Bio-inspired locomotion robots dynamics: from discrete to continuous systems

Authors: Frédéric Boyer

Laboratory: IMTA-LS2N

Venu: Séminaire de l'ENSTA-Bretagne

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This talk aims at introducing a unified framework devoted to the study of locomotion systems in bio-inspired robotics…

⇨ In particular we will attempt to answer the following two questions:

« How can we model and classify these systems? »

« How can we efficiently compute there models ? »

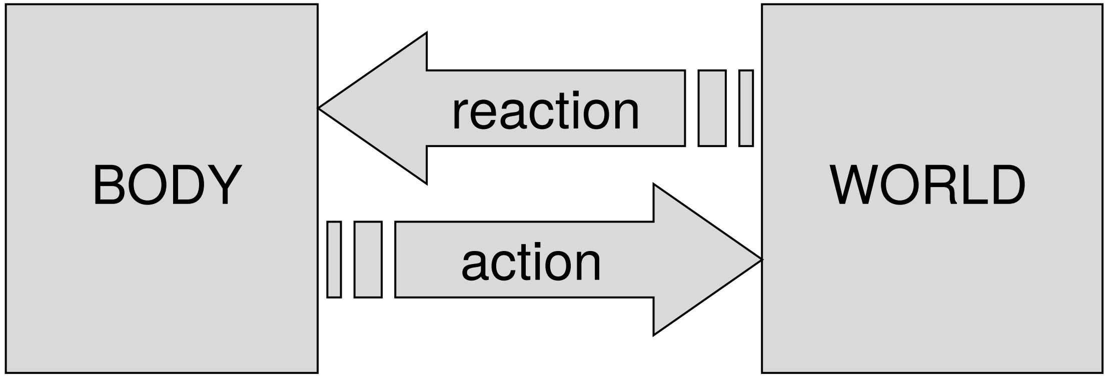
ECOLE DES MINES DE NANTES

I Basic definitions

II Locomotion model

III Extension to continuous systems

If we had to retain one principle to explain locomotion… the action-reaction principle!

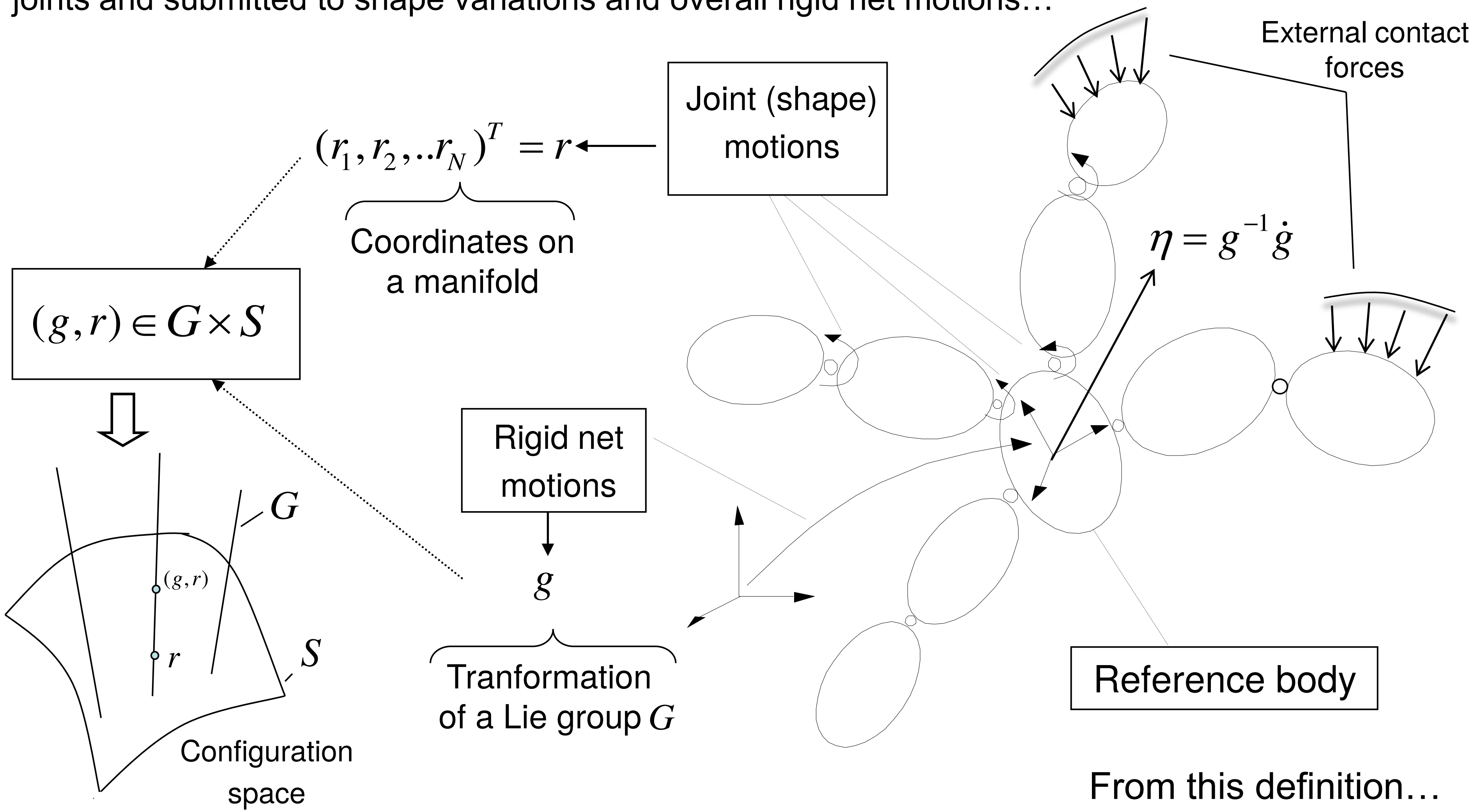


- Endo skeleton : vertebrates
- Exo skeleton : arthropodes
- Soft bodies : mollusques…

- Fluid: swimming, flying
- Solid : creeping, walking
- Exotic media…
- Void

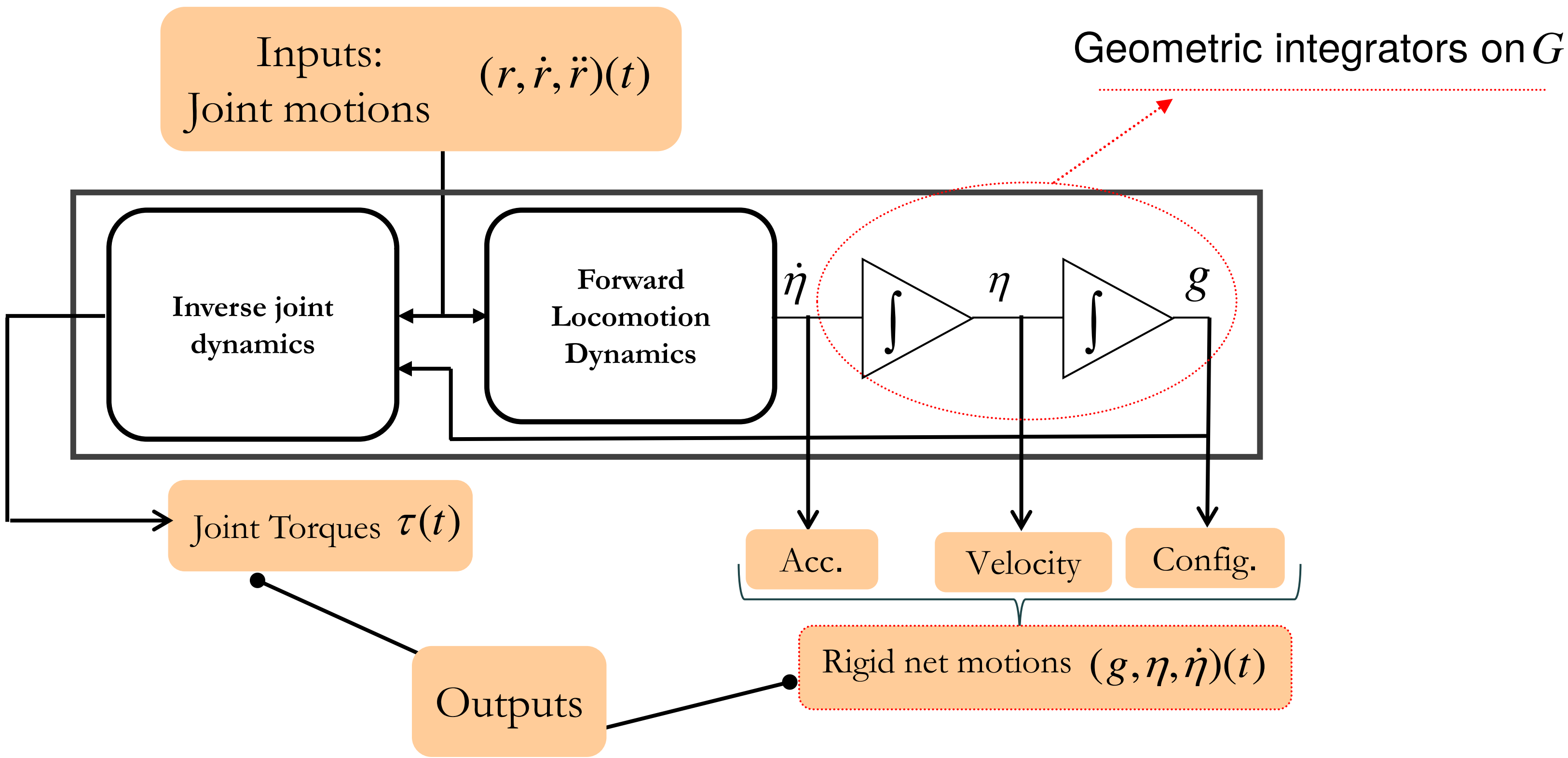
amphibot

To investigate these systems, we use the model of MMS, i.e. a set of rigid bodies connected by joints and submitted to shape variations and overall rigid net motions…



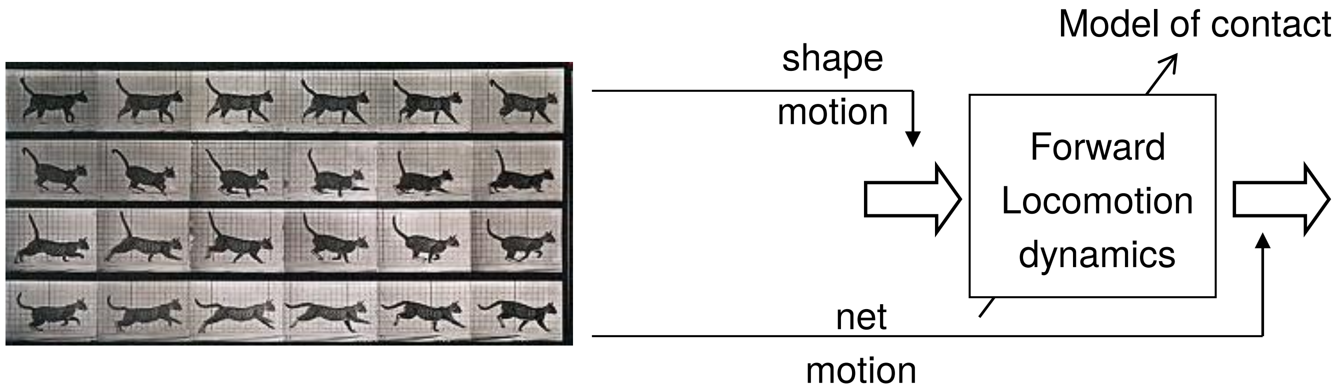
From this definition…

In order to structure our investigations, we will seek the following algorithm…



Why this choice, why not take the joint torques as inputs?

- More intuitive to define locomotion gaits by specifiying joint motions
- This algorithm can be coupled to biological experiments based on films…



The computation of torques allows to check the feasibility of the motions

Here we concentrate on locomotion dynamics

ECOLE DES MINES DE NANTES

I Basic definitions

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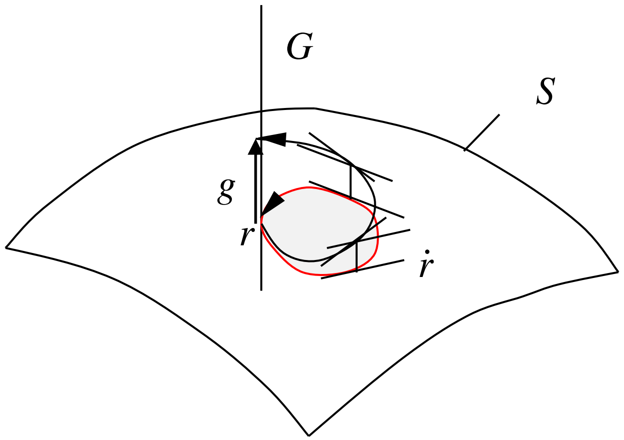
The locomotion is generally ruled by a dynamic model which can turn into kinematics, when we have a linear relation :

Net vel. Shape vel.

$$\eta + \mathcal{A}(g,r)\dot{r} = 0$$

$$\mathcal{A}(\not{g},r)$$



For a cyclic change of shape (gait) the net displacement is prop. to the enclosed area and $d\mathcal{A}$

- Defines a connexion on $G \times S$ [Ehresmann,1950]
- Enjoys nice geometric properties…

In bio-inspired robotics there are two well known cases where locomotion is modelled by a connexion: Conservation moment law, NH platforms [Marsden, 78]

First case: conservation law (ex. falling cat…)

$$\sigma = \sigma_{ref} + \sigma_{sh} = R(J\Omega + \alpha\dot{r}) = 0$$

⇩

$$\Omega = -(J^{-1}\alpha)(r)\dot{r}$$

⇩

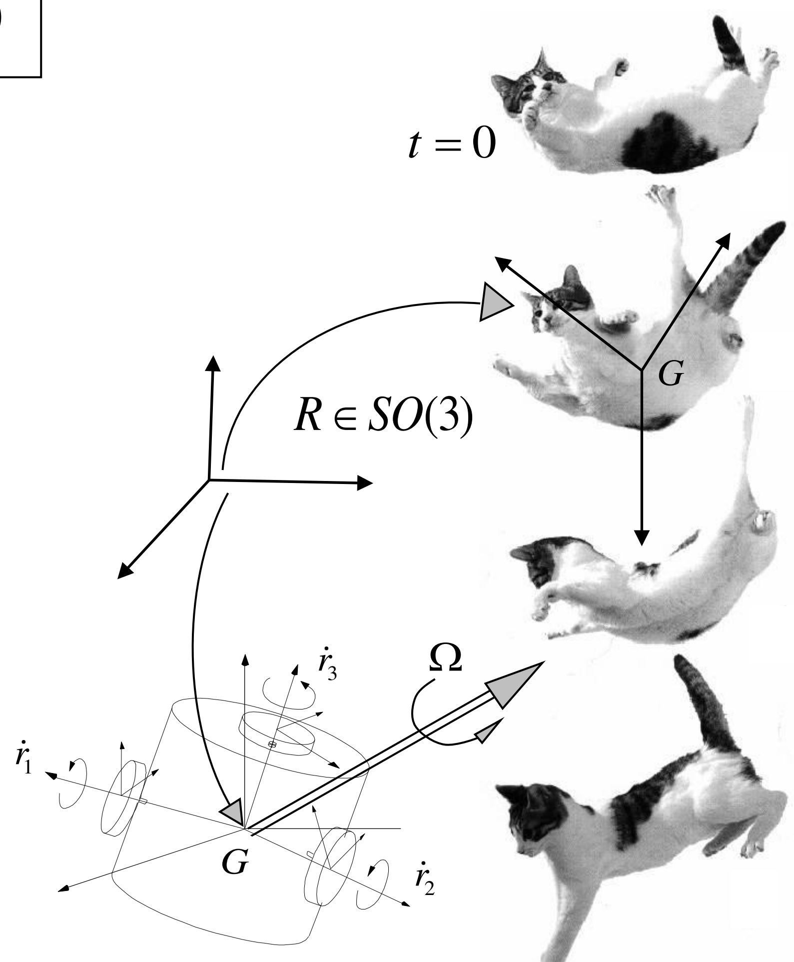
$$\mathcal{A}(r) = J^{-1}(r)\alpha(r)$$

Mechanical connexion

[Marsden 78, Montgomery 93]

Remark: Applying the same idea to translations of the reference frame…

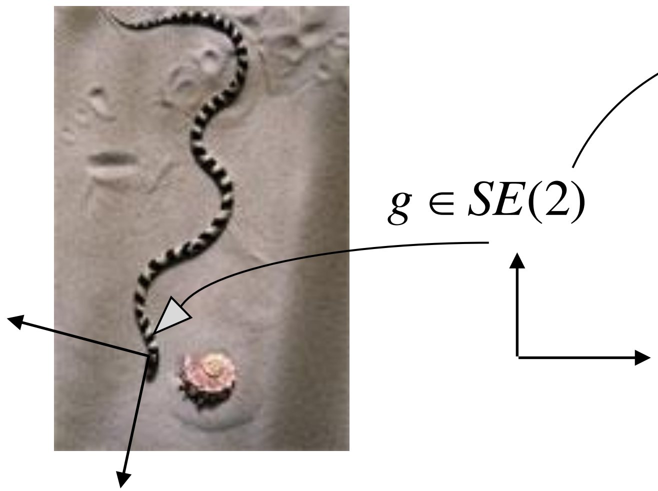
⇨ $\mathcal{A}(r) = 0$

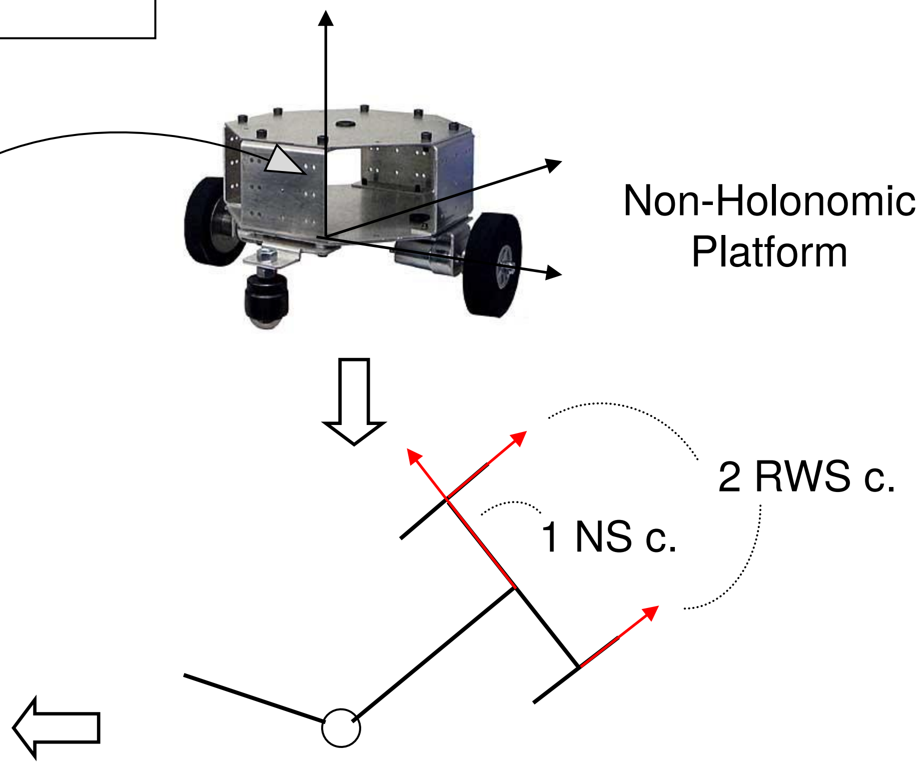


Satellite with rotors

Falling cat

Second case: snakes in lateral undulation





$$\eta = -\mathcal{A}(r)\dot{r}$$

⇨ $\mathcal{A}(r)$: Principal kinematic connexion [Kelly & Murray, 95]

In the general case, a dynamic model is required…

To get it, take the Lagrangian: $l(g,r,\eta,\dot{r}) = \frac{1}{2}(\eta^T,\dot{r}^T)\begin{pmatrix} \mathcal{M} & m \\ m^T & \mathrm{M} \end{pmatrix}\begin{pmatrix} \eta \\ \dot{r} \end{pmatrix} - U(g,r)$

Because η is the velocity on G we need Poincaré eq. [Poincaré, 1901]:

$$\Rightarrow \quad \frac{d}{dt}\left(\frac{\partial l}{\partial \eta}\right) - ad_\eta^T\left(\frac{\partial l}{\partial \eta}\right) = f_{ext}$$

⇨ Locomotion dynamics :

$$\Rightarrow \begin{pmatrix} \dot{\eta} \\ \dot{g} \end{pmatrix} = \begin{pmatrix} \mathcal{M}^{-1}\mathcal{F} \\ g\eta \end{pmatrix} \qquad \mathcal{F} = f_{inert} + f_{ext}$$

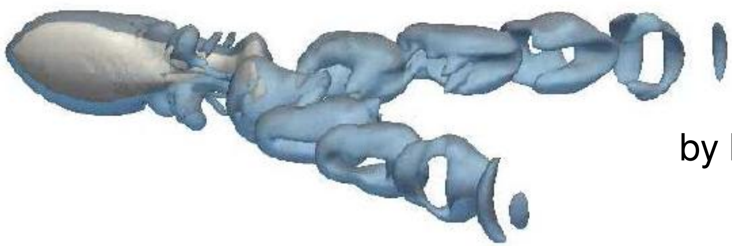
reconstruction eq. from η to g

In general, f_{ext} requires to solve the contact dynamics of the system / world …

⇨ Which can be extremly difficult and incompatible with robotics needs!

For example in swimming, f_{ext} requires to solve Navier-Stokes equations…

vorticity



by M. Bergmann

Fortunately, there exists some simple situations where f_{ext} only requires geometry (no physics)… ⇨ two cases…

• Fst case: when f_{ext} is Lagrangian [Birkhoff, 66], i.e. when there exists $l_{ext}(r,\eta,\dot{r})$ …

s.t.: $f_{ext} = -\frac{d}{dt}\left(\frac{\partial l_{ext}}{\partial \eta}\right) + ad^*_\eta\left(\frac{\partial l_{ext}}{\partial \eta}\right)$ $\Rightarrow$ Locomotion dynamics:

$$\frac{d}{dt}\left(\frac{\partial (l+l_{ext})}{\partial \eta}\right) - ad^*_\eta\left(\frac{\partial (l+l_{ext})}{\partial \eta}\right) = 0$$

But then…

if at $t=0$, $\frac{\partial (l+l_{ext})}{\partial \eta} = 0$ $\Rightarrow$ $\frac{\partial (l+l_{ext})}{\partial \eta} = 0 \ , \ \forall t$: Locomotion dynamics turn into kinematics

Swimming at high Reynolds in a quiescent potential flow:

$$l_{ext} = T_{fluid} \Rightarrow l + l_{ext} = \frac{1}{2}(\eta^T, \dot{r}^T)\begin{pmatrix} \tilde{M} & \tilde{m}^T \\ \tilde{m} & \tilde{\mathrm{M}} \end{pmatrix}\begin{pmatrix} \eta \\ \dot{r} \end{pmatrix}$$

Tensor of virtual inertia = solid + added

Fluid is quiescent

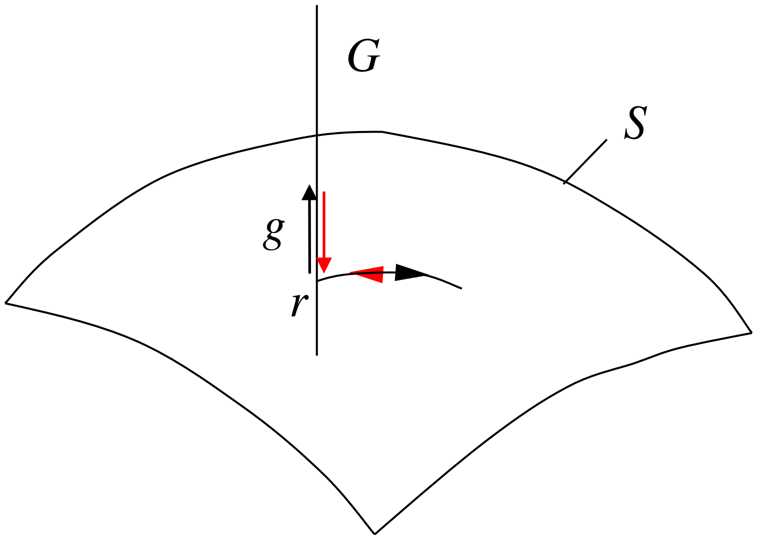
$\Rightarrow$ Conservation law of kinetic wrench: $\tilde{M}\eta + \tilde{m}^T\dot{r} = 0 \Rightarrow \eta + \tilde{A}(r)\dot{r} = 0$

Mechanical connection: encodes kinetic momentum exchanges body / fluid…[Kanso, 2005]

Remarks:

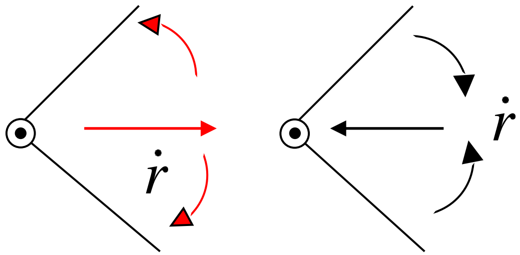
1°) By contrast to the cat, the fish can change its orientation but also its position

2°) A cyclic change of a 1-dof shape system $\Rightarrow$ no phase shift on G



$\Leftrightarrow$

Theorem of Scallop …



3°) Similar context at low Reynolds with viscous forces [Hatton, 13]…

⇨ At high Reynolds, kinetic conservation laws can be prolonged to the case with vorticity… applying the balance of impulses wrench [Saffmann, 92], gives:

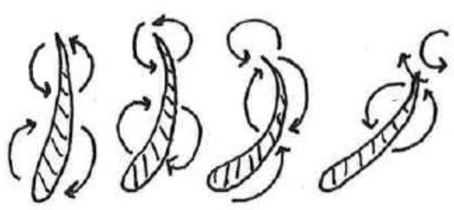
$$\left\{ \overbrace{\underbrace{\begin{pmatrix} p_{sh} \\ \sigma_{sh} \end{pmatrix}}_{\text{Intern. dof}} + \underbrace{\begin{pmatrix} p_{net} \\ \sigma_{net} \end{pmatrix}}_{\text{Ext. dof}}}^{\text{Previous context}} + \underbrace{\begin{pmatrix} \int_{\partial B} x \times (n \times u_{\omega}) da + \frac{1}{2} \int_{F} x \times \omega \, dv \\ -\frac{1}{2} \int_{\partial B} \|x\|^2 (n \times u_{\omega}) da - \frac{1}{2} \int_{F} \|x\|^2 \omega \, dv \end{pmatrix}}_{\text{Fluid: wrench of impulses due to vorticity}} = \underbrace{\begin{pmatrix} 0 \\ 0 \end{pmatrix}}_{\text{Starting at rest}} \right.$$

⇨ Animals generate (and control) vortices to move efficiently!

⇨ A scallop escapes from its theorem…

⇨ Generate vorticity for what?

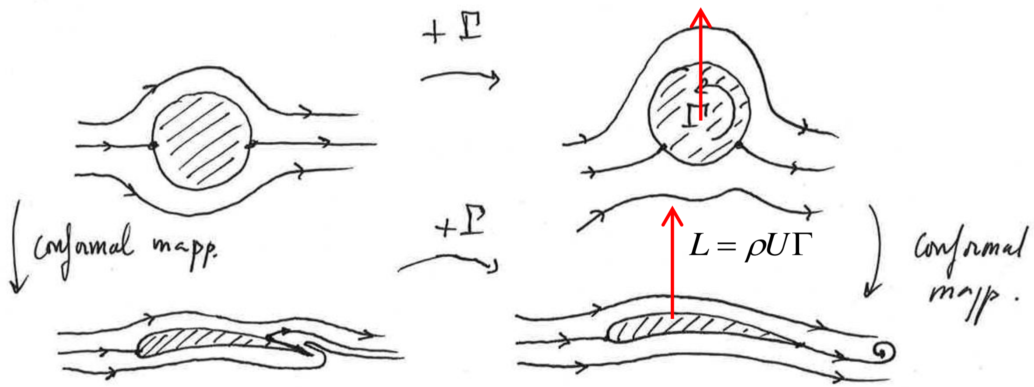
- To manoeuver (turn, plung…) in the case of fishes [Triantafyllou, 08]



More generally…

- To generate lift (used for sustentation, thrust…) against drag:

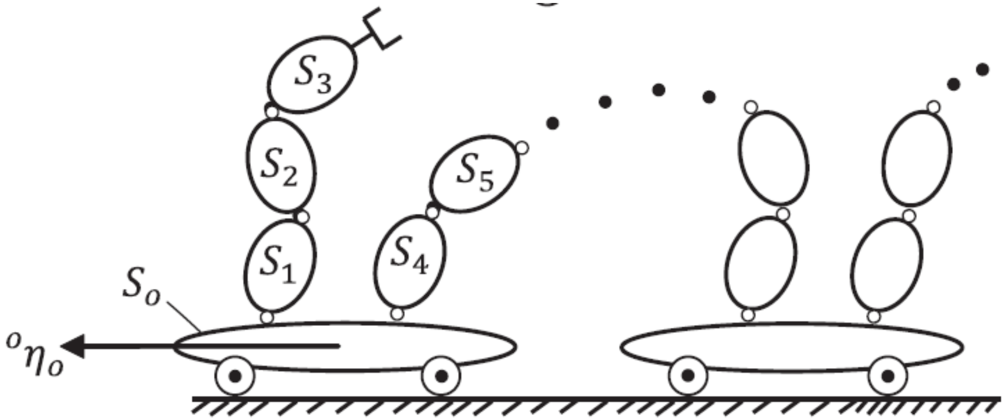
⇨ Remind the basic Kutta picture of lift generation in steady aerodynamics…



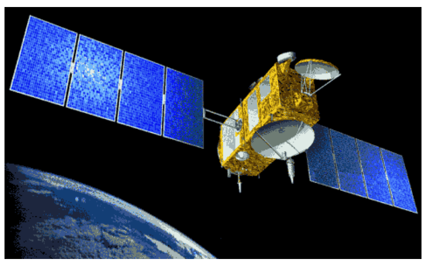
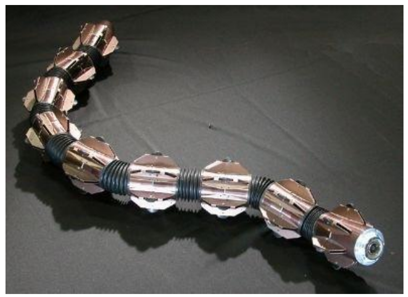
⇨ Shed vorticity
⇩
bound vorticity
⇩
circulation
⇩
lift!

• Snd case : when the contacts are defined by ideal kinematic constraints …

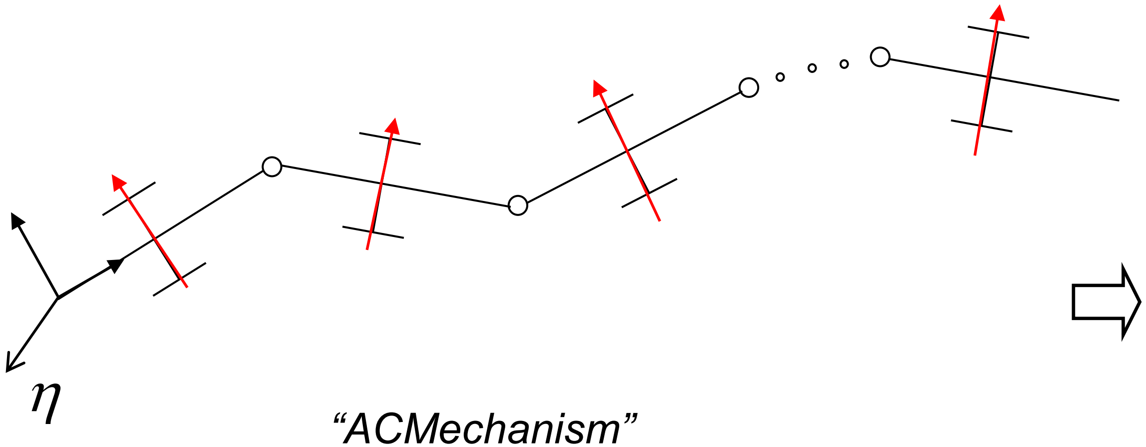
⇨ This is the case of wheeled MMS [Boyer & Ali TRO, 11] :



"Hirose ACM-R5"

 ,  ,  ,  ,  …

The ACM is a serial assembly of passive wheeled axels connected by active joints…



"ACMechanism"

Reproduces the principle of Snake creeping:

Body undulations

⇩

Lateral reaction forces

⇩

Axial resultant

Gathering all the constraint equations on $\underset{\parallel}{\overset{SE(2)}{G}} \times S$:

⇨ (*) $A(r)\eta + B(r)\dot{r} = 0$ ⇨ $A =$ Matrix of locked constraints

Can also models contacts in legged locomotion…

⇨ 2 cases depending upon $rank(A)/\dim(G)=3$

- Case 1 (fully constrained): $rank(A)=3$

⇨ The system has enough constraints to be governed by kinematics only!

Ex. ACM: 3 first axels ←

$$\begin{pmatrix}\bar{A}(r)\\ \tilde{A}(r)\end{pmatrix}\eta+\begin{pmatrix}\bar{B}(r)\\ \tilde{B}(r)\end{pmatrix}\dot{r}=\begin{pmatrix}0\\ 0\end{pmatrix}\begin{matrix}\rightarrow (1)\\ \rightarrow (2)\end{matrix}$$

(1) ⇨ $\eta=-\bar{A}(r)^{-1}\bar{B}(r)\dot{r}=-\mathcal{A}(r)\dot{r}$ ⇨ Kinematic connexion [Ostrowsky,1999]

The forward locomotion dynamics turn into a kinematic model (of contacts)

(2) ⇨ Compatibility eq.: give the motion of other joints in order to preserve mobility

⇨ Each axle follows the track of its predecessor (follower-leader)

- Case 2 (under constrained): $rank(A) < 3$

⇨ The system has not enough constraints to be governed by kinematics only!

Generalized Inversion of (*) ⇨ $$\eta = \underbrace{H(r)\,\eta_r}_{\in \ker(A)} + \underbrace{J(r)}_{= -A^{(-1)}B}\,\dot{r}$$

Where: η_r is a "reduced velocity" kinematically undetermined!

⇨ To determine η_r we need a dynamic model ⇨

⇨ Dynamics of η_r : projection of those of η in $\ker(A)$

Can be generalized to systems with passive internal dofs (NH and soft systems) [Boyer, Belkhiri TRO 2014]. ⇨

I Basic definitions

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Up to now we developed a Lagrangian model: good for analysis, not for computations…

⇨ For computational purposes: Newton-Euler model MMS…

① Dynamic model of the isolated bodies

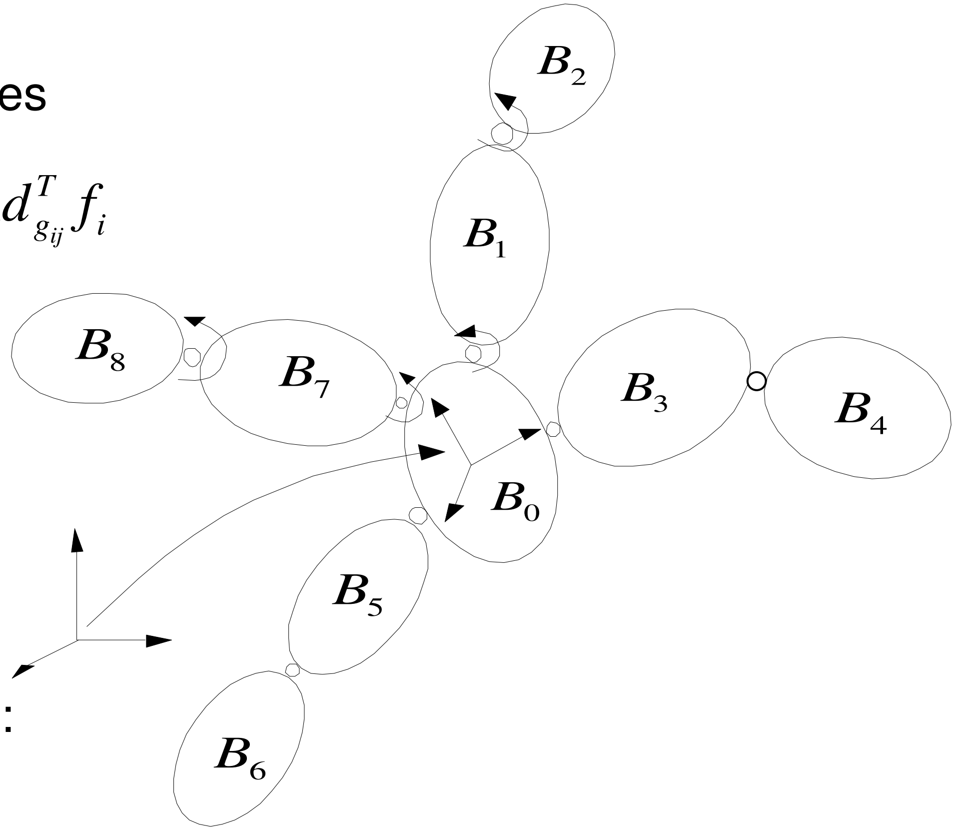
$$\mathcal{M}_j \dot{\eta}_j = f_{inert,j} + f_{ext,j} + f_j - \sum_{i \backslash j = a(i)} Ad^T_{g_{ij}} f_i$$

② Kinematic model of joints:

$$g_j = g_i \, g_{ij}(r_j)$$

$$\eta_j = Ad_{g_{ji}} \eta_i + A_j \dot{r}_j$$

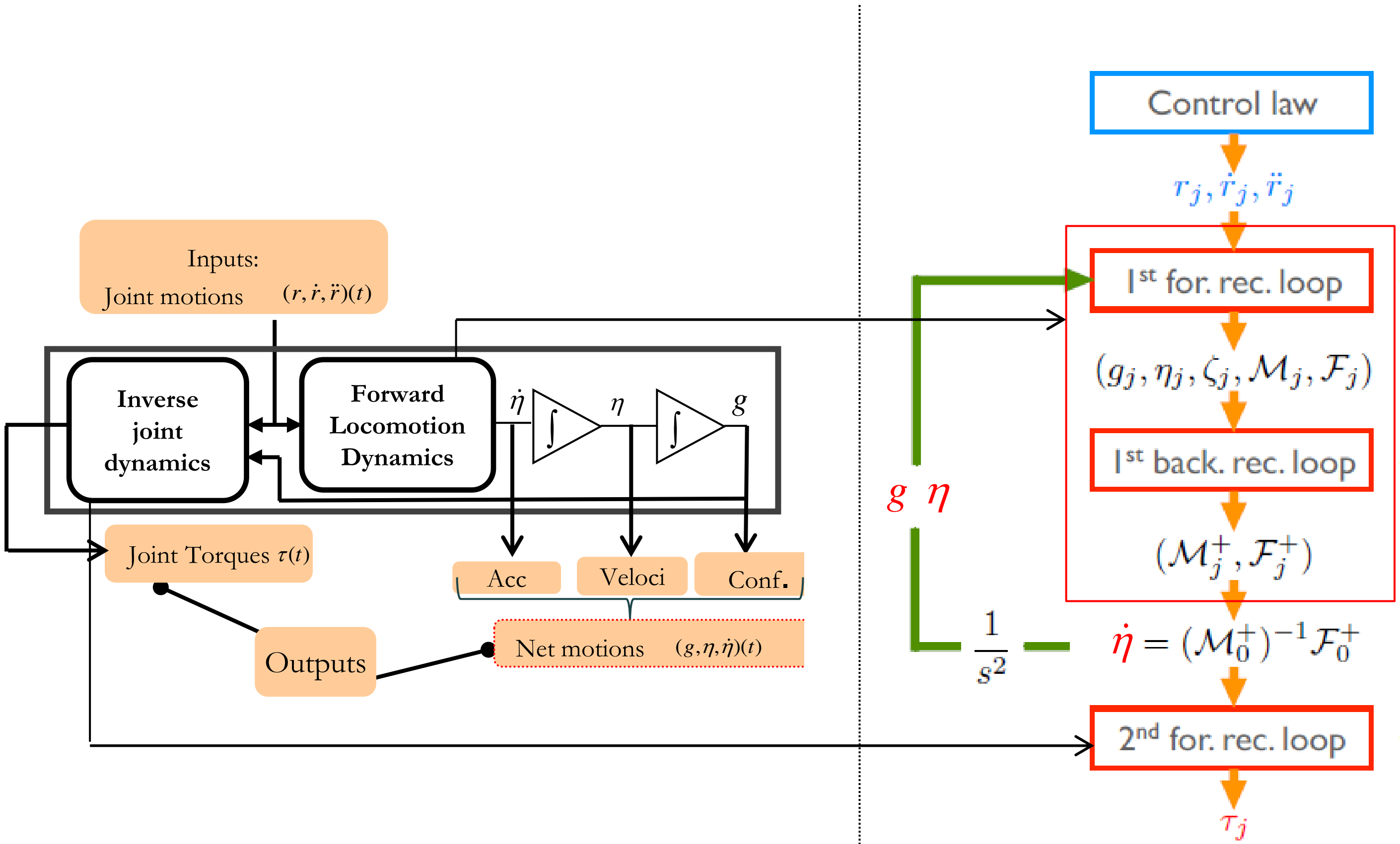
$$\dot{\eta}_j = Ad_{g_{ji}} \dot{\eta}_i + \zeta_j(\dot{r}_j, \ddot{r}_j)$$



⇨ Advantages of NE/Lagrange models:

- Easy to program
- Their recursive nature can be used to design fast algorithms…

Newton-Euler algorithm solving our starting problem:



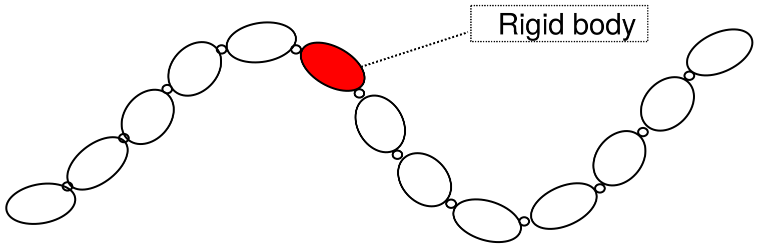
$$\left\{\begin{array}{l} \text{For } j = 1, ..., N: \\ \quad g_j = g_i g_{j,i} \\ \quad \eta_j = Ad_{g_{j,i}} \eta_i + A_j \dot r_j \\ \text{End.} \end{array}\right.$$

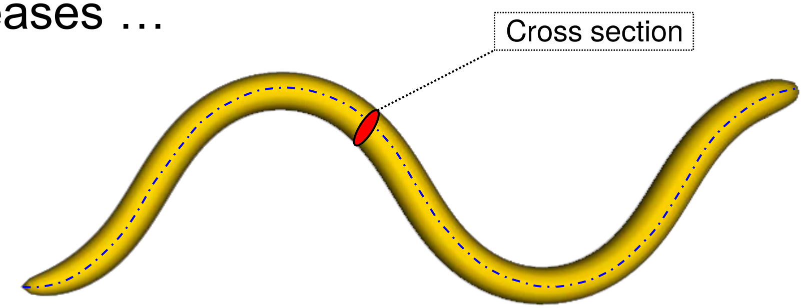
$$\left\{\begin{array}{l} \text{For } j = N, ..., 1: \\ \quad \mathcal{M}_i^+ = \mathcal{M}_i^+ + Ad_{g_{j,i}}^T \mathcal{M}_j^+ Ad_{g_{j,i}} \\ \quad \mathcal{F}_i^+ = \mathcal{F}_i^+ + Ad_{g_{j,i}}^T (\mathcal{F}_j^+ - \mathcal{M}_j^+ \zeta_j) \\ \text{End.} \end{array}\right.$$

$$\left\{\begin{array}{l} \text{For } j = 1, ..., N: \\ \quad \dot\eta_j = Ad_{g_{j,i}} \dot\eta_i + \zeta_j \\ \quad \tau = A_j^T (\mathcal{M}_j^+ \dot\eta_j - \mathcal{F}_j^+) \\ \text{End.} \end{array}\right.$$

- Furthermore NE models can be extended to continuous systems…

⇨ When the number of internal DoFs increases …



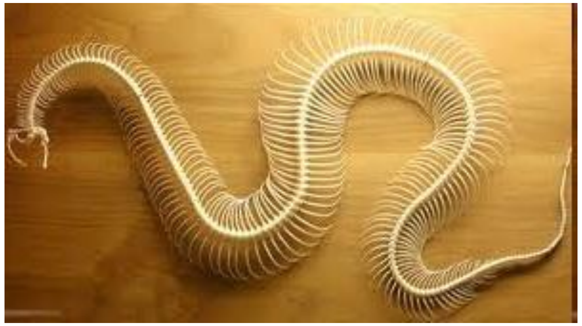


Discrete Mobile MS … ➡ Continuous MMS = Cosserat beam

➢ Rigid bodies	Cross sections
➢ Vertebral column (backbone)	Beam centroidal line
➢ Discret body indices j	Beam sections label X
➢ Joint coordinates r	Strain field ξ
➢ Interbody wrenches f_j	Stress field Λ

Can be used to model Hyper-redundant (HR) Systems

Elongated (slender body) animals



Snakes, worms (earthworms, inchworms), fish…

[Boyer, Ali, Porez, TRO 2012].

Snakes

Earthworms

Inchworms

Slender-fish

Cosserat Beam Kinematics / Locomotion modes

Case	Controlled dof	Nature	Example
1	01	Stretching	Earth worm
2	01	Bending (pitch)	Inch worm
3	02	Bending (yaw)	2D snakes
4	02	Bending (pitch, yaw)	3D snakes
5	05	Idem + 2 transverse shearing	3D snakes + model of the scales

Based on this correspondance, we can extend the NE model to continuous systems

① Dynamic model of the isolated bodies:

$$\mathcal{M}\dot{\eta} = ad_{\eta}^{T}(\mathcal{M}\eta) + \bar{f} + \Lambda' - ad_{\xi}^{T}(\Lambda)$$

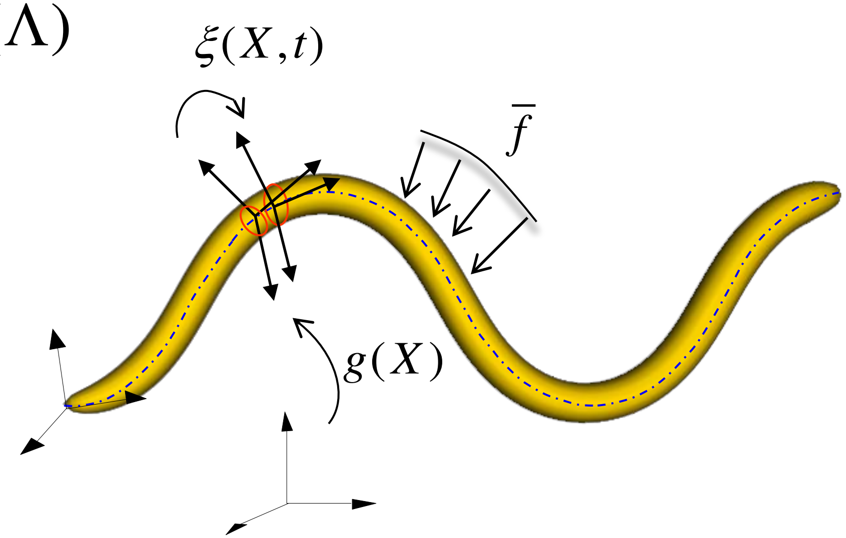
Poincaré equations of 1-dim Cosserat media

② Kinematic model of strains:

$$g' = g\hat{\xi}(t)$$

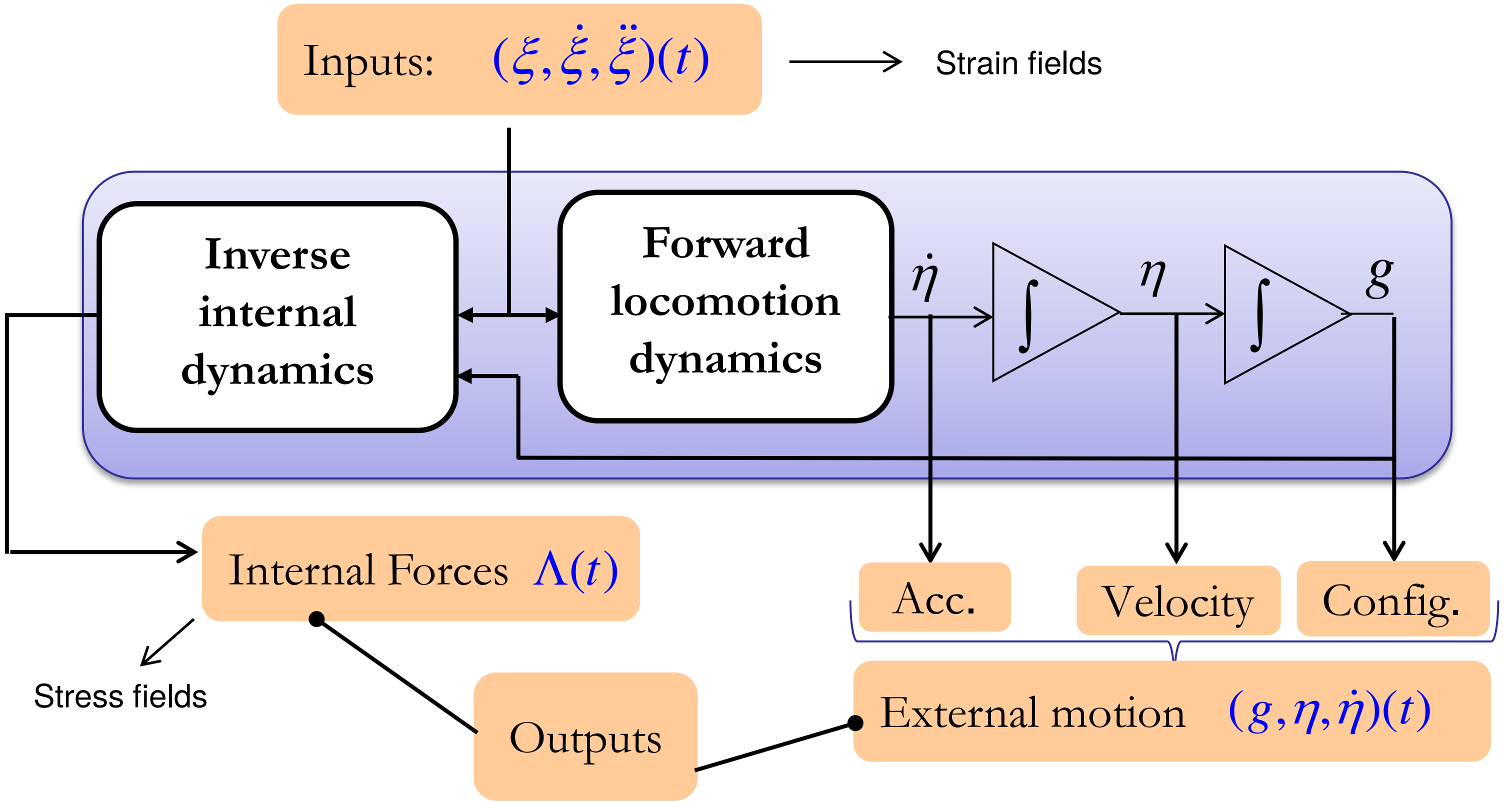
$$\eta' = -ad_{\xi(t)}(\eta) + \dot{\xi}(t)$$

$$\dot{\eta}' = -ad_{\xi(t)}(\dot{\eta}) - ad_{\dot{\xi}(t)}(\eta) + \ddot{\xi}(t)$$



[Boyer , Porez , Kahlil, TRO 2006]

Macro-continuous algorithm



Can be used when the contacts are modeled by forces…

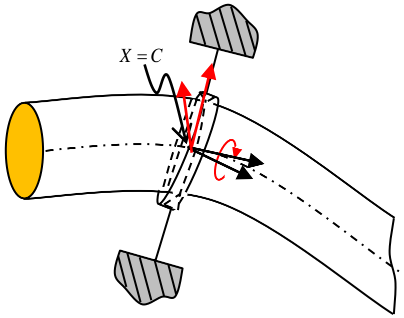
lighthill

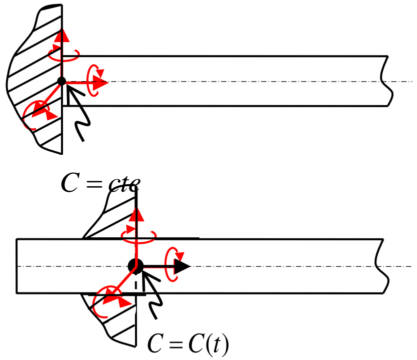
When the contacts are modelled by kinematic constraints…

1°) Anchorages (locked, sweeping)

2°) Annular supports

Ideal contacts





⇨ Defined by geometric and/or kinematic constraints

⇨ Each scalar constraint introduces one reaction unknown

⇨ Reaction unknowns $(f_-, f_+, \bar{f})$ define f_{ext}

Locomotion model

When the total number of independent constraints $= \dim(G)$

⇨ Locomotion entirely ruled by kinematics of contact and controlled strains

$$\eta = F(g, \dot{\xi}(t), \xi(t), \xi'(t), \xi''(t), \ldots) \Leftrightarrow$$ Forward locomotion kinematics

⇨ Locomotion dynamics are not used to compute the external motion but to compute the contact forces:

$$f_{ext} = \mathcal{M}\dot{\eta} - f_{inert} \quad \Rightarrow \quad f_{ext} = \mathcal{M}\dot{F} - f_{inert}$$

⇔ Inverse locomotion dynamics

Torque computation

But f_{ext} is also the resultant of reaction unknowns (forces and torques)

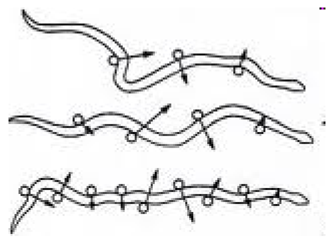
$$\Rightarrow \quad f_{ext} = -f_- + Ad_{k(1)} f_+ + \int_0^l Ad_k^T \bar{f} \, dX = \mathcal{M}\dot{F} - f_{inert}$$

That one solves / $(f_-, f_+, \bar{f})$ with some assumption on distribution

since the solution is not unique (in the over-constrained case)…

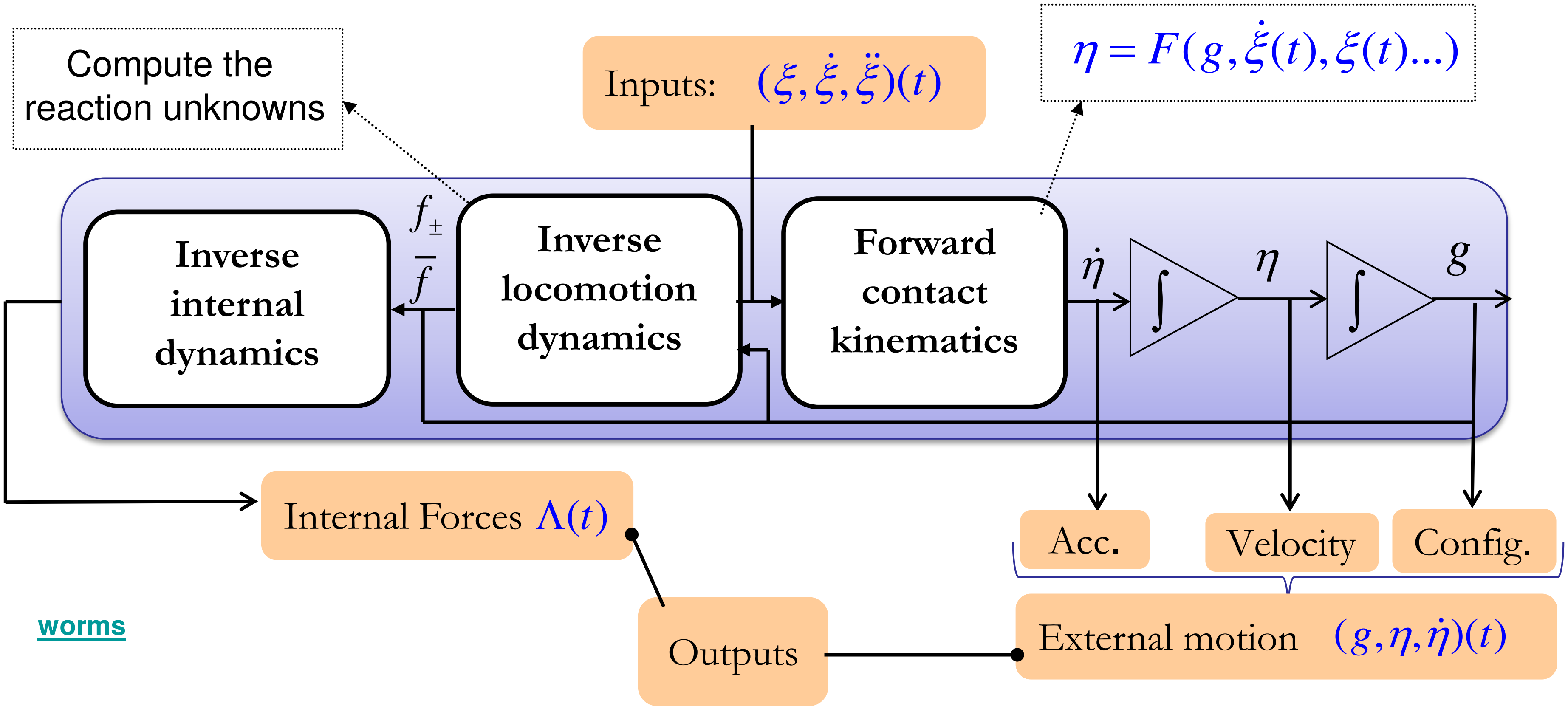
Once $(f_-, f_+, \bar{f})$ fixed…

Computation of $\Lambda(t)$ from beam pde's:



$$X\text{-ODE: } \Lambda' = \mathcal{M}\dot{\eta} - ad_\eta^T(\mathcal{M}\eta) + ad_\xi^T(\Lambda) - \bar{f} \quad \text{BC: } \Lambda(0) = -f_-$$

Macro-continuous algorithm



worms

The forward locomotion model is a kinematic model

Soft locomotion… sphynx

Model the soft bodies as Cosserat beams with stress-strain laws:

$$\Lambda = \Lambda(\xi, \dot{\xi})$$

Geometrically Exact Approach (finite def.)

Hovering flight GEA   Passive swimming   squid

Alternate approach: separate deformations from the rigid overall motions

Floating Frame Approach (small def. + modal reduction)

Less accurate but better for fast-simulation and control…

Hovering flight FFA

Thank you…