A Platform for Studying Locomotion Systems: Modular Reconfigurable Robots

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ABSTRACT

There are many fundamentally different mechanical motions that a system can use to achieve locomotion. Two standard examples are the wheels on a car or the legs of an artificial ant, but many others exist as well. As with all systems, there is an obvious desire to quantify how "well" each locomotion method performs. Unfortunately, as with many metrics, this is far from being a well-defined problem. Apart from the usual difficulty of deciding exactly what is the most important measure (peak speed, efficiency, etc), there is the question of divorcing the underlying locomotive concept from the particular implementation (just like a universal machine such as Turing Machine divorces hardware implementations from algorithms).

This paper proposes a particular platform which the authors believe can be used as part of a standard system for evaluating many different means of locomotion. Since one of the fundamentally different aspects of each of these locomotive methods is the underlying mechanism, then any standard platform must be capable of changing its shape and fashion of moving so as to be able to faithfully perform the locomotion to be tested. The PolyBot system, developed at PARC, is capable of just this.

KEYWORDS: *locomotion systems, locomotion gaits, modular self-reconfigurable robots, experimental platforms, performance measures*

1. MOTIVATION

Locomotion is an important attribute for many intelligent systems. All known intelligent species of life are capable of locomotion by some means or other. The focus of this paper will be a little narrower, focusing only on locomotion on solid surfaces (thus excluding swimming or flying). Over the last century human beings have invented various kinds of locomotion systems for motion over ground, mostly for fast and efficient transportation. Probably the two most widespread of these are as cars and trains. Most cars or trains cannot be considered intelligent systems, because (1) they are not autonomous to any significant degree, (2) despite a large internal sensor network, their perception of the outside world is very limited, (3) they are intended for use in very specialized artificial environments -- (cars on highways and trains on railways).

The world is being constantly changed through the increasing availability of progressively cheaper and more powerful computation. Predictions have been made suggesting that in twenty years time, cars and trains will become intelligent robotic systems. Like animals, these vehicles will not only have a brain (central control) but also nervous systems (networking) connecting all sensing and actuation components.

The majority of existing man-made locomotion systems is wheeled, since that is simple and efficient in a conveniently engineered environment (flat surfaces or rails). However natural locomotive systems (such as used by animals) have almost exclusively favored employing legs. The use of wheeled vehicles is largely limited to flat environments. Tracked vehicles tend to handle a wider variety of terrain but suffer in efficiency. Legged machines tend to be less efficient and harder to control but have the potential of traversing an even wider variety of terrains. While much research has been done on legged locomotion, little has been usefully commercialized. Even though legged locomotion is generally recognized to be more flexible, and has the potential to effectively traverse natural environments, as yet more knowledge and understanding of how to engineer such systems is needed.

It is hard to compare two locomotion systems with radically different design, or two systems engineered for use in different environments. This paper proposes the use of modular self-reconfigurable robots as a standard platform for studying various types of locomotion and developing concrete performance metrics. By using this one platform for testing all locomotive ideas, the fundamental locomotive principle being tested is somewhat divorced from the specific physical implementation.

A modular self-reconfigurable robot, named PolyBot, has been developed over the last three years at the Palo Alto Research Center (http://www.parc.com/modrobots). PolyBot consists of many component modules (possibly hundreds), each of which has sensing, actuation and computation. These modules can be configured into many different shapes, such as wheels/loops, snakes and centipedes. It is due to this versatility that PolyBot is able to implement a wide variety of different locomotive systems, allowing concrete performance metrics to be calculated and clear comparisons to be performed.

With PolyBot, it is possible to develop various types of locomotion gaits for different types of configurations, and study the effectiveness of various control strategies. The results can be used to develop the performance metrics, which in turn allows quantitative improvements to be made in the quality of locomotion systems.

This paper is organized as follows. Section 2 characterizes some initial concepts on locomotion systems and gaits, Section 3 discusses terrain evaluations, Section 4 presents locomotion performance metrics; Section 5 describes more completely PolyBot, the modular reconfigurable robot. Finally, there are possible directions for future research using PolyBot as a platform for studying locomotion systems.

2. LOCOMOTION SYSTEMS AND GAITS

A *locomotion system* is a powered system being able to move from one position/orientation to another. There is a considerable body of knowledge on animal locomotion [1] and vehicle locomotion [2]. The most typical classification of land locomotion divides locomotion into four types: wheeled, tracked, legged, and other. From authors' point of view, this is unsatisfactory for several reasons. First, the last area is a catchall, and would include such dissimilar means of locomotion as snake-like sidewinding, concertina, screw locomotion, etc. Second, there are too many instances of ambiguity. For example, a child cartwheeling may be considered legged locomotion since the child has legs. Would a spoked wheel with no rim or partial rims also be considered legged locomotion? Tracked locomotion is defined as traveling on endless belts. Is a belt around a tire then tracked locomotion? What about a slightly flat tire? Yim [3] in his PhD thesis in 1994 studied various locomotion systems and first characterized locomotion gaits systematically.

A *locomotion gait* is defined as one cycle of a pattern of motion that is used to achieve locomotion. There are *simple* gaits and *compound* gaits; compound gaits are combinations of two or more simple gaits. There are maybe finite classes of simple gaits, but combination of these can generate infinite number of compound gaits. For example as wheeled locomotion is one type of locomotion and bipedal walking clearly is another, the two can be combined as with a person wearing roller skates.

A large portion of ground-based locomotion gaits can be characterized as *statically stable gaits*. To achieve statically stable locomotion in general, one has to repeatedly do three things in any order:

1. remove ground contact points from the rear,
2. place ground contact points in front,
3. shift weight forward.

Throughout all of these steps, maintain static equilibrium throughout all motions. A statically stable gait defines a cyclical pattern that achieves these steps.

The simple ground-based statically stable locomotion gaits are characterized by three categories [3]: *(R)oll/(S)wing, (D)iscrete/(C)ontinuous, (B)ig/(L)ittle Footed*. For examples, a 4-wheel passenger car is RCL, a treaded tank is RCB, a cockroach is SDL, an earthworm is SCB, human is SDB, etc.

Yim [3] also characterized three fundamental ways that a simple gait may be combined: *articulated*, *hierarchical* and *morphological*. Articulated combination is to unite more than one locomotion systems, e.g., track and trailer. Hierarchical combination is to add one locomotion system on the top of another, e.g., roller skating. Morphological combination is to merge locomotion systems with different axis, e.g., a rolling sphere.

When deciding which gait would be most appropriate for a given situation, it would be useful to know the characteristics of each type of classification. For simple gaits, rolling systems tend to be simpler and more efficient. Continuous motion can be smoother over hard flat terrains. The larger the footprint, the better the performance in terms of speed, efficiency and mobility, etc. For compound gaits, single chain articulated gaits have several desirable features: the ability to travel in highly constrained areas, to fit between or cross large obstacles, with a large payload. Hierarchical gaits can achieve higher speeds than individual gaits, e.g., walking on a moving track belt is faster than walking on a ground. Morphological gaits add degrees of freedom to locomotion, which make the system more flexible.

3. TERRAIN EVALUATIONS

Simply comparing the locomotion capabilities of a horse to a wheeled car is meaningless, just like comparing apples and oranges. In nature, each form of locomotion exists in the environment that fits it best. Locomotion performance metrics will not be complete without terrain evaluations. Yim [3] defined the taxonomy of terrain effects (Figure 1).

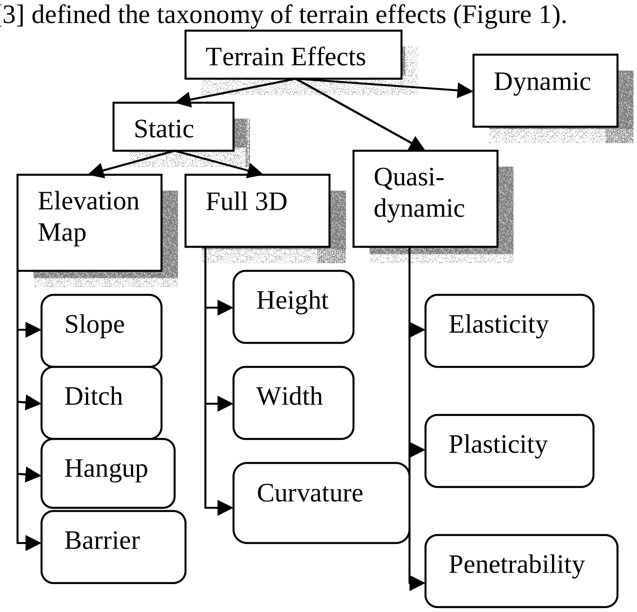

Figure 1: Taxonomy of Terrain Features

Static 2.5D terrain features include *slopes*, gradual elevation with height, *ditches*, holes in the ground, *hang-ups*, bumps in the ground, and *barriers*, a vertical object to cross like a wall. Full 3D terrain features include *height* constraints, obstacles on the top, *width* constraint, obstacles on the sides, and *curvature* constraint, the radius to turn. Quasi-dynamic terrain features include *elasticity*, *plasticity* and *penetrability* of ground surface, for example, a locomotion system will perform differently on soft mud terrain and hard wood floors. Dynamic terrain features include moving wind/current, moving terrain and obstacles, etc.

4. LOCOMOTION PERFORMANCE METRICS

The complexity inherent in intelligent systems means that it is rare for a useful metric to measure just one aspect of performance. In general, the evaluation function which serves as the metric will have multiple objectives which must be appropriately scaled and weighted. There are two main types of measurements for locomotion systems: system centric and environment centric.

In system-centric measurements, the type of environment is fixed (e.g. a dirt road) and other aspects (e.g. *speed*, *acceleration*, *efficiency*, *stability*, *payload*) are compared. In an environment-centric measurement, the value is some measure of the terrain which can be traversed (e.g. how steep the environment can be, or how rough) in terms of metrics of slopes, ditches, hang-ups, barriers, height, width and curvature constraints etc.

In addition to mechanical capabilities, computational capabilities can also be measured, such as *adaptability*, *robustness*, *self-repair-ability*, as well as the underlying computational components such as *CPU speed*, *memory*, *communication rate*, etc.

In addition to these "hard" measurements of locomotion systems, there are also "soft" measurements reflecting quality of system design (both hardware and software); these include *maintainability*, *modularity*, *scalability* and *reusability*. Some of these attributes are not directly related to performance, but are relevant to the total cost of ownership. Others are even less of interest to an end-user, but are still of importance for decision-making by the developer.

The authors do not claim to have yet developed a complete metric which satisfies all the conditions discussed above–this is work in progress. However they do put forward the idea of employing a uniform platform for locomotion testing. This, they argue, will simplify the measurement and comparison process, allowing effort to be directed towards refining the base metric. This universal platform is described in the next section.

5. MODULAR ROBOTICS PLATFORM

A modular reconfigurable robot is one that consists largely (or entirely) of identical components which can be assembled into many topological configurations. These different configurations generally equate to different physical shapes – each with different abilities and limitations. In this way the platform can be used to test many fundamentally different forms of locomotion. The platform proposed here is a modular *self* re-configurable robot: one that can change from one configuration to another autonomously. While this capability is not actually essential for its use as a universal platform as proposed here, the sensing, distributed computation, communications and control middleware required to support self reconfiguration will prove useful in carrying out the measurements for the performance metric. There are a growing number of modular self-reconfigurable robotic [4][5][6][7][8][9]. This paper focuses on one particular modular self-reconfigurable robot, named PolyBot [10].

PolyBot, is a modular reconfigurable robot system composed of two types of modules, one called a *segment* and the other called a *node*. The segment module has two connection ports and one degree of freedom (DOF) motion. The node module is a rigid cube with six connection ports but no internal DOF. PolyBot has been designed for applications including planetary exploration, undersea mining, search and rescue and other tasks in unstructured, unknown environments. PolyBot has been developed through its third generation at the Palo Alto Research Center. The latest design features smaller module size (5cm), more sensors (IR range, touch, force) and multiple actuators for locomotion, manipulation and reconfiguration, as well as bridged networks using CAN (Controller Area Networks).

Each PolyBot module has a Motorola PowerPC *MPC555* embedded processor with 448K internal flash ROM and 1M of external RAM. Software architecture has been developed for PolyBot, with a higher layer CAN protocol MDCN (Massively Distributed Control Nets) [11][12] and an Attribute/Service Model [11][13] for coordination of multiple tasks in multiple processes.

PolyBot is a good platform for studying various forms of locomotion. The PolyBot systems have demonstrated versatility by showing multiple modes of locomotion with a variety of characteristics, distributed manipulation and the ability to self-reconfigure. PolyBot can be configured into various shapes (see Figure 2,3,4). Each configuration has pros and cons in terms of performance. Snakes can traverse terrains with narrow entrance, such as pipes, and is the most robust among other configurations. Loops or wheels are most efficient over flat terrains. With deformed loops (conformance to terrains) it can also traverse effectively over stairs. Centipedes or spiders are good for avoiding obstacles and traverse rough terrains.

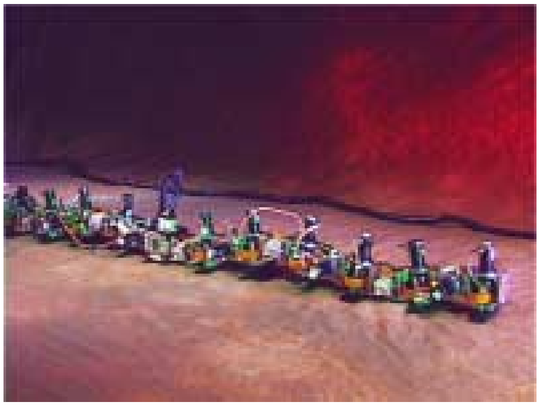

Figure 2: Snake Configuration

Figure 3: Loop Configuration

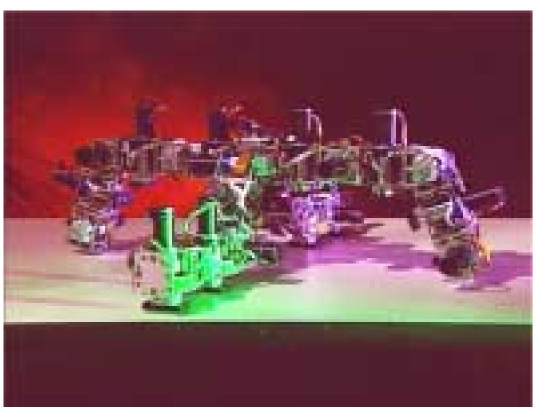

Figure 4: Spider Configuration

6. FUTURE WORK

There will be 100+ PolyBot modules built by the October this year. Various locomotion configurations and gaits will be tested and compared in the near future. A more complete understanding of and development of locomotion performance metrics will commence.

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