Variable Twist Angle of Flexible Electromagnetic Hyper Redundant Robot

Amir Sharizam Ismail, Samsi Md Said, Ishkandar Baharin

Abstract— Denavit Hartenberg (D-H) Kinematic structure representation of robot having revolute joint normally have fix arm length a, offset distance d, twist angle α and only varied joint angle θ. This paper introduce two (2) inputs variable of twist angle α and joint variable θ besides fix value of arm length a and offset distance d. Variable value of α and θ are dependent on polar electromagnetic actuator actuation sequence. The actuator extension and their combination will determine the joint variable value of joint angle θ and twist angle α. This electromagnetic muscle is arranged in four (4) polar arrays around disk body. Even though the electromagnetic muscles are classified as prismatic joint, their sequence and combination of operation producing two joint variables of joint angle θ and twist angle α. Output from this forward kinematic model is the end effector $NOAP$ matrix and its yaw, pitch and roll orientation representation. This novel module is intended for building a high assemblage of Hyper Redundant Robot. A low cost polycarbonate plastic and spring are used for structure of flexible body module. Coil of more than 1000 $turns$ is employ in order to generate distance extension. The Programmable Logic Controller (PLC) is used to manage the sequence of energizing the coils for having value of $\propto$ and θ.

Index Terms— Snake Robot, Low Cost, Flexible Body, Kinematic Model

1 INTRODUCTION

DENAVIT Hartenberg [1] representation of single degree of freedom robot requires four parameters such as arm length a, offset distance d, twist angle α and joint angle θ. Arm length a is the arm extension distance between adjacent joint, offset distance d is the distance between the origin of two neighbouring coordinate frame along Z reference axis, twist angle $\propto$ is the angular different between Z axis of both joints and joint angle is the angular displacement between X axes measured about reference Z axis of the specified degree of freedom. Normally joint angle θ become joint variable for revolute joint and offset distance d is a joint variable for prismatic joint [2].

This kind of representation is used to model industrial robot successfully from 1950's. Since the current trend of robotic research is diversifying into service, humanoid and biomimetic robot which having large numbers of degree of freedom, a new approach is required to serve this computational intensive requirement. Using Denavit Harternberg requires four parameters to describe a single degree of freedom or joint. In hyper redundant robot design normally requires more than 30 degree of freedom [3]. Refer to Chirikjian and Burdick [4], the term hyper-redundant is to describe robots which have a very large number of independent degrees of freedom. A simple approach is needed in order to model just one module or segment of snake robot.

Since D-H algorithm is an established and standard method to model any robot, a modification of D-H system is required for high degree of freedom robot. Maintaining D-H approach with novel simplification will retain the robustness of robot modeling while reducing the computational burden in hyper redundant robot design. This simplified approach will accommodate four degree of freedom into a single representation of Denavit Hartenberg algorithm.

In this work a robot module or segment consist of four prismatic joints is being developed. The combination of this module will become an assemblage for multiple degree of freedom of hyper redundant robot or snake robot. Normal approach is to treat a single prismatic joint as a single degree of freedom with four Arm matrices. A unique approach in this research is to model this four degree of freedom into single arm matrix representing a segment or a module. The actuator extension and their combination will determine the joint variable value of joint angle θ and twist angle α. This electromagnetic muscle is arranged in four (4) polar arrays around disk body. Even though the electromagnetic muscles are classified as prismatic joint, their sequence and combination of operation producing two joint variables of joint angle θ and twist angle α. Output from this forward kinematic model is the end effector $NOAP$ matrix and its yaw, pitch and roll orientation representation. This novel module is intended for building a high assemblage of Hyper Redundant Robot. Employing this actuation sequence representation technique 40 DOF system requires only ten arm matrices in contrast to normal modeling of using 40 arm matrices.

- *Amir Sharizam Ismail is currently pursuing master's degree program in control & robotic engineering technology in Universiti Kuala Lumpur, ID.51311212118. E-mail: amirsharizam@mfi.unikl.edu.my*
- *Samsi Md Said is co-supervisor and a senior lecturer at Universiti Kuala Lumpur Malaysia France Institute, Email: samsi@mfi.unikl.edu.my*
- *Ishkandar Baharin is a member of IFR Industry Associations and Professor at Universiti Kuala Lumpur Malaysia* Type equation here.*France Institute, E-mail: ishkandar@mfi.unikl.edu.my*

2 PROTOTYPE OF ROTATING SEGMENT

2.1 Actuator Description

The actuator is cylindrically symmetrical configuration shown in Figure 1. It consists of three polycarbonate plastic layers, a spring and four armatures in polar array.

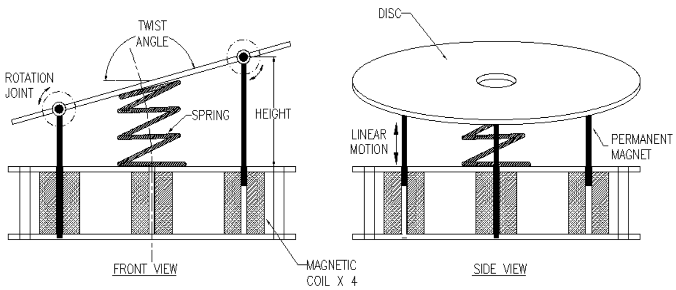

Figure 1: Prototype of Rotating Segment

It is a special design electromagnet that consists of a coil and a movable iron core called the *armature*. When current flows through a wire, a magnetic field is set up around the wire. When the coil of the solenoid is energized with current, the core moves to increase the flux linkage by closing the air gap between the cores. The movable core is usually spring-loaded to allow the core to retract when the current is switched off. The force generated is approximately proportional to the square of the current and inversely proportional to the square of the length of the air gap. This high-speed electromagnetic actuator is highly consistent of high pressure application. Therefore, the new actuator can provide high response over short strokes [5] and is suitable for variable twist angle of flexible electromagnetic hyper redundant module.

2.2 Programmable Logic Controller

A Programmable Logic Controller (PLC) is a digital computer used for automation of electromechanical processes [6]. A PLC is an example of a hard real time system since output results must be produced in response to input conditions within a limited time, otherwise unintended operation will result.

For this work, we used PLC Omron CP1A-CPU20 with 8 bit input and 8 bit output relay. Table 1 is the specification of the PLC that we used:

PLC Type: Compact
Voltage Supply: 100VAC-240VAC
Model number: CQM1H-CPU51
I/O capacity: 512 points
Program capacity: 7.2 Kwords
DM Area size: 6 Kwords
CPU Unit built in I/O points: 16 DC Inputs
Communication ports: Peripheral/ RS-232C
Inner board: Supported
Communication Units: Supported

We controlled the sequence of the four bits to make variation of twist angle α. Figure 2 and Table 2 shown the inputs and outputs wiring and list of input and output PLC.

To operate the sequence, we programmed the PLC using ladder language to active these four actuators of a module.

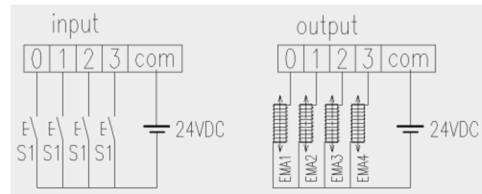

Figure 2: Wiring I/O PLC for One Segment

Table 2: List of Input / Output PLC

Item	Description	PLC i/o Address
S1	Switch 1 Push Button (N/O)	000.00
S2	Switch 2 Push Button (N/O)	000.01
S3	Switch 3 Push Button (N/O)	000.02
S4	Switch 4 Push Button (N/O)	000.03
EMA1	Electromagnetic Actuator 1	100.00
EMA2	Electromagnetic Actuator 2	100.01
EMA3	Electromagnetic Actuator 3	100.02
EMA4	Electromagnetic Actuator 4	100.03

3 OPERATION OF ROTATING TWIST ANGLE MODULE

3.1 Denavit Hartenberg Modeling

The module consists of reference disk and orientation disk. The XYZ axis is attached on the reference disk while the NOAP orientation axis is at the outer disk (Refer Figure 2). The difference between origins of these two frames along X axis is arm length *a.* The offset distance *d* is zero since theoretically there is no displacement among the frame's origin along Z axis. Twist angle α is a product of prismatic actuator combination. The similar value of angular variable θ is achieved with varied value of twist angle α. The bang-bang control scheme is employed in electromagnetic actuator since the objective of this work to show the effect of twist angle variation on *NOAP* homogeneous orientation and position matrix. In future, servo control for electromagnetic extension will be explored in order to give varied value of joint angle θ and twist angle α.

3.2 Variable Twist Angle, α

The combination of these four electromagnetic actuator will determine the twist angle α. Twist angle α is the angle between Z reference axis and Z transition axis about X transition axis. By energizing actuator number one, the frame angular displacement is about 90°. If both actuator 1 and 2 is being energized the transition frame will rotate further to become 135°. Refer Figure 3 and Table 3 for complete transition axis rotation and their derived twist angle α.

These arm matrixes normally represent single degree of freedom but in this work it represents the whole single module of robot, $A_i = M_i$.

$$M_i = Rot_{z,\theta i}.Trans_{z,di}.Trans_{n,ai}.Tw(bit,bit,bit,bit)_{n,\alpha i} \quad (14)$$

$$T_i^n = \prod_{i=1}^{n} M_{i-1}^i M_i^{i+1} .. M_{i+1}^n \quad (15)$$

$$T_i^n = \begin{bmatrix} n_x & o_x & a_x & P_x \\ n_y & o_y & a_y & P_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (16)$$

The position and orientation representation of the *Yaw* $\emptyset$, *Pitch*θ, and *Roll* ψ for this twist module can be derived from matrix (16) as in (17) to (19).

$$\phi = atan2(n_y, n_x) \quad (17)$$
$$\theta = atan2(-n_z, cos\phi.n_z + sin\phi.n_y) \quad (18)$$
$$\psi = atan2(sin\phi.a_x - cos\phi.a_y, -sin\phi.o_x + cos\phi.o_y) \quad (19)$$

4 RESULT ANALYSIS

Consider the combination of individual module into a hyper redundant robot system represented symbolically in Figure 4. The configuration can be scaled into any number of N degree of freedom. Tables 4 summarize the Denavit Harternberg table for the total segment or module. The result for every individual segment and their incremental value is displayed in Table 5 and Table 6.

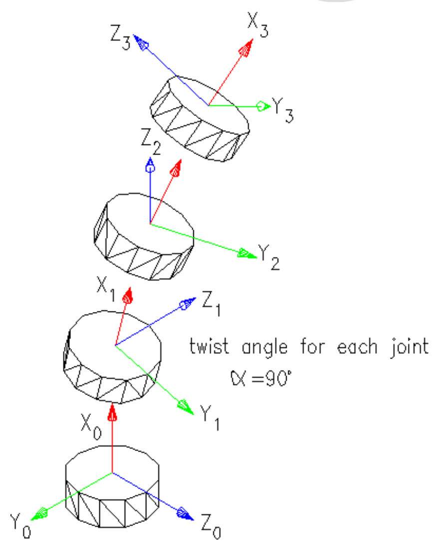

Figure 4: Three-Link Segment with Twist Angle, $\alpha = 90°$

Table 3: D-H Parameters for Six Segments

Tw(1,0,0,0)				
Link	a_i	α_i	d_i	θ_i
1	25	90°	0	15°
2	25	90°	0	15°
3	25	90°	0	15°
4	25	90°	0	15°
5	25	90°	0	15°
6	25	90°	0	15°

Table 5: Result NOAP for Six DOF

Variable Twist Angle, α = 90° for each joint module						
Module	Position (mm)			Orientation (°)		
	P_{xi}	P_{yi}	P_{zi}	Yaw, $\emptyset$ $atan2(n_y$	Pitch, θ $atan2(-n_{zi}, cos\emptyset.$ $+ sin\emptyset.n_{yi})$	Roll, ψ $atan2(sin\emptyset.a_{xi}$ $- cos\emptyset.a_{yi}, -sin\emptyset.o_{xi}$ $+ cos\emptyset.o_{yi})$
J 1	24.1	6.5	0.0	15.0	0.0	90.0
J 2	47.5	12.7	6.5	15.0	-39.4	180.0
J 3	71.7	12.5	12.7	-0.5	-45.0	-86.0
J 4	96.7	12.7	12.5	0.5	134.7	3.8
J 5	120.8	19.4	12.7	15.5	-6.5	93.8
J 6	144.1	25.4	19.4	15.5	-6.5	-176.3

Table 6: Result NOAP for Six DOF

Variable Twist Angle, α = 360° for each joint module						
Module	Position (mm)			Orientation (°)		
	P_{xi}	P_{yi}	P_{zi}	Yaw, $\emptyset$ $atan2(n_y$	Pitch, θ $atan2(-n_{zi}, cos\emptyset.$ $+ sin\emptyset.n_{yi})$	Roll, ψ $atan2(sin\emptyset.a_{xi}$ $- cos\emptyset.a_{yi}, -sin\emptyset.o_{xi}$ $+ cos\emptyset.o_{yi})$
J 1	24.1	6.5	0.0	15.0	0.0	0.0
J 2	45.8	19.0	0.0	30.0	0.0	0.0
J 3	63.5	36.6	0.0	45.0	0.0	0.0
J 4	76.0	58.3	0.0	60.0	0.0	0.0
J 5	82.4	82.4	0.0	75.0	0.0	0.0
J 6	82.4	107.4	0.0	75.0	0.0	0.0

5 CONCLUSION

Denavit-Hartenberg (D-H) is an accepted robot modeling technique since 1950's. It is being used successfully to model Six degree of Freedom modern industrial robot in industries. Since the current trend of robotic is to move toward the service and military application which requires robot in great number of degree of freedom deviate from a standard six degree of freedom, a new mathematical modeling is required.

This work shows the improvement of Denavit - Hartenberg usage in robot modeling which reduce the computational burden. Normally one degree of freedom robot requires one arm matrices as proposed by D-H method. This research proposes the compression of four degree of freedom robotic system into single module M. The robustness of Denavit Hartenberg is retained while improving the computational efficiency. The outcome of this work is lay foundation for the new robotic era that mimic biological creature such as snake robot which posses a high number of degree of freedom. The spiral gait motion for climbing or planar surface locomotion can be achieved easily by employing the incremental twist angle or constant value of 360° of twist angle.

REFERENCES

[1] J Denavit, R S Hartenberg," *A Kinematic Notation for Lower-Pair Mechanisms based on Matrices*", Journal of Apllied Mechanics, pp. 215-221, 1955.

[2] Norton, Robert, "*Design of Machinery (4th Edition)*".Boston, MA: McGraw Hill Higher Education, pp. 33. ISBN 978-0-07-312158-1.

[3] Chirikjian, G S, Burdick, J W. "*Design and Experiments with 30 DOF Robot*". IEEE, Robotics and Automation, pp. 113-119, Vol. 3, 1993.

[4] Chirikjian, G S, Burdick, J W. "*A Hyper-Redundant Manipulator*". IEEE, Robotics and Automation Magazine 1(4), pp. 338-341.

[5] Jun Man et al "*Novel High-Speed Electromagnetic Actuator With Permanent-Magnet Shielding for High-Pressure Applications*" IEEE Transaction on Magnetics, Vol. 46, No. 12, December 2010.

[6] E.A. Parr."Industrial Control Handbook, Industrial Press Inc. 1999, ISBN 0-8311-3085-7.

[7] Gray, J. "*The Mechanism of Locomotion in Snakes*". Journal of Experimental Biology, 23(2), pp. 101-120.

[8] S. Hirose."*Biologically Inspired Robots: Snake-Like Locomotors and Manipulators*". Oxford University Press, 1993.

[9] Burdick, J.W.; Radford, J.; Chirikjian, G.S.; "*A `sidewinding' locomotion gait for hyper-redundant robots*," Robotics and Automation, 1993.

[10] Kevin J. Dowling, "*Limbless Locomotion: Learning to Crawl with a Snake Robot*", PhD Thesis, The Robotics Institute, Carnegie Mellon University, December 1997.

[11] Kevin J Dowling, William L. Whittaker."*Limbless Locomotion: Learning to Crawl with a Snake Robot*". Robotic and Automation, 1999.

[12] Hartenberg, Richard Scheunemann; Denavit, Jacques, "*Kinematic Synthesis of Linkages*", McGraw-Hill series in Mechanical Engineering. New York. McGraw-Hill, pp 435.

[13] T. Kajima and Y. Kawamura, "*Development of a high-speed solenoid valve: Investigation of solenoids,*" *IEEE Trans. Ind. Electron.*, vol. 42, no. 1, pp. 1–8, Feb. 1995.

[14] J. Kim and J. Chang, "A new electromagnetic linear actuator for quick latching," *IEEE Trans.Magn.*, vol. 43, no. 4, pp. 1849–1852, Apr. 2007.