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Biologically Inspired Locomotion Strategies: Novel Ground Mobile Robots at RoMeLa

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Abstract - This paper presents some of the ground mobile robots under development at the Robotics and Mechanisms Laboratory (RoMeLa) at Virginia Tech that use biologically inspired novel locomotion strategies. By studying nature's models and then imitating or taking inspiration from these designs and processes, we apply and implement new ways for mobile robots to move. Unlike most ground mobile robots that use conventional means of locomotion such as wheels or tracks, these robots display unique mobility characteristics that make them suitable for certain environments where conventional ground robots have difficulty moving. These novel ground robots include; the whole skin locomotion robot inspired by amoeboid motility mechanisms, the three-legged walking machine STriDER (Self-excited Tripedal Dynamic Experimental Robot) that utilizes the concept of actuated passive-dynamic locomotion, the hexapod robot MARS (Multi Appendage Robotic System) that uses dry-adhesive “gecko feet” for walking in zero-gravity environments, the humanoid robot DARwIn (Dynamic Anthropomorphic Robot with Intelligence) that uses dynamic bipedal gaits, and the high mobility robot IMPASS (Intelligent Mobility Platform with Active Spoke System) that uses a novel wheel-leg hybrid locomotion strategy. Each robot and the novel locomotion strategies it uses are described, followed by a discussion of their capabilities and challenges.

Keywords - Bio-inspiration, locomotion, mobile robots.

1. Introduction

In a report [1] prepared for the Office of the Secretary of Defense Joint Robotics Program on the lessons learned from the robot assisted search and rescue efforts at Ground Zero following the 9/11 World Trade Center tragedy, robot mobility is noted as one of the major limitations of current robotic technology for such missions. The report further states that all the robots employed at the Ground Zero site used track drives which are generally superior to wheels on uneven ground; however, other alternative locomotion strategies which are more effective must be further investigated. Unlike aerial or marine vehicles which can reach almost any destination point in their travel domain, most ground vehicles used today have difficulty traversing over obstacles and climbing steep inclines due to their limited mobility, especially in unstructured environments.

As the technology of robotics intelligence advances, and new application areas for mobile robots increase, the need for alternative fundamental locomotion mechanisms for robots that can enable them to maneuver into complex unstructured terrain becomes critical. Current methods of ground vehicle locomotion are based on wheels, tracks or legs, and each of these methods has its own strengths and weaknesses [2, 3]. In order to move a robot into an area of complex terrain a new method of locomotion is needed. For example, to be able to find people trapped in a collapsed building, a robot would need to be able to move over, under and between rubble, and maneuver itself into tight corners. Current methods of locomotion can do some part of this, but they have only had limited success in achieving all of these capabilities [4].

By studying nature's models and then imitating or taking inspiration from these designs and processes, we apply and implement new ways for mobile robots to move. In this paper we present five of the ground mobile robots under development at the Robotics and Mechanisms Laboratory (RoMeLa) at Virginia Tech that use biologically inspired novel locomotion strategies. Unlike most ground mobile robots that use conventional means of locomotion such as wheels or tracks, these robots display unique mobility characteristics that make them suitable for certain environments where conventional ground robots have difficulty moving.

2. Biologically Inspired Novel Locomotion Strategies

2.1 Locomotion inspired by amoeboid motility mechanisms

Whole Skin Locomotion (WSL) [5, 6] is a biologically inspired alternative fundamental locomotion mechanism for mobile robots inspired by the motility mechanisms of single celled organisms that use cytoplasmic streaming to generate pseudopods for locomotion. The name comes from the fact that the entire outer surface of the robot, which has a body of a shape of an elongated torus, is used as a surface for traction and that the skin is used for the actuation by cycling through contraction and expansion.

The inspiration for this novel locomotion strategy comes from the way certain single celled organisms, such as the *Amoeba proteus* (giant amoeba) move. The motion of these organisms is caused by the process of cytoplasmic streaming (Fig. 1) where the liquid form endoplasm that flows inside the ectoplasmic tube transforms into the gel-like ectoplasm outer skin at the front, and the ectoplasm outer skin at the end transforms back into the liquid form endoplasm at the rear. The net effect of this continuous ectoplasm-endoplasm transformation is the forward motion of the amoeba [7, 8].

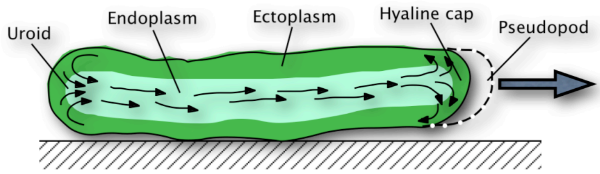


Fig. 1. Motility mechanism of a monopodial amoeba

Directly imitating this cytoplasmic streaming process with a robot is very difficult to do if not possiblee. Thus, instead of using the process of liquid to gel transformation of cytoplasm, the WSL is implemented by a flexible membrane skin in the shape of a long torus. The skin of this elongated torus can then rotate in a fashion of turning itself inside out in a single continuous motion, effectively generating the overall motion of the cytoplasmic streaming ectoplasmic tube in amoebae (Fig. 2).

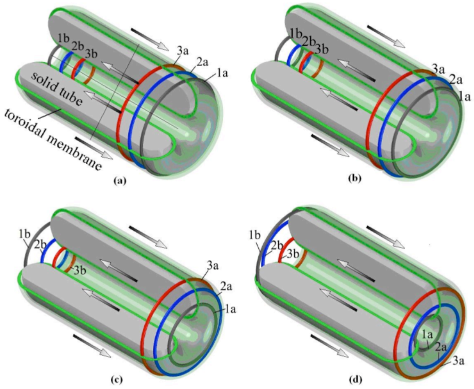
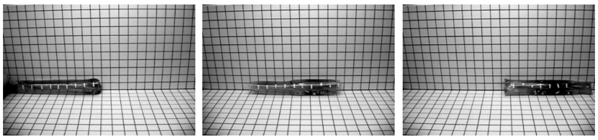


Fig. 2. Everting motion generated by the contracting (1a, 2a, 3a) and expanding (1b, 2b, 3b) actuator rings for the concentric solid tube WSL model.

Figures 3 and 4 show simple experiments using a long elastic silicone skin toroid filled with water to demonstrate the feasibility of the locomotion mechanism.



(a) At 0.0 sec (b) At 0.30 sec (c) At 0.46 sec

Fig. 3. Sequence of pictures of the locomotion of the pre tensioned elastic skin model

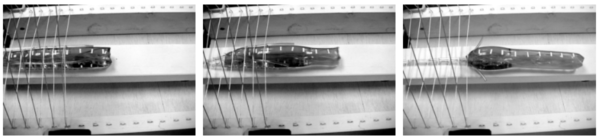


Fig. 4. Sequence of pictures of the tension cord actuated model locomotion

A robot that uses WSL can move as long as any surface of the robot is in contact with the environment, be it the ground, walls or obstacles on the side, or the ceiling, since the entire skin is used for locomotion. With an elastic membrane or a mesh of links acting as its outer skin, the robot can easily squeeze between obstacles or under a collapsed ceiling, and move forward using all of its contact surfaces for traction, or even squeeze itself through holes with diameters smaller than its nominal width as demonstrated in [5].

2.2 Tripedal locomotion utilizing the concept of actuated passive-dynamic locomotion

STriDER (Self-excited Tripedal Dynamic Experimental Robot) is a novel three-legged walking machine (Fig. 5) that exploits the concept of actuated passive dynamic locomotion [9 to 11], to dynamically walk with high energy efficiency and minimal control using its unique tripedal gait (Fig. 6). Unlike other passive dynamic walking machines, this unique tripedal locomotion robot is inherently stable with its tripod stance, can change directions, and is relatively easy to implement, making it practical to be used for real life applications.

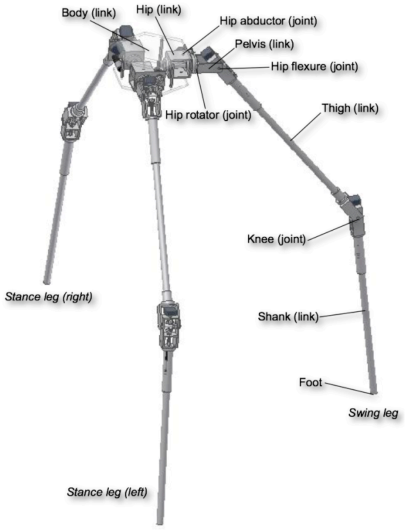
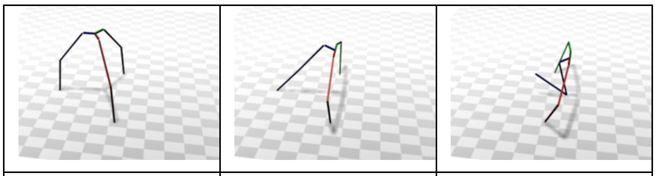


Fig. 5. STriDER: Self-excited Tripedal Dynamic Experimental Robot

Fig. 6 shows the concept of the single step tripedal gait. From its starting position (Fig. 6 (a)), as the robot shifts its center of gravity by aligning two of its pelvis links (Fig. 6 (b)), the body of the robot can fall over in the direction perpendicular to the stance triangle (Fig. 6 (c)), pivoting about the line defined by the two supporting legs. As the robot falls over, the leg in the middle (swing leg) naturally swings between the two stance legs (Fig. 6 (d)) and catches the fall (Fig. 6 (e)). As all three legs contact the ground, the robot resets its posture by actuating its joint, storing potential energy for its next gait (Fig. 6 (f)). The key to this tripedal gait is the natural swinging motion of the swing leg, and the flipping of the body about the aligned pelvis joints connecting the two stance legs. With the appropriate mechanical design parameters (mass properties and dimension of the links), this motion is repeated with minimal control and power consumption exploiting the actuated passive dynamic locomotion concept utilizing its built in dynamics.


(a) Starting position (b) CG shift (c) Falling over

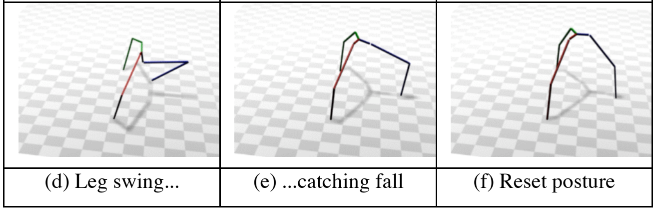

(d) Leg swing... (e) ...catching fall (f) Reset posture

Fig. 6. Single step tripedal gait

Gaits for changing directions are implemented in a rather interesting way: by changing the sequence of choice of the swing leg, the tripedal gait can move the robot in 60° interval directions for each step (Fig. 7)

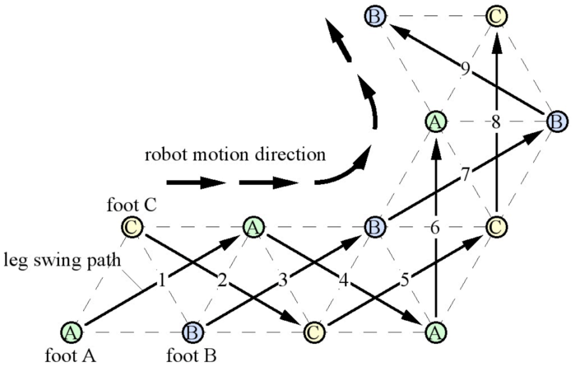


Fig. 7. Gait strategies for changing directions

The simple tripod configuration and tripedal gait of STriDER has many advantages over other legged robots; it has a simple kinematic structure (vs. bipeds, quadrupeds, or hexapods) that prevents conflicts among its legs and between a leg and the body; it is inherently stable (like a camera tripod); it is simple to control (vs. bipeds) as the motion is a simple falling in a predetermined direction and catching its fall; it is energy efficient, exploiting the actuated passive dynamic locomotion concept utilizing its built in dynamics; it is lightweight enabling it to be launched to difficult to access areas; and it is tall making it ideal for deploying and positioning sensors at high position for surveillance, for example.

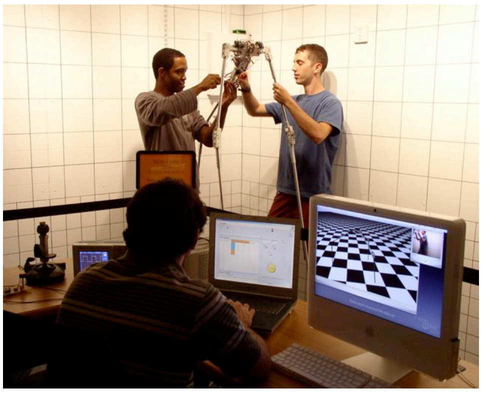


Fig. 8. Experiment setup for a single step tripedal gait

2.3 Dry-adhesive gecko feet for walking in zero gravity environments

Inspired by NASA JPL's LEMUR class robots [12, 13] (Fig. 9), *RoMeLa* at Virginia Tech is developing a hexapod robotic platform for research in multi-limbed locomotion and manipulation. Shown in figure 10, the Multi Appendage Robotic System (*MARS*) has six 4-degree-of-freedom (DOF) limbs arranged axi-symmetrically about the robot body with kinematically spherical joints at the shoulder for a large workspace. Interchangeable end-effector/feet allow it to be used for studying various research areas such as walking in unstructured environments, climbing, and for dexterous manipulation tasks.

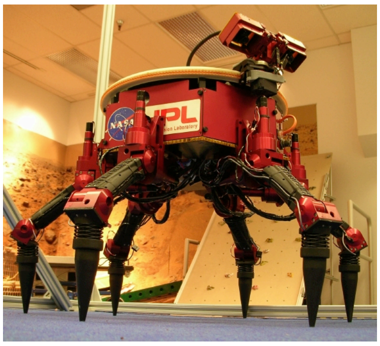


Fig. 9. NASA JPL's LEMUR IIa

MARS's six axi-symmetrically arranged limbs are each connected to the body by a 3 DOF kinematically spherical joint which provides a wide range of motion similar to a shoulder of hip joint. Midway along each limb is a single DOF joint which provides a range of motion similar to an elbow or knee joint. This arrangement allows each limb to have a wide workspace. The entire platform is approximately 16 inches in diameter standing 10 inches tall with the appearance of an insect or spider. The carbon fiber composite body carries Li-Poly batteries, a PC104 single board computer, and interchangeable sensors including stereovision Firewire cameras. The limbs are constructed with a lightweight aluminum frame and carbon fiber composite exoskeleton skin for stiffness. Each joint is actuated by Maxon's RE-max coreless DC motors via distributed control with variable compliance. At the end of each limb, interchangeable end-effector/feet allow it to be used for various experiments and applications.

Fig. 10. MARS: Multi Appendage Robotic System

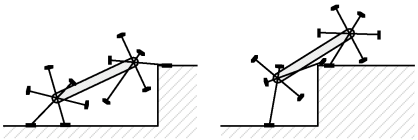
Unlike other robot design approaches that seek to mimic biology and engineering together, LEMUR's origins lack any necessary biological elements [12]; biological elements are used exclusively as a design tool. As the robot is intended to move along the surface of the structure, inspiration was taken from multi-limbed, dexterous sea creatures that tend to move along the bottom and among rocks. Immediately applicable examples are octopi and starfish which are notable for their axi-symmetry. The creatures' limbs are long relative to body size. Being axi-symmetric, the robot is omni directional, saving operationally expensive movement to face a particular direction for mobility or manipulation. Also, the long limbs generate a generous workspace.

One of the key application areas of MARS is autonomous in-space inspection and maintenance of space vehicles and structures in zero gravity. Using limbed robots is the most promising technology for such EVA tasks; to crawl outside on the outer surface of space vehicles or structures using legs for inspection and maintenance operations. However using limbed robots in zero gravity environments creates a whole new set of problems and requirements. Locomotion in zero gravity environments requires using methods of securing its feet to the walking surface. This may be accomplished by grabbing certain features on the surface, using magnets, suction cups. Inspired by the ability of geckos to climb vertical walls and walk upside down on the ceiling, future version of MARS will be using dry adhesive feet to walk on surfaces in zero gravity environments as this is the most promising technology for stabilizing the robot on its walking surface for locomotion and for manipulation tasks.

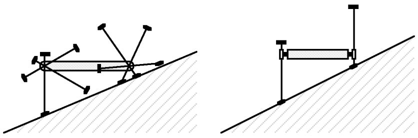
2.4 A novel wheel-leg hybrid locomotion strategy

IMPASS (Intelligent Mobility Platform with Active Spoke System) is a novel high mobility locomotion platform for unmanned systems in unstructured environments [14 to 16] (Fig. 11). Utilizing rimless wheels with individually actuated spokes, it can follow the contour of uneven surfaces like tracks and step over large obstacles like legged vehicles while retaining the simplicity of wheels (Fig. 12). Since it lacks the complexity of legs and has a large effective (wheel) diameter, this highly adaptive system can move over extreme terrain with ease while maintaining respectable travel speeds, and thus has great potential for search-and-rescue missions, scientific exploration, and anti-terror response applications.

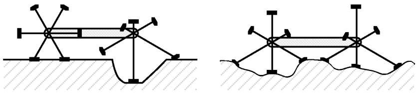
Fig. 11. Rendered image of a version of IMPASS using two actuated spoke wheels and a mock up of the system



(a) Climbing up steps up to 4 times its nominal height



(b) Staying level or maintaining pitch and roll on inclines



(c) Terrain adaptation, multiple contacts with surface for stability

Fig. 12. Some examples of the mobility and terrain adaptability of *IMPASS*

We have analyzed the kinematics and simulated the motion of a robot using two actuated spoke wheels on flat terrain using a one-, two-, and three-point contact per wheel scheme (Fig. 13). It is shown that the one-point contact mode has two degrees of freedom and that the motion output can be arbitrarily selected. This mode would allow for moving while maintaining a constant height for the center of mass, which we have demonstrated by simulation. Turning for this mode is shown to occur discretely by changing the heading angle for every step by taking steps of different lengths with the right and left wheels. The two-point contact mode is shown to have one degree of freedom, and that by choosing a step length, the path of the center of the axle in the sagittal plane is determined as a function of the wheel angle. This mode of locomotion allows for statically stable walking with only two wheels, and could be used for carrying heavy payloads. The three-point contact scheme is shown to have zero degrees of freedom, but would allow for additional stability during stationary tasks by letting the robot assume a wide stance.

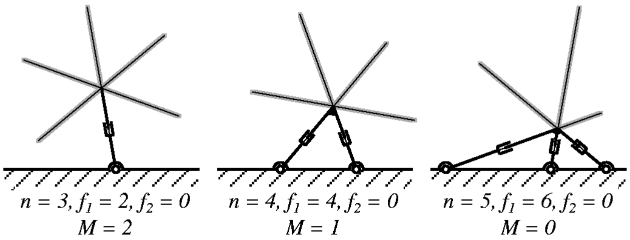


Fig. 13. Kinematic diagram of a single actuated spoke wheel and its degrees of freedom for different modes

The concept for transient turning was then developed by having three contact points at the step transition, forcing the pivot line to be skew with the axle of the robot (Fig. 14). Insight into this configuration was gained by analyzing the robot in this configuration as an SPPS spatial mechanism. The insight gained from the spatial analysis is used to describe a more general kinematic model that could be used to analyze both cases of the coplanar pivot line and the skew pivot line, as well as allow analysis of the effects of differentially driving the two actuated spoke wheels.

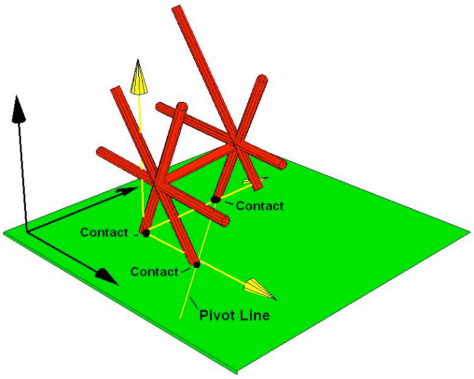


Fig. 14. Turning strategy for the actuated spoke wheel

To verify our analytical model and to evaluate the concept in the next phase of the project, we have designed and fabricated our first prototype of the actuated spoke wheel (Fig. 15) to be used for *IMPASS*.

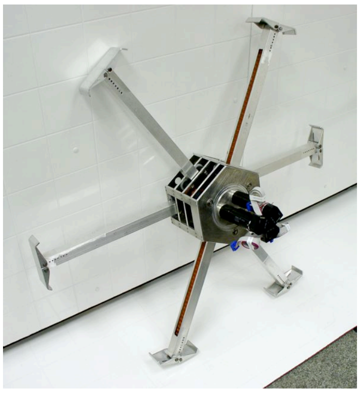


Fig. 15. Prototype of the actuated spoke wheel

2.5 Bipedal locomotion for humanoid robots

DARwIn (Dynamic Anthropomorphic Robot with Intelligence) is a humanoid robot capable of bipedal walking and performing human like motions, developed as a research platform for studying robot locomotion and also as the base platform for Virginia Tech's first entry to the 2007 Robocup competition (Fig.s 16, 17). The 600 mm tall, 4 Kg robot has 21 degree-of-freedom (DOF) with each joint actuated by coreless DC motors via distributed control with controllable compliance. Using a computer vision system on the head, IMU in the torso, and multiple force sensors on the foot, *DARwIn* can implement human-like gaits while navigating obstacles and will be able to traverse uneven terrain while implementing complex behaviors such as playing soccer.

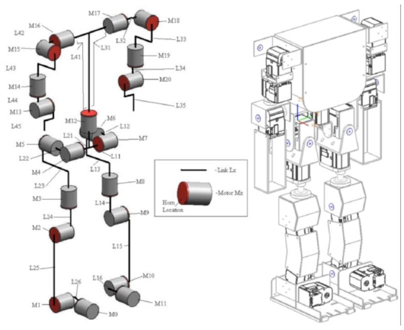


Fig. 16. Kinematic diagram and the CAD model of *DARwIn*

The goal of this on going research project is to develop the robotic platform for, and study the issues related to participating in the 2007 Robocup competition (generating and implementing a dynamic walking gait using Zero Moment Point control, developing algorithms and strategies for intelligent motion planning and obstacle avoidance, vision based control, uneven terrain walking, complex behaviors for playing soccer, etc.)

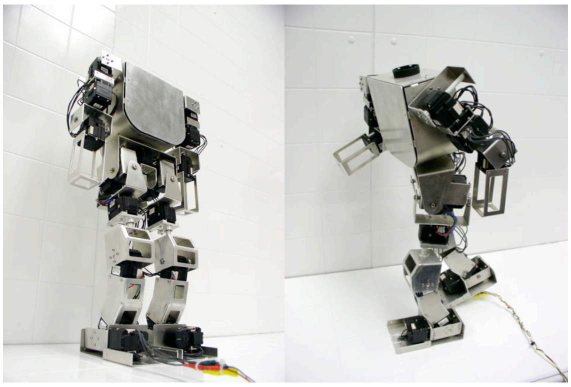


Fig. 17. *DARwIn*: Dynamic Anthropomorphic Robot with Intelligence

DARwIn has a lightweight aluminum skeletal structure with rapid prototyped plastic skin covers. The arms and legs are connected to the body by 3 DOF kinematically spherical joints which provide a wide range of motion similar to a shoulder and hip joint. Each joint is actuated by Maxon's RE-max coreless DC motors via distributed control with variable compliance. The robot carries two 2100 mAh/7.4V Li-Poly batteries as its power source, a PC104 single board computer for processing, three rate gyros to track orientation of the body, and various sensors including a Firewire camera for vision and eight force sensors on the foot. The new version of *DARwIn* currently under development for the 2007 Robocup is being designed through collaboration of graduate students and senior undergraduate students from both the Department of Mechanical Engineering and the School of Architecture + Design at Virginia Tech.

3. Conclusion

In this paper, we have presented five of the unique ground mobile robots under development at the RoMeLa at Virginia Tech that use novel locomotion strategies for high mobility. As demonstrated, using bioinspiration was the key for the development of these robots. By studying nature's models and then imitating or taking inspiration from these designs and processes, we have successfully applied and implemented new ways for mobile robots to move in various environments with unique mobility.

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