Dynamics of Biomimetic Robotic Self-Assemblages

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***Abstract*—This paper explores the dynamics of active structures made up of individual robots. This approach is inspired by the living bridges that army ants create to cross large gaps. Similarly, to Army Ants each robot is independent, however, they all need to create one active structure. To achieve this goal each robot must understand its individual kinematics and dynamics to move so that the overall structure achieves the desired behavior. We propose the usage of one dynamic model to find the required vectors for the movement of the structure, and the usage of another to simulate the dynamics of each individual robot. We conclude this paper with a simulation of an active structure made up of individual robots and a discussion of their potential uses.**

***Index Terms*—Active Structures, kinematics, dynamics, biomimicry**

I. Introduction

Modular and active structures have a wide range of uses, ranging from containing oil spills by attentively linking together to surround and contain the oil to rapidly and autonomously constructing temporary bridges in disaster ridden areas. To create this technology engineers must look towards biomimicry, specifically the behavior that army ants exhibit while traversing large gaps. In nature if a group of army ants needs to cross a large gap, they form a "living bridge" to cross the gap. To achieve this goal each ant must understand where it must be in the 'bridge' and understand how it must move to create said 'bridge', in other words the ants must have an internal kinematic and dynamic model, as well as an understanding of the 'bridge's' kinematic and dynamic model.

This paper endeavors to demonstrate a primitive version of this technology by utilizing omniwheel driven robots to create a 'virtual' object that exhibits its own specific behaviors. This paper utilizes this kind of robot because are "… a much sought solution to mobile robotic applications.", as well as the presence of pre-existing gazebo models for use in simulation. In addition to this in "Dynamical Models for Omni-Directional Robots with 3 and 4 Wheels" there are pre-written dynamics equations that were utilized to create an inverse kinematic algorithm to allow the robots to achieve a pre-specified velocity vector. This velocity vector was calculated by utilizing a custom written algorithm that takes in the over all "shape" of the imaginary object composed of the robots, as well as its desired behavior to generate a required velocity vector for each individual robot.

We have demonstrated the dynamic model of the individual robots, however due to a lack of time we were unable to demonstrate the dynamic model of a self-assemblage made up of 3 robots. In the future we can develop a dynamic model for the self-assemblage which will have an impact on the future creation and utilization of dynamic structures.

II. Background

A. Omni-directional Robot Dynamics

Omni-directional robots are a much sought after solution due to their greater maneuverability and efficiency, compared to other more traditional wheeled robots. This extra maneuverability allows omni-directional robots to follow any vector on the 2d plane.

B. Insect Behavior

In many insect societies, including but not limited to army ants, adaptive and dynamic structures are formed by individual insects linking together. Examples of this behavior include army ants building bridges to cross gaps rapidly, building rafts in floods to avoid drowning, and many more. These structures can typically be categorized into 5 non-exclusive categories,"... defense, pulling structures, thermoregulation, colony survival under inclement conditions, and ease of passage when crossing an obstacle". Each structure forms to solve problems for the entire society of insects.

C. Claytronics

Claytronics is a concept derived from programmable matter where an item can be made up of individual 'Catoms', which can assemble into various objects. This can allow for a swarm of robots to assemble static and dynamic structures ranging from bridges and cups to robotic arms and cars.

D. Modular Robotics

Robots in dynamic and changing environments must be able to adapt to their changing circumstances. One way of doing this is for the robots to change their shape depending on the situation. For example a robot made up of only hinge joints could shape itself like a tank tread and roll, or it can change into a more worm or serpent-like configuration depending on the environment. This can allow for a robot to go achieve differing tasks without requiring additional components.

III. CAD and URDF Models

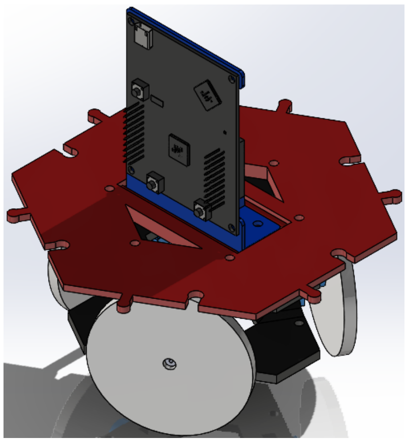

Fig. 1. Robot Design Orthogonal

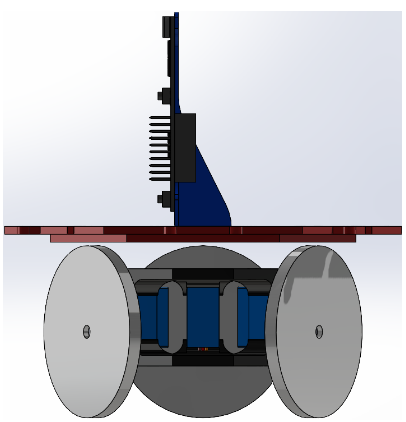

Fig. 2. Robot Design Side

A. Design Philosophy

The robot design, as seen in figures 1-3, is centered around a 'puzzle-piece' like component for maximum flexibility. This component allows for easy assembly of different configurations of robots. The hexagonal shape is used due to it providing the maximum amount of locations that the robots can be configured in while still being capable of maintaining a filled in shape. Due to this arrangement, the amount of robots in each configuration is theoretically infinite, while still potentially allowing the robots to work individually.

B. Creating the URDF Model for the Design

To create the URDF model from the Solidworks model the Solidworks to URDF exporter plugin was used.

C. Reasoning behind utilizing a different URDF Model

Due to difficulties in importing the generated URDF model into Gazebo a more simplistic model was used for simulation as seen in Figure 4.

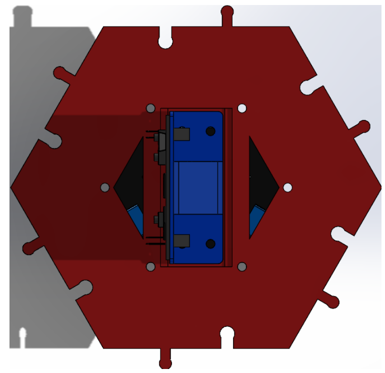

Fig. 3. Robot Design Top

IV. Equations

1) Kinematic Model: The input for the model is a position trajectory in (x, y, θ). We can find the desired velocity by taking a derivative of the positions to get (v_x, v_y, ω).

The robot velocities in the world frame are represented by (v_x, v_y, ω). The robot velocities in the robot frame are represented by (v, vn, ω). One should note that ω is common in the world frame and the robot frame.

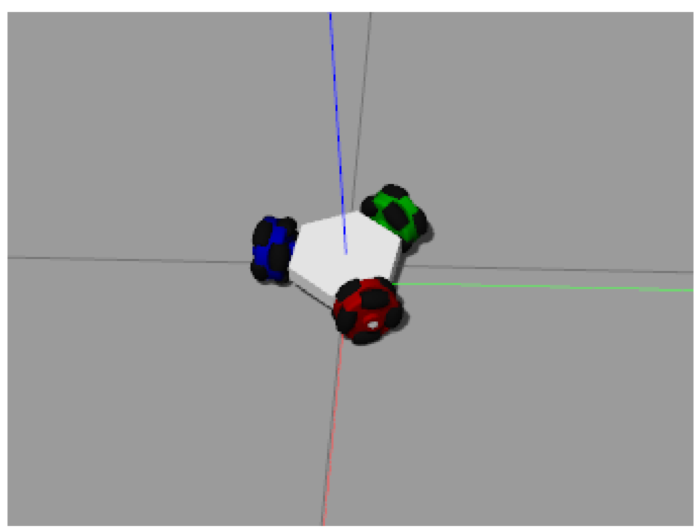

Fig. 4. Image of the Simulation of 1 Robot

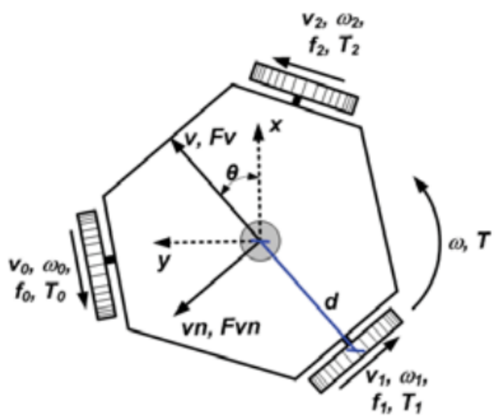

Fig. 5. 3-Wheeled Robot

The transformation from the world frame to robot frame is given by the following rotation matrix

$$\begin{bmatrix} c\theta & s\theta & 0 \\ -s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The relation between the wheel velocities and the robot velocities in robot frame is as follows

$$\begin{bmatrix} v_0(t) \\ v_1(t) \\ v_2(t) \end{bmatrix} = \begin{bmatrix} -\sin(\pi/3) & \cos(\pi/3) & d \\ 0 & -1 & d \\ \sin(\pi/3) & \cos(\pi/3) & d \end{bmatrix} \cdot \begin{bmatrix} v(t) \\ vn(t) \\ \omega(t) \end{bmatrix}$$

2) Dynamic Model: Before we see the Dynamic model, let us define a few terms

K_t = Motor torque constant
l = Gear box reduction
B_v = Viscous friction coefficient in direction of v
r = Radius of the wheels
R = Motor resistor
M = Mass of the robot
d = Distance between wheels and the robot center
B_{vn} = Viscous friction coefficient in direction of vn
B_w = Viscous friction coefficient for ω
J = Inertia moment
C_v = Coulomb friction, coefficient in direction of v
$C_v n$ = Coulomb friction coefficient in direction, of, vn
C_w = Coulomb friction coefficient for ω

The values for these parameters can be found in the code.

As presented in "Dynamical Models for Omni-directional Robots with 3 and 4 Wheels" [1], the Dynamic Model in the State-Space representation is as follows:

$$\dot{x} = Ax(t) + Bu(t) + Ksign(x)$$

where

$$A = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix}$$

$$A_{11} = \frac{-3(K_t)^2 l^2}{2r^2 RM} - \frac{B_v}{M}$$

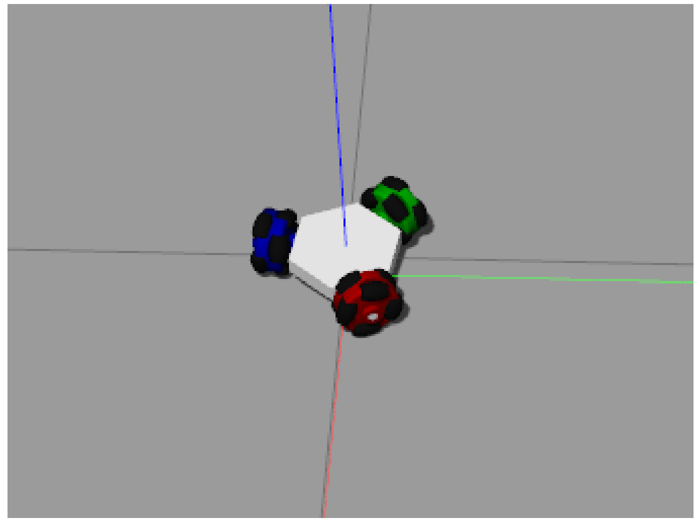

Fig. 6. Image of the Simulation of 1 Robot

$$A_{22} = \frac{-3(K_t)^2 l^2}{2r^2 RM} - \frac{B_{vn}}{M}$$

$$A_{33} = \frac{-3d^2(K_t)^2 l^2}{r^2 RJ} - \frac{B_w}{J}$$

$$B = \frac{lK_t}{rR} \begin{bmatrix} -\frac{\sqrt{3}}{2M} & 0 & \frac{\sqrt{3}}{2M} \\ \frac{1}{2M} & \frac{1}{M} & \frac{1}{2M} \\ \frac{d}{J} & \frac{d}{J} & \frac{d}{J} \end{bmatrix}$$

$$K = \begin{bmatrix} -\frac{C_v}{M} & 0 & 0 \\ 0 & \frac{C_{vn}}{M} & 0 \\ 0 & 0 & \frac{C_w}{J} \end{bmatrix}$$

V. Simulation

A. Single Robot Simulation

Originally, we planned to create our own model within the URDF format. However, it quickly became apparent to us that modelling the omniwheels correctly would be a major task in an of itself. To get around this issue we found an open source library called OpenBase. OpenBase allows us to spain a very similar robot to our own and command it to move to a desired position. The outputs from our trajectory generation could be used to command the robot to follow our desired path and verify its accuracy.

Our model accounts for the positions of three robots simultaneously. Unfortunately, we found out too late that this library only works with a single model and behaves erratically with multiple models in the simulation at once. We utilized a custom Gazebo model and ran the robot through a pre-planned trajectory to test the dynamic model.

B. Individual Robot Dynamics

Based off of the paper "Dynamical Models for Omni-directional Robots with 3 and 4 Wheels" a dynamic model of a 3 wheeled robot was created in Gazebo.

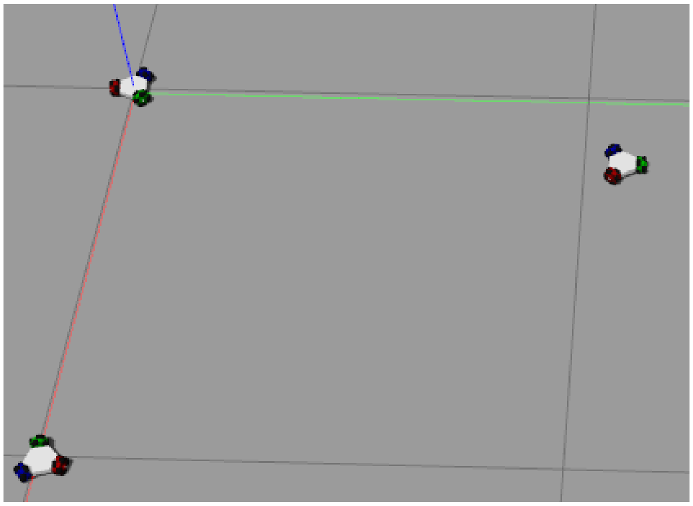

Fig. 7. Image of the Simulation of 3 Robots

C. Robot Self-Assemblage Dynamics

The dynamic model worked as expected for a single robot but we were unable to verify the model for multiple robots.

VI. Practical Demonstration

The CAD model was designed in the first place to have a working model of 3 robot to demonstrate the concept talked about in the above sections. Besides the CAD model, we were able to test the motors that were purchased for the robots. A 16-channel Servo driver was to be used for controlling the wheels of the robots.

We generated 5^{th} order trajectories for position, velocity, and acceleration for the robot in world frame. The equations can be found in the MATLAB codes in the repository for this project.

Fig. 8. 16-Channel Servo Driver

We planned to use 360°continuous rotation servos for running the omniwheels. The servos need a signal line, 5V supply, and a ground connection to operate.

Due to time constraints we were unable to assemble the system of robots for a practical demonstration, however, we have managed to connect the electronics together for a partial demonstration.

VII. Discussion

We were able to study the Kinematics and Dynamics of a 3-Wheeled Omni-Directional Robot, and successfully implemented the models in C++. Additionally, we worked on

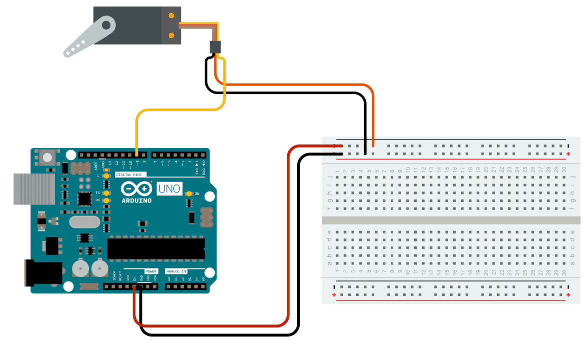

Fig. 9. Servo Motor connection with Arduino

generating quintic trajectories for the robot in world frame as reference path to follow in simulation as well in our practical demonstration. We moved on to design a CAD for our robot, but we were unable to 3-D print the model due to time and resource constraints.
The team spawned the OpenBase omniwheeled robot in Gazebo and was able to control the position of the robot. Further work on simulation can be carried out by feeding in the velocity trajectories that were generated. A considerable amount of effort was put in to spawn the custom CAD model in Gazebo and to conttrol it, but this step was not completed. Moreover, were able to test and implement randomly generated position trajectories on Servo motors. A primitive demonstration can be found in the presentation. MATLAB was used to generate all the trajectories.

VIII. Conclusion

To truly create modular and active structures, researchers must look towards biomimicry. These structures have uses ranging from making temporary bridges to cross large gaps ,by connecting together to form a bridge, to rapidly creating rafts in disaster situations, by connecting the robots together to form it. However, to start creating this technology the primitive versions of it must be developed. Sadly in this paper due to time constraints we were unable to demonstrate the use of our equations to simulate self-assemblage dynamics. However, in the future it should be possible to demonstrate this capability since we have already demonstrated the dynamic model of an individual omni-directional robot.

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