Proceedings of RTC:
Graduate Student and Entry-Level Engineers Technical Conference
April 7-9, 2005, Jacksonville, Florida

DESIGN OF AN ALL-TERRAIN 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 proposed. The robot is designed as simple as possible by using only a one-degree-of-freedom module that will allow the platform to reconfigure itself to use two different locomotion methods inspired by biological systems: quadruped and caterpillar locomotion. Specifically, this paper describes the development of the module that forms the reconfigurable robot, and then focuses on the gait definitions of crawling and quadruped modes of locomotion. A prototype of this robot has been built and the described gaits are tested at FIU's Robotics & Automation Laboratory.

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].

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], [14]. 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.

In the robotic locomotion field, many theories have been developed by studying animal locomotion. Many robots are octopods imitating spiders and scorpions, hexapods imitating insects (many of them cockroaches) [6], quadrupeds imitating reptiles and mammals [7-9], and even bipeds imitating human locomotion. Other biologically inspired platforms imitating snake and worm locomotion for traveling through rough environments have been proposed in the past [8-10].

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.

Gait generation for quadruped locomotion will be addressed on a modular robot. Balance equations and leg position equations are also presented. 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.

PLATFORM

As we have mentioned, we aim for an all-terrain platform that can transport a group of sensors and/or a manipulator to any desired location. Because this objective is quite broad and the posible scenarios endless, we feel that making the robot reconfigurable and endowing it with multiple forms of locomotion will allow for better adaptability to any situation

One of the main objectives of the design is to minimize the number of module types. By reducing the number of different modules, we simplify the production and construction process and we make any repair process relatively simple. Another design consideration is to make the module itself simple. A module design that includes two degrees-of-freedom (pich and

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roll) results in a robot that is incredibly dexterous. Such approach is currently rejected for two reasons: Firstly, the design of the link is far more simlple with just one degree-of-freedom. Secondly, only one of the two servos is normally used for a given gait, while the other is used only occasionally when reconfiguring. If a servo is not typically used, including it in the design would make the module significantly larger and heavyer for transportation, yet the benefits of a second degree-of-freedom are not completely exploited. This observation introduces another design contraint, the scale. By designing a small module we make it relatively stronger: smaller, lighter, links require less powerful servos that in turn require smaller and lighter batteries. Thus, our current module consists of a single actuator that controls the revolute joint that links it to the next module (fig. 1), and the robot consits of a chain of such links.

Figure 1. Basic module concept

The most obvious choice of locomotion for modular robots is caterpillar motion. This type of motion is slow, but works in un-even terrains and can also be used to overcome certain obstacles. This motion (wave propagation) is achieveable with as few as four links, but it becomes more and more efficient as the number of links increases. Moreover, if the number of links is redundant the robot becomes fault tolerant, as it can still move with oversized links (two links that become one when the joint fails)

In order to obtain legs, a second chain of links was added to the design, and attached to the existing one in parallel. The resulting platform can concieveably walk using the “heads” and the “tails” of the two chains as legs (fig. 2). The accepted minimum number of degrees-of-freedom for a walking leg is three, which means that each snake should be at least seven links long. Unfortunatelly, the controller currently in use can only handle 8 servos, which controls both chains of 5 links each. This requires special planing of the walking gait of the robot .

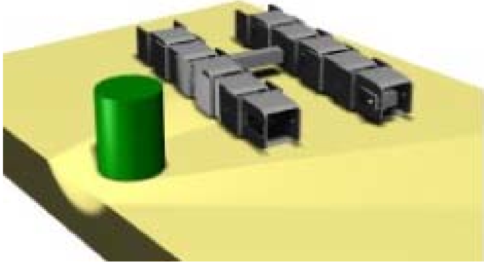

Figure 2. Modules assembled

CRAWLING GAIT

The robot treated here does not posses scales or legs to aid in its crawling 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 its original one. The existing friction on the support modules prevents the robot from slipping with the inertia created by the ondulatory movement. This rectilinear gait is an effective one that does not slip or slide much along the ground [20]. The gait sequence is shown below:

Once 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

$$x = 2\cdot L - 2\cdot L\cdot \cos(\theta) \tag{1}$$

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 $0 < \theta < \pi/4$ for $L = 7.2$ cm.

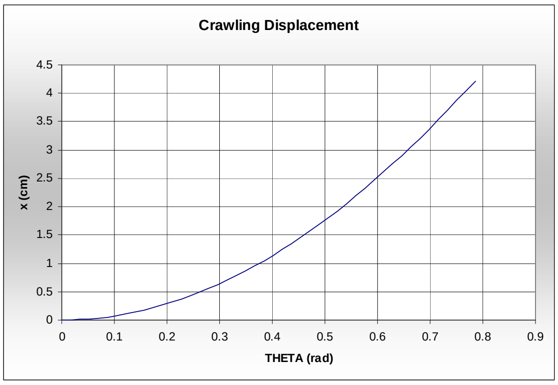

Figure 3. Crawling displacement as a function of the link angle

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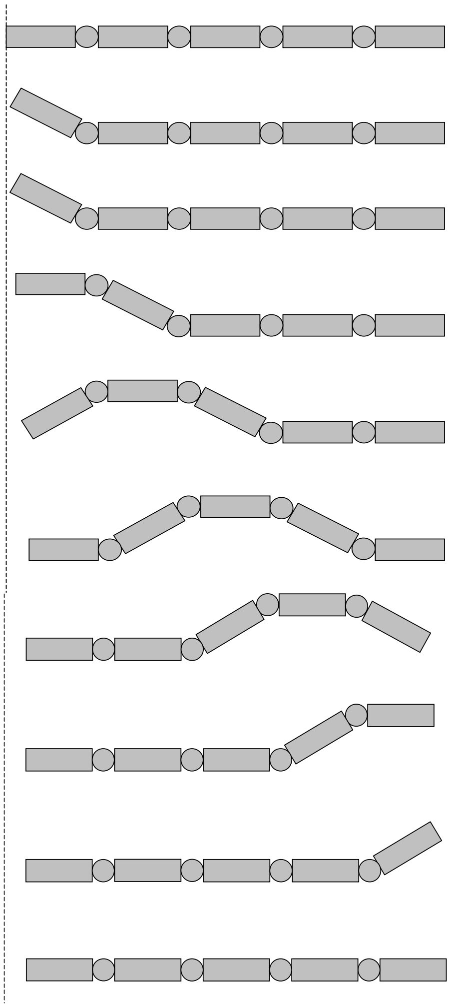


Figure 4. Crawling gait sequence

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:

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

$$t = 14 \cdot \theta \cdot \left(\frac{T}{2 \cdot \pi} \right) \qquad 3$$

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

$$v = 2 \cdot L \cdot \frac{1 - \cos\theta}{14 \cdot \theta \cdot \dfrac{T}{2 \cdot \pi}} \qquad 4$$

The equation above was plotted for values of $0 < \theta < \pi/4$ where L = 7.2 cm and T = 1.14s.

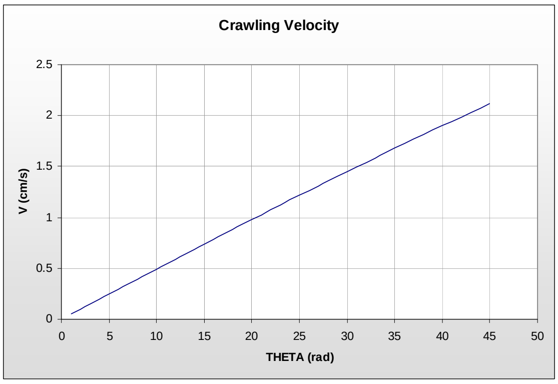


Figure 5. Crawling velocity as a function of the link angle

As seen from Figure 5, 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 represented on graphs shown in Figures 6 and 7.

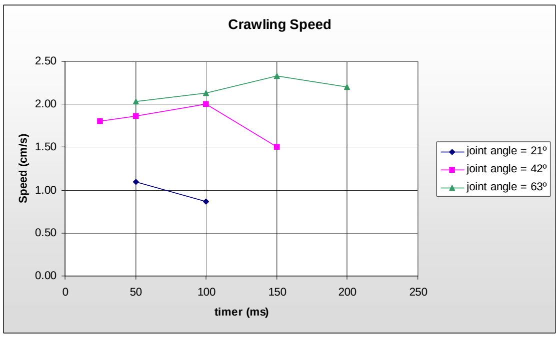


Figure 6. Robot crawling speed

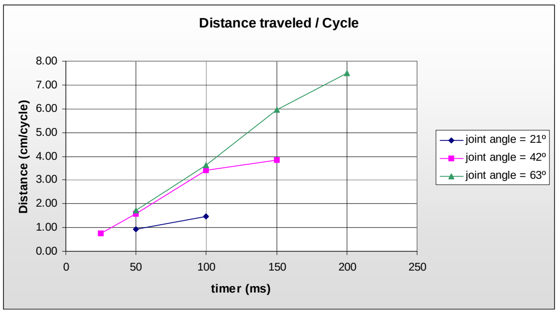


Figure 7. Crawling distance per cycle

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:

$$x = 2 \cdot L - 2 \cdot L \cdot \cos(\theta)$$
$$x = 2 \cdot 7.2 - 2 \cdot 7.2 \cdot \cos(21^o) = 0.96cm$$
$$x = 2 \cdot 7.2 - 2 \cdot 7.2 \cdot \cos(42^o) = 3.70cm$$
$$x = 2 \cdot 7.2 - 2 \cdot 7.2 \cdot \cos(63^o) = 7.86cm$$

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

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

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

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

Figure 6 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.

QUADRUPED GAIT

Balance is a key element if the robot is to walk in a stable manner with only four legs. Robots with more legs such us hexapods are not so concerned with balance because they are stable by nature. If a quadruped's feet are forming a square on the ground, its center of gravity is in the center of that square and one leg is risen, it has equal chances of falling or not. In order to keep its balance while the robot is on three legs, the center of gravity has to be moved forward, backwards, right or left with respect to the plane formed on the ground by the supporting legs. Moving the robot's balance back and forth can be achieved by simply giving the necessary inputs to the servos to move the modules to the optimal position without moving the feet. Lateral displacement of the robot's balance cannot be achieved in such a direct way due to the lack of degrees of freedom in the legs in the desired direction of motion.

In order to maintain stability, calculations are needed in order to know where the center of gravity is located for a specific configuration of the modules. A simple sketch representing the robot is shown below.

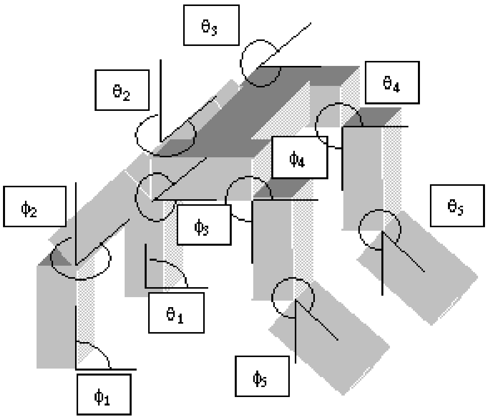


Figure 8. Robot module angles

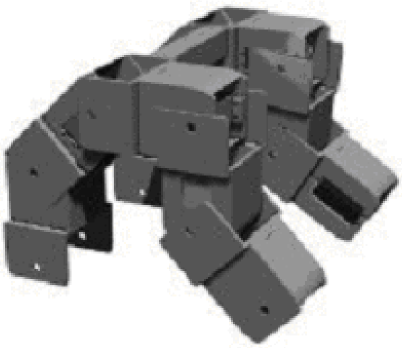


Figure 9. 3D Model of the quadrupled mode

In order to calculate the position of the center of gravity (COG), the position of the COG of every module must be computed first. For the first two modules, the following relations may be found [15]:

$$x_1 := \left(\frac{1}{2}\right) \cdot \cos\left(\phi_1\right)$$

$$y_1 := \left(\frac{1}{2}\right) \cdot \sin\left(\phi_1\right) \qquad 5$$

$$x_2 := \left(1 \cdot \cos\left(\phi_1\right)\right) + \left[\left(\frac{1}{2}\right) \cdot \cos\left(\phi_1 + \phi_2\right)\right]$$

$$y_2 := \left(1 \cdot \sin\left(\phi_1\right)\right) + \left[\left(\frac{1}{2}\right) \cdot \sin\left(\phi_1 + \phi_2\right)\right] \qquad 6$$

Once the COGs of the modules have been computed, the global COG of the chain of links can be computed:

$$X := \frac{\left[x_1 + x_2 + \left(n\, x_3\right) + x_4 + x_5\right]}{7}$$

$$Y := \frac{\left[y_1 + y_2 + \left(n\, y_3\right) + y_4 + y_5\right]}{7} \qquad 7$$

The COG will vary depending on the weight of the component linking both chains of modules. The weight of this component varies because several components such as the micro-controller, batteries and any extra equipment will be carried here. *n* relates the weight of a normal module to half of the weight of the linking component.

$$W_{\text{component}} = 2n\, W_{\text{normal module}} \qquad 8$$

The procedure shown above must be repeated for the other chain of links. *R* and *S* will replace coordinates X and *Y*. Once the COG of both chains has been computed, by simply averaging both COGs, the COG of the robot is found.

$$M := \frac{(R + X)}{2}$$

$$N := \frac{(S + Y)}{2} \qquad 9$$

The method described above was used in MATHCAD in order to show any configuration and its COG. The results obtained for a specific example can be seen below.

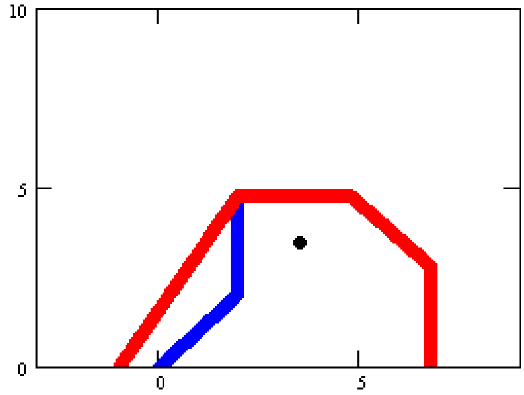


Figure 10. Sketch of the robot with COG in Mathcad

The sketch shown above represents the configuration shown below.

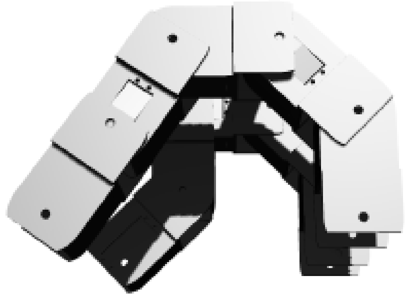


Figure 11. View of the robot in quadruped gait

Once balance is defined for a specific configuration, gaits may be developed. Gaits can be classified into two groups: static and dynamic [19]. Static gaits neglect the dynamic effects of the robot's actions due to its slow movement. It is characterized by the center of gravity projecting on the polygon formed by the supporting legs. On the other hand, dynamic gaits need to consider the dynamic effects of the system due to their high velocity, and the projection of the center of gravity is not necessarily projected on that polygon. However, dynamic balance is to be maintained. Dynamic gaits include trotting and running. Dynamic gaits have the advantage of a higher velocity and higher energy efficiency [17], while static gaits are usually more stable and simpler to develop. For the robot presented here, static gaits are more adequate as one of the robot's main purpose is to traverse rough terrain.

In order to develop the gait the robot will use, it must be taken into account that the system has no feedback from the environment. It includes no sensors as an aid for walking. Gaits have to be planned ahead and no modifications on the field can be done. Again, this fact simplifies the system enormously, but the robot will be slower and less stable. Thus, gaits must be planned in order to maximize its stability. Velocity is not the main concern, stability is.

Legs are composed of two links that move in the same plane (parallel to the robot's movement). Because legs only have two degrees of freedom, and move in two dimensions, only the position of the end-point can be fixed, orientation has to be free to avoid over constraining the system. A path must be defined for the endpoint of the leg. There is no need to make this path complex, so a rectangular path will be chosen.

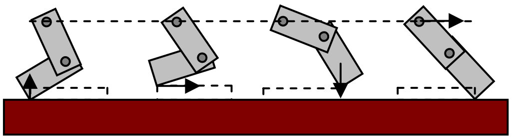


Figure 12. Leg sequence for quadruped locomotion

A MATHCAD program was created to perform an inverse kinematic analysis in order to calculate the angles for the four different leg positions shown on Figure 12. The maximum height of the robot was fixed based on two factors: stability and leg versatility. The higher the COG is located, the less stable the system will be, but is positioned too low, the limbs won't be able to perform well due to large torques having to be applied by the servo-motors and greater energy consumption. A height of $h = 1.707 \cdot L$ was chosen, being "L" the link length. The system proved good performance when simulated for that fixed height.

A fact of great importance is the number of leg positions available during the gait. 2 and 3 intermediate positions were considered for each leg in order to develop the gait. With only 2 positions per leg, the gait turned out to be somewhat unstable, unnatural and not as fast as expected.

Table 1. Gait pattern with 2 leg positions

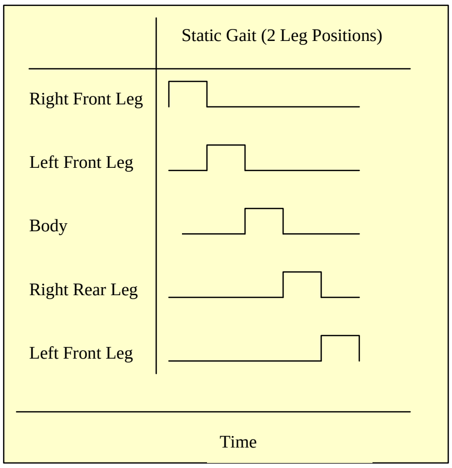
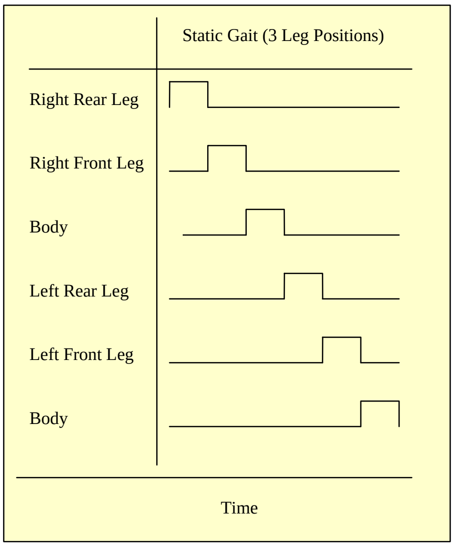


Table 2. Gait pattern with 3 leg positions



The most important difference between both gait patterns is the double body movement used with 3 leg positions. After the legs on one side move, the body is moved. On the other hand, with only two leg positions, the body is moved only once per gait. Using 3 leg positions makes the gait more stable and suitable for our objective, thus, this gait will be implemented on our platform.

CONCLUSIONS AND FUTURE WORK

A modular robot has been presented capable of reconfiguring to use two different types of locomotion: quadruped and crawling.

Two gait patterns have been developed and simulated for quadruped locomotion. The second walking gait (3 intermediate leg positions) proved to work better than the first one. The robot performed as expected and it has proved to be a feasible way of traveling even with limited degrees of freedom.

Crawling locomotion has proven to be a good complement for the robot proposed. The motion is smooth and relatively fast. 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 crawling 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.

It is noted that only the static locomotion is considered in this paper. This is done so to eliminate the dynamic effects of motion since the velocities that are dealt with in this type of locomotion are considerebly small in magnitude. However, the increase in mass and inertia of the system due to the increase in link lengths could also be studied.

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Future work on this robot will include the development of other gaits such as turning (both in quadruped and crawling configurations), and another, and more demanding function that would change the robot from one configuration into the other. Thus far, the robot does not need to be reconfigured or reassembled in order to crawl or walk, but it cannot change its mode by itself yet.

Future work also includes module optimization in order to increase the torque/weight ratio. This will allow for better performance and easier autonomous reconfiguration..

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