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Distributed Sensor-Driven Control for Bio-Inspired Walking and Ball Rolling of a Dung Beetle-Like Robot

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Abstract: Bio-inspired robotics is an approach that looks at how nature solves a (complex) problem and applies the solution to a robot. Based on this approach, we have looked at walking animals that can exploit their legs for multiple functions, like locomotion and object manipulation/transportation. This is to expand the ability of walking robots. According to this, we have developed our robotic model based on a dung beetle, an animal that can walk and roll a dung ball using its legs. In this paper, we present distributed sensor-driven control for generating dung beetle-like walking and ball rolling behaviors of the developed model. The control mechanism is based on the Walknet bio-inspired controller. Furthermore, this paper gives a proof of concept that locomotion and object manipulation/transportation can be achieved without installing additional manipulators and/or grippers on a robot as shown by other works. To this end, the bio-inspired strategy can avoid the requirement of additional energy to power the manipulator or gripper system; thereby leading to an energy-efficient multi-functional robotic system.

Keywords: Locomotion control, Insects, Bio-inspired robotics, Embodiment, Subsumption architecture

1. INTRODUCTION

Bio-inspired robotics is a category of robotics wherein designs from nature are applied to robots. An example of this is the legged robot Stickybot, which mimics the adhesive ability of the gecko to climb smooth vertical surfaces [1]. The main idea is that nature has spent millennia perfecting specific abilities which we should try to mimic instead of reinventing.

When a task requires that a robot should have both locomotive and manipulative abilities, it is rare that the robot is able to use its existing legs for both abilities. The robot will instead have dedicated actuators or mechanisms for each task. An example of this is a humanoid robot, where the legs and arms have no shared actuators, but are essentially two separate systems conjoined. Another example is legged robots which are outfitted with a manipulator [2] or a gripper [3] such that they can move or manipulate an object using the extra manipulator or gripper. The alternative of splitting the tasks into two separate systems is to let the robot perform both tasks with the same actuators or legs.

While a dung beetle can control its legs to perform remarkable locomotion and object manipulation/transportation tasks (i.e., walking and dung ball rolling), developing a controller that allows a legged robot to use its legs like the beetle is nontrivial. Some works have developed control mechanisms of legged robots for solving the complex tasks [4-6]. However, they use either precise kinematics [4], complex force feedback [5], or a centralized control scheme [6], which are all computationally expensive, less flexible and adaptable.

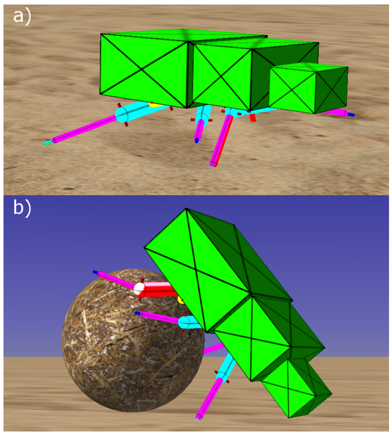

Fig. 1 A simulated dung beetle-like robot. The robot has the overall body size of 10.6 mm x 18.6 mm x 4.3 mm and the leg length 10.2 mm for the front legs, 10.0mm for the middle legs and 14.1 mm for the hind legs . Each leg has three joints. The thoraco-coxal (TC-) joint enables forward (+) and backward (–) movements, the coxa-trochanteral (CTr-) joint enables elevation (+) and depression (–) of the leg, and the femur-tibia (FTi-) joint enables extension (+) and flexion (–) of the tibia. a) Walking behavior generated by Walknet. b) Ball rolling behavior generated by Rollnet, a modification of Walknet. The dynamic properties of the simulated robot are based on the Open Dynamics Engine. We set the robot weight to 1 kg. We manually adjusted friction coefficients between the robot feet, the ball and the ground such that the robot does not slip during walking and rolling the ball.

† Theis Strøm-Hansen is the presenter of this paper.

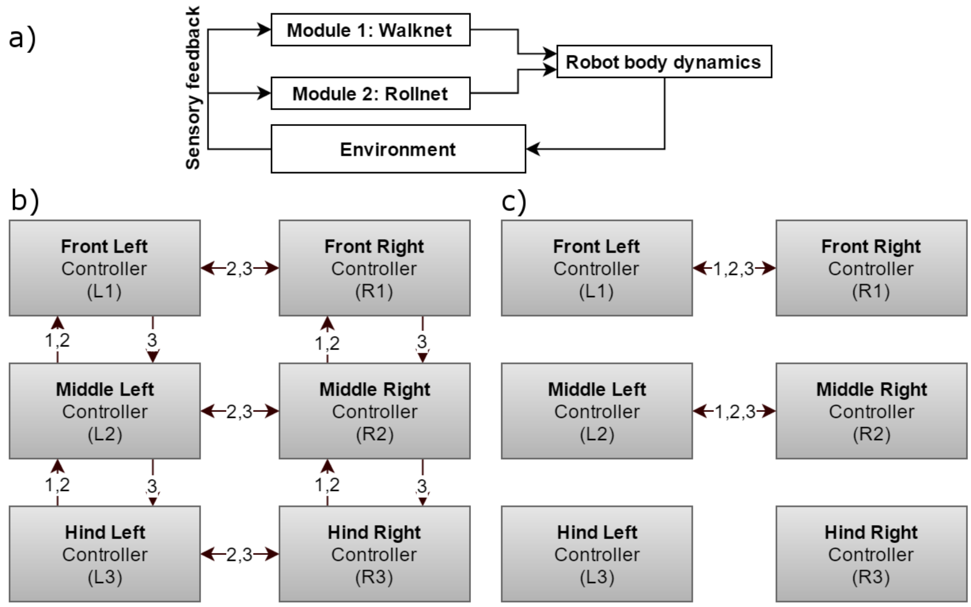

Fig. 2 a) Distributed sensor-driven control of a dung beetle-like robot. It consists of two subnetworks or modules: Walknet for walking and Rollnet for ball rolling. b) The influences of the Walknet rules on the legs for walking. c) The influences of the Rollnet rules on the legs for rolling a ball.

From this point of view, in this paper, we purpose a distributed sensor-driven control approach consisting of two modules: One for walking and another one for ball rolling, like a dung beetle. The walking control module is driven by the Walknet bio-inspired controller [7] while the rolling module is generated by Rollnet, a modification of the Walknet controller. Each module consists of six individual distributed controllers (one for each leg) and relies on joint angle, foot contact, and tilt sensory feedback of the robot. We apply our control approach to a simulated dung-beetle like robot [8] (see Fig. 1) for evaluation and demonstration. Here we show our preliminary results of emerging walking and object rolling behaviors of the robot generated by the control approach.

2. DISTRIBUTED SENSOR-DRIVEN CONTROL

The distributed sensor-driven control approach of the simulated robot (Fig. 2a) has two control mechanisms for walking (Fig. 2b) and ball rolling (Fig. 2c). We use the Modular RObot COntrol environment (MOROCO) embedded in the LPZRobots simulation toolkit [9] to simulate the robot and implement the control.

For walking behavior, we use only three rules of Walknet with foot contact and joint angle signals to coordinate the six legs (Fig. 2b). They are implemented as a finite state machine as follows:

Rule 1: Suppress lift-off rule. A posterior leg in a swing phase, i.e., when it is lifted off the ground, suppresses the swing of the neighboring anterior leg. This rule avoids potentially harmful situations of static instability for a hexapod that must not fall over.

Rule 2: Facilitate early swing phase rule. A leg experiencing a touch-down, i.e., reaching a given Anterior Extreme Position (AEP), facilitates the lift-off/swing phase of the neighboring legs in front and besides the leg. This favors a temporal cohesion.

Rule 3: Enforce late swing phase rule. A leg in late stance, i.e., approaching its Posterior Extreme Position (PEP), facilitates the lift-off/swing phase of the neighboring legs behind and besides the leg. This causes the two neighboring legs to catch up in order to maintain the temporal cohesion.

Based on these rules, walking behavior with a tripod gait emerges from interactions between sensory feedback, body dynamics, and the environment.

For ball rolling behavior, we first observed a dung beetle during rolling a dung ball and then derived a new leg coordination mechanism (called Rollnet) based on the Walknet rules. In addition to joint angle and foot contact sensors, the mechanism includes a tilt sensor to detect the inclination of the robot body. As soon as the body is in an inclined position, Rollnet (Fig. 2c) takes over Walknet (Fig. 2b) and drives the robot. Rollnet is implemented as follows:

- Apart from Rules 2 and 3, Rule 1 is added between the two front legs and the two middle legs.
- No rules affect the neighboring legs are used.
- The hind legs are set to a fixed position, to keep the ball from rolling away.

The implementation ensures that the robot uses the hind legs to hold the ball by statically placing on it, the middle legs to manipulate (or push) the ball by acting as forward walking with small steps, and the front legs to walk backward. This results in a ball rolling behavior. Note that the Anterior Extreme Position AEP and Posterior Extreme Position PEP of Walknet and Rollnet were empirically adjusted to obtain stable behavior. It is only by adjusting the AEP and PEP, that the walking behavior changes from forward to backward direction.

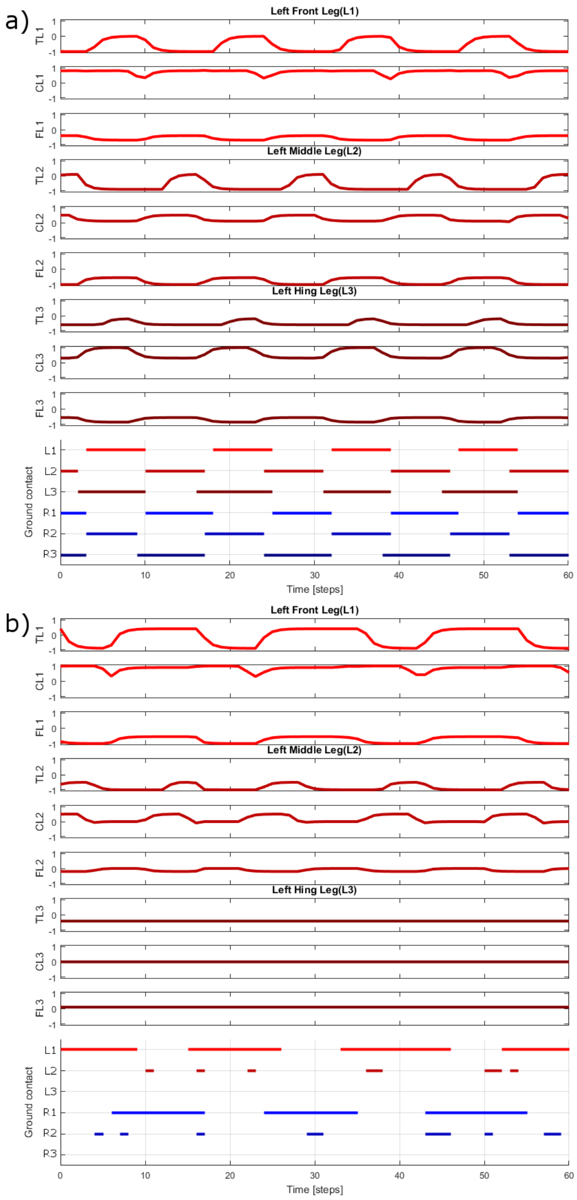

Fig. 3 Joint angle and foot contact sensor signals during a) walking and b) ball rolling. Abbreviations are: TL1, CL1, FL1 = TC-, CTr-, and FTi-joints of the left front leg (L1); TL2, CL2, FL2 = left middle leg (L2); TL3, CL3, FL3 = left hind leg (L3). During walking, all color bars show the periods that the tips of the legs touch the ground. During ball rolling, the color bars of L1 and R1 show the periods that the tips of the front legs touch the ground while the ones of L2 and R2 show the periods that the tips of the middle legs touch the surface of the ball. Note that only the tibia parts of the hind legs touch the surface of the ball; therefore, the ground contact signals of the legs are inactive during ball rolling.

3. EXPERIMENTAL RESULTS

To assess the performance of the distributed sensor-driven controller (i.e., a combination of Walknet and Rollnet) for walking and ball rolling, we ran the experiments for 120 seconds in the MOROCO environmental simulation. With the control approach, walking and ball rolling gaits are not predefined but emerge from the interactions between sensory feedback, body dynamics, and the environment. Thus, at the beginning, the robot started with an unstable pattern and through the interactions it can adapt its motion to achieve stable walking and ball rolling behaviors. According to this, the first 50 data samples or approx. 12 seconds were ignored, and only the steady state was used for analysis.

Figure 3 exemplifies leg movements during forward walking and ball rolling. For walking where all legs are used for locomotion, a tripod gait (see ground contact signals of all legs in Fig. 3a) is emerged with an average walking speed of 0.2 cm/s. For ball rolling where the hind legs are kept fixed (i.e., holding the ball), the middle legs perform ball rolling with a walking forward-like motion, and the front legs walk backward, a bipedal gait with a double-support phase (see ground contact sig-

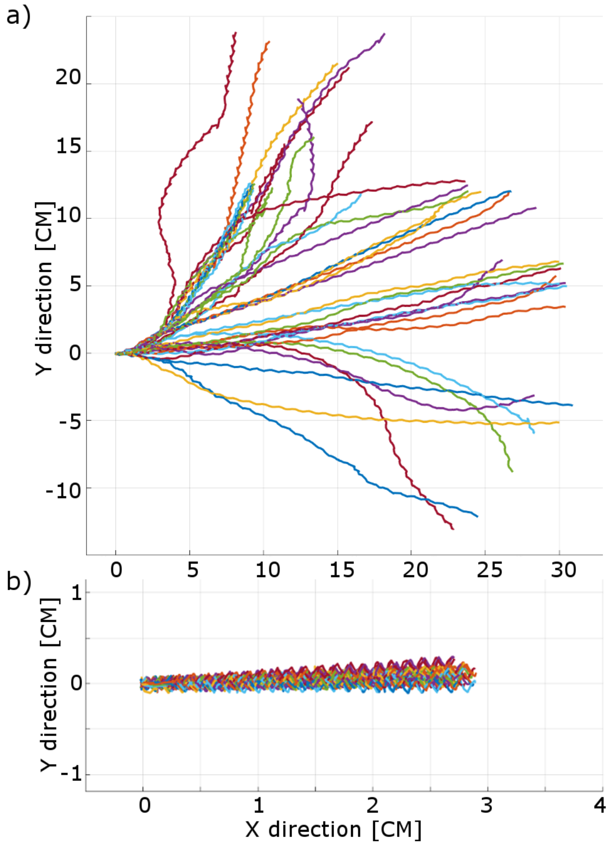

Fig. 4 a) The walking experiments show robot trajectories for 45 runs within about 120 seconds for each run. b) The ball rolling experiments show robot trajectories for 50 runs within about 110 seconds for each run.

nals of L1 and R1 in Fig. 3b) is emerged with an average walking speed of 0.03 cm/s. We encourage readers to also see the video showing the two behaviors at www.manoonpong.com/DungBeetle/SuppleVideo1.wmv.

Figure 4 shows the trajectories of walking (Fig. 4a) and ball rolling (Fig. 4b). At the beginning, the robot is started at the 0,0 position. It can be seen that the robot can cover about 25 cm during normal walking with some deviation from the straight line and about 3 cm during rolling the ball with a small deviation. The large deviation occurs sometimes during normal walking. This is a timing problem that is inherited from the manually set AEP and PEP values. The nature of the implemented controller makes it such that there is no margin of error if the timings are off. The solution to this is utilizing the neural network controller, which the original Walknet is built upon. In contrast to normal walking, when rolling the ball, the robot moves with a very small deviation in the y-direction. This is because the ball acts as a constraint preventing the robot from walking freely and, as Fig. 3b shows, the front legs have roughly the same amount of ground contact, so the robot pushes itself to one side, and then immediately corrects itself with the other leg.

During the study, multiple complications with the LPZrobots simulation toolkit appeared. The LPZrobots simulation provides only box, cylinder, and sphere objects. Thus the simulated dung beetle robot is an approximation of a real beetle. The most approximate body parts are the head, thorax and abdomen. The body of the real has an ellipsoid share, which is not provided by the LPZrobots simulation. Thus boxes are used instead. The coxa, femur, and tibia, are simulated by cylinder objects. The real femur has a complex shape with different diameters. As an abstraction, we use an average diameter and scale it down to a proper size. It is however important to note that this is mostly a visual approximation, that presumably does not affect the behavior and kinematics of the simulated robot.

4. CONCLUSION

By adding a tilt sensor and modifying the leg coordination strategy of Walknet, a ball rolling behavior for a dung beetle-like robot is achieved. The robot shows proper emergent locomotion and object transportation (i.e., ball rolling). This suggests that a bio-inspired approach could help to enhance the performance of different controllers that are needed in different applications. This study is one example where a hexapod with the biologically correct kinematics of the dung beetle is able to perform both locomotion and object transportation tasks that conventional hexapods are unable to achieve. Since the principle of the control approach replies on sensory feedback-body dynamics-environment interactions rather than a robot kinematic model, it can be also applied to other hexapods which in-turn should be able to walk and roll objects. In the future, we will implement a segmented tarsus at each robot leg in order to increase contact points between the leg and the ball. This will improve the performance of ball rolling. Furthermore, we will also investigate locomotion, object transportation, and navigation of the robot on rough terrain, like a real dung beetle.

5. ACKNOWLEDGEMENT

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