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DEVELOPMENT OF A QUADRUPED GAIT FOR A MODULAR ROBOT

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ABSTRACT

This research focuses on enabling a quadruped gait for a modular robot. The main challenge when working with modular robots is to achieve the given task while maintaining the modularity of the robot. Due to the modularity of the robot, some additional constrains are induced in the system. Modularity will reduce the limbs of the robot to redundant robotic arms. Each leg's trajectory was carefully selected to avoid singularities. Initially, an inverse kinematic position analysis was employed to calculate the different joint angles that would achieve the desired motion. Subsequently, an inverse kinematic velocity analysis was performed to better address the redundancy introduced by the modularity of the robot. A simulation through CosmosMotion was generated to demonstrate the kinematic results.

INTRODUCTION

Modularity in robotics is a concept that has been increasing in popularity over the last years. The principal advantage of working with a modular robot is that different modes can be enabled with the same robot; for instance, a modular robot could walk, crawl, or roll over [1]. The subject of this research project was to develop a quadruped gait for a modular robot, while addressing the additional constrains induced by the modularity. The studied robot possesses four legs. Each leg of the robot consists of links actuated by servomotors at the joints. Each leg can be simplified into a robotic arm with three revolute joints that are articulating three links; which are ultimately attached to the center platform of the robot.

Although modularity brings some advantages in the system, it also induces additional constrains. For instance, the servomotors employed to power the revolute joints have a limited degree of motion. A servomotor can only provide motion in a range of 180 degrees. Such a limited range will make many kinematic maneuvers go into singular positions. In addition, because of the configuration of the robot, the legs will undergo planar motion, making some maneuvers, like turning quiet challenging.

The development of quadruped gaits is a concept long studied. Many researchers have analyzed the motion of the legs for different quadruped robotic systems. Some of those systems differ on the number of the degrees of freedom for each one of the legs and the configuration of the legs [2] [3] [4] [5] [6]. Another fundamental difference between these studies is the type of terrain for operation [3] [5]. Even though all systems have differences, they are approached in the same way. The previously mentioned works differ from this project mainly because they are not concerned about the extra constrains induced by the modularity, and their robotic systems were optimized for quadruped locomotion.

To design the walking gait for the quadruped mode of the modular robot, first a CAD model was developed for kinematic simulation. The initial design consisted in perform an inverse kinematic analysis based on the position of the foot. Because each limb of the robot is a redundant robotic arm, there are infinite solutions for the desired trajectory. Thus, one of the joint was restricted. Subsequently, an inverse kinematic analysis for velocity was performed; the limbs were treated as redundant robotic arms. The redundant velocity analysis does not require a joint angular velocity to be specified. This analysis also optimizes the velocity function by minimizing the norm of the angular velocity vector.

MODELING AND SIMULATION

A 3D CAD model of the modular robot was generated in order to test and simulate all the different gates before implementing them in the actual robot.

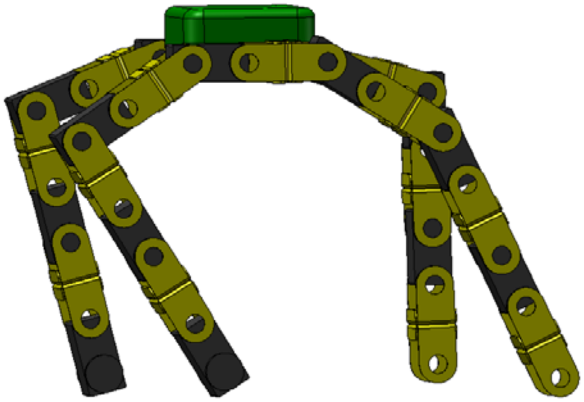


Figure 1. CAD model of the modular robot

QUADRUPED GAIT DESIGN

It was previously stated that each leg possesses three revolute joints that are articulating 3 links. Because each link and joint has to be equally positioned with respect to the others in order to maintain the concept of modularity; it will cause the motion of each leg to be planar. The previous restriction has interesting implications, allowing us to categorize each leg as a redundant robotic arm. A redundant robotic arm is one that possesses more degrees of freedom than necessary to operate in a given geometry. In this particular case, each leg has three degrees of freedom, but only two are necessary to fully describe the kinematic properties of the system. Moreover, the number of kinematic equations is directly related to the dimensions of the space. In this case, a two dimensional or planar space will allow us to characterize two equations for the kinematic analysis based on position.

If a system possesses more degrees of freedom than the ones required to describe the system; thus, infinite number of solutions will hold true. A set of two linearly independent equations will allow us to find a unique set of solutions for only two different variables. In this case, there are three variables, one for each revolute joint. Therefore, it is necessary to continuously define the position of one of the joints in order to define the system with a unique set of solutions.

The first step was the trajectory planning for an individual leg. All the legs move with similar trajectories, but in different phase. Thus only small changes are required to characterize the trajectory of the four legs. The first analyzed trajectory corresponded to an arc, half of an ellipse. When the inverse kinematics was solved for that trajectory it was found that the leg was reaching singular positions; thus, the trajectory had to be modified. In order to find out the joint angles, the trajectory was discretized and the inverse kinematic was solved for each discretized position along the intended trajectory. The trajectory was

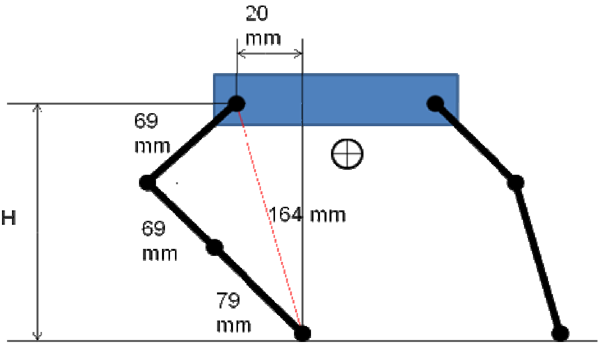
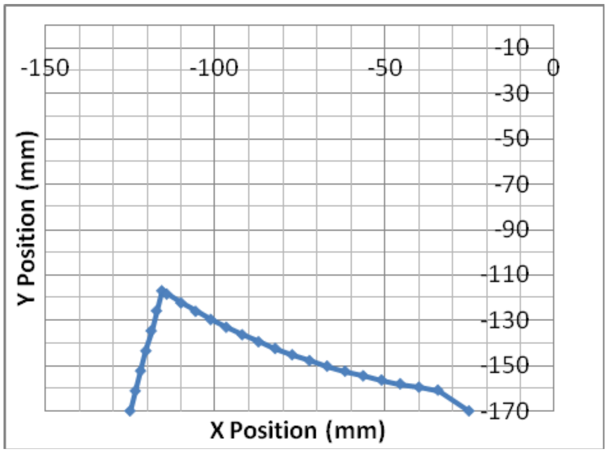
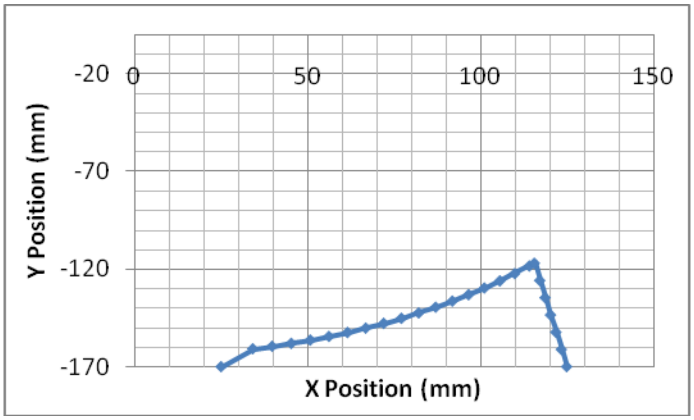


Figure 2. Schematics describing the limiting point of the trajectory



(a)

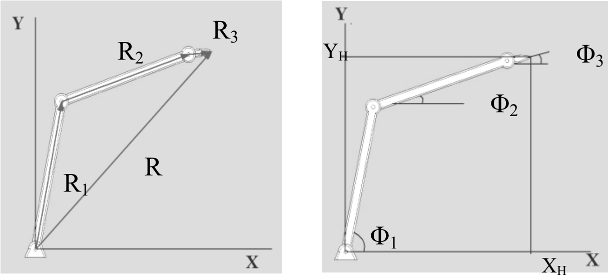


b)

Figure 3. Modified trajectory for (a) rear leg, and (b) front leg

Kinematic Position Analysis

The governing equations for the kinematic analysis based on the position analysis are derived from the vectorial representation of the links and dividing them into their orthogonal components.



(a) (b)

Figure 4. (a) Vector representation of the robot arm, (b) Joint angle definition

$$\vec{R}_H = \vec{R}_1 + \vec{R}_2 + \vec{R}_3$$

where

$$\overrightarrow{R_i} = a_i Cos\theta_i \hat{i} + a_i sin\theta_i \hat{j} \qquad i = 1, 2, 3$$

Thus,

$$x_H = a_1 \cos\phi_1 + a_2 \cos\phi_2 + a_3 \cos\phi_3$$
$$y_H = a_1 \sin\phi_1 + a_2 \sin\phi_2 + a_3 \sin\phi_3$$

It was necessary to continuously define the position of one of the joints. Several possibilities were contemplated, until it was decided that the angle of the second joint would be equal to the angle of the third joint, to simplify the initial analysis, resulting in the following simplified set of equations.

$$x_H = a_1 \cos\varphi_1 + (a_2 + a_3) \cos\varphi_2$$
$$y_H = a_1 \sin\varphi_1 + (a_2 + a_3) \sin\varphi_2$$

For each leg position, there are two possible solutions. Those two solutions are often referred as closures of the system.

Kinematic Position Analysis Results

Only one set of solution is valid, and the other one violates the joint range imposed by modularity.

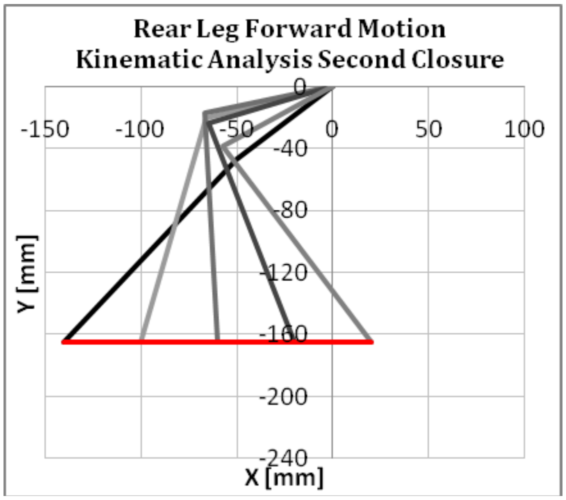


Figure 5. Kinematic analysis for rear leg, second closure

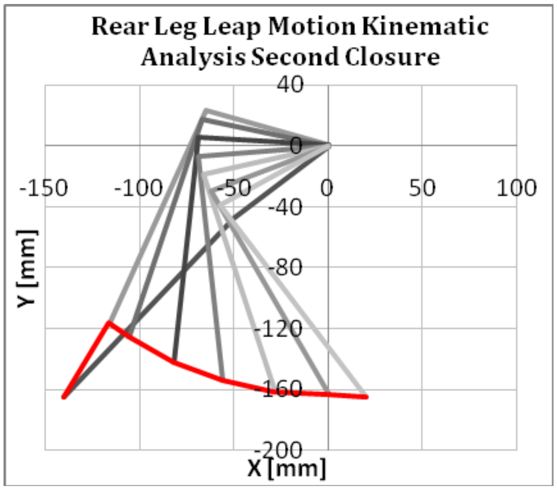


Figure 6. Kinematic analysis for rear leg, second closure

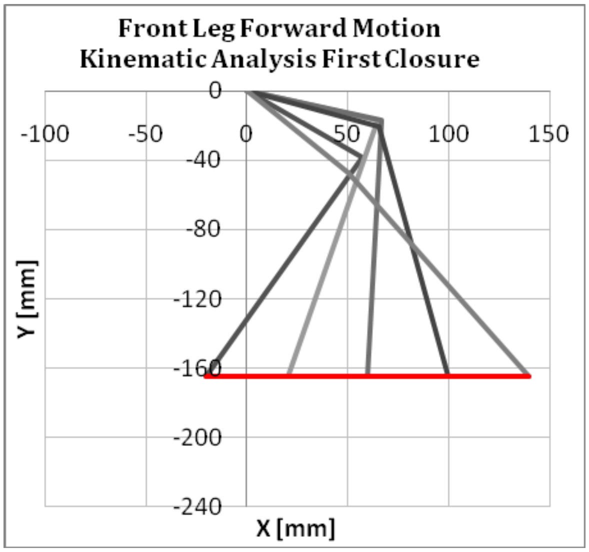


Figure 7. Kinematic analysis for front leg, first closure

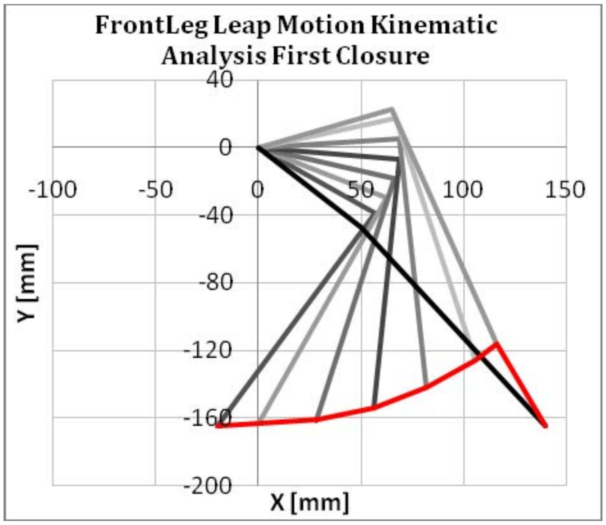
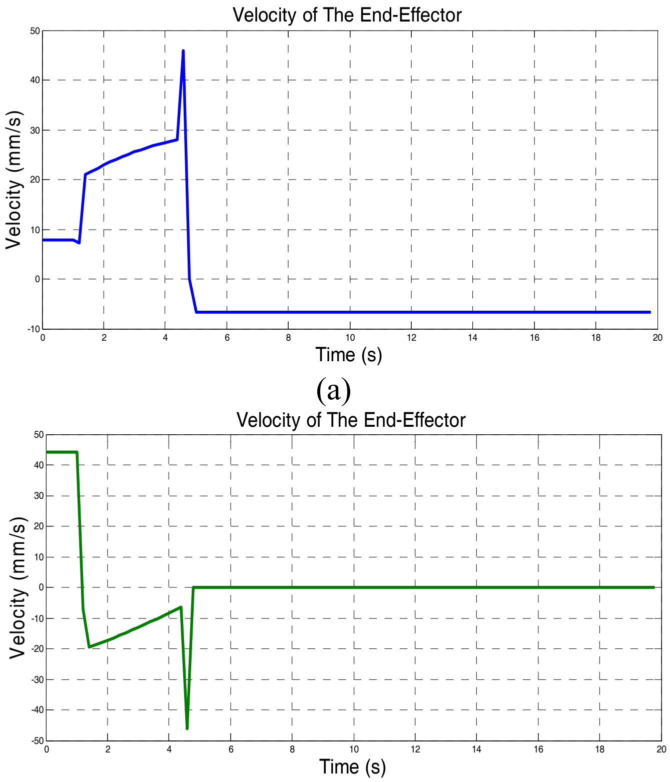


Figure 8. Kinematic analysis for front leg, first closure

Kinematic Velocity Analysis

The trajectory selected for the position analysis was employed to derive the reference velocity for the kinematic analysis. The derived equation corresponds to the input velocity of the foot in X and Y direction. Numerical diferenciation was employed to obtain the reference velocities.



(a)

(b)

Figure 9. Input velocity of the end-effector for (a) the x-axis, and (b) the y-axis

Once the position equations are differentiated with respect to time the result is

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} \frac{\partial x_h}{\partial \phi_1} & \frac{\partial x_h}{\partial \phi_2} & \frac{\partial x_h}{\partial \phi_3} \\ \frac{\partial y_h}{\partial \phi_1} & \frac{\partial y_h}{\partial \phi_2} & \frac{\partial y_h}{\partial \phi_3} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

In short form: $\vec{v} = J \cdot \vec{w}$

The best way to solve this system is through the pseudo Jacobian matrix (J^+)

When the pseudo Jacobian method is employed the square of the norm of the velocity vector is minimized.

$$\|\vec{w}\| = w_1^2 + w_2^2 + w_3^2$$

Is minimized, resulting in the optimal solution from the velocity point of view.

To calculate the pseudo Jacobian the following relationship is employed.

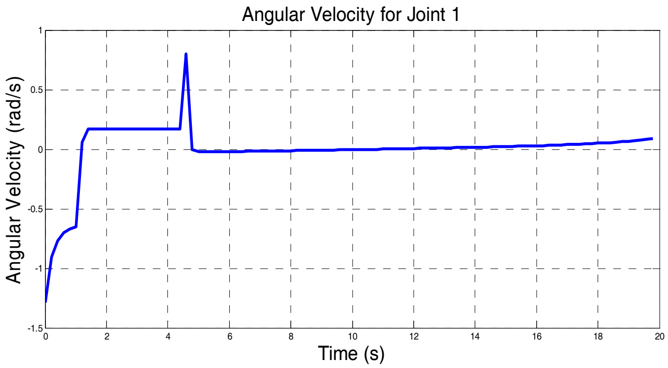
$$J^{+} = J^{T}\left(J \cdot J^{T}\right)^{-1}$$

Once the pseudo Jacobian is computed, the solution of the system can be found with the following relationship

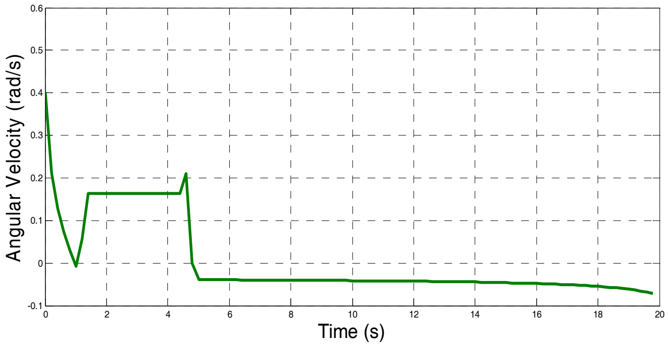
$$\vec{w} = J^{+} \cdot \vec{v}$$

Kinematic Position Analysis Results

Once the previously described equations for the angular velocities were solved employing the discretized set of input velocities, the results are:



(a)



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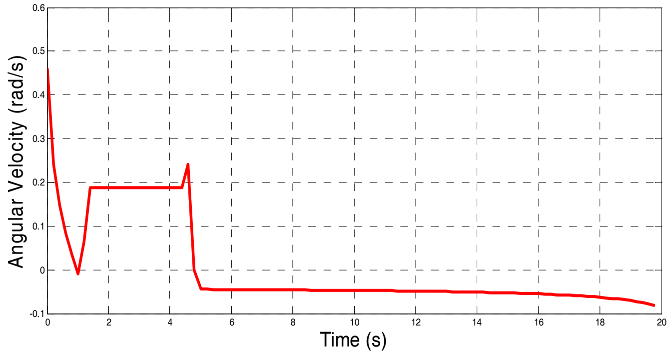
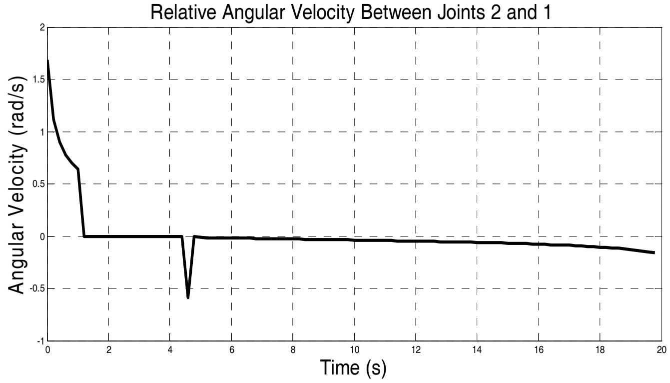


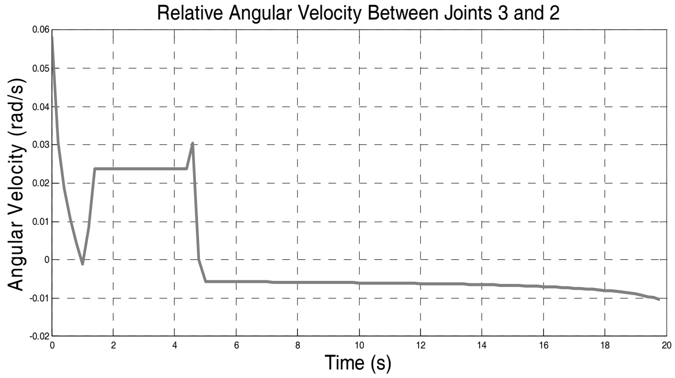
(c)

Figure 10. Angular velocities of (a) Joint 1, (b) Joint 2, and (c) Joint 3

It is also significant to take a closer look to the relative velocities between adjacent links:



(a)



(b)

Figure 11. Relative Angular Velocities between (a) links one and two, and (b) links three and two

The set of values obtained for the front leg look very similar but flipped around the y-axis. To calculate the position of the end-effector at any given time, numerical integration was employed.

CONCLUSION AND DISCUSSION

It was possible to successfully develop a quadruped gait for the modular robot. The inverse kinematics analysis was proven to be extremely effective to model de angles of the joints. The kinematic position analysis was solved employing a spreadsheet, this solution allowed us to modify all the different parameters influencing the desired path until the desired solution was acquired.

Subsequently, for the kinematic velocity analysis matlab was employed to solve for the different equations and compute the pseudo Jacobians of each point. This solution is preferred over the position analysis, since this solution minimizes the norm of the angular velocity vector, which implies in minimum changes in angular velocity, resulting in less power consumption.

For this initial development, the surface in which the robot would be walking was modeled as flat and parallel to the horizon. It was observed that the walking surface can be modeled as an inclined plane, but its implementation will be suggested as future work, It could not be simulated due to time constrains. In addition, it was observed that it is possible to develop a turning maneuver. A sharp turn would be impossible due to hardware limitations, since all the leg of the robot are planar and do not undergo side motion. A slight turning maneuver can be enabled by slightly varying the length of the planed path for one side of the robot, or by slightly modifying the speed of one side of legs with respect to the other one.

Another limitation was found with the robot microcontroller, because its memory only allows about 500 lines of code. The quadruped gait pretty much consumed the memory of the microcontroller, since each joint angle has to be specified every 20 milliseconds, otherwise the joint will not hold their position and the robot will fail. It is necessary to upgrade the microcontroller or to insert an additional one to enable more capabilities.

FUTURE WORK

There are many areas that can be implemented to increase the functionality of the robot.

As previously mentioned, the ground can be modeled as an inclined plane to improve the maneuverability of the robot in front of different scenarios. It was observed that an inclined plan can be easily modeled and implemented in the kinematic analysis and simulation. Not only inclined planes can be easily modeled and simulated, other maneuver such as the turning maneuver can be implemented just by slightly varying the path length, or velocity on one side of the robot's gait.

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