Bio-inspired motion control for soft-body pedundulatory robotic locomotors

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Drawing inspiration from biology, where the relationship between organism morphology and the control of movement has been effectively addressed by the evolutionary process, can help in designing efficient and agile robots, able to adapt robustly to a variety of environmental conditions in unstructured substrates. Our work focuses on robotic systems inspired by the morphology and locomotion of the polychaete annelid marine worms and of the centipede terrestrial arthropods, which combine body undulations with the oscillatory action of numerous lateral appendages (polychaete – parapodia; arthropods - legs), to propel themselves efficiently on sand, mud, sediment, burrow underground, as well as swim underwater. This hybrid type of locomotion, combining body undulations with parapodial oscillations appropriately synchronized with the body movement, has been termed *pedundulatory*, and robotic prototypes replicating these capabilities have been developed.

(a) *Nereis virens*, a polychaete annelid

(b) *Scolopendra heros*, a centipede

When crawling rapidly or swimming, polychaete combine tail-to-head body undulations with alternating waves of parapodial activity, coordinated so that the thrust-producing power stroke of each parapodium occurs at the crest of the body wave, while its recovery phase occurs in the trough of the body wave. Centipedes, on the other hand, combine, for forward locomotion, head-to-tail undulations of their segmented body with leg movements, synchronized so that the legs make contact with the substrate when the corresponding body segment is in the trough of the body wave. Most undulatory robotics research focuses on this type of head-to-tail undulations (as in snakes, eels, etc.). Therefore, it is quite intriguing, from the robotics point of view, to attempt to understand, replicate and study how polychaete are able to exploit such a different type of body undulations to achieve their outstanding locomotion capabilities. Moreover, we attempt to replicate both types of this synchronized body/appendage movement on the same robotic apparatus, merely by altering its motion control strategy.

Computational models for the mechanics and motion control of such systems, are based on their Lagrangian dynamics and on resistive models of their frictional interaction with the substrate. Computational tools were developed to assist

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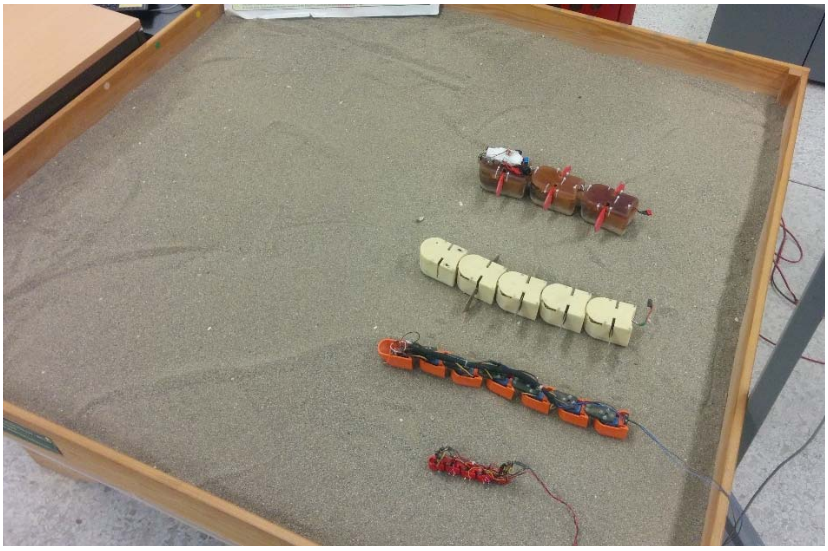
modelling, as well as robot and control design. The generation of open-loop pedundulatory gaits, both by the direct actuation of the system’s many degrees-of-freedom, and by actuation schemes inspired by the neuromuscular control of living organisms was studied, involving the use of direct or retrograde body waves, as well as the appropriately synchronized movement of the lateral appendages. Moreover, joint compliance was modeled computationally, and its effects on the achieved velocities and on locomotor efficiency were investigated.

In the context of the *soft robotics* paradigm, our work explores the development of soft-body pedundulatory robotic prototypes, moving on unstructured terrains, like sand, dry mud, grass, tall vegetation, etc. We consider, in particular, the fabrication of the robot body from compliant materials (e.g., polyurethane) with the assistance of rapid prototyping tools and CAD software. Moreover, we evaluate the effect of compliant elements joining the segments of the robot on the characteristics of its propulsion.

The corresponding modes of locomotion were investigated, and comparatively assessed, via extensive experimental studies on *granular* (as well as on other unstructured) substrates, which validate the proposed models and highlight the performance of pedundulatory robots. Furthermore, these robotic prototypes and their computational models are exploited, in combination with appropriate sensory information, for the design of closed-loop control schemes (e.g., pedundulatory visual servoing), which give rise to bio-inspired reactive behaviors like centering, corridor following and swarming.



The Nereis family of soft- and rigid-body undulatory and pedundulatory robots on sand

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