# DESIGN OF A CRAWLING GAIT FOR A MODULAR ROBOT

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## ABSTRACT

*In order to reduce the cost and development time of an all-terrain autonomous robot, a modular approach is used. The robot is designed as simple as possible by using one-degree-of-freedom modules that allow the platform to auto-reconfigure to use two different locomotion models inspired by biological systems: quadruped and crawling locomotion. The pros and cons of crawling are discussed and the use of this type of locomotion is justified. Moreover, the gait is outlined and the distance traveled per cycle and its velocity are calculated and analyzed. Finally, several experiments are performed and the results are compared to the theoretical results obtained before.*

## 1. Introduction

A versatile, inexpensive robot is proposed capable of traveling through diverse environments. The approach proposed here attempts to palliate some of the problems that still plague present robots: cost, reliability, long development time and sufficient mobility [1], [4].

Modularity is a key element in the design. Much research has been put into this field, and many designs use an assembly of independent modules which can reconfigure with respect to each other [1-5], [10]. Modularity is used to design a more reliable robot as well as reducing its manufacturing cost. In case of failure, the robot is easier to repair than a regular robot due to the fact that modules are interchangeable and thus a spare module can be used to repair any mechanical failure. Modularity also facilitates increasing fault tolerance by simply adding redundant modules to the proposed design and developing an adequate control system.

The ability to traverse rough terrain is one of the main characteristics of the robot. Without it, the robot would not be able to perform many of the tasks it is suitable for. In order to increase its mobility, two different locomotion types are implemented on the robot: quadruped pace and crawling. In this sense, the robot is reconfigurable, as it is capable of traveling in any of the two ways depending on which one is best suited for the mission and the terrain involved.

Crawling has been the second type of locomotion implemented on the robot. Crawling is the perfect complement for legged locomotion on rough terrain. Crawling is implemented on the modular robot to grant it with a stable, simple and robust type of locomotion.

Several biologically inspired platforms imitating snake and worm locomotion for traveling through rough environments have been proposed in the past [6-9].

## 2. Crawling Gait Discussion

Crawling animals can be found scattered across the planet. Their different locomotion modes have allowed them to adapt to different environments and terrain. Crawling locomotion is particular in the sense that body motion alone allows progression, while in wheeled locomotion, movement results from wheel turning and in legged locomotion, movement results from the legs pushing on the ground.

The ability of crawling animals to travel almost through any kind of terrain is well known. Crawling animals succeed where animals with other locomotion types fail. Examples of such environments include tight passages and travelling over loose terrain. Other advantages include its stability, redundancy and high traction. These are very desirable properties for modern robots which can be applied to exploration, medicine, inspection and recognition fields.

Crawling robots are challenging in several ways: actuation, form and structure, electronics, sensing and control. Wheels offer smooth, fast and efficient locomotion, but it is highly dependent on terrain and for best results, modifications are needed on the surface on which they move. Even the most versatile wheeled mechanisms (all-wheel-drive) are limited in the type and form of terrain they can travel though [11]. Walking robots offer exceptional terrain negotiation, and provides discrete contact with the ground. However, walking poses many balance, sensing and control problems due to its complexity.

Crawling locomotion poses many advantages beyond the capabilities of most wheeled and legged vehicles. It is almost impossible for a crawling machine to tip over. Wheeled and legged vehicles are highly concerned about stability. These machines must keep their center of gravity within the polygon formed by the points of contact with the ground (wheels or legs). Crawling robots keep most of their body in contact with the ground in most situations.

Terrainability is another advantage of crawling vehicles. Terrainability is defined as the ability to traverse rough terrain [12]. The greatest advantage of crawling vehicles over wheeled and legged ones is their ability to travel through narrow passages where maneuverability is low. Common crawling machines are thin. Their small cross section enables them to travel through narrow environments where conventional wheeled or legged equivalents cannot penetrate. Crawling robots like serpentine ones often result in very long machines. Crawling vehicles can climb obstacles and steps whose height approaches their own. Few wheeled or legged machines can climb such high obstacles, except for dynamic legged hoppers which can jump many times their height [13]. Another fact which favors crawling machines is their lack of appendages, and thus the absence of parts which can get stuck while moving. Legs and wheels may get stuck with roots, undergrowth holes.

Crawling animals can exert large traction forces. Traction is the force applied to propel a vehicle, and its maximum is given by the product of the coefficient of friction and the vehicle's weight. A snake's tractive force can be as large as a third of its own weight. Due to the large surface area in contact with the ground, the resulting stresses may not reach those necessary for plastic deformation of soil. On the other hand, wheels and legs often deform the ground they step on, which may lead to the vehicle getting trapped. Limbless locomotion is superior in many situations when travelling through soft terrain.

Crawling animals are as efficient as legged animals. Despite the energy loss due to large frictional forces and to partial elevations of the body, energy is saved because of the low energy need for body support and also because of the absence of the limb's accelerations and decelerations. These pros and cons compared to legged animals seem to balance one another [14].

Crawling machines are redundant. In case of failure of an actuator, the machine is still capable of maneuvering and can still advance. In case of failure, repairing them is easier than repairing other robots due to their modular architecture. Crawling vehicles employ few different modules, as their structure allows for the sequential repetition of a single module.

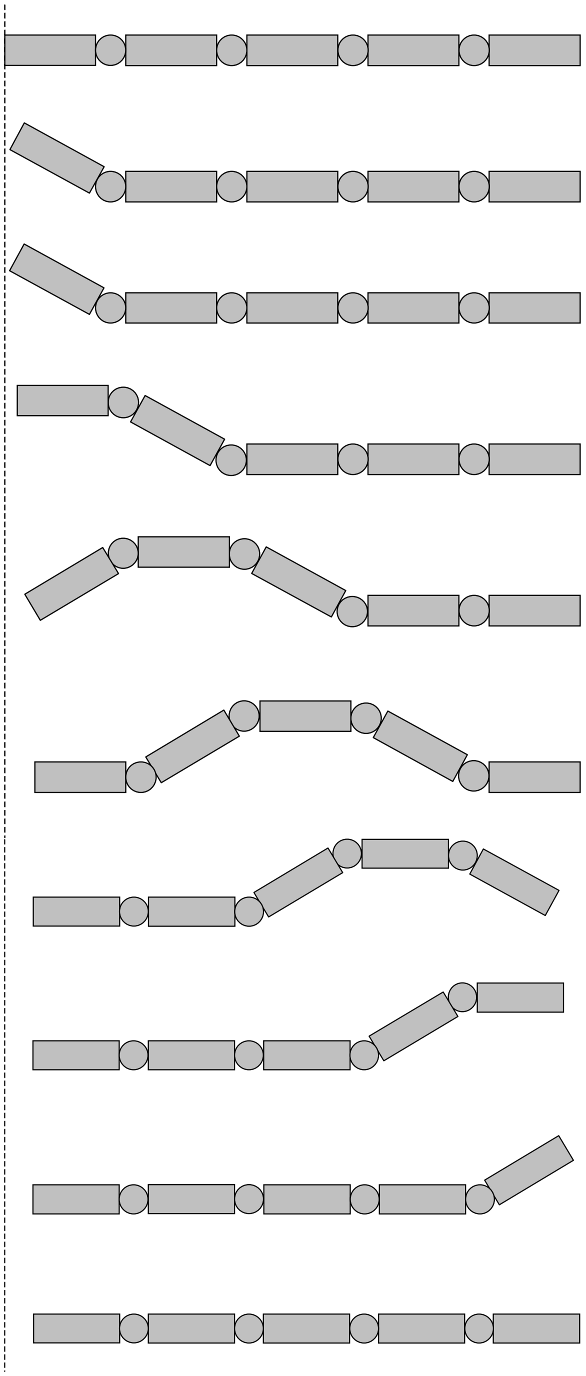
However, some disadvantages prevent crawling vehicles from being widely used. To begin with, these machines are complex. It is much simpler to drive a wheeled platform with one actuator per wheel and with direct relationship between the actuators' output and the vehicle's movement. Crawling machines need the coordinated output of several actuators to produce motion, leading to the problem of controlling a large number of degrees of freedom.

Crawling vehicles are not a good option for tasks such as transporting a payload. Their thin and long shape is not adequate for this task. The vehicle's dynamics are not the most appropriate to transport a payload. A static platform is preferred for this purpose.

Speed is another problem associated with crawling locomotion. The fastest snakes can move at a speed of 3 m/s (black mamba), and most limbless animals are much slower. Robotic crawlers are unlikely to reach that velocity, but due to the applications these machines are focused to and the environments they are designed for, limited speed should not be a major problem.

## 3. Gait Planning

The robot treated here does not posses scales or legs to aid in its movement, and progression is achieved by the propagation of an ondulatory wave from the rear to the front of the robot. Each module advances when raised, avoiding any friction with the ground. When the module is lowered and reaches the ground, its position is beyond the original one. The existing friction on the support modules prevent the robot from slipping due to the inertia created by the ondulatory movement. This rectilinear gait is an effective one that does not slip or slide much along the ground [12]. The gait sequence is shown below:



Now that the gait is outlined, the model must be analyzed in order to define its only variable: the joint angle.

To begin with, the distance traveled by cycle will be calculated. Moreover, the speed of the crawling robot will be computed as a function of the link angle. This will help deciding the link angle that must be chosen for the robot.

The distance traveled by the robot per complete cycle is

$$x = 2 \cdot L - 2 \cdot L \cdot \cos(\theta)$$

where θ is the angle of the risen module and *L* is the module length. The following graph shows the distance traveled per cycle for values of 0 < θ < π/4 for L = 7.2 cm.

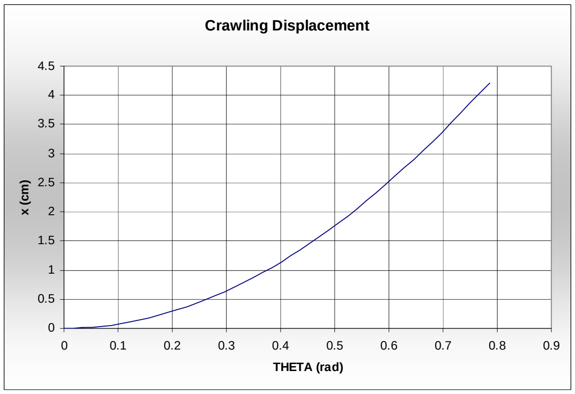


Figure 1: Crawling Displacement as a Function of the Link Angle

In order to calculate the velocity of the robot when crawling, the time needed to run a cycle must be calculated. The period of the servos is 1.14s. The servo with the largest rotation is 2θ for all stages except for the first and last, in which it is only θ. The cycle is composed of eight stages, so the time needed to complete a cycle can be calculated as:

$$cycle\_angle = 6 \cdot (2 \cdot \theta) + 2 \cdot \theta = 14 \cdot \theta$$

$$t = 14 \cdot \theta \cdot \left( \frac{T}{2 \cdot \pi} \right)$$

The velocity can now be calculated as the distance traveled per cycle over the time needed to complete the cycle:

$$v = 2 \cdot L \cdot \frac{1 - \cos\theta}{14 \cdot \theta \cdot \dfrac{T}{2 \cdot \pi}}$$

The equation above was plotted for values of 0 < θ < π/4 where L = 7.2 cm and T = 1.14s.

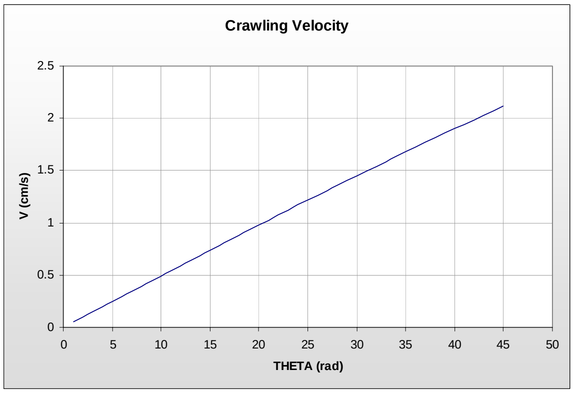


Figure 2: Crawling Velocity as a Function of the Link Angle

As seen from graph 47, the velocity achieved by the robot is almost linear when increasing the link angle.

It must be noted that this is the maximum theoretical speed. It must be noted that constant servo velocity has been assumed for these calculations, but the results are valid to decide the angle θ to be chosen for the robot.

It seems reasonable to choose the largest angle possible to increase the speed to its maximum.

In order to decide the joint angle to be applied to the robot, several experiments were conducted. Different configurations, consisting of different joint angles and different timer values were tested. The timer defines the time the control program waits before reading the next value on the input file and thus moving the servos to the new positions. The results obtained are shown below.

Table 1: Crawling Experiment Data

| Joint angles (degrees) | Timer (ms) | Frequency (Hz) |
|---|---|---|
| 21º | 50 | 1.18 |
| 21º | 100 | 0.59 |
| 42º | 25 | 2.35 |
| 42º | 50 | 1.18 |
| 42º | 100 | 0.59 |
| 42º | 150 | 0.39 |
| 63º | 50 | 1.18 |
| 63º | 100 | 0.59 |
| 63º | 150 | 0.39 |
| 63º | 200 | 0.29 |

| Joint angles (degrees) | Timer (ms) | Speed (cm/s) |
|---|---|---|
| 21º | 50 | 1.10 |
| 21º | 100 | 0.87 |
| 42º | 25 | 1.80 |
| 42º | 50 | 1.87 |
| 42º | 100 | 2.00 |
| 42º | 150 | 1.50 |
| 63º | 50 | 2.03 |
| 63º | 100 | 2.13 |
| 63º | 150 | 2.33 |
| 63º | 200 | 2.20 |

| Joint angles (degrees) | Timer (ms) | Distance traveled / Cycle (cm/cycle) |
|---|---|---|
| 21º | 50 | 0.94 |
| 21º | 100 | 1.47 |
| 42º | 25 | 0.77 |
| 42º | 50 | 1.59 |
| 42º | 100 | 3.40 |
| 42º | 150 | 3.83 |
| 63º | 50 | 1.73 |
| 63º | 100 | 3.63 |
| 63º | 150 | 5.95 |
| 63º | 200 | 7.48 |

The results shown on table 1 are represented on graphs

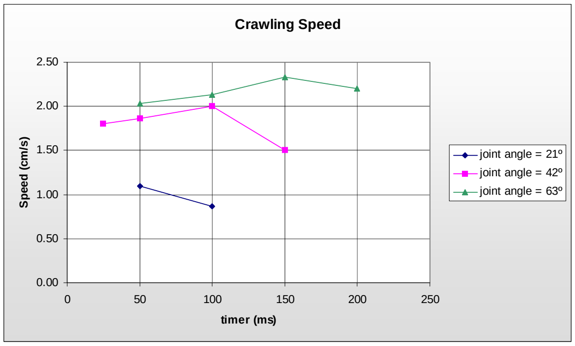


Figure 3: Robot crawling speed

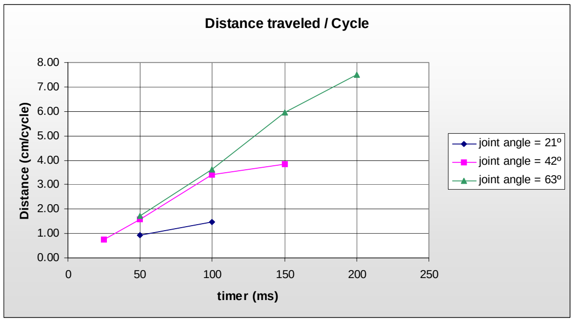


Figure 4: Crawling distance per cycle

The experimental results are similar to the theoretical ones. According to the calculations, for 21, 42 and 63 degrees joint angles, the velocity and net displacement per cycle should be:

$$x = 2 \cdot L - 2 \cdot L \cdot \cos(\theta)$$

$$x = 2 \cdot 7.2 - 2 \cdot 7.2 \cdot \cos(21^{o}) = 0.96cm$$

$$x = 2 \cdot 7.2 - 2 \cdot 7.2 \cdot \cos(42^{o}) = 3.70cm$$

$$x = 2 \cdot 7.2 - 2 \cdot 7.2 \cdot \cos(63^{o}) = 7.86cm$$

$$v = 2 \cdot L \cdot \frac{1 - \cos\theta}{14 \cdot \theta \cdot \frac{T}{2 \cdot \pi}}$$

$$v = 2 \cdot 7.2 \cdot \frac{1 - \cos\left(21^{o}\right)}{14 \cdot 0.367 \cdot \frac{1.14}{2 \cdot \pi}} = 1.027 cm/s$$

$$v = 2 \cdot 7.2 \cdot \frac{1 - \cos\left(42^{o}\right)}{14 \cdot 0.733 \cdot \frac{1.14}{2 \cdot \pi}} = 1.99 cm/s$$

$$v = 2 \cdot 7.2 \cdot \frac{1 - \cos\left(63^{o}\right)}{14 \cdot 0.100 \cdot \frac{1.14}{2 \cdot \pi}} = 2.82 cm/s$$

Table 1 shows that the largest crawling speed was obtained for a joint angle of 63º with a timer interval of 150 ms. However, the most efficient crawling configuration was obtained for the same joint angle (63º) and a timer interval of 200 ms. From the results above it can be concluded that the servos cannot reach their final position at each step with the timer set to 150ms. Despite this fact, due to the extra cycles gained by the lower timer, the robot crawls faster.

The robot has been set by default to the configuration that reaches the highest speed, 2.33 cm/s. Even though many robots can travel faster, specially wheeled ones, the prototype is capable of traveling 84 m/h or 2.016 km/day, more than enough for the proposed applications.

Figures 5 to 9 below show the resulting gait simulated on Working Model.

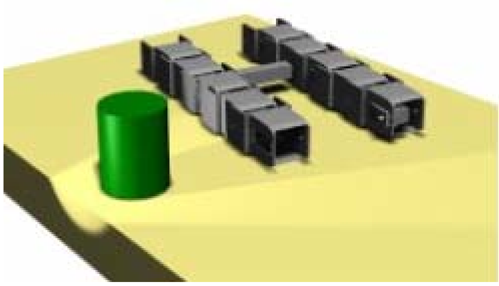


Figure 5: Initial Crawling Position

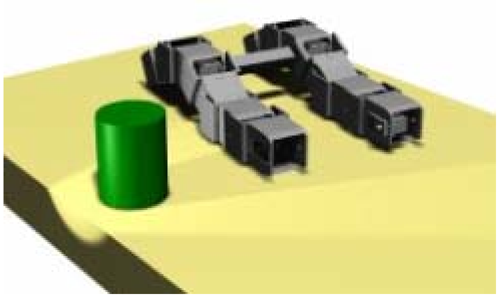


Figure 6: 1st Crawling Position

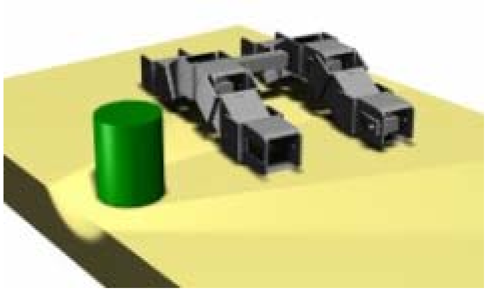


Figure 7: 5th Crawling Position

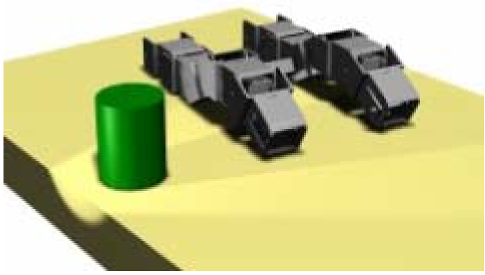


Figure 8: 6th Crawling Position

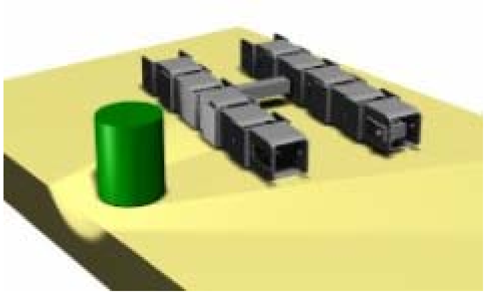


Figure 9: Back to Initial Position

## 4. Conclusions

Crawling locomotion has proven to be a good choice for the robot proposed. The motion is smooth and relatively fast as expected. This type of locomotion can be of interest for traveling through low passages, such as air conditioning ducts, through rough terrain where obstacles can pose a problem when walking and through plastically deformable terrain such as sand.

The robot performance was more than acceptable. The expected experimental results were close to the theoretical ones. The difference between them can be explained by some assumptions made such as the constant servo velocity.

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