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Position Control of a Four Link Hyper Redundant Robotic Manipulator

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ABSTRACT

Hyper-Redundant robotic manipulators like Serial robots, Snake robots, Tentacle robots or Continuum robots have very large number of degrees of kinematics redundancy. Position control of such a robotic manipulator comprising of more than three links and articulated joints is a big challenge due to the involvement of large number of trigonometric terms in its inverse kinematics equations. In this paper, a simple algorithm for the inverse kinematics solution (IKS) of a four-link serial robotic manipulator has been proposed, which is then validated experimentally. The proposed method divides the robot into two two-link virtual sub-robot and solves the inverse kinematics analytically for joint variables of each sub-robot successively. A validation experiment was conducted on a 4-link prototype to check the validity of the proposed algorithm. The experimental results showed satisfactory results with good repeatability.

Key words: Hyper redundant, robotic manipulator, kinematics

INTRODUCTION

Hyper-Redundant in robotics refers to have more degrees of freedom (DOF) than are necessary to perform a specific task (Chirikjian and Burdick, 1990). The control of a hyper-redundant robotic manipulator is very complex due to infinite number of the inverse kinematic solutions. Literatures on hyper-redundant robots show various approaches for their inverse kinematic solutions. A kinematic algorithm for a planer hyper-redundant manipulator was proposed approximating continuous curve through the joints of the robots using Bessel function and then applying differential geometry, which helps to avoid calculation of pseudo inverse matrices (Chirikjian and Burdick, 1990, 1995). This method works well for high level of redundancy that occurs in continuous robots and shows poor performance for reduced level of redundancy in discrete robots. To reach desired position avoiding obstacles, Variable length links and artificial potential functions have been used by Ivanescu *et al.* (2005). In solving IKS of hyper-redundant robots, optimization techniques has been applied by Li and Trabia (1996) and Bham (2007) while Anfis, Fuzzy and ANN approaches have been attempted by Alavandar and Nigam (2008), Howard and Zilouchian (1998), Bouallegue and Chaari (2007) and Mayorga and Sanongboon (2005), respectively. All these methods discussed involve complex mathematics and some of them take considerable time to come up with useful IKS solution. When a manipulator is made of more than three links, the conventional technique of finding the joint variables is no more useful. To come up with inverse

kinematic solution, the hyper-redundant robots are divided into small sub-robots and the small sub-robots are controlled separately and successively to control the parent robot.

Ashrafioun and Nataraj (2002) have come up with two IKS techniques of hyper-redundant robots, where one of these techniques known as VLA assumes few virtual layers with two, three or four link subrobots and the other one known as DDS uses proportional distribution of displacements of the virtual layers. The DDS is used when the VLA gives singular configuration. Whereas Chetty *et al.* (2011) come up with distributed formation planning and navigation framework method to solve the problem. In the present research, a similar method with virtual layers has been proposed. However, this new method instead of checking singular configuration at every step assumes the first virtual layer in singular configuration and then gradually removes the singularities to arrive at the final configuration that gives a coil shape.

This study has proposed a control algorithm using simple kinematics solution of a four-link serial robotic manipulator considering the robot made of two sub-robots and solved the inverse kinematics analytically for joint variables of each sub-robot successively. Simulation has been done using MATLAB to realize the feasibility of the proposed control algorithm. A four-link prototype has been built manually. Finally, the validity of the proposed algorithm is checked through random experiments with repeatability.

MATERIALS AND METHODS

Mechanical design: The prototype designed here consists of four links. Each of the four links designed with identical size. One end of each of the links except the last link is designed to house a servomotor rigidly and the other end with a hole to connect with the servo shaft of the consecutive link. The actual length of the first three links is 13.0 cm, however, the distance between the two pivots is 10.0 cm. The end-effector is 11 cm long and distance between the pivot and the free tip is 10 cm. The width of all the links is 2.0 cm and depth is 0.3 cm. To provide necessary support against gravitational load, an extended portion made of small piece of Plexiglas is attached half way of all the three links. The free end of this extended portion is made of a ball point tip to reduce the effect of coulomb friction during contact with the ground. Detail drawing of each link is shown in Fig. 1. The base servo motor is housed in the groove of the platform so that the axis of rotation is aligned with the origin.

Electrical and electronics design: Four servo motors are used as articulated actuators. The actuators are selected through dynamic analysis to produce sufficient torque to maneuver the

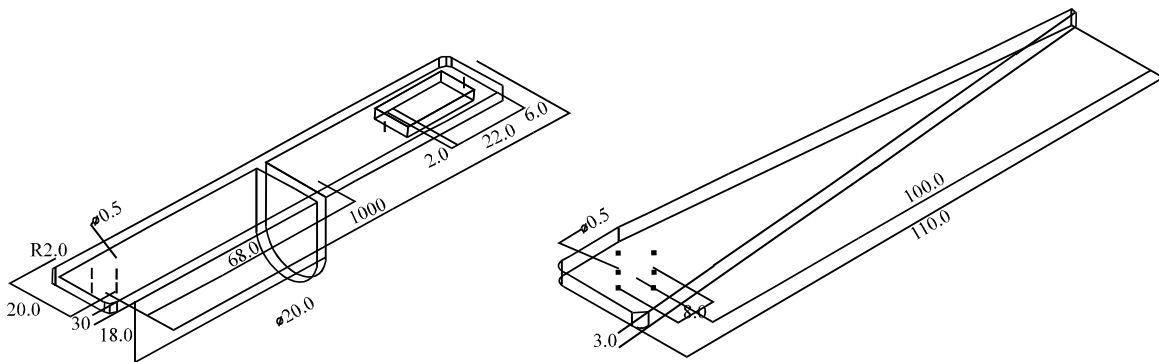


Fig. 1: Dimension for Links 1, 2,3 and end-effector

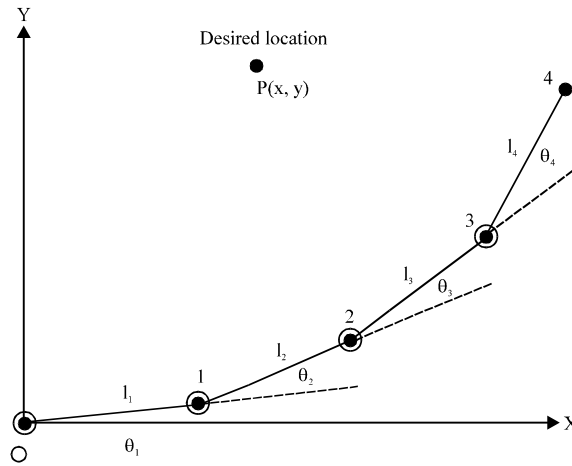


Fig. 2: Initial configuration of the links and desired location

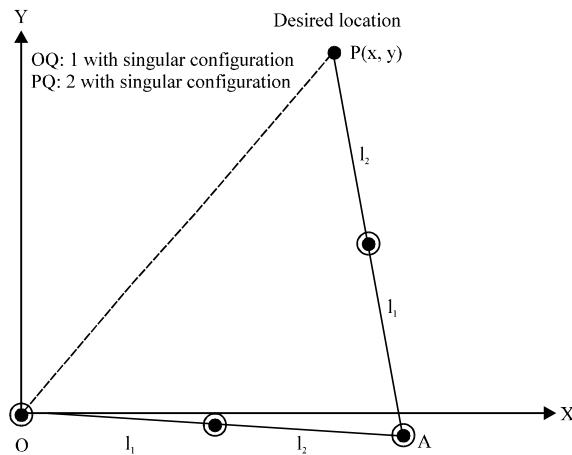


Fig. 3: Virtual triangle made up by SR1 and SR2

prototype. On the self servo driver such as SC16A is used as the servo driver for this prototype. The joint parameters for the desired position of the end-effector, is given to the servo controller using MATLAB interfacing through serial communication. A constant voltage source is used to power the servo controller as well as servo actuators.

Programming and interfacing: The calculated joint parameters using proposed algorithm are sent to the controller through serial port. A MATLAB based Graphical User Interface (GUI) is developed for inputting the desired end-effector location. The robot is able to respond instantaneously placing the end-effector to the desired location through actuation of the servomotors according to the inverse kinematics data sent from the computer.

Algorithm development: The proposed algorithm, at the beginning, considers some virtual configuration with singularities. The virtual configuration subsequently is reconfigured to eliminate the singularities. Thus the inverse kinematic solution is singularity free. Steps of the algorithm are discussed in conjunction with the Fig. 2 and 3.

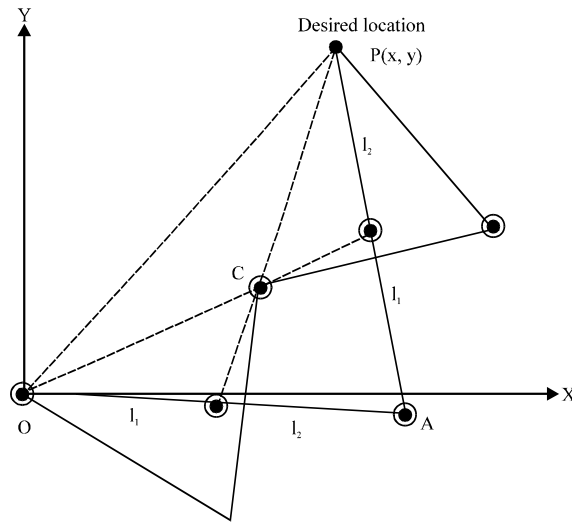


Fig. 4: Singularity free configuration of SR1 and SR2

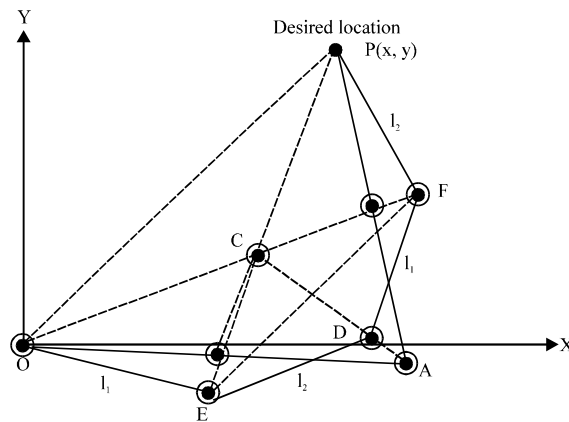


Fig. 5: Elbow-up configuration of second and third link

Let us consider O-1-2-3-4 be the initial configuration of the robot consisting of four links and P be the desired location to be reached as shown in Fig. 3. Let the hyper-redundant robot is divided into two sub-robot 1 (SR1) consisting of the first two links (l_1 and l_2) and sub-robot 2 (SR2) consisting of the last two links (l_3 and l_4). From the known lengths of the links the configuration O-A-P can easily be determined considering the SR1 and SR2 in their singular configurations, respectively. This configuration along with the position vector OP forms the triangle OAP.

In the next step, we locate the centroid C of the triangle OAP as shown in Fig. 4 and determine inverse kinematics of the two sub-robot in such a way that for SR1, C is the desired point and for SR2, C is the base point and P is the desired end point. In the case of links of almost equal lengths, the distances OC and CP will be shorter than that of the respective sub-robot. This geometric feature will help remove the singularities from both the sub-robot.

In determining the configurations, if both the sub-robots are configured elbow up, links l_2 and l_3 together may become elbow down. To make this portion elbow up, we can simply reconfigure links l_2 and l_3 shifting the joint at C symmetrically on the other side of the line joining the points E and F (Fig. 5) say at D. This fine tuning will make the whole robot elbow up.

MATHEMATICS OF 2-LINK ROBOT

Kinematic analysis

Forward kinematics: Once two consecutive links with their arm lengths known (say l_1 and l_2) the joint variables θ_1 and θ_2 for specified tip position (x,y) can be determined from the following forward kinematic equations:

$$X = l_1 \cos \theta_1 + l_2 \cos (\theta_1 + \theta_2) \dots \dots \dots (1)$$

$$y = l_1 \sin \theta_1 + l_2 \sin (\theta_1 + \theta_2) \dots \dots \dots (2)$$

While the joint space (θ_1, θ_2) is known, the desired Cartesian space (x,y) can be found using these two equations.

Inverse kinematics: Solutions of Eq. 1 and 2, are available in any standard book on robotics and are presented in Eq. 3 and 4.

$$\cos \theta_2 = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1 l_2} (3)$$

$$\sin \theta_2 = \pm \sqrt{1 - (\cos \theta_2)^2} (4)$$

Here, '+ve' sign is used for elbow up while the '-ve' sign for elbow down configuration.

$$\sin \theta_1 = \frac{k_1 y - k_2 x}{2l_1 l_2} (5)$$

$$\cos \theta_1 = \frac{k_1 x - k_2 y}{2l_1^2 + k_2^2} (6)$$

where, $k_1 = (l_1 + l_2 \cos \theta_2)$ and $k_2 = l_2 \sin \theta_2$.

Therefore,
$$\theta_1 = \alpha \tan^{-1} (\sin \theta_1, \cos \theta_1) (7)$$

$$\theta_2 = \alpha \tan^{-1} (\sin \theta_2, \cos \theta_2) (8)$$

SIMULATION

Inverse kinematics for 4-link robot: The new algorithm has been applied for one 4-link robot. In Fig. 6 and 7, IKS for 4-link robots have been presented for two different desired locations, where one is close to the base of the robot called the inner point and the other close to the outer boundary called outer point of the work space, respectively. In both the cases the IKS are solved for elbow up configuration so that the robot configuration can be shaped as a coil, a configuration often seen in arthropods like spiders or crabs. The joint variables are plotted in Fig. 6b and 7b, respectively against an estimated time span of 7 sec. The simulation results show that the changes of Joint variables are smooth and quite satisfactory.

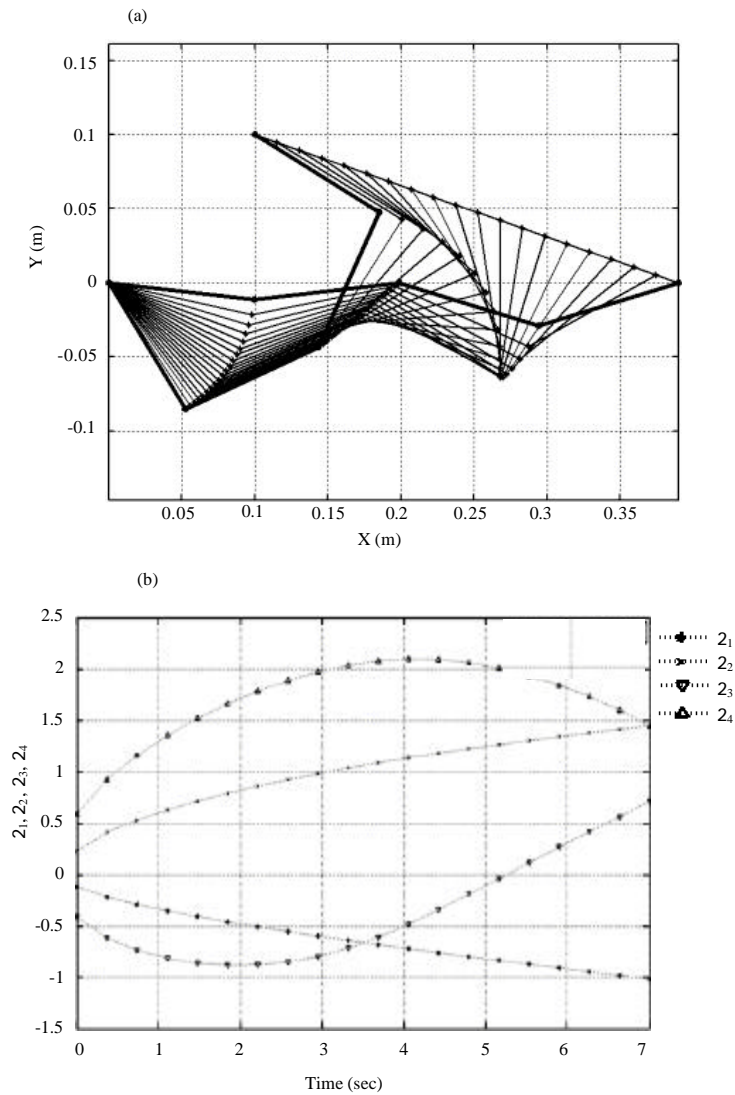


Fig. 6(a-b): 4-link robot for a point close to the base point (a) IK configuration and (b) Joint values

EXPERIMENTAL VALIDATION

Experimental data: To check the validity of the algorithm, randomly fifty desired positions are chosen and IK are solved for these fifty positions keeping in mind that the joint limit for each joint is $\pm 90^\circ$. The joint space mapping for fifty positions is converted into servo values. Typical Cartesian to Joint space mapping is illustrated in the following Table 1.

Experimental procedure: The prototype is interfaced with PC using developed Graphic User Interface (GUI). Before conducting the experiment, calibration of servo motor with respect to GUI is done using following conversion (Table 2). All servos meet 90° CCW angular position in response of input servovalues with a lagging of about $2.5^\circ \sim 3.0^\circ$. But, all servos fail to attain 90° CW

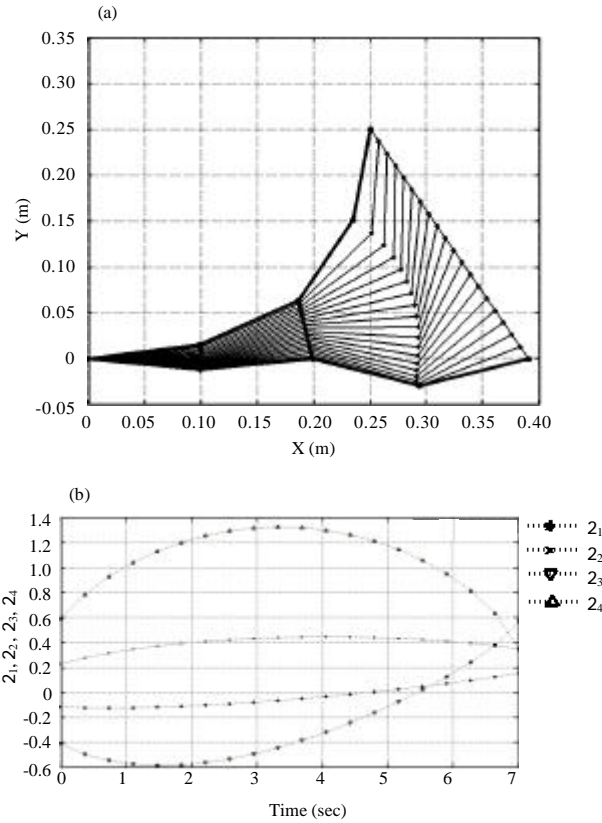


Fig. 7(a-b): 4-link robot for a point close to the boundary(a) IKS configuration and (b) Joint values

Table 1: Cartesian space to joint space mapping for proposed IKS algorithm

Sl.	Cartesian space (m)		Joint space values				Servo position values ($180^\circ = 1462$)			
	X_D	Y_D	θ_1°	θ_2°	θ_3°	θ_4°	S_1	S_2	S_3	S_4
1	0.35	0.05	-28.03	20.00	32.31	20.00	959	569	469	569
2	0.3	0.16	-13.37	23.33	36.20	23.33	840	542	437	542
3	0.05	0.35	45.68	20.00	32.31	20.00	740	403	339	403

The range of motion of servo motors is from -90° to 90° and corresponding servo position values ranges from 0~1462

positions in response of input servo values due to joint limitation. Both the servo controller and servo motors are powered using a constant voltage power source of 6.0V.

Experiments are conducted for all simulated data using GUI based interfacing. To attain a particular position of the tip, the servo values corresponding to the IKS are implemented sequentially starting from the fourth actuator. When the prototype completely stops, the coordinate of the attained position is recorded. Similar procedure is followed for positioning the tip for 50 locations selected arbitrarily. For each of the location, the experiment is carried out three times to ascertain repeatability. Randomly, the simulation shape and obtained shape of the prototype for several location is verified, one of the verification is illustrated in Fig. 8.

Table 2: Angular position to servo value conversion for calibration

CCW Rotation				CW Rotation			
Position (°)	Servo value	Position (°)	Servo value	Position (°)	Servo value	Position (°)	Servo value
90	0	45	366	-5	772	-50	1137
85	41	40	406	-10	812	-55	1178
80	81	35	447	-15	853	-60	1218
75	122	30	487	-20	893	-65	1259
70	162	25	528	-25	934	-70	1300
65	203	20	569	-30	975	-75	1340
60	244	15	609	-35	1015	-80	1381
55	284	10	650	-40	1056	-85	1421
50	325	5	690	-45	1097	-90	1462

The range of motion of servo motors is from -90 to 90° and corresponding servo position values ranges from 0~1462, CW: Clockwise, CCW: counter clockwise



Fig. 8: Shape verification between simulation and prototype

After accomplish the experiment, three types of error are defined as follows:

$$x_{err} = |x_{desired} - x_{attained}| \quad (9)$$

$$y_{err} = |y_{desired} - y_{attained}| \quad (10)$$

$$Err = \sqrt{x_{err}^2 + y_{err}^2} \quad (11)$$

Using above equations, the x_{err} , y_{err} and E_{rr} are calculated for each position. To check the repeatability of the prototype, three arbitrary locations in the work envelope are randomly selected. Now, positioning of these three locations are carried out repeatedly twenty times.

RESULTS AND DISCUSSION

To study the performance of the prototype, the x_{err} , y_{err} and the resultant error, E_{rr} are plotted in Fig. 9 against the experiment numbers.

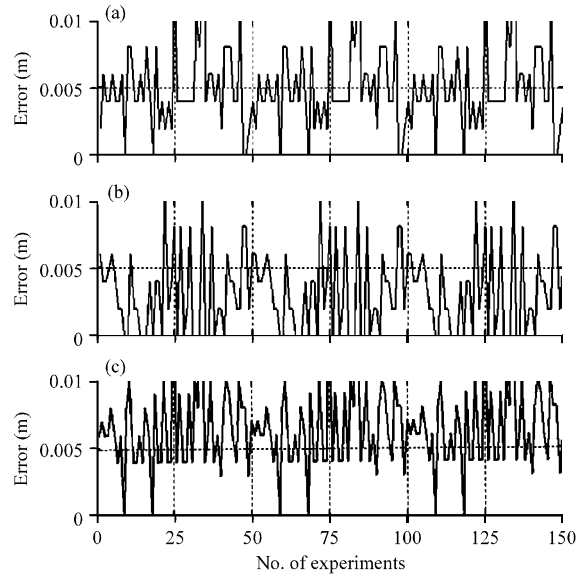


Fig. 9(a-c): Error in positioning of different locations by the prototype, (a) Along x-direction, (b) Along y-direction and (c) Resultant error

The graph shows that the prototype attains the desired position with acceptable error in most of the cases. Also, it is found that, the error in the x-direction is more than the error in y-direction. It is due to the high error in two consecutive joints along the x-direction than the y-direction because of manual assembly. Backlash of 2.5 to 3.0° also contributes to the reduction in accuracy of positioning. From the repeatability experiment, it is found that the prototype has good repeatability with an error of 2 mm in the case of rotation of the motors in the same direction for two consecutive locations. It infers that the cause of error in positioning is mainly due to large backlash in servo motors. However, the objective is not to achieve high positioning accuracy, rather to investigate the viability of the proposed algorithm and achieve functionality of a robot with redundant links, which is exactly what is demonstrated.

Ivanescu *et al.* (2005) derived a hypothesis such as the control of a hyperredundant robot to a desired position is possible if the artificial potential is a potential functional whose point of minimum is attractor of this dissipative controlled system by simulation of several tentacle models in 2D and 3D space. But implementation of artificial potential function involves cumbersome mathematical burden (Chirikjian and Burdick, 1990). A simulation result of IKS for a 3DOF planar manipulator using a meaningful performance index and null space vector by two properly trained ANNs was presented (Mayorga and Sanongboon, 2005), whereas, the more is the DOF, the more is the mathematical computation. In addition, training of two ANNs need more time for real time implementation. Also, this scheme was not validated by experimentation. In VLA approach, the IKS of a four link and a three link robot was solved assuming constant length virtual link and one or two joint angle constant. In DDS approach, the lengths of virtual links were variable and instantaneous displacement is distributed to each subrobots with two normalized displacement vector. To avoid singularity, switching between VLA to DDS is implemented using a defined configuration index based on subrobot determinants that were functions of the angles between consecutive virtual/real links (Ashrafioun and Nataraj, 2002). The proposing VLA and DDS

approaches are based on simulation and have not been investigated much. The proposed algorithm in this paper is free from any constraints and singularity as the solution is initiated with assumed singular configuration.

CONCLUSION

Inverse kinematics solutions of hyper-redundant robots generally give multiple solutions, where some of these solutions often are found to be in singular configurations. In this research a novel algorithm for inverse kinematics solution of hyper-redundant manipulator is developed to eliminate such singularities. The algorithm is capable of mapping joint space values without involving complex mathematics and can provide unique solutions for Cartesian space positions. Using the proposed algorithm, the robot can reach a desired location assuming a coil shape, which is an essential criterion in reaching locations behind obstacles. The new IKS is able to avoid both interior and boundary singularities that makes the algorithm attractive for real life application. Viability of the new algorithm is also validated through controlling a 4-link functional prototype using off-the-shelf servo motors.

RECOMMENDATION

In realizing the objectives of this research it is observed that further works are necessary to come up with real life solutions of hyper-redundant robots. A generalized solution capable of solving IK for spatial hyper-redundant robots could lead to develop steerable endoscope for minimal invasive surgery. The present solution provides with a single coil shape of the manipulator, which is not capable of negotiating cluttered environment that exists inside human body or inside an engine compartment. As such multiple coil shapes needs to be studied. Instead of using servomotors for controlling the joints, active materials may be used as actuators, which could help make the structure of the robot slimmer.

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