}_\theta$$

$$\mathbf{V}_{\theta,\dot\theta} = -l\mathbf{S}_\theta\mathbf{K}\mathrm{diag}(\dot{\boldsymbol{\theta}})\mathbf{A}_3 + l\mathbf{C}_\theta\mathbf{K}\mathrm{diag}(\dot{\boldsymbol{\theta}})\mathbf{A}_6 - l\mathbf{K}_5\mathbf{K}_2\mathrm{diag}(\dot{\boldsymbol{\theta}})\mathbf{K}^T\mathbf{S}_\theta - l\mathbf{K}_5\mathbf{K}_1\mathrm{diag}(\dot{\boldsymbol{\theta}})\mathbf{K}^T\mathbf{C}_\theta$$
$$+ l\mathbf{K}_6\mathbf{K}_4\mathrm{diag}(\dot{\boldsymbol{\theta}})\mathbf{K}^T\mathbf{S}_\theta - l\mathbf{K}_6\mathbf{K}_3\mathrm{diag}(\dot{\boldsymbol{\theta}})\mathbf{K}^T\mathbf{C}_\theta + \boldsymbol{\Lambda}_2 + \boldsymbol{\Lambda}_3\mathrm{diag}(|\dot{\boldsymbol{\theta}}|)$$

$$\mathbf{N}_{\theta,\dot\theta} = (l\mathbf{S}_\theta\mathbf{K}\mathbf{S}_\theta\mathbf{C}_\theta\mu + l\mathbf{C}_\theta\mathbf{K}\mathbf{C}_\theta^2\mu - \mathbf{K}_5\mathbf{K}_2 + \mathbf{K}_6\mathbf{K}_4)\,\mathrm{diag}\dot{\boldsymbol{\theta}}$$

$$\mathbf{P}_{\theta,\dot\theta} = (l\mathbf{S}_\theta\mathbf{K}\mathbf{S}_\theta^2\mu + l\mathbf{C}_\theta\mathbf{K}\mathbf{S}_\theta\mathbf{C}_\theta\mu + \mathbf{K}_5\mathbf{K}_1 + \mathbf{K}_6\mathbf{K}_3)\,\mathrm{diag}(\dot{\boldsymbol{\theta}})$$

ANALYSIS

LOCOMOTION: HOW TO MOVE FORWARD?

LAND-BASED SNAKES

Lateral undulation   Sidewinding

Concertina motion   Rectilinear crawling

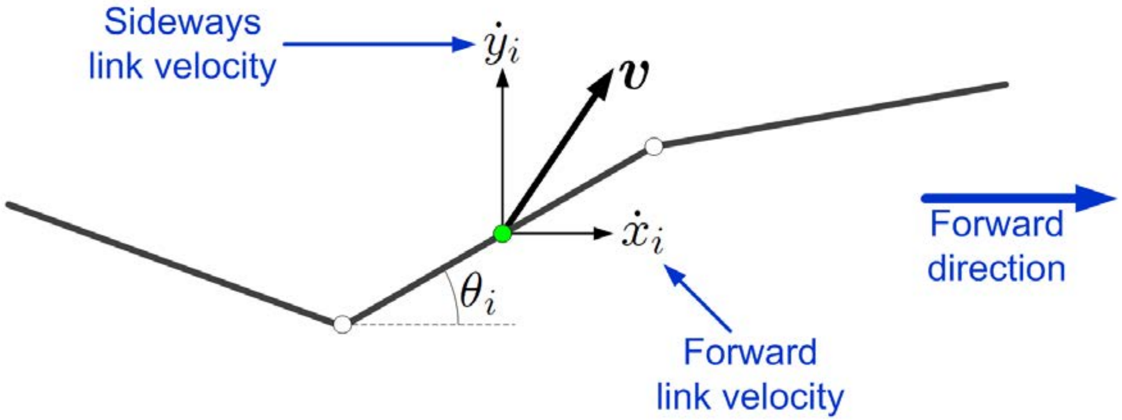
SWIMMING SNAKES/EELS

Lateral undulation/Eel-like motion

LOCOMOTION:
HOW TO MOVE FORWARD?

P. Liljebäck, K.Y. Pettersen, Ø. Stavdahl and J.T. Gravdahl (2013). *Snake Robots: Modelling, Mechatronics, and Control,* Springer-Verlag.

Analysis of the propulsive forces:



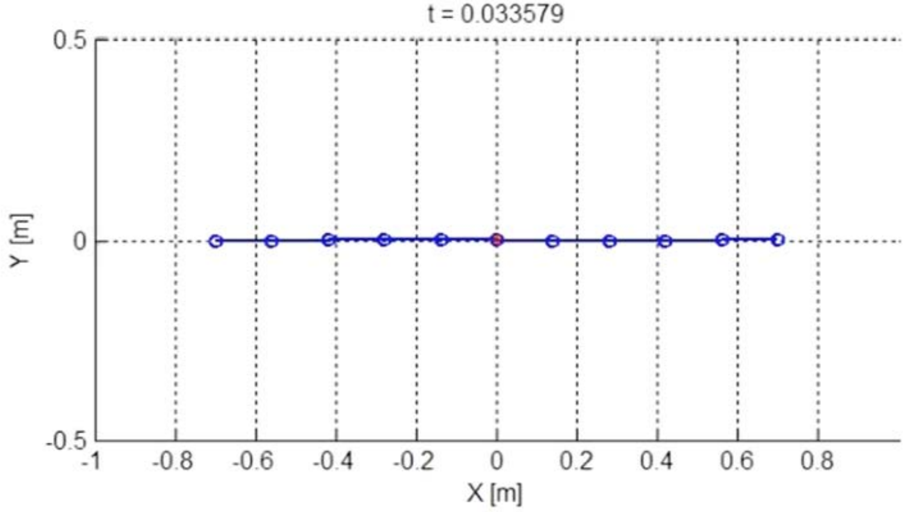
Total force on the snake robot in the forward direction:

$$N m \ddot{p}_x = \underbrace{-\sum_{i=1}^{N} F_x(\theta_i)\dot{x}_i}_{\leq 0} \underbrace{- \sum_{i=1}^{N} F_y(\theta_i)\dot{y}_i}_{\geq 0 \text{ when } \mathrm{sgn}(\theta_i) = \mathrm{sgn}(\dot{y}_i)}$$

The **sideways** link displacements are what propel the snake robot **forward**.

BODY UNDULATION

- Waves propagating backward
- Reference angle of joint $i \in \{1, \ldots, N-1\}$



$$\phi_{i,\mathrm{ref}} = \alpha \sin\left(\omega t + (i-1)\,\delta\right) + \phi_o$$

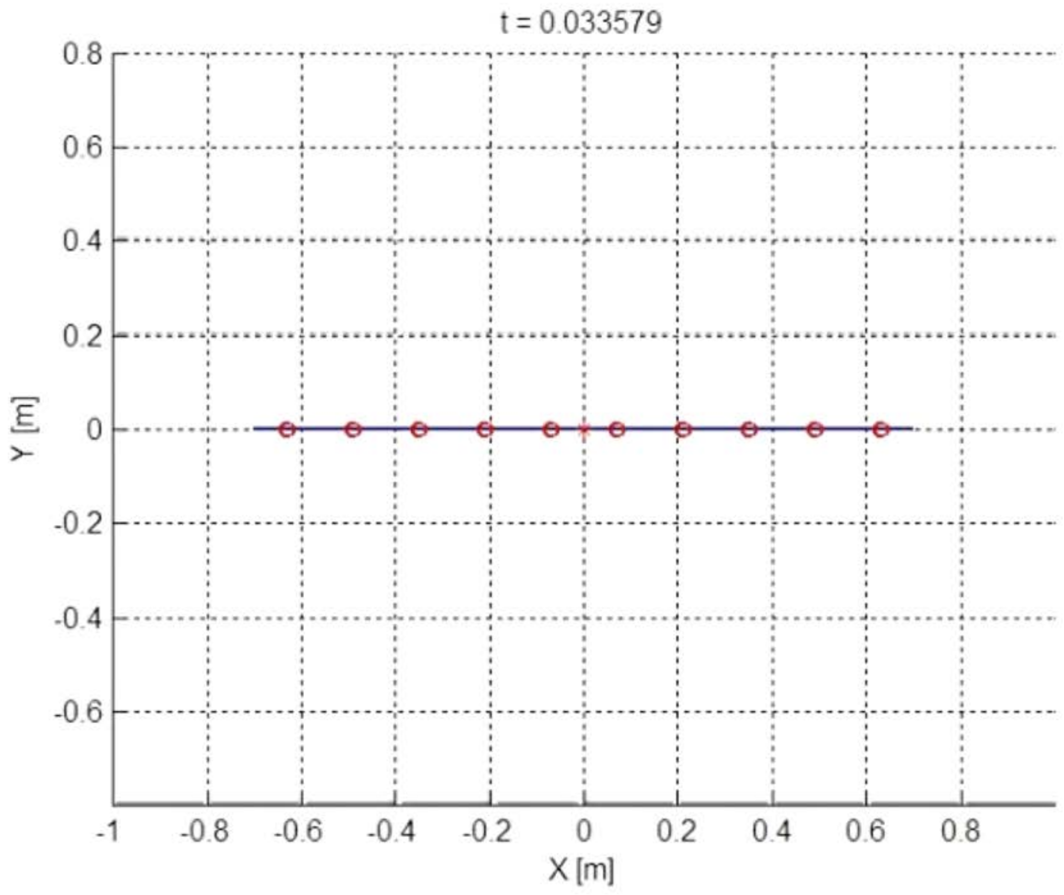
Amplitude

Frequency

Phase shift between joints

Joint offset coordinate

BODY UNDULATION



<u>Locomotion using undulation:</u>
mainly consists of relative link displacements **sideways** with respect to the direction of motion.

UNDERWATER SNAKE ROBOT LOCOMOTION

Kelasidi, Pettersen and Gravdahl (2014). Stability Analysis of Underwater Snake Robot Locomotion Based on Averaging Theory, in *Proc. 2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014),* Bali, Indonesia, 2014.
Kelasidi, Liljebäck, Pettersen and Gravdahl (2015). Experimental Investigation of Efficient Locomotion of Underwater Snake Robots, *Springer Robotics and BIomimetics,* Vol. 2, No. 8, 2015.

→ Undulatory motion – makes the snake robot move forward

A general sinusoidal motion pattern (gait)

$$\phi_{i,\mathrm{ref}} = \alpha g(i) \sin\left(\omega t + (i-1)\delta\right) + \phi_0$$

Describes a broad class of motion patterns
for underwater snake robot locomotion

- Lateral undulation
- Eel-like motion

ANALYSIS OF THE VELOCITY USING AVERAGING

General sinusoidal gait pattern:

$$\phi_{i,\mathrm{ref}} = \alpha g(i) \sin\left(\omega t + (i-1)\delta\right) + \phi_0$$

Control-oriented model

Averaging

$$\dot{\boldsymbol{v}} = \frac{1}{T}\int_0^T \cdots$$

Forward velocity during undulatory locomotion:

$$\boxed{v_t^* = \alpha^2 \omega k_\delta} \frac{N c_n c_p}{2(c_n c_t N^2 - 4(N-1)^2 c_p^2 \phi_0^2)} + V_t$$

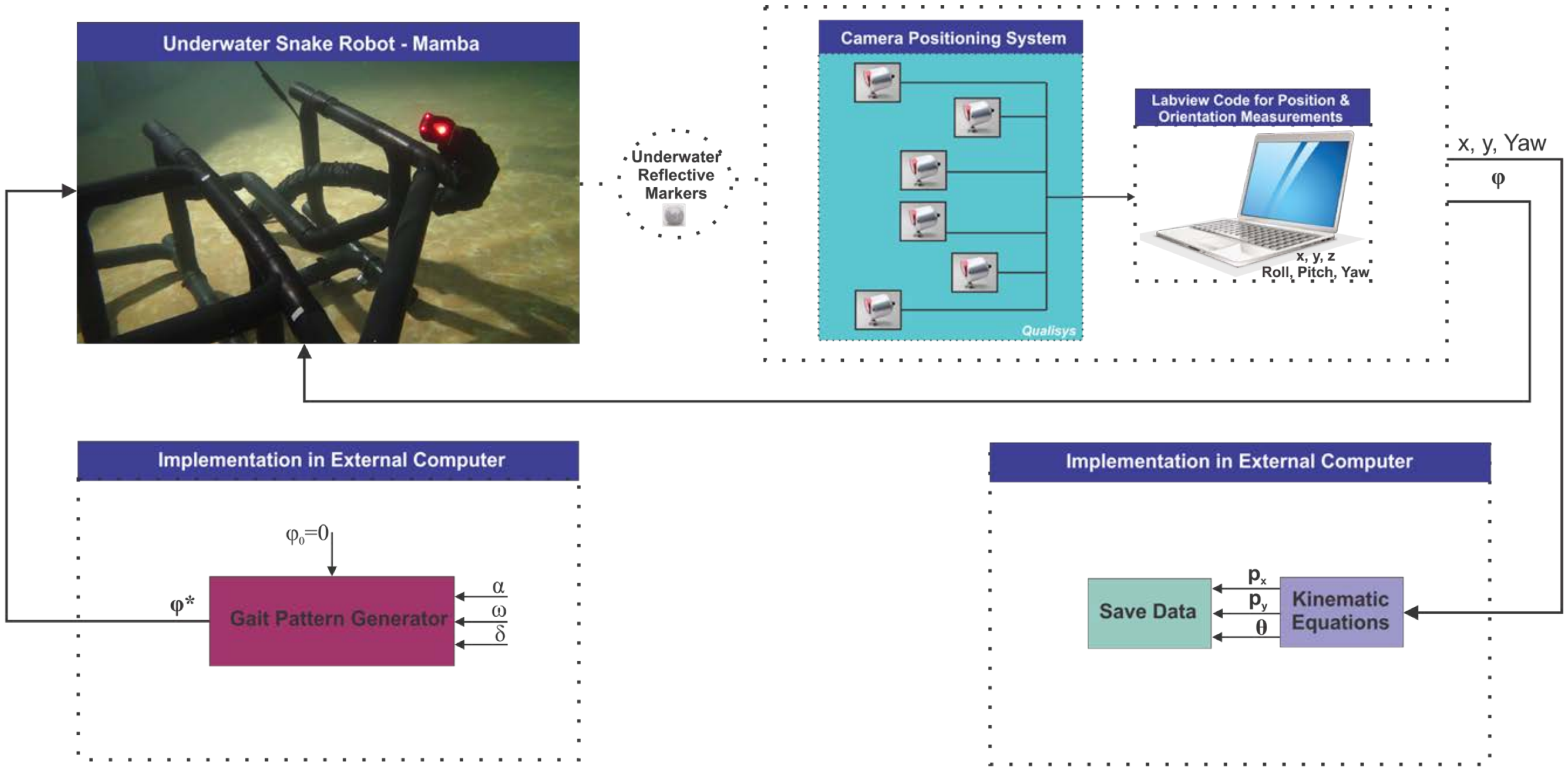
$$v_{t,\mathrm{rel}}^* \propto \alpha^2$$

$$v_{t,\mathrm{rel}}^* \propto \omega$$

$$v_{t,\mathrm{rel}}^* \propto k_\delta = \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} a_{ij} g(i) g(j) \sin((j-i)\delta)$$

UNDERWATER SNAKE ROBOT LOCOMOTION

Kelasidi, Liljebäck, Pettersen and Gravdahl (2015). Experimental Investigation of Efficient Locomotion of Underwater Snake Robots, *Springer Robotics and Biomimetics,* Vol. 2, No. 8, 2015.



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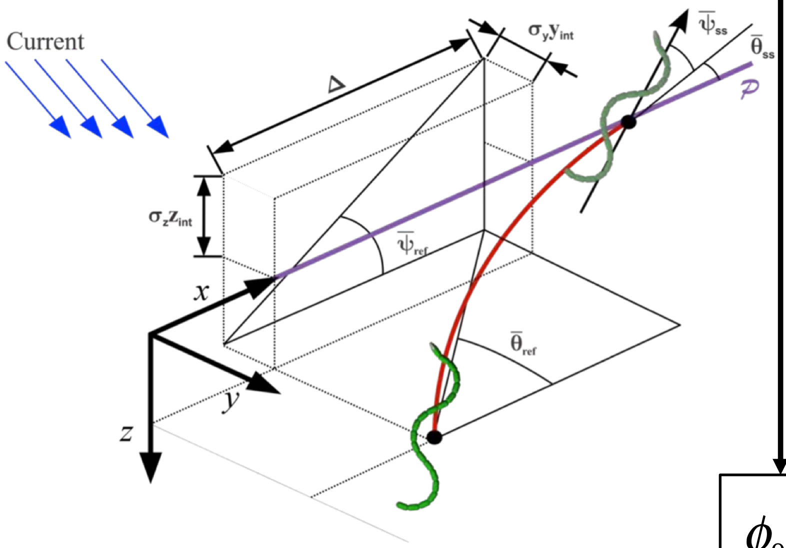
CONTROL

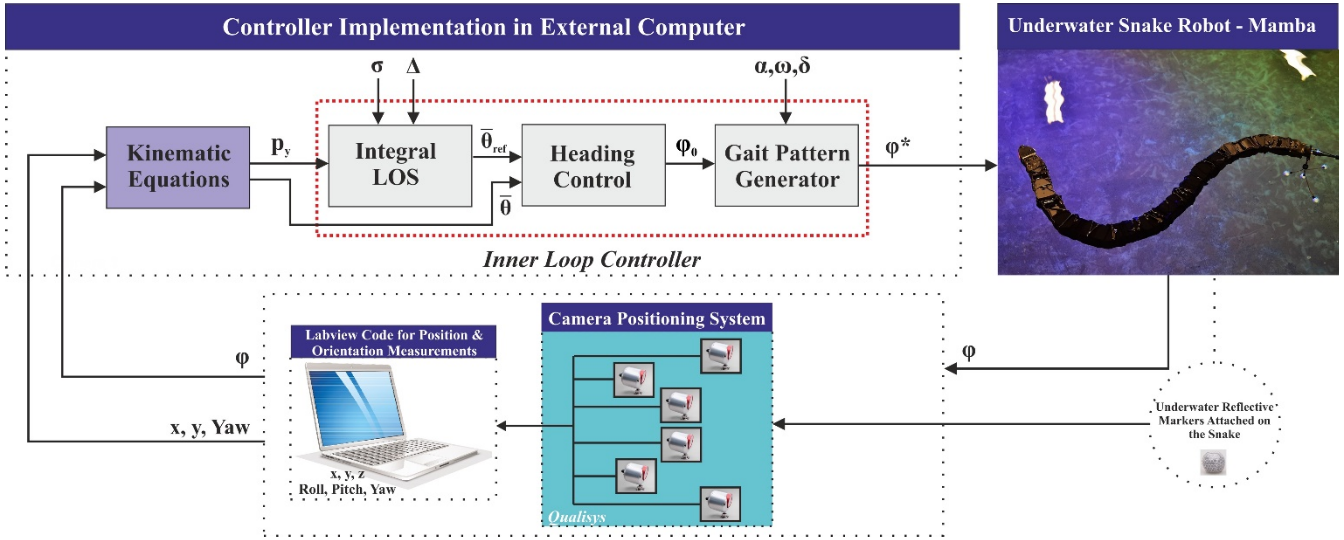
PATH FOLLOWING CONTROL

Kelasidi, Pettersen, Liljebäck and Gravdahl (2014). Integral line-of-sight for path-following of underwater snake robots, in *Proc. IEEE Multi-Conference on Systems and Control*, Nice, Antibes, France, Oct. 8-10 2014.

Experimental validation of a straight line path following controller for underwater snake robots compensating for constant currents of unknown direction and magnitude.

$$\phi_{i,\mathrm{ref}} = \alpha g(i) \sin\left(\omega t + (i-1)\delta\right) + \phi_0$$





$$\phi_0 = k_\theta \left(\bar{\theta} - \bar{\theta}_{\mathrm{ref}}\right)$$

Directional control

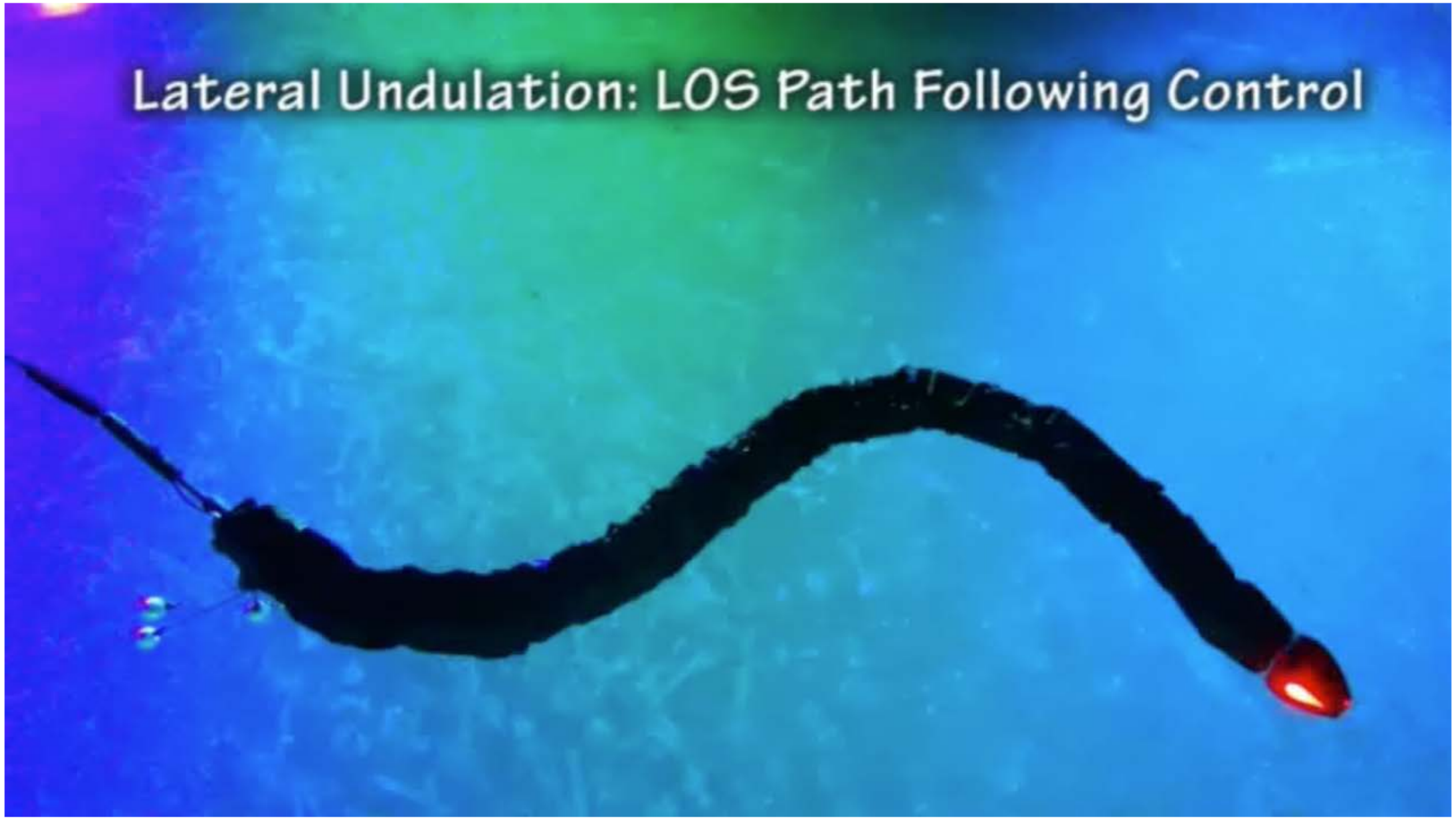
$$\bar{\theta}_{\mathrm{ref}} = -\arctan\left(\frac{p_y + \sigma y_{int}}{\Delta}\right), \qquad \Delta > 0$$

$$\dot{y}_{int} = \frac{\Delta p_y}{(p_y + \sigma y_{int})^2 + \Delta^2}$$

EXPERIMENTAL VERIFICATION – IN MC LAB

Kelasidi, Liljebäck, Pettersen and Gravdahl (2016). Biologically Inspired Swimming Snake Robots: Modeling, Control and Experimental Investigation, *IEEE Robotics and Automation Magazine*, Vol. 23, No. 1, 2016.

Experimental validation of the straight line path following controller **– LOS, without current**



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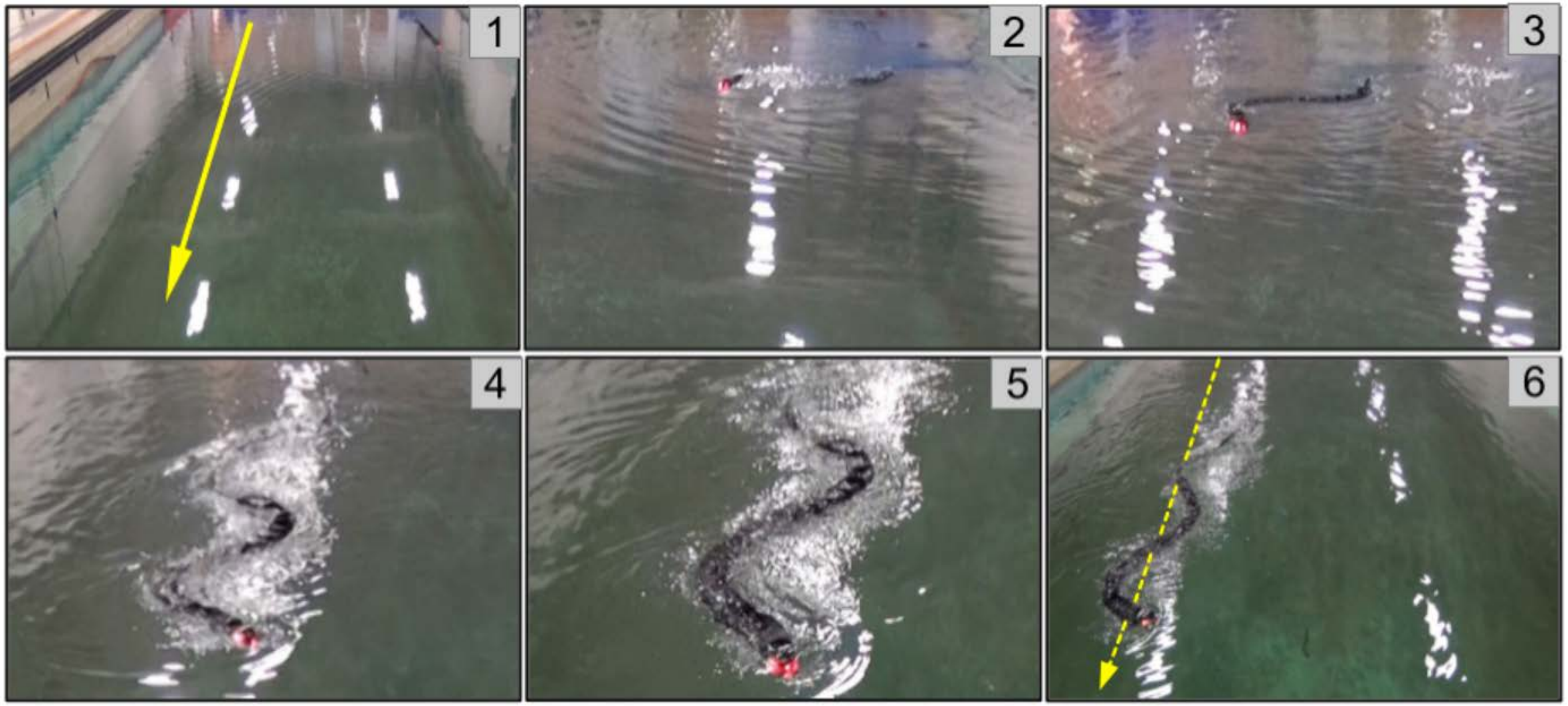


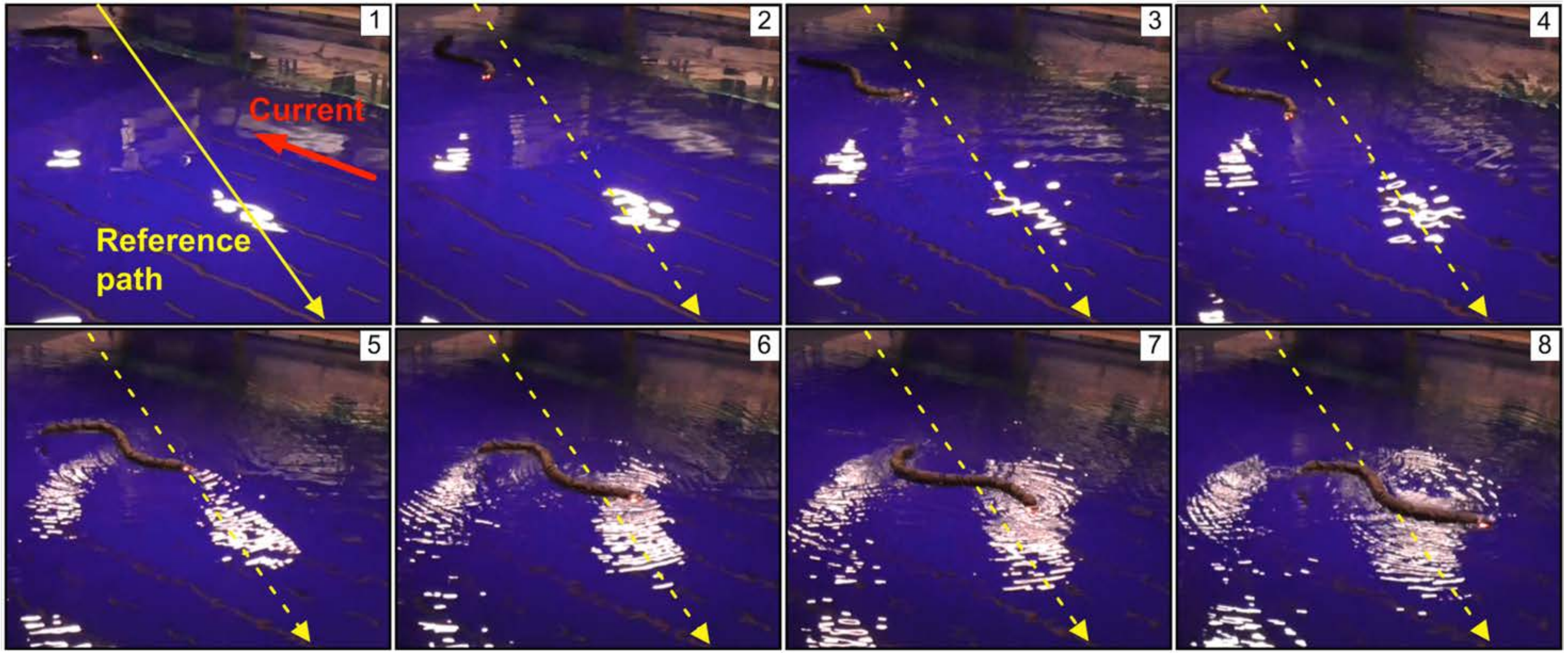
EXPERIMENTS

NORTH SEA CENTRE FLUME TANK

EXPERIMENTAL VERIFICATION
– IN FLUME TANK

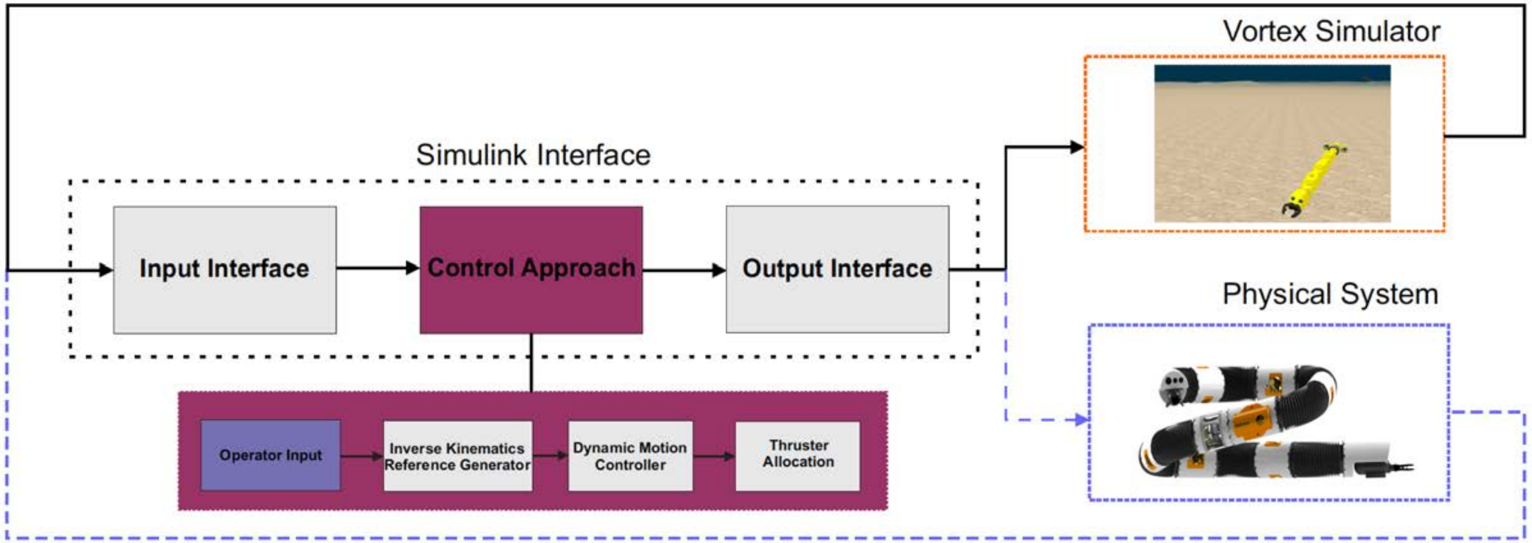
Kelasidi, Liljebäck, Pettersen and Gravdahl (2016). Integral Line-of-Sight Guidance for Path Following Control of Underwater Snake Robots: Theory and Experiments", *IEEE Transactions on Robotics,* Vol. 33, No. 3, 2017.

Experimental validation of a straight line path following controller – **iLOS, with current**



SNAKE ROBOTS WITH THRUSTERS (USMs)

- **J. Sverdrup-Thygeson, E. Kelasidi, K.Y. Pettersen and J.T. Gravdahl (2016).** Modeling of underwater swimming manipulators, *Proc. 10th IFAC Conference on Control Applications in Marine Systems.*
- **J. Sverdrup-Thygeson, E. Kelasidi, K.Y. Pettersen and J.T. Gravdahl (2016).** A control framework for biologically inspired underwater swimming manipulators equipped with thrusters, *Proc. 10th IFAC Conference on Control Applications in Marine Systems.*
- **J. Sverdrup-Thygeson, E. Kelasidi, K.Y. Pettersen and J.T. Gravdahl (2018).** The Underwater Swimming Manipulator – A Bio-Inspired Solution for Subsea Operations, *IEEE Journal of Oceanic Engineering.*



ARTICULATED AUVS:
NEXT GENERATION INTERVENTION-AUVS

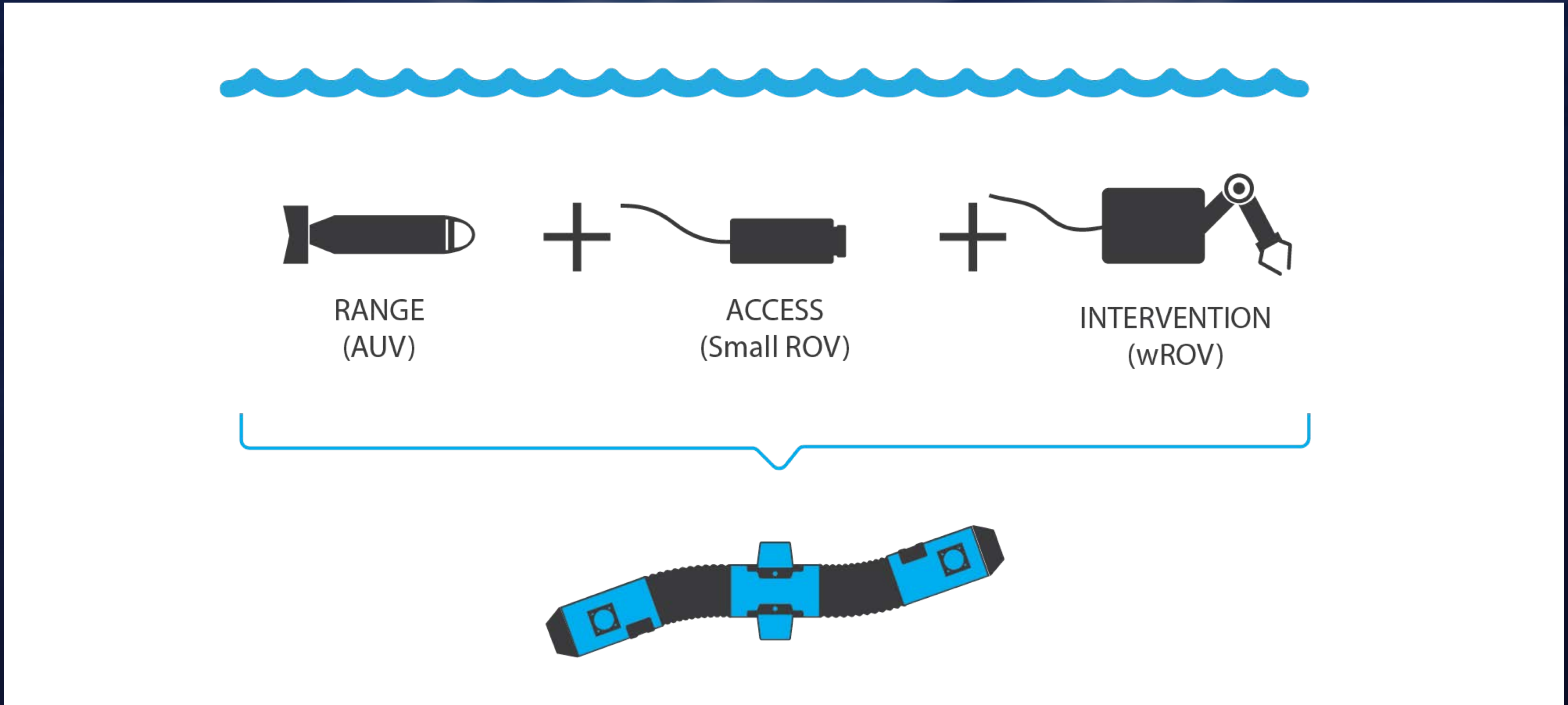
Swimming snake robots =
Hyperredundant Underwater Robot Manipulators

Characterized by
- High number of DOF
- Slender and flexible body

→ Superior access capabilities
→ Intervention capabilities

Bio-inspired system
- Increased agility and maneuverability
- Energy efficiency

QUALITIES



FROM BIOLOGY

THROUGH UNIVERSITY RESEARCH

TOWARDS INDUSTRY:

EELUME

Part III:

EELUME


Eelume
SUBSEA INTERVENTION
Testing at PREZIOSO Linjebygg
Subsea Test Center

THE UNDERWATER SNAKE ROBOTICS RESEARCH GROUP AT NTNU

KRISTIN Y. PETTERSEN

J. TOMMY GRAVDAHL

PÅL LILJEBÄCK

ELENI KELASIDI

ANNA KOHL

JØRGEN SVERDRUP THYGESON

SIGNE MOE

IDA-LOUISE BORLAUG

HENRIK SCHMIDT-DIDLAUKIES

FILIPPO SANFILIPPO

ØYVIND STAVDAHL