Design and Control of Variable Length Hyper Redundant Robot

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Abstract

This paper puts forward a design concept of Variable length Hyper-redundant robot, consisting of eight links and their encloser system. Each of the rigid links is connected via actuated revolute joints in a chain. The robot will operate on the principle that one by one link will be coming out of the housing and moving towards the desired position. The robot can be a practical and cost saving approach in complex and unstructured area. In one particular operation, the variable length Hyper-redundant robot can provide shorter trail and shorter time as well compared to fixed number of links. The basic robotics analyses, dynamics simulation and experiment are also shown. The prototype developed is used as a proof of the concept.

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Keywords: Redundant Robot; Robot Manipulator; Variable Length HRR.

Nomenclature

2-D Two Dimensions
3-D Three Dimensions
ORM Oriented Redundant Manipulator
HRR Hyper Redundant Robot
DOF Degree of Freedom
FOP Fourth order polynomial
IO Input Output
DC Direct Current
VHRR Variable length Hyper Redundant Robot
FHRR Fixed length Hyper Redundant Robot
ρ Density (lb/in.³)
W Weight (lb)
R Radius (in)
g Gravitational constant (386 in/sec²)
JL Load inertia (lb-in-sec²)
JLS Worm gear / lead screw inertia (lb-in-sec²)

1. Introduction

The existence of hyper redundant robot (HRR) manipulator gathers many attentions due to their various applications in industries such as robot surgeon in surgery, rescue robot for mapping disaster scenario, multi tasking robot for autonomous nuclear plant operation, space exploration and maintenance and so on. Thus, the study of planar robot (2-D) as well as
spatial robot (3-D) is important. Formerly, HRR designs have been referred to a variety of names including Oriented Redundant Manipulator (ORM) [1], spine robot [2-3], snake-like manipulator [4], elastic manipulator [5], elephant's trunk like elastic manipulator [6], and tentacle manipulator [7]. However, the term ‘Hyper-redundant’ was first used by Burdick and Chirikjian [8].

Rigid-link manipulators have dominated the robotics community because of the simpler design construction. Thus, it becomes the most popular approach to build hyper redundant robot by connecting several rigid links via actuated revolute joints in a chain [9]-[13]. The earliest hyper-redundant robot design was implemented by Anderson and Horn in 1967 which was known as ‘Tensor-Arm Manipulator’. Other authors also suggested hyper-redundant designs or developed hyper-redundant robot mechanisms such as [14] developed Magnetically Activated Robotic Tensor Arms and [15] implemented a large number of working high DOF systems. Chirikjian and Burdick [16] developed 30 degree-of-freedom planar hyper-redundant robot by using ratchet wheel that implements special friction properties. Besides, a wire-driven system that offers an alternative by utilizing an actuated windlass to drive the joints of the machine was developed in [17].

To date, even though many researchers have successfully developed different design concepts for the hyper redundant robots, the robots are mostly limited to the fixed length of hyper redundant manipulator. Fixed length HRR needs to actuate all the links for each operation and thus consumes time and energy to reach desired location. Thus, it makes the operation slower. Therefore, a Variable length Hyper Redundant Robot (VHRR) would offer advantage over a Fixed length Hyper Redundant Robot (FHRR).

In Fig. 1, a desired point is shown close to the origin. By having knowledge of the optimum numbers of link needed for the operation, only minimum numbers of links are utilized to accomplish this job using a VHRR; however, the same situation would demand zigzag configuration from a FHRR. In this paper a VHRR is proposed so that unnecessary actuations of many links can be avoided to reach positions within the work space of the robot. The paper is organized as follows; section 2 presents VHRR design concept; section 3 describes kinematics analysis; section 4 dynamic analysis; section 5 delivers the mechanical structure; section 6 verifies the concept through experiment and compares with simulation result; and section 6 draws conclusions based on the practicality of the design concept.

![Diagram of Fixed and Variable links](image.jpg)

**Figure 1:** A point close to origin reached by FHRR and VHRR.

2. Variable length Hyper Redundant Robot (VHRR) Design Concept

2.1 Hyper Redundant Robot manipulator

The main concept of the VHRR is that a robot with big number of links connected in series as shown in Fig. 2 will be put inside an enclosure. A motor attached to the enclosure and connected to the far end of the robot through a mechanism will help bring calculated number of links out of the enclosure so that the desired point in the work space can be reached with actuation of minimum number of links. The enclosure is shown in Fig. 3. The robot developed in this research consists of 8-links and 1 dummy link, serially connected by revolute joints in a chain fashion. Each of the revolute joint would be actuated by servo motor individually. Detail drawing of each link is shown in Fig. 4(a) and Fig. 4(b) respectively.
Figure 2: Isometric view of the manipulator after assembly

Figure 3: Isometric view of HRR Manipulator enclosure system.

Figure 4: (a) Isometric views of links 1, 2, 3, 4, 5, 6 and 7. (b) Dimension of the End-effector.
2.2 Enclosure System

The enclosure shown in Figure 4 functions to assist the VHRR manipulator to move into and out from the workspace. The VHRR system is actuated by a dc motor which is assembled at the rear frame of the enclosure. The VHRR manipulator is attached to linear bearing block by screwing the dummy link at the remote end of the bearing block. As a result, the VHRR manipulator slides atop L-shape aluminium guide at the top of the enclosure which ensures that the movement of each link is not off the straight line before reaching the workspace.

3. Kinematics Analysis

3.1 Geometrical Method of Inverse Kinematics of HRR

In selecting motors, inverse kinematics and kinetics solutions of robots are very essential. In this research a new Geometric Method of Inverse Kinematics is used for these purposes. The technique is proposed for HRR whose length is variable. The method involves repetitive use of inverse kinematics solution of 2-link manipulator based on some geometric proposition. This depends on the selection of some reference point and virtual configuration which resulting in a zigzag configuration. The zigzag configuration is then transformed to coil shape robot using another algorithm. A coil shape is then formed out of the serially connected n-link which allows the system to avoid singularity. Details of the step have been presented in [19].

4. Dynamic Analysis

In determining the sizes of the motors dynamics analysis was carried out. A ‘linear segment with fourth order polynomial blend’ in joint space was used to study the dynamic performances. The displacement, velocity and acceleration profile for all the eight joints of the prototype of the HRR was calculated using MatLab. Based on desired motion, the values of displacement, velocity and acceleration of each joint were determined with respect to desired operating time and the kinematics profile for each joint. The results show that velocity varies from a magnitude of 0.055 rad.sec\(^{-1}\) to 0.48 rad.sec\(^{-1}\), and acceleration varies from 0.1 rad.sec\(^{-2}\) to 1 rad.sec\(^{-2}\) for the proposed VHRR with eight links.

This research used the ‘Recursive Newton-Euler Formulation’ to generate the equation of motion for our system. This method can produce a large system of equations and solve all the forces simultaneously including the forces of constraint. The functions of the torque variation depend upon the trajectory to be followed by the manipulator, masses of links, friction in link joints and force applied by or payload at the end-effector. The actuating time was assumed to be three second to reach the desired position. In order to ensure more accurate dynamical model, viscous damping and rotor inertia were taken into consideration. The viscous damping used was 0.08 kgf.cm.s\(^{-1}\). Meanwhile, the rotor inertia was estimated through simple experiment which involved servo motor directly, that was 0.102 kg.cm\(^2\). The highest torque value was 0.9 kgf.cm required by the first joint. The trend also showed a decrease of torque from the first joint to the last joint. This trend is due to the fact that the first actuator has to drive all the eight manipulator links while the number of manipulator reduces when it moves towards the last manipulator link.

5. Mechanical Structure Design

The complete structure of the VHRR robot is shown in Fig. 5. The robot consists of two main parts that is robot manipulator and an enclosure system.
5.1 Design Specifications

Servo motor is used as a means of actuation for the position control of articulated manipulator. As the base actuator is responsible to move the whole manipulator, the second actuator is responsible to move the last seven links of the manipulators and so on, thus the actuator housed in the base is subjected to the highest inertial load. Though the last seven actuators require less torque, same size servo motor is chosen to keep uniformity and good looking of the manipulator. As depicted in the last section, the torque required by the base actuator with viscous damping friction of 0.08 kgf.cm.s\(^{-1}\) and rotor inertia of 0.102 kg.cm\(^2\) is 0.9 kgf.cm. Thus, the servomotors specification for the system must be more than 0.9 kgf.cm.

For the links, a light weight material with smooth surface was chosen. The mass of each link with a servomotor and connector was about 16.5 gm and the highest value of mass moment of inertia was 6.738 \(\times\) 10\(^{-6}\) kg.m\(^2\) with a servomotor. The mass of each link with servomotor holder was below 5 gm and the highest value of mass moment of inertia was 2.042 \(\times\) 10\(^{-6}\) kg.m\(^2\). The design specification for robot manipulator is summarized in Table 1.

<table>
<thead>
<tr>
<th>Servomotor</th>
<th>Torque</th>
<th>Mass</th>
<th>Moment of Inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Links with servomotor holder</td>
<td>Nil</td>
<td>&lt;5 gm</td>
<td>2.042 (\times) 10(^{-6}) kg.m(^2)</td>
</tr>
</tbody>
</table>

Hi-Tec HS-56HB with the mass of 11.2g, and a torque capacity of 1.2 kgf.cm/4.8V, 1.4kgf.cm/6.0V is selected to keep uniformity for the rest of the system. The motor selected is sufficiently strong compared to 0.9 kgf.cm.

Meanwhile, for the enclosure system, the design under consideration would attach a dc motor to lead screw. The lead screw driver requires reflecting the load parameters back to the motor. Thus, both the lead screw and the load inertia have to be considered. If a lead screw inertia is not readily available, the equation for a cylinder may be used. Based on Fig. 6, calculation of lead screw and the load inertia are shown below;

![Figure 6: System attaches dc motor with lead screw.](image-url)

Inertia load;

\[
I_i = \frac{W}{g} \times \left( \frac{1}{2\pi P} \right)^2 = \frac{0.8}{386} \left( \frac{1}{2\pi \times 20.32} \right)^2 = 1.271 \times 10^{-7} \text{ lb.in.sec}^2
\]
Inertia lead screw;

\[ J_{ls} = \frac{\pi L p R^4}{2g} = \frac{\pi \times (25.59)(0.28)(0.3149)^4}{2(386)} = 2.869 \times 10^{-4} \text{lb.in.sec}^2 \]

Total Inertia for the system;

\[ J_{ts} = J_{ls} = (1.271 \times 10^{-7} + 2.869 \times 10^{-4}) \text{lb.in.sec}^2 \]

\[ = 2.87 \times 10^{-4} \text{lb.in.sec}^2 = 0.324 \text{kg cm}^2 = 0.000324 \text{kgm}^2 \]

Based on the total load of the robot structure, a Faulhaber Motor model 2657W012CR was chosen for driving a power screw to bring out the robot links out of the enclosure. This motor has a maximum speed up to 6000rpm and maximum torque of 0.044N.m. The lead screw use in this system has pitch 1.25mm/revolution. Since each link length is 70mm, thus 56 turns are required to move one link out to the workspace.

6. Experiment

The prototype is interfaced with PC using Matlab software version R2010b which is compatible with Arduino, an electronics prototyping platform. The schematic interfacing of the whole system is shown in Fig. 7, while the real set up is shown in Fig. 5 in previous section.

Experiment is conducted to reach a desired position (0.1, 0.05) which is near to the origin. Variable length HRR shows that it just need minimum of 2 links to reach the desired position. However, if the HRR is assumed to have fixed four links, it still can reach final desired position but all four motors need to be actuated. Besides, it will take longer route, thus not economic. Experiments are conducted based on simulated data. Fig. 8 and Fig. 9 show the positioning of robot end-effector of the VHRR and FHRR respectively. The FHRR was consisting of four links.
Figure 8: (a) Initial position for variable links (b) Position in the midst of the movement for variable links. (c) Final position for variable links.

Figure 9: (a) Initial positions for fixed 4-link. (b) Position in the midst of the movement for fixed 4-links. (c) Final position for fixed 4-links.

The simulated and experimental shapes of the robots of different number of links are plotted in Fig. 10 and Fig. 11 respectively.

Figure 10: Final configurations for simulated and attained joint of variable link VHRR (2-link).
The graphs in Fig. 10 and Fig. 11 show that the prototype attains the desired position with a maximum error of 2 cm in various locations for each experiment. The error in the x-direction is almost the same with the error in y-direction. The error could be due to time based open loop control to move the VHRR in and out of the workspace. Also, the backlash of $2.5^\circ$–$3.0^\circ$ in the motor contribute to the positioning error.

7. Conclusion

In this paper, we have presented a simple concept of designing variable length HRR manipulator. The construction of an eight link HRR prototype with controller and PC interface software is presented. The practicality of having variable length HRR is shown as well as the performance of the prototype for positioning desired location is verified. The robot configured as was intended in the simulation, thus affirming the hypothesis that such design concept is viable.

References