

Bio-control of a Modular Design Robot—NOROS

Fan Yang, Xilun Ding and Saijin Peng

Abstract The modular walking machine NOROS is a bio-inspired robot designed to serve as a robotic system usable for Moon or Mars soil exploration. It consists of up to eight autonomous leg modules, each equipped with various sensors. The individual leg is controlled by a behavior-based system, which performs well walking behaviors and reflexes immediately to the local terrain. The individual leg control system is coordinated by an additional planning system, which allows the robot to anticipate changes in its gait according to the terrain condition and avoiding extreme situations. The proposed system in this paper is also verified in a co-simulation environment.

Keywords Modular design · Hexapod robot · Biomimetic control

1 Introduction

Nowadays, autonomous exploration missions, such as planetary or volcanic exploration or various missions in hazardous areas or construction sites, require the robot having high locomotion performance in terms of power consumption, traversability and reliability, etc. Modular robots, which is defined as a robotic system constructed from a set of standardized components (or building blocks), attracted more interests these years [1], because they permit the construction of a wide variety specialized robots from the set of standard components. By using this concept, Tests can be easily performed with single leg modules and multiple other machine configurations.

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Even the broken legs can be immediately replaced during the exploration, the robot performs more robust and reliable to the extreme working conditions [2].

When take the control of the multi-legged robot into consideration, the previous solution is to allow operators to remotely place each leg [3]. Other solutions utilize full pre-planning based knowledge [4]. However, the legged robots controlled by these methods move slowly on the rough terrain. Inspired from the fact that even small insects manifest impressive capabilities for dealing with rough terrain, many researches have been devoted to the bio-based control of walking robot. Rodney Brooks' propose a subsumption architecture [5] to control the robot, which regards the control system as different levels of competence. Then a well-known locomotion approach "Walknet", which uses only reflex systems is introduced by Cruse [6]. It is based on the assumption that only local sensory feedback at the legs and a coupling between the control of neighbored legs is sufficient for stable walking. A more recent development is that of reconfigurable robots [7] where either the user makes the system more versatile and robust to failure of individual modules. Behavior based control methods [8], which is also known as finite state controllers are proved to be effective for dealing with the dynamic environments.

In our previous work, we have built a control system that senses and models the terrain, plans a coordinated sequence of actions, and decomposes these actions into servo position commands [9]. This approach has proved to be too slow and complex to keep up with the pace of the environment. Here we implement the behavior-based control methods to each robot leg, and integrate the planning methods to coordinate individual legs motion. The control system can perform various gaits and robust to the number of legs to control. The rest of paper is organized as follows. Section 2 introduces the modular design of the hardware of NOROS robot. The control architecture is described in Sect. 3. Simulations are performed in Sect. 4 and conclusions are drawn in Sect. 5.

2 Hardware Architecture of NOROS Robot

The hardware design of NOROS robot is roughly inspired by the fact that the legs of insects are modular designed and the control system is decentralized. The robot may consist of up to eight isomorphic leg modules, resulting in 4-, 6- and 8-legged machines (Fig. 1). Each leg is mechanically and electronically connected to the body via a bonding mechanism, which allows simply and quickly plugging legs to differently shaped bodies, even during operation and without reset.

2.1 Mechanics

NOROS is a robust multi-legged robots, its skeleton is made of aluminum alloy. Each leg module is fully autonomous, containing servo motors, sensors, and control

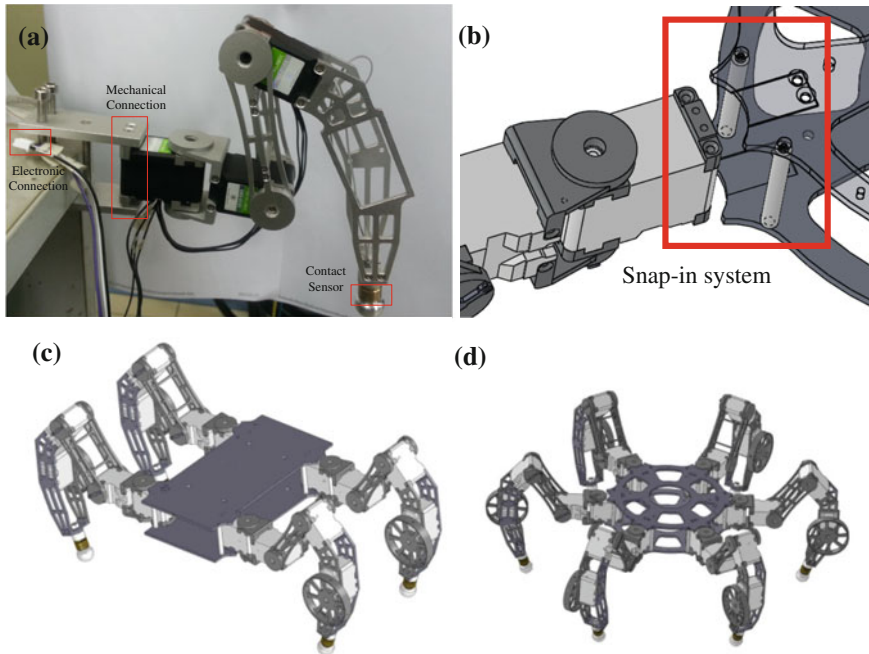


Fig. 1 **a** Prototype of individual leg. **b** Mechanical connector (snap in system). **c** Modular walking robots with 4 legs. **d** Modular walking robots with 6 legs

electronics, furthermore it can be easily replaced by a snap-in system construction (Fig. 1b). Based on the bio-observation that the degrees of freedom of each leg of an insect are decoupled, the leg of NOROS is built up of four segments connected by three active joint with one degree of freedom (DOF) and one passive joint with one DOF instead of using the common approach of a pantograph or frame design, The active joints are driven by professional servo motors (Herkulex DRS-0101), which provides not only position and torque sensory feedbacks but also an active stiffness control. The passive joint is equipped with a spring and a force sensor, which can detect the contact of the leg to the ground. Passive and active compliance are used incorporate to conform to irregular surfaces. The robot is reconfigurable, which is determined by the respective torso connected (Fig. 1c, d).

2.2 Electronics

Each leg module is controlled by a small pluggable circuit board (shown as Fig. 2a), which is connected to sensors, servo motors and global bus. Its central device, an 8-bit Microcontroller with 256K Bytes, is responsible for controlling individual leg

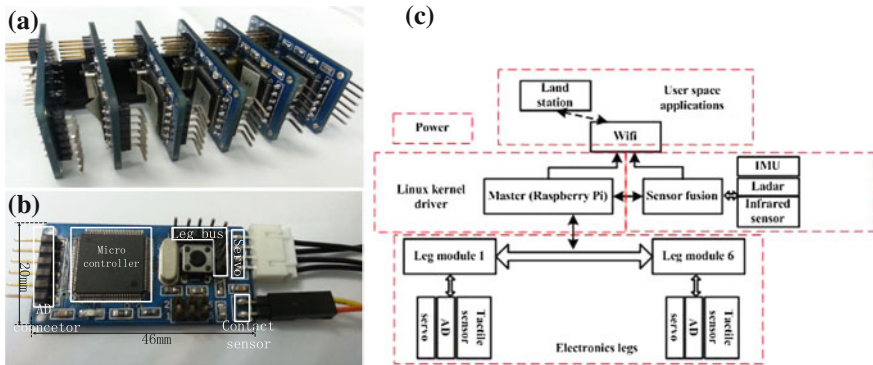


Fig. 2 a Pluggable circuit board as used in each leg module. b Assembling of individual leg control module. c Overview of the control architecture

to perform basic behaviors, such as swinging and supporting legs behavior. Every leg possesses three digital servomotors, which is connected to the circuit board via a control bus. By using Multi Drop TTL Full Duplex UART Serial communications protocol with maximum speed of 0.667 Mbps, single command can set the speed, position, LED, operational compliance, stop and operational status of up to 254 servos simultaneously at once. A sensor that reliably detects the ground contacts is connected the processor via an extern interrupted pin, three axis's contact forces are measured by the force sensors through the AD connectors. The leg control modules can be electronically and mechanically assembled together conveniently by a plug-in system construction (Fig. 2b). A global bus (leg bus IIC) is used for communication between all leg modules, which provides the robot with the competence of wandering aimlessly around with hitting things.

An overview of the processor connectivity to other component on and outside of the circuit board is shown as Fig. 2c. Optionally extra sensor boards and an on-board PC (Raspberry Pi), which is used for planning anticipating productive actions, may take part in the leg bus communication. The terrain information could be sensed by fusion of IMU, Ladar and infrared sensor data. These data is used for the navigation and gait generation. The robot could also be teleported by a remote controller through the wireless connection.

The system is modular designed and organized according to the principle of increasing precision of control in the lower layers with decreasing intelligence. One advantage of the modular design is that the system could be extended without completely rebuilding the physical control system. The processors can be upgraded to an architecturally compatible but faster system, such as the Raspberry Pi can be upgraded to a single board computer without any other changes. The control system is also compatible with different legs numbers to control.

3 Bionic Control Methods

According to our experience with previous walking hexapod robots [10], the deliberative control methods, which is known as the robot uses all of the sensory information, and all of the internally stored knowledge, to reason about what actions to take next, is a computationally complex process. This method is insufficient for guiding a walking robot in a noisy, dynamic world, where the time for generating a plan is limited and the change is unpredictable. Inspired by the biological notion of stimulus–response, reactive control method is proved to be suited to dynamic and unstructured worlds. It does not rely on the types of complex reasoning processes or the precise sensed model utilized in deliberative control. Rather, rule-based methods and no internal representations or knowledge of the world are typically used. The reactive control method directly relates the sensation and the action, it is powerful in respond to rapidly changing environments. However, limitations to pure reactivity include the inability to store information or have memory or internal representations of the world, and therefore the inability to learn and improve over time. To fully combine the best aspects of reactive and deliberative control method, our approach, like other hybrid planning/reacting architectures [11], seeks to utilize the advantage of planning for anticipating productive actions, and on reacting for quickly accommodating disturbances in the desired goal state. Here the individual leg is controlled by the behavior-based method, and the gaits are generated in a deliberative way.

3.1 Behavior-Based Control of Individual Leg

According to the bio-research, the movement of an individual leg can be modeled as controlled by a “leg-movement pattern generator”. The cyclic movement of a walking leg consists of two parts, the power stroke (also stance phase or support phase) and the return stroke (also swing phase or recovery phase). During the power stroke, the leg is on the ground where it can support and propel the body. During the return stroke, the leg is lifted off the ground and swung to the starting position for the next power stroke. With respect to the temporal pattern of stepping, the critical question is how the pattern generator decides whether or not the transition from one mode (power or return stroke) to the other should be made. Experimental results have shown that for insects, three parameters influence this transition position, load, and phase in the step cycle of the other leg. The relay characteristic produces the two alternative target positions AEP and PEP (anterior and posterior extreme positions).

Here, the behavior-based control methods, which directly map the sensed state of the world into actions, are adopted to control individual leg. The control schematic of the individual leg is illustrated in Fig. 3. Each box is a module which implements a specific behavior, and all these behaviors interact through suppressor

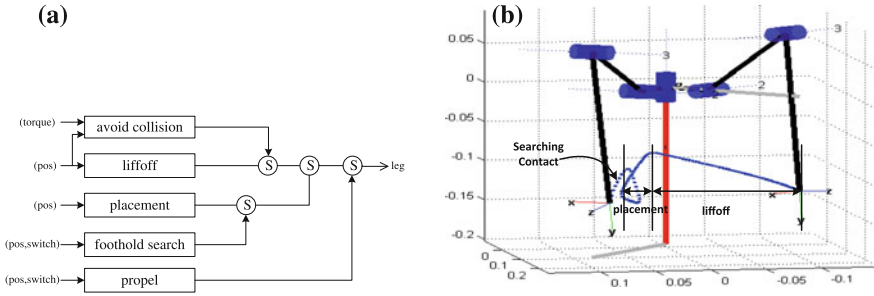


Fig. 3 a Behavior based individual leg control module. b The trace of a simulated leg motion

nodes, the function of the suppressor node is that a signal coming into the side of a node can override the signal passing through the node.

The liffoff behavior is triggered when the foot tip is close to the PEP and it causes the robot lift its legs. At the same time, the collision avoiding behavior also monitors the torques in the motor, when the torques gets above a set thresholds, it takes control of the leg and reduce the force to a reasonable level. These processes drop out when the leg-tip reaches its extreme up position. Then the leg is controlled by the placement behavior which forces the leg to land towards its AEP.

If the leg-tip exceeds its AEP and the contact has not been examined, the foothold search behavior will be triggered, the detail of this behavior will be introduced in the next paragraph. After an appropriate foothold is founded, the propel behavior takes over the leg and makes the leg propel the body. All these behaviors form the local control system, in which smaller local problems like midsize obstacles can be solved locally. The system described above has been simulated and worked well in the MATLAB, a trace of an simulated run is shown in Fig. 3b, which can prove the effectiveness of the system.

The searching behaviors are revealed in most insects, which is a crucial ability of travelling through the extreme environments, such as walking on a forest floor or climbing in a bush. The searching movement occurs after loss of ground contact. We implement this searching behavior in our robot, which imitates the kinematic sequence of leg searching movements of the stick insect *Carausius morosus* [12]. The searching behaviors begin when the preceding step continued through the fictive anterior extreme position (AEP), i.e. the location where ground contact would have occurred during normal walking. The robot searches for an acceptable foothold by moving the legs inward in circles of increasing radius for 2–4 conspicuous loops, if no appropriate foothold has been found, a home behavior will be triggered and the robot attempts to bring the foot-tip back to the special parking location. With this local behavior, the robot behaves more robustly on the rough terrain.

3.2 Integrating Planning with Individual Leg

Walking robots need fast reaction to survive bumps and slips, but also foresight and planning to be productive and efficient in an unstructured environment [13]. The hybrid control system takes the advantages of various control structure types thereby integrating them in a way that results in an overall increase in synergy. Our hexapod’s control system applies hybrid approaches which takes the terrain model into consideration and adjusts the gait and the posture of the robot simultaneously during the walk (Fig. 4).

The walking movement is created by the coordination of each individual leg’s behavior, which also performs as the gait. A gait is a cyclic motion pattern that produces locomotion through a sequence of foot contacts with the ground. The legs provide support for the robot while the forces resulting from ground contact propel the body forward. Proprioceptive information is used to generate timing signals to coordinate the preprogrammed leg motions. The timing signals take the form of excitatory and inhibitory messages which are biologically motivated. The robot developed can walk in the tripod, tetrapod, and free gait. The free gait is generated following Cruse’s leg coordination rules [14], where the coordination of several legs requires coupling between the step cycles of adjacent legs, optimizing synergistic propulsion, but ensuring stability through flexible adjustment to external disturbances.

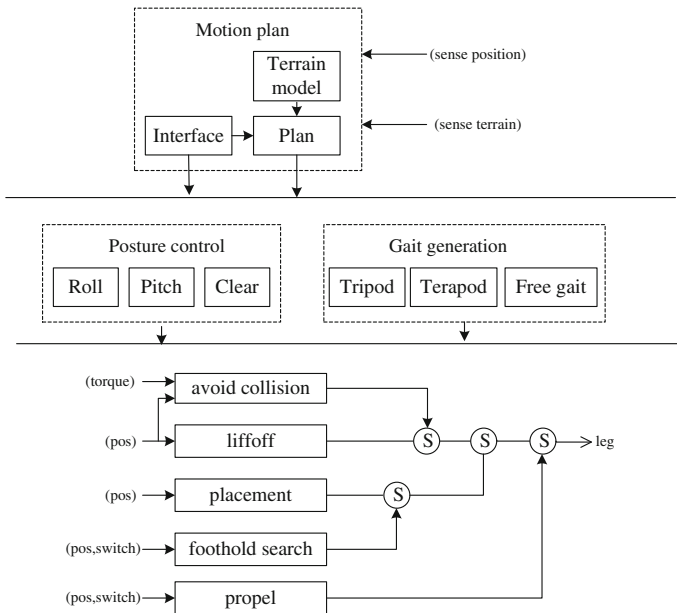


Fig. 4 The individual leg controls system are coordinated by the motion plan system

The three gaits differ not only in their capability but also in their computational complexity. The tripod and tetrapod gaits are coordinated in a fixed pattern, in which leg groups move in conjunction. These gaits are suitable for moderate terrain and require little computational power. The free gait is based on a biologically inspired variable coordination and more complex. This gait allows coping with more challenging terrain and is even able to handle leg loss. Thus a motion plan module is introduced, which senses and models the terrain around the robot. By extracting these terrain features, we can avoid too rough terrain and decide which gaits to adopt.

4 Simulations and Experiments

In order to verify the control methods proposed in this paper, a MATLAB and ADAMS co-simulation environment is utilized, which has been widely adopted and proved effective for the simulation of the real robot. Developed by MDI Company, ADAMS as software provides powerful model and simulation environment and has strong analysis function about kinematics and dynamics, which is popular in mechanical project fields in the world. Though ADAMS is a powerful software for modeling and simulation, however, it has some disadvantages with respect to the motion planning and controller-design. So the MATLAB/Simulink package is used to make the controller design. During the simulation, ADAMS gains joint angles from motion controller, which is designed in MATLAB and then the robot performs the designed motions in ADAMS.

A computer-generated terrain that includes small hills and ditches is utilized to emulate the outdoor environment. The simulation results is shown as Fig. 5, the robot adopts the fixed tripod gait and follows the planned path, motion profiles for the feet are shown in green and the trajectories of the center of the body are displayed in red. It is noticeable that the leg controlled by the behavior based

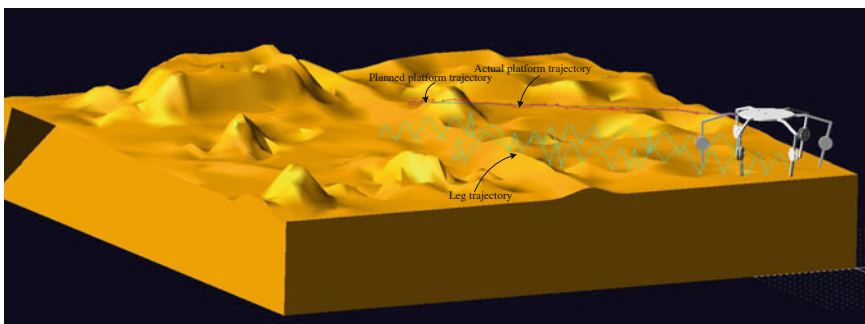


Fig. 5 Simulation results of the bio-based control system (Color figure online)

module performs well with the local terrain, the robot can walk fast in a certain rough terrain without the footholds calculation. The simulation results evidently prove the effectiveness of the control system proposed in this paper.

5 Conclusions

This paper introduces the modular design of the mechanical and electronic parts of the NOROS robot. By using the mechanical connector (plug-in system) and the pluggable electronic circuit board proposed in this paper, the robot can easily form different configurations, even the broken legs can be replaced immediately. The control system proposed in this paper adopts behavior based control module for each leg, which proves to speed up response time and improve the terrain adaptability. We have added the plan module to extend the applicability of behavior based control. The robot can perform various gaits according to the terrain condition.

The control architecture is now validated in a simulation environment as the prototype of the robot is under development. Consequently, we believe that the performance of the hexapod robot walking in real terrain, switching gaits are the main work we want to improve in the future.

References

1. Will, P.M., Castaño, A., Shen, W.-M.: Robot modularity for self-reconfiguration. In: *Photonics East'99*, pp. 236–245 (1999)
2. Von Twickel, A., Hild, M., Siedel, T., Patel, V., Pasemann, F.: Neural control of a modular multi-legged walking machine: simulation and hardware. *Robot. Auton. Syst.* **60**, 227–241 (2012)
3. Song, S.-M., Waldron, K.J.: *Machines that walk: the adaptive suspension vehicle*. MIT press, Cambridge (1989)
4. Siciliano, B., Sciavicco, L., Villani, L., Oriolo, G.: *Robotics: modelling, planning and control*. Springer Science and Business Media, Berlin (2009)
5. Brooks, R.A.: A robust layered control system for a mobile robot. *IEEE J. Robot. Autom.* **2**, 14–23 (1986)
6. Cruse, H., Kindermann, T., Schumm, M., Dean, J., Schmitz, J.: Walknet—A biologically inspired network to control six-legged walking. *Neural Netw.* **11**, 1435–1447 (1998)
7. Yim, M., Shen, W.-M., Salemi, B., Rus, D., Moll, M., Lipson, H., et al.: Modular self-reconfigurable robot systems [grand challenges of robotics]. *IEEE Robot. Autom. Mag.* **14**, 43–52 (2007)
8. Klaassen, B., Linnemann, R., Spennberg, D., Kirchner, F.: Biomimetic walking robot SCORPION: Control and modeling. *Robot. Auton. Syst.* **41**, 69–76 (2002)
9. Wang, Z., Ding, X., Rovetta, A., Giusti, A.: Mobility analysis of the typical gait of a radial symmetrical six-legged robot. *Mechatronics* **21**, 1133–1146 (2011)
10. Xu, K., Ding, X.: Gait analysis of a radial symmetrical hexapod robot based on parallel mechanisms. *Chin. J. Mech. Eng.* **27**, 867–879 (2014)

11. Wettergreen, D., Pangels, H., Bares, J.: Behavior-based gait execution for the Dante II walking robot. In: Proceedings. 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems 95. Human Robot Interaction and Cooperative Robots, pp. 274–279 (1995)
12. Durr, V.: Stereotypic leg searching movements in the stick insect: kinematic analysis, behavioural context and simulation. *J. Exp. Biol.* **204**, 1589–1604 (2001)
13. Wettergreen, D., Thorpe, C.: Developing planning and reactive control for a hexapod robot. In: Proceedings of 1996 IEEE International Conference on Robotics and Automation, 1996, pp. 2718–2723 (1996)
14. Dürr, V., Schmitz, J., Cruse, H.: Behaviour-based modelling of hexapod locomotion: linking biology and technical application. *Arthropod Struct Dev* **33**, 237–250 (2004)