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Abstract—In order to control a modular wheeled snake robot, there is a complexity of generating a control input that satisfies non-holonomic constraints which depends on the robot configuration. For a pole climbing application in which the modular snake robot is required to climb a cylindrical pole vertically, we proposed a control method for the modular snake. By generating the control input such that the pose of the robot follows a helical curve configuration, the control input is constrained to be within the null space of the non-holonomic constraint where the desired velocity can be mapped directly to one-dimensional control input signal of the robot. The proposed controller was successfully implemented and tested in our modular pole climbing snake robot.

Index Terms—Modular Snake Robot, Non-holonomic Control, Pole Climbing.

I. INTRODUCTION

A modular snake robot is the robot that is constructed in the modular structure where joints and links are ... design type. This robot is also considered as hyper-redundant [1] because the robot degrees of freedom are much larger when compare to the number of dimensions of the task. Most research in this area concern with the generation of snake-like or crawling gaits [2, 4]. Some research focus on the inverse kinematic problem which complex due to the hyper-redundant of the robot. By adding wheel to each module of the snake robot, its complexity is additional from the non-holonomic constraints created from the wheel.

Our specific interest in a modular snake robot is in pole climbing applications. There are needs in service and construction industry for a robot that can climb a pole or a pipe or even a tree. Thus, we have designed and constructed a modular wheeled snake robot that can be used for pole climbing application because of its light weight and its ability to adapt to various size of structure. There has been many works in climbing gait for snake robot. The first grasping gait that applied from travelling wave amplitude constant (TWAC) was presented by Chirikjian and ... [1]; they use this gait to control the snake robot to coil around the pole. After that, numerical solution for discretized 3D path and inverse kinematic for snake robot was also presented by [3]. Then, Choset [4, 5] applied piecewise differentiable gait to create climbing gait of the snake robot. This gait can climb by rolling up vertically with helical configuration. He also su... Drive (TSD) which the robot ... using wheels. He had the locomo... driving such as crossing the gap, ... helical trajectory. Suresh [6] built the comme... pruning machine to cut tree's bra... the helical rolling concept to c... wheels that lock around the tree'...

Our research is focus on the mo... With the wheeled modular snake ro... climbing can be reduced ... non-holonomic constraints created by the wheel. In this paper, a ... controller is proposed to use fo... algorithm for the robot with non-holonomic constraints. In the next sectio... system's overview e.g. the struct... system, dynamics model of robot's ... constraint; the proposed helical ... from our experiment.

II. SYSTEM'S OVERVIEW

A. Robot structure

The robot's structure of modular ... links and joints which has 3 degrees of freed... the robot has length of 11.75 cm with height ... link attached with two active wheels 10 cm diameter, 1 cm thickness. The rob... aluminium sheet. The motors ... (Robotis Dynamixel RX-28) ... use one motor ... drive link's wheels. The total ... approximately 3 kg.

Fig. 1. CAD model of the modular snake robot.

B. Control system

The motor that use in the robo... which has low-level position control, we onl...

protocol RS-485 to control the motor. The position of each motor is calculated and then sent from the computer as position control. The microcontroller (ATMEGA128) is used to convert the position data that received from computer via RS-232 to motor's protocol packet and send to the motor. The Robot's power is supplied from external power supply. The simple control system diagram is shown in fig. 2.

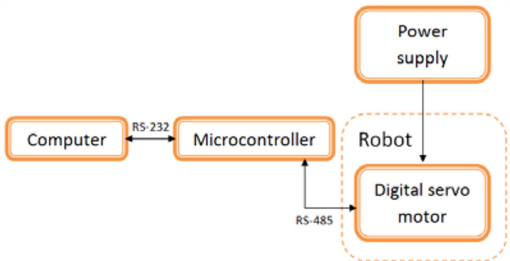

Fig. 2. System design of the modular snake robot.

C. Reference frame description

The world reference frame was set that the axis y is normal to the ground plane. Each link's reference frame can be described as follow. X axis located along the link's length. The angle that rotates around x axis is the roll angle. Pitch angle and yaw angle are the angles that rotate around z axis and y axis respectively.

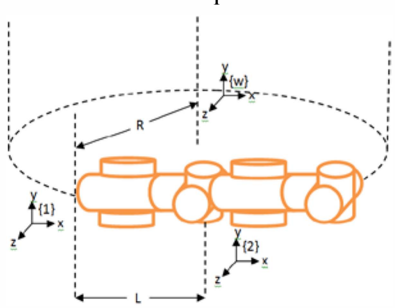

Fig. 3. Robot's frame assignment.

III. DYNAMIC MODEL OF THE ROBOT

The dynamic model of the snake robot is derived from Lagrangian method. Robot's structure is assumed to be a rigid. The robot's wheels are also assumed to be in a non-slip condition. The link's dynamic model of the robot can be written in general form like equation

$$\tau_i = M_i(q_i)\ddot{q}_i + V_i(q_i, \dot{q}_i) + G_i(q_i) + J_i^T(q_i)\lambda \quad (1)$$

With $q_i = [\alpha_i\ \beta_i\ \gamma_i\ \theta_i]^T$ and $\tau_i = [\tau_\alpha\ \tau_\beta\ \tau_\gamma\ \tau_\theta]^T$

Assumes n as the number of link.

The angles $\alpha_i, \beta_i, \gamma_i, \theta_i$ and $\tau_\alpha, \tau_\beta, \tau_\gamma, \tau_\theta$ are the roll angle, pitch angle, yaw angle, rolling angle of robot's wheel, roll torque, pitch torque, yaw torque, and wheel's torque, respectively. $J_i(q_i)$ is the non-holonomic constraint term that has the null space matrix of form

$$M = O \quad (2)$$

Let,

I_x, I_y, I_z : Moment of inertia of the whole link,
I_w : Moment of inertia of the wheel,
l : Link's length,
m : Link's mass,
r : Wheel's radius, and
g : Acceleration due to the gravity.

Then the matrices used in the link's

$$M_i = \begin{bmatrix} M_{11} & 0 & 0 & 0 \\ 0 & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & 0 \\ 0 & 0 & 0 & M_{44} \end{bmatrix} \text{ with}$$

$M_{11} = ml^2 + I_x$, $M_{33} = ml^2 + I_y$,
$M_{22} = ml^2 + I_z$, $M_{44} = mr^2 + I_w$

$V_i = 0$ and

$G_i = [G_1\ G_2\ 0\ 0]^T$ with

$G_1 = -mlg \sin\alpha_i \cos\beta_i$

$G_2 = -mlg \cos\alpha_i \sin\beta_i$

After that, global dynamic model can be expressed in matrix form as follows:

$$\begin{bmatrix} \tau_1 \\ \vdots \\ \tau_n \end{bmatrix}_{4n\times 1} = \begin{bmatrix} M_1 & & \\ & \ddots & \\ & & M_n \end{bmatrix}_{4n\times 4n} \begin{bmatrix} \ddot{q}_1 \\ \vdots \\ \ddot{q}_n \end{bmatrix}_{4n\times 1} + \begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_n \end{bmatrix}_{4n\times 1} \quad (3)$$

From the local matrix, one link has 4 control parameters in joint variables. So, the consideration of n links robot has $4n$ parameters in joint variables. In the task space that transforms the joint coordinate to Cartesian coordinate

$$\tau_X = M_X(X)\ddot{X} + V_X(X, \dot{X}) + G_X(X) + J_X^T(X)\lambda \quad (4)$$

With $X_i = [x_i\ y_i\ z_i\ \beta_i]^T$

IV. ROBOT'S MOTION CONSTRAINT

From the structure of the robot each links, the assumption about slip that prevent the links from side slip can be derived the constraint that consist of holonomic and non-holonomic constraint.

Holonomic constraint can be written

$$x_i = x_1 + \sum_{j=1}^{i-1} L C\beta_j C\gamma_j + \frac{L}{2} C\beta_i C\gamma_i \quad (5)$$

$$y_i = y_1 + \sum_{j=1}^{i-1} L(C\alpha_j S\beta_j C\gamma_j - S\alpha_j S\gamma_j) + \frac{L}{2}(C\alpha_i S\beta_i C\gamma_i + S\alpha_i S\gamma_i) \quad (6)$$

$$z_i = z_1 + \sum_{j=1}^{i-1} L(S\alpha_j S\beta_j C\gamma_j + C\alpha_j S\gamma_j) + \frac{L}{2}(S\alpha_i S\beta_i C\gamma_i + C\alpha_i S\gamma_i) \quad (7)$$

We will get the trajectory of the robot by differentiate the equation 5-7

$$\dot{x}_i = \dot{x} - \sum_{j=1}^{i-1} L\left(\dot{\gamma} C\beta_i S\gamma + \dot{\beta} S\beta_i C\gamma\right)_i - \frac{L}{2}\left(\dot{\gamma} C\beta_i S\gamma_i + \dot{\beta} S\beta_i C\gamma_i\right) + r\dot{\theta}\left(C\beta_i C\gamma_i\right) \quad (8)$$

$$\dot{y}_i = \dot{y} + \sum_{j=1}^{i-1} L\begin{pmatrix} \dot{\beta} C\alpha_i C\beta_i C\gamma_i - \dot{\gamma} C\alpha_i S\beta_i S\gamma_i \\ -\dot{\alpha} S\alpha_i S\beta_i C\gamma_i + \dot{\alpha} C\alpha_i S\gamma_i - \dot{\gamma} S\alpha_i C\gamma_i \end{pmatrix}_i + \frac{L}{2}\begin{pmatrix} \dot{\beta}_i C\alpha_i C\beta_i C\gamma_i - \dot{\gamma}_i C\alpha_i S\beta_i S\gamma_i \\ -\dot{\alpha}_i S\alpha_i S\beta_i C\gamma_i + \dot{\alpha}_i C\alpha_i S\gamma_i - \dot{\gamma}_i S\alpha_i C\gamma_i \end{pmatrix}_i \quad (9)$$

$$\dot{z}_i = \dot{z} + \sum_{j=1}^{i-1} L\begin{pmatrix} -\dot{\gamma} S\alpha_i S\beta_i S\gamma_i + \dot{\alpha} C\alpha_i S\beta_i C\gamma_i \\ +\dot{\beta} S\alpha_i C\beta_i C\gamma_i + \dot{\alpha} S\alpha_i S\gamma_i - \dot{\gamma} C\alpha_i C\gamma_i \end{pmatrix}_i + \frac{L}{2}\begin{pmatrix} -\dot{\gamma}_i S\alpha_i S\beta_i S\gamma_i + \dot{\alpha}_i C\alpha_i S\beta_i C\gamma_i \\ +\dot{\beta}_i S\alpha_i C\beta_i C\gamma_i + \dot{\alpha}_i S\alpha_i S\gamma_i - \dot{\gamma}_i C\alpha_i C\gamma_i \end{pmatrix}_i$$

For non-holonomic constraint of each link, it simply describe in local coordinate of the link as

$$\dot{y}_{local} = 0 \quad (10)$$

In global coordinate consideration, we multiply with rotational term to transform non-holonomic constraint as follow

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{z}_i \end{bmatrix} = \begin{bmatrix} {}^{W}_{i}R \end{bmatrix} \begin{bmatrix} 0 \\ \dot{y}_{local} \\ 0 \end{bmatrix} \quad (11)$$

V. HELICAL PATH CONTROLLER

The objective of this research is to develop a modular wheeled snake robot that can be used for pole climbing application. For climbing a pole vertically, the snake robot must be able to [illegible] two objectives. First, it should be able to grasp the pole without falling vertically by gravitational force. Second, it should use non-holonomic constraint to support the robot weight while grasping and climbing the pole. For the first objective, robot must coil around the pole in order to generate the necessary amount of grasping force. For the second objective, moving path of the robot should have sufficient angle of elevation with the [illegible] to move robot upward. Another consideration is the non-holonomic constraint in each link of the robot. Constraint of each link should not conflict with others.

We can use 3 equations to define the helix moving path as follow.

Fig. 4. Circular helix path.

$$z = R\cos(\theta) \quad (12)$$

$$x = R\sin(\theta) \quad (13)$$

$$y = \frac{P \cdot \theta}{360} = \theta R \tan\phi \quad (14)$$

Where P, R, θ, and φ are the pitch distan[ce], radius on z-plane, the angle parameter, helical pitch angle.

The helical path has two input[s] ... helical radius. After we define he[lical] ..., it simply discretize the helical curve to ... link's frame respect to the world frame. Because the helical path is genera[l] function, we multiply with rotational ... follow tangent between helical ... length. We then use the relation ... calculate the rotation matrix of ... of the link i-1.

The inverse kinematics can by ... between rotation matrix and Eul[er] ... Equation 15-17 use to find the angle that us[e] command the robot to assume the h[elix]

$$R = \begin{bmatrix} c\beta c\gamma & -s\beta & c\beta s\gamma \\ c\alpha s\beta c\gamma + s\alpha s\gamma & c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma \\ s\alpha s\beta c\gamma - c\alpha s\gamma & s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma \end{bmatrix}$$

$$\alpha = \operatorname{atan2}(r_{32}, r_{22}) \quad (15)$$

$$\beta = \operatorname{asin}(-r_{12}) \quad (16)$$

$$\gamma = \operatorname{atan2}(r_{13}, r_{11}) \quad (17)$$

After the helical path control is [illegible] the non-holonomic constraint of each link will have the same value. If we c... and the pole by spread out the po... see that all the vector of non-holonomic constraint are parallel (Fig. 5). This implies that actual wheel velocity input for each link ... within the null space of non-holonomic constraint.

(equation 2). Thus, for each module, the control input can be reduced to 4 ... parameter of the helical path from used to control 5 degrees of helical. At pitch ...

The implementation of this proposed controller consists of at 3 main parts. The first part is the inner control loop which is built in position control function of each motor for all modules. Each motor receives angular position command. The second part is the helical controller that used to transform the helical path into the rotation angle for each motor. The last part is velocity generator that receives the climbing velocity command and transforms it to the desired angular velocity of the robot's wheel. The system diagram can show in fig. 6.

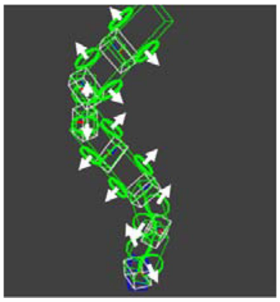

Fig. 5. the robot after apply the result angle and holonomic

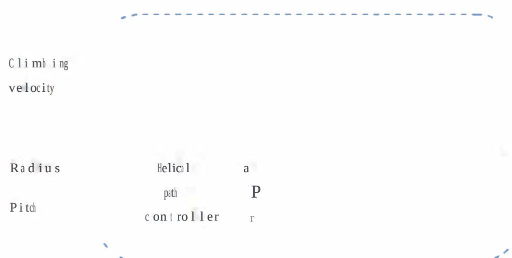

Fig. 6. System diagram.

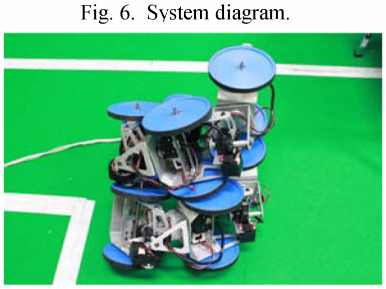

Fig. 7. The prototype snake robot.

The helical climbing gait is simply to control climbing speed than non-holonomic wheeled that is needed to control joint angle. This is because the structure is more complex for the ... climbing.

VI EXPERIMENTAL RESULTS

We applied the helical controller to the robot and set up the climbing experiment to confirm the effectiveness of the proposed controller in real situation. The pole used in the experiment has diameter of 45 cm. The pole was wrapped with 1 mm thick carpet to create the high friction surface. Due to the wheel offset, we used 12.75 cm radius as the input

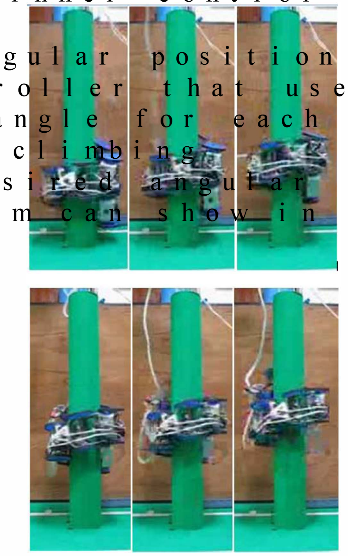

Fig. 8. Climbing experiment of the robot.

VI CONCLUSIONS

In this paper, we proposed the ... provides the control solution for ... robot for pole climbing. The complexity of non-holonomic constraints that exist in ... snake robot can be reduced by imp... to keep the robot in the helical path ... velocity ... input of all modules to lie with ... holonomic constraints. The helical ... the real robot and the experiment ... successfully climb the pole at the ...

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