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Editorial

Special Feature on Bio-Inspired Robotics

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1. Introduction

Modern robotic technologies have enabled robots to operate in a variety of unstructured and dynamically-changing environments, in addition to traditional structured environments. Robots have, thus, become an important element in our everyday lives. One key approach to develop such intelligent and autonomous robots is to draw inspiration from biological systems. Biological structure, mechanisms, and underlying principles have the potential to feed new ideas to support the improvement of conventional robotic designs and control. Such biological principles usually originate from animal or even plant models for robots, which can sense, think, walk, swim, crawl, jump or even fly. Thus, it is believed that these bio-inspired methods are becoming increasingly important in the face of complex applications. Bio-inspired robotics is leading to the study of innovative structures and computing with sensory-motor coordination and learning to achieve intelligence, flexibility, stability, and adaptation for emergent robotic applications, such as manipulation, learning, and control.

This Special Issue invites original papers of innovative ideas and concepts, new discoveries and improvements, and novel applications and business models relevant to the selected topics of "Bio-Inspired Robotics". Bio-Inspired Robotics is a broad topic and an ongoing expanding field. This Special Issue collects 30 papers that address some of the important challenges and opportunities in the broad and expanding field. We group these papers as follows.

2. Legged and Mobile Robots

Developing legged moving robots or wheeled mobile robots inspired by animals or human beings is one of the major research direction in bio-inspired robotics. This section collects papers in this domain by grouping the papers as follows: biped robots, quadruped robots, multi-legged robots and wheeled robots.

2.1. Biped Robots

Yang et al. perform a review summarizing the chronological historical development of bipedal robots and introducing some current popular bipedal robots. The basic theory-stability control and key technology-motion planning of bipedal robots are introduced and analyzed [1]. Hu and Mombaur present an optimal control-based approach for the humanoid robot iCub that allows to generate optimized walking motions using a precise whole-body dynamic model of the robot. The optimal control problem is formulated to minimize a set of desired objective functions with respect to physical constraints of the robot and contact constraints of the walking phases [2]. Jiang et al. propose a jumping control scheme for a bipedal robot to perform a high jump taking into account the motion during the launching phase. The half-body of the robot is modeled as three planar links. A geometrically simple motion is conducted through which the gear reduction ratio that matches the maximum motor output for high jumping is selected, followed by the strategies to further exploit the motor output performance via criteria including the location of ZMP (zero moment point) and the torque limit [3]. Zang et al. introduce a novel foot system with passively adjustable stiffness for biped robots which is adaptable to small-sized bumps on the ground. The robotic foot is attached by eight pneumatic variable stiffness units. Each variable stiffness unit mainly consists of a pneumatic bladder and a mechanical reversing valve. When walking on rough ground, the pneumatic bladders in contact with bumps are compressed, and the corresponding reversing valves are triggered to expel out the air, enabling the pneumatic bladders to adapt to the bumps with low stiffness, while the other pneumatic bladders remain rigid and maintain stable contact with the ground, providing support to the biped robot [4]. Gerardo Muscolo et al. present a novel method to determine the center of mass position of each link for human-like multibody biped robots. They optimize the formulation to determine the total center of mass position tested in other works on a biped platform with human-like dimensions. This formulation is able to give as output the center of mass positions of each link of the platform [5]. Liu et al. describe a hybrid control approach aiming to integrate the main characteristics of human walking into a simulated seven-link biped robot. Three bipedal gaits are considered, including a fully actuated single support phase with the stance heel supporting the body, an under-actuated single support phase, with the stance toe supporting the body, and an instantaneous double support phase when the two legs exchange their roles. The walking controller combines virtual force control and foot placement control, which are applied to the stance leg and the swing leg, respectively [6]. Otani et al. propose a stabilizing control method for humanoids during the stance phase while hopping and running by considering swinging the legs rapidly during the flight phase to prevent rotation in the yaw direction. They develop an angular momentum control method based on human motion for a humanoid upper body. The method involves calculation of the angular momentum generated by the movement of the humanoid legs and calculation of the torso and arm motions required to compensate for the angular momentum of the legs in the yaw direction. They also develop a humanoid upper-body mechanism having human link length and mass properties, using carbon-fiber-reinforced plastic and a symmetric structure for generating large angular momentum [7].

2.2. Quadruped Robots

In order to effectively plan the robot gaits and foot workspace trajectory (WT) synchronously, Zeng et al. present a novel biologically inspired control strategy for the locomotion of a quadruped robot based on central pattern generator—neural network—workspace trajectory (CPG-NN-WT). A neural network is designed and trained to convert the CPG output to the preplanned WT, which can make full use of the advantages of the CPG-based method in gait planning and the WT-based method in foot trajectory planning simultaneously [8]. Ba et al. propose a position-based impedance control method for the hydraulic drive unit on the joints of bionic legged robots. They propose a first-order sensitivity matrix to analyze the dynamic sensitivity of four main control parameters under four working conditions. Two sensitivity indexes are defined and verified by experiments to study the parameter sensitivity quantificationally [9].

2.3. Multi-Legged Robots

To find a common approach for the development of an efficient system that is able to achieve an omnidirectional jump, Zhu et al. present a jumping kinematic of a legged robot based on the behavior mechanism of a jumping spider. To satisfy the diversity of motion forms in robot jumping, a kind of 4 degrees of freedom (DOF) mechanical leg is designed. Taking the change of joint angle as inspiration by observing the behavior of the jumping spider during the acceleration phase, a redundant constraint to solve the kinematic is obtained. A series of experiments on three types of jumping—vertical jumping, sideways jumping and forward jumping—is carried out, while the initial attitude and path planning of the robot is studied [10]. To better understand how animals control locomotion, Rubeo et al. model animals and their nervous systems with dynamical simulations, namely synthetic nervous systems (SNS). In order to pick up the parameter values that produce the intended dynamics, they introduce a design process that solves this problem without the need for global optimization, by test this method on SimRoach2, a dynamical model of a cockroach. Each leg joint of SimRoach2 is actuated by an antagonistic pair of Hill muscles. A distributed SNS is designed based on pathways known to exist in insects, as well as hypothetical pathways that produced insect-like motion. Each joint's controller is designed to function as a proportional-integral (PI) feedback loop and tuned with numerical optimization [11].

2.4. Wheeled Robots

Villaseñor et al. use a Germinal Center Optimization algorithm (GCO) which implements temporal leadership through modeling a non-uniform competitive-based distribution for particle selection. GCO is used to find an optimal set of parameters for a neural inverse optimal control applied to all-terrain tracked robot. In the Neural Inverse Optimal Control scheme, a neural identifier, based on Recurrent High Orden Neural Network trained with an extended kalman filter algorithm, is used to obtain a model of the system, then, a control law is designed using such model with the inverse optimal control approach [12]. Wang et al. address trajectory tracking of an omni-directional mobile robot (OMR) with three mecanum wheels and a fully symmetrical configuration. The omni-directional wheeled robot outperforms the non-holonomic wheeled robot due to its ability to rotate and translate independently and simultaneously. A kinematics model of the OMR is established and a model predictive control algorithm with control and system constraints is designed to achieve point stabilization and trajectory tracking [13].

3. Animal and Plant Inspired Robots

This section introduce the collect papers on developing animal and plant robots, including monkey, snake, fish, flying and plant robot.

3.1. Monkey Inspired Robots

Zhu et al. study member-to-member transition and its utility in global path searching for biped climbing robots. To compute operational regions for transition, hierarchical inspection of safety, reachability, and accessibility of grips is taken into account. A novel global path rapid determination approach is subsequently proposed based on the transition analysis. This scheme is efficient for finding feasible routes with respect to the overall structural environment, which also benefits the subsequent grip and motion planning [14]. Lo et al. report a model-based development of a monkey robot that can perform continuous brachiation locomotion on swingable rod, as the intermediate step toward studying brachiation on the soft rope or on horizontal ropes with both ends fixed. The model, which is composed of two rigid links, is inspired by the dynamic motion of primates. The model further serves as the design guideline for a robot that has 5 DOF: two on each arm for rod changing and one on the waist to initiate a swing motion [15].

3.2. Snake Inspired Robots

In nature, snakes can gracefully traverse a wide range of different and complex environments. Snake robots that can mimic this behaviour could be fitted with sensors and transport tools to hazardous or confined areas that other robots and humans are unable to access. In order to carry out such tasks, snake robots must have a high degree of awareness of their surroundings (i.e., perception-driven locomotion) and be capable of efficient obstacle exploitation (i.e., obstacle-aided locomotion) to gain propulsion. Sanfilippo et al. survey and discuss the state-of-the-art, challenges, and possibilities of perception-driven obstacle-aided locomotion for snake robots. To this end, different levels of autonomy are identified for snake robots and categorised into environmental complexity, mission complexity, and external system independence. From this perspective, they present a step-wise approach on how to increment snake robot abilities within guidance, navigation, and control in order to target the different levels of autonomy. They put obstacle-aided locomotion into the context of perception and mapping. Finally, they present an overview of relevant key technologies and methods within environment perception, mapping, and representation that constitute important aspects of perception-driven obstacle-aided locomotion [16]. Kelasidi et al. take into account both the minimization of the power consumption and the maximization of the achieved forward velocity in order to investigate the optimal gait parameters for bio-inspired snake robots using lateral undulation and eel-like motion patterns. They consider possible negative work effects in the calculation of average power consumption of underwater snake robots. To solve the multi-objective optimization problem, they propose transforming the two objective functions into a single one using a weighted-sum method. In this way, they are able to obtain some observations about the optimal values of the gait parameters, which provide very important insights for future control design of bio-inspired snake robots [17]. Wang et al. develop a novel snake-like robot which can perform common gaits to adapt to different environments. A multi-gait is established and used as a reference for the articulation design. A non-snake-like mechanism with linear articulation is combined with the classical swing joint. A prototype is designed and constructed for verification and analysis. Two basic main gaits, namely, serpentine and rectilinear locomotion, are fused, and a novel obstacle-aided locomotion based on rectilinear motion is developed [18].

3.3. Fish Inspired Robots

In order to efficiently harness tidal flow energy in a cost-efficient manner, development of a mechanism that is inherently resistant to these harsh conditions is required. Yamamoto et al. develop a simple oscillatory-type mechanism based on robotic fish tail fin technology. This uses the physical phenomenon of vortex-induced oscillation, in which water currents flowing around an object induce transverse motion. They consider two specific types of oscillators, firstly a wing-type oscillator, in which the optimal elastic modulus is being sort, and secondly, the optimal selection of shape from 6 basic shapes for a reciprocating oscillating head-type oscillator. Analysis of the flow field clearly showed that the discontinuous flow caused by a square-headed oscillator results in higher lift coefficients due to intense vortex shedding, and that stable operation can be achieved by selecting the optimum length to width ratio [19]. Koca et al. develop a complete non-linear dynamic model comprising entirely kinematic and hydrodynamic effects of Carangiform locomotion based on the Lagrange approach by adapting the parameters and behaviors of a real carp. In order to imitate biological features, swimming patterns of a real carp for forward, turning and up-down motions are analyzed by using the Kineova 8.20 software. The proportional optimum link lengths according to actual size, swimming speed, flapping frequency, proportional physical parameters and different swimming motions of the real carp are investigated with the designed robotic fish model. Three-dimensional locomotion is evaluated by tracking two trajectories in a MATLAB environment. A Reaching Law Control approach for inner loop (Euler angles-speed control) and a guidance system for the outer loop (orientation control) are proposed to provide an effective closed-loop control performance [20]. Xing et al. present a novel, multiply gaited, vectored water-jet, hybrid locomotion-capable, amphibious spherical robot III (termed ASR-III) featuring a wheel-legged, water-jet composite driving system incorporating a lifting and supporting wheel mechanism (LSWM) and mechanical legs with a water-jet thruster. The LSWM allows ASR-III to support the body and slide flexibly on smooth (flat) terrain. The composite driving system facilitates two on-land locomotion modes (sliding and walking) and underwater locomotion mode with vectored thrusters, improving adaptability to the amphibious environment [21]. Gu and Guo present a novel propulsion system for the third-generation Spherical Underwater Robot (SURIII), the improved propulsion system is designed and analyzed to verify its increased stability compared to the second-generation Spherical Underwater Robot (SURII). With the new propulsion system, the robot is not only symmetric on the

X axis but also on the Y axis, which increases the flexibility of its movement. The new arrangement also reduces the space constraints of servomotors and vectored water-jet thrusters. The experimental results demonstrate the propulsive force is better than a previous version [22].

3.4. Plant Inspired Robots

Del Dottore et al. present a plant root behavior-based approach to define the control architecture of a plant-root-inspired robot, which is composed of three root-agents for nutrient uptake and one shoot-agent for nutrient redistribution. By taking inspiration and extracting key principles from the uptake of nutrient, movements and communication strategies adopted by plant roots, they develop an uptake–kinetics feedback control for the robotic roots. Exploiting the proposed control, each root is able to regulate the growth direction, towards the nutrients that are most needed, and to adjust nutrient uptake, by decreasing the absorption rate of the most plentiful one [23].

3.5. Flying Robots

This Special Issue also collects one paper for UAV robot, although it is for data processing not for flying robots design. This work aims at the reconnaissance task by a UAV to survey an area and retrieve strategic information. Cisneros et al. present a data-foraging-oriented reconnaissance algorithm based on bio-inspired indirect communication. The approach establishes several paths that overlap to identify valuable data sources. Inspired by the stigmergy principle, the aerial vehicles indirectly communicate through artificial pheromones. The aerial vehicles traverse the environment using a heuristic algorithm that uses the artificial pheromones as feedback [24].

4. Bio-Inspired Robotic Components

Three papers in this section present some interesting work on the design of robotic parts or components which are inspired by living animals or human beings.

Fuller and Schultz present the modeling, characterization and validation for a discrete muscle-like actuator system composed of individual on–off motor units with complex dynamics inherent to the architecture. The dynamics include innate hardening behavior in the actuator with increased length. A series elastic actuator model is used as the plant model for an observer used in feedback control of the actuator [25]. Wang et al. present the design of a legged robot with gecko-mimicking mechanism and mushroom-shaped adhesive microstructure (MSAMS) that can climb surfaces under reduced gravity. The design principle, adhesion performance and roles of different toes of footpad are explored and discussed in this paper. The effect of the preload velocity, peeling velocity and thickness of backing layering on the reliability of the robot are investigated. Results show that pull-force is independent of preload velocity, while the peeling force is relying on peeling velocity, and the peel strength increased with the increasing thickness of the backing layer [26]. Aiming at the inspection of rough stone and concrete wall surfaces, Jiang and Xu design a grasping module of cross-arranged claw which can attach onto rough wall surfaces by hooking or grasping walls. Based on the interaction mechanism of hooks and rough wall surfaces, the hook structures in claw tips are developed. Then, the size of the hook tip is calculated and the failure mode is analyzed. The effectiveness and reliability of the mechanism are verified through simulation and finite element analysis. Afterwards, the prototype of the grasping module of claw is established to carry out grasping experiment on vibrating walls. The experimental results demonstrate that the proposed cross-arranged claw is able to stably grasp static wall surfaces and perform well in grasping vibrating walls, with certain anti-rollover capability [27].

5. Bio-inspired Medical and Rehabilitation Robotic Technology

The rest papers collected by the Special Issue are summarized here for medical and rehabilitation application.

Jiang et al. propose a robot inverse kinematics solver based on a particle swarm optimization (PSO) back propagation (BP) neural network algorithm to solve the inverse kinematics problem of a 6 DOF UR3 robot, overcoming some disadvantages of BP neural networks. The back propagation neural network improves the convergence precision, convergence speed, and generalization ability. The results show that the position error is solved by the research method with respect to the UR3 robot inverse kinematics with the joint angle less than 0.1 degrees and the output end tool less than 0.1 mm, achieving the required positioning for medical puncture surgery, which demands precise positioning of the robot to less than 1 mm [28]. Human locomotion is a synergetic process of the musculoskeletal system characterized by smoothness, high nonlinearity, and quasi-periodicity. Duan et al. use previous and current inertial measurement unit readings to predict human locomotion based on their kinematic properties. Takens' reconstruction method is used to characterize quasi-periodicity and nonlinear systems. With Takens' reconstruction framework, they develop following methods, including Gaussian coefficient weighting and offset correction which is based on the smoothness of human locomotion, Kalman fusion with complementary joint data prediction and united source of historical embedding generation which is synergy-inspired, and Kalman fusion with the Newton-based method with a velocity and acceleration high-gain observer also based on smoothness [29]. Jiang et al. present a hardware-based method that utilizes a shielded drive circuit to eliminate extraneous interferences on biopotential signal recordings, while also preserving all useful components of the target signal. The performance of the proposed method is evaluated by comparing the results with conventional hardware and software filtering methods in different biopotential signal recording experiments [30].

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