Bioinspired Underwater Legged Robot for Marine Conservation

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Abstract

Biodiversity is the life support system of our planet and it mostly resides within the oceans. The impact of humans is degrading or destroying the biodiversity in the marine environment. It is crucial to have a deep understanding of this environment and take appropriate conservational measures. Henceforth, an extensive number of explorations, observations, sampling, and monitoring are required, which are difficult to achieve solely through sheer human effort. Robotic systems can provide a possibility of efficient and precise measurement of ecological processes in these environments at unprecedented scales, pushing the frontiers of our existing methodologies. Conventional propeller-based Remotely Operated Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) can be detrimental to the seabed marine life and cause unwanted suspension of sediment when they are closer to the seabed. In this kind of operational scenario, an alternative approach that exploits the physical contact between the robot and the substrate can complement the swimming robots. Traditional benthic robots based on wheels or belts have constrains on the type of substrate as well as they are very invasive if used in marine protected areas or over seabeds covered with Posidonia or any other type of living organisms. These robots may leave deep marks on the ground and damage benthic flora and fauna. Underwater legged robots are a promising alternative to traverse over uneven benthic terrain creating minimum disturbance to the natural state of the sediment. In this approach, benthic animals that perform pedestrian locomotion can serve as a benchmark to direct the development of bio-inspired benthic robotics technology with enhanced capabilities.

In this work, marine-living crab, *Pachygrapsus marmoratus* was taken as the model animal for bioinspiration. We detected both active and passive phases of terrestrial running and underwater running (punting) through the observation of crab locomotory behavior in standardized settings and by three-dimensional kinematic analysis of its dynamic gait using high-speed video cameras. Variations in different stride parameters were studied and compared. The comparison was done based on the dimensionless parameter, the Froude number (Fr) to account for the effect of buoyancy and size variability among the crabs. The template called Underwater Spring-Loaded Inverted Pendulum (USLIP) model fitted the dynamics of aquatic punting. USLIP takes account of the damping effect of the aquatic environment, a variable not considered by the spring-loaded inverted pendulum (SLIP) model in reduced gravity; a model that was reported in the literature to predict punting locomotion. Our results highlight the underlying principles of underwater legged locomotion by comparing it with terrestrial locomotion. Comparing punting with running, we show an increased stride period, decreased duty cycle, and orientation of the carapace was more

inclined to the ground, indicating the significance of fluid forces on the dynamics due to the aquatic environment. Moreover, we discovered periodicity in punting locomotion of crabs and two different gaits, namely, long-flight punting and short-flight punting, distinguished by both footfall patterns and kinematic parameters. The gaits were studied in detail by tracking the footfall pattern, leg joint angles, and orientation of the carapace. The study of crab locomotion laid a foundation for the design and development of a novel breed of benthic machine.

Inspired by the underwater legged locomotion of crabs, we developed *Seabed Interaction Legged Vehicle for Exploration and Research v.2* (SILVER 2.0), a hexapod robot with segmented legs. SILVER 2.0 features an inertial navigation system, contact sensors, a pressure sensor, and two cameras. The segmented leg consists of serial elastic actuators in the knee joints to provide compliance similar to the muscle and connective tissue in animals. The design of the robot was anchored on USLIP dynamics. The robot was capable of forward hopping, rotating, and omnidirectional walking. The compliant elements on the legs enabled the robot to transverse uneven terrain.

Based on the leg kinematics of the *Pachygrapsus marmoratus*, crab-inspired gait was implemented in SILVER 2.0. The gait mimicked the footfall pattern and the foot trajectories of the punting crab. The foot trajectories of the crabs were parameterized and scaled to the size of SILVER 2.0. With the crab-inspired gait, the robot was able to reach a mean velocity of 0.16 m/s with a Cost of Transport (CoT) of 2.9. The crab gait produced USLIP dynamics in the robot, which validated our hypothesis that underwater punting gaits in animals followed USLIP dynamics.

Detailed analysis on the passive station keeping performance of SILVER 2.0 was also performed by studying the effects of leg configuration, net weight, and the nature of the substrate. The performance increased with an increase in width of the leg position, a decrease in height of the Center of Mass (CoM), and an increase in the friction coefficient between the robot's foot and the substrate. A numerical model was developed to study the effect of geometrical and physical parameters on the station keeping performance. Comparing with the experimental results, the model accurately predicted the station-keeping behaviour of the robot. Eventually, we showed that underwater legged robots have higher station keeping efficiency than commercial propeller-based ROVs. The locomotion and station keeping capabilities of the robot were tested and validated by a series of field experiments.

The robot also holds the space to host additional modules for various operations like manipulation, sediment sampling, etc. A sediment sampling mechanism was designed, fabricated, and tested. The module consisted of an underactuated mechanism, coupling four-bar arm mechanism and a grab mechanism. The underactuation allowed the arm to extend towards the sediment, collect the sediment, retract, extent towards a collecting box, and deposit with a single actuator. The module successfully collected sediments of various sizes and compositions. The sediments collected were analysed to study the presence of microplastics. Moreover, the camera system in SILVER 2.0 enabled the visual monitoring of marine species.

The bioinspired underwater legged robot integrated well into the marine environment with its locomotion and station keeping capabilities extracted from its biological counterparts.

SILVER 2.0 served as a promising tool for marine research and ocean conservation.