Inclined Links Hyper-Redundant Elephant Trunk-Like Robot

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Hyper-redundant robots (HRR) have many more degrees of freedom (DOF) than required, which enable them to handle more constraints, such as those present in highly convoluted volumes. Consequently, they can serve in many robotic applications, while extending the reachability and maneuverability of the operator. Many degrees of freedom that furnish the HRR with its wide range of capabilities also provide its major challenges: mechanism design, control, and path planning. In this paper, we present a novel design of a HRR composed of 16DOF. The HRR is composed of two concentric structures: a passive backbone and an exoskeleton which carries self-weight as well as external loads. The HRR is 80 cm long, 7.7 cm in diameter, achieves high rigidity and accuracy and is capable of 180 deg bending. The forward kinematics of the HRR is presented along with the inverse kinematics of a link. [DOI: 10.1115/1.4007203]

Keywords: hyper-redundant arm, robot manipulator, snake robot

1 Introduction

A redundant robot has at least one more DOF than required, in order to compensate for simple constraints, i.e., using an elbow up versus an elbow down configuration, to reach a target position. HRR have many more DOF than required, which enable them to handle more constraints, such as those present in highly convoluted volumes, and at the same time enable them to perform a variety of tasks. It is no surprise that HRR are versatile—look at their biological counterparts: snakes, elephant trunks, and worms, all of which can poke through and crawl through crevices as well as manipulate objects. Starting in 1972 with Hirose’s [1] pioneering work in HRR design, following with the work of Chirikjian and Burdick [2], there has been considerable attention paid to HRR design. The maneuverability inherent in these types of mechanical structures and their compliance, i.e., their ability to conform to environmental constraints, allow them to overcome obstacles of significant complexity compared to conventional robots, hence they have become a challenge for robotic mechanism designers [3,4]. Recently, other researchers, such as Yim [5] at PARC, Miller [6,7] on his own, and Haith at NASA Ames [8], have extended Hirose’s pioneering work on snake locomotion, where Yim and Haith used Yim’s Polybot modules to design a modular hyper-redundant robot. Takanashi developed at NEC [9,10] a new two-DOF joint for snake robots that allowed a more compact design. This joint used a passive universal joint to prevent adjacent bays from twisting while at the same time allowing two degrees of freedom: bending and orienting. This universal joint was enveloped an angular swivel joint, which provided the two degrees of freedom. The universal joint, which was installed on the outside, rendered the joint relatively bulky. Researchers at the JPL [11] “inverted” Takanashi’s design by placing a small universal joint in the interior of the robot. This allowed for a more compact design but came at the cost of strength and stiffness because backlash problems were introduced. Other known designs use cable/tendon actuation systems for driving the robot, yet these designs are somewhat cumbersome and require quite a large external driving system [1,3,12]. Ma et al. have also presented the mechanical design of a HRR and its control algorithm for the inspection of confined spaces [13]. An actuated universal-joint design was presented in Ref. [14]. For this design, U-joint “crosses” are connected to one link with a pitch pivot joint and to the next with a yaw pivot joint. The pitch and yaw joints are always orthogonal and intersect along the link centerlines; this leads to a relatively simple kinematic system. The pitch and yaw joints are actuated by linear actuators placed within the link’s envelope. The links are configured such that at each end of any link are parallel; thus, one link has pitch joints at both ends actuated by its two linear actuators; the next link has two yaw joints. This arrangement facilitates packaging of the two linear actuators side-by-side within the link. In Ref. [15], the authors reported on design of a new lightweight, hyper-redundant, deployable binary robotic articulated intelligent device (BRAID), for space robotic systems. The BRAID is intended to meet the challenges of future space robotic systems that need to perform more complex tasks than are currently feasible. It is lightweight, has a high degree of freedom, and has a large workspace. The device is based on embedded muscle type binary actuators and flexure linkages. Such a system may be used for a wide range of tasks, and requires minimal control computation and power resources. In Ref. [16], the authors used wires to design a wire-driven weight-compensation mechanism. The mechanism consisted of a parallelogram linkage mechanism that had an extended portion with the wired double pulley.

In recent years, several papers have been published related to hyper-redundant robots, which utilized and improved upon previously reported joint mechanisms. Several researchers have iterated on Chirikjian and Burdick’s [2] design of a serially connected parallel mechanism. In Ref. [17], a hybrid approach for serially connected parallel mechanism units was introduced. Each unit is composed of two platforms connected by three linear actuators with spherical pairs at both ends (3PR) and a center rod fixed perpendicular to the upper platform with a spherical joint at one end resulting in a 3DOF rotational motion. Both forward and inverse kinematics of each link and of the manipulator was presented. Gallardo et al. [18] also introduced a hybrid approach for serially connected parallel mechanisms, where each limb is constructed of a 3DOF parallel mechanism capable of three rotations. Wolf et al. [19] introduced a serially connected parallel mechanism robot; each link is a 4DOF parallel mechanism having 3RR plus R between each link.

In recent years, several researchers have also been working on continuous hyper-redundant robots. These robots are composed of flexible continuous structure capable of 3D motion. Example for such robots are Shapiro et al.’s [20] bi-bellows: pneumatic bending actuator, Nakamura et al.’s [21] shape-memory alloy based bending actuator, Dario et al.’s shape-memory alloy based bending actuator [22], and Ivanescu et al.’s shape-memory alloy based bending actuator [23].

Iterations on Hirose et al.’s [16] cable-driven robots are introduced by Ning and Worogtot [24], and a cable-driven Snake-like robot with a flexible backbone presented by Zhang [25]. Examples for medical hyper-redundant robots, which are cable driven, are presented by Simaan et al.’s [26] multibackbone flexible snake robots. Michael et al.’s [27] two nested superelastic nitinol which are controlled in plane with two independently actuated cables in a pull–pull configuration. Another example for a cable-driven medical robot is Medrobotics flexible robot for minimally invasive surgery [28,29].
In the current report, we present a novel design composed of 16DOF using serially chained links (Fig. 1(a)). The hyper-redundant arm was designed to maximize precision and strength. These goals were achieved by constructing an arm composed of two concentric skeletons: internal and external. The internal skeleton is responsible for the kinematics of the arm and serves as a backbone, whereas the external skeleton serves as a mechanical “exoskeleton” carrying the self-weight of the arm and the external loads. Total length of the arm is 80 cm, curving to an overall bend of up to 180 deg and capable of manipulating its own weight with an additional payload of 25% at its tip (at horizontal stretch) which can be equipped with a camera or a gripper.

2 Mechanical Architecture of the Mechanism and Low Level Controller

2.1 Mechanical Architecture. The HRR arm is composed of eight modular links (Fig. 1(a)). The links are connected by centralized passive universal joints (Fig. 1(b)) surrounded by a cylindrical cover (Fig. 1(c)). The cylindrical cover is decomposed into two cylinders, upper and lower, connected along two 11.25 deg inclined planes, facing opposite each other (Fig. 2(a)).

The two cylinders can be rotated independently using two axially positioned dc motors through a 22:1 external gear (Figs. 3 and 4). Relative rotation of the motors results in an inclination angle of 0–22.5 deg between the centerlines of the upper and lower cylinders (Fig. 2(b)). When both motors are rotated simultaneously in the same direction and speed, the inclined link rotates 360 deg around the link’s vertical axis (Fig. 2(b)). Consequently, the orientation of the inclination of that link is rotated 0–360 deg in free space.

One of the biggest challenges in the design of a hyper-redundant long manipulator is maintaining reasonable dimensions and low self-weight, while not compromising the rigidity of the structure and its accuracy. Usually, these design criteria are counter-intuitive, i.e., rigidity is usually achieved by large physical dimensions and high self-weight. The novelty of the proposed structure is that it achieves high rigidity and accuracy while still maintaining a relatively low weight of 480 g per link at a total length of 800 mm and an outer diameter of 77 mm.

As described before, the inclination angle of the link is achieved by rotating one the cylinders with respect to the other. Also, the orientation of the inclined cylinder is achieved by a synchronized rotation of both cylinders.

As can be observed in Fig. 2(a), inclination and orientation of the inclined link are achieved using rotational motors; both rotations occur only at the inclined cylinders, while the base of the link is not rotating and acts as a support for the motor and gear. This kinematic arrangement results in a backbone composed of passive universal joints, which is supported and actuated by the cylindrical structure that serves as an exoskeleton. Consequently, this mechanical design can withstand high bending and twisting torques because bending torques resulting from self-weight and external loads are handled by the exoskeleton structure, i.e., at the inclined plane connecting the two cylinders and the contact planes with the link bases. Furthermore, the torque applied on the motors results only from the friction forces along the inclined plane or the base planes when the inclination or orientation changes. Relative to the HRR arm self-weight, these torques are very low and can be further reduced by lowering the friction coefficient between the surfaces.

For actuation, we used 4 W Maxon RE-Max17 dc motors with an internal 128:1 gear ratio and 128 clicks-per-turn encoders. The motor axis is connected to an external gear (Figs. 3 and 4),
having three stages with an overall ratio of 1:22. Teflon (PTFE) Journal bearings were used against the 7075-T6 aluminium base and cylinders to achieve light weight and low friction.

2.2 Low Level Controller. Distributed control architecture was implemented by having a local control board connected to a groove at the back of the base of each link (Fig. 5). A RS485 communication central data bus connects all the local control boards to a single high-level controller, where motion planning and inverse kinematics are performed.

Each control board, located between two link bases, consists of a Digital Signal Processor Micro Control Unit (DSP MCU) (dsPIC33FJ128MC204), an integrated 3 A H-Bridge driver, a quadrature encoder interface, including differential line decoders and supports two adjacent dc motors and encoders.

Each control board is connected to a central power bus (14AWG main electric dual cable) delivering 24 V. As mentioned in Sec. 2.1, an important mechanical feature of the mechanism is that the bases of the link are fixed and not rotating. This feature is important for keeping the electrical wires running along the mechanism from twisting, hence not limiting the rotation of all the links.

Position control feedback is achieved using the dc motor encoders, with an additional magnetic reed switch used as the index for each half link full rotation which enables homing of each link (Fig. 6). The reed switch is located inside a through hole in the base which does not rotate, while a magnet is located inside the rotating cylinder connected to the outer gear as seen in Fig. 6. An assembly of two links including the low level controller along with a full assembly of the arm is shown in Fig. 7.

2.3 Motor Torque Calculation. The maximal applied torque on each motor can be calculated at a fully stretched configuration (Figure 8).

The bending torque in each link is given by

\[ M_{Bi} = \sum_{j=1}^{i} m_j g l_{i-j} \]  

(1)

Starting from the payload link (1) to the current link (j)

The axial force in each link can be written as a function of the bending torque and is given by

\[ F_i = \frac{M_{Bi}}{r} \]  

(2)

Hence, the torque applied on each motor is given by

\[ T_i = \frac{F_i \cdot \mu \cdot r}{\eta \cdot G} \]  

(3)

where \( l_{i-j} \) is the distance from link \( i \) to current link \( j \), \( r \) is the effective link radius, \( \mu \) is the friction coefficient, \( G \) is the gear ratio, and \( \eta \) is the gear efficiency.

A modular identical design for all links was chosen, which will simplify the design and lower overall costs. Hence, for the calculation of the required motor’s torque, we refer to the base motor, which bears the maximal torque

\[ T_n = \frac{\mu \cdot M_{Bn}}{\eta \cdot G} \]  

(4)

The linear dependency between the motor torque required and the friction coefficient for each of the links along the arm can be observed in Fig. 9, where each line refers to a different link and the fixed link requires the highest torque. The friction coefficient of PTFE and aluminium is about 0.15, which is indicated in Fig. 9.

It is worth mentioning that the friction coefficient can be reduced even further by thrust bearings or better yet by using special low-friction coatings on the aluminium which have no additional weight and which are known to reduce the friction coefficient to as low as 0.02 [30]; consequently; the base motor torque can be reduced from 180 N mm to 25 N mm, meaning smaller and lighter motors or an improved capability to lift heavier payloads.

3 Forward Kinematics of the Mechanism

The backbone of the mechanism is basically a series of universal joints, which are never twisted around their axis but only bent using rotational actuators. Hence, the kinematics of each link can be modeled as two revolute joints perpendicular to each other and to the trunk’s backbone axis (Fig. 10). Moreover, the actual angle of rotation of the motor is a function of the bending angle of
the universal joint. The forward kinematics solution of the arm is given using the Denavit–Hartenberg convention, accordingly (Table 1).

The resulting transformation matrix that expresses the position and orientation of the origin of the end-effector with respect to the base frame is given by a multiplication of all the local transformation matrices between two successive joints

$$A_{0}^{i} = A_{0}^{i}A_{1}^{i} \cdots A_{15}^{i}$$ (5)

where, for example

$$A_{1}^{0} = \begin{bmatrix}
\cos(\theta_1) & -\sin(\theta_1) & 0 & a_1 \cos(\theta_1) \\
\sin(\theta_1) & \cos(\theta_1) & 0 & a_1 \sin(\theta_1) \\
0 & 0 & 1 & 0 \\
\end{bmatrix}$$

$$A_{2}^{1} = \begin{bmatrix}
\cos(\theta_2) & -\sin(\theta_2) & 0 & a_2 \cos(\theta_2) \\
\sin(\theta_2) & \cos(\theta_2) & 0 & a_2 \sin(\theta_2) \\
0 & 0 & 1 & 0 \\
\end{bmatrix}$$

As mentioned, $\theta_i$ and $\theta_{i+1}$ are the two bending angles of each U-joint. Both angles are a function of the rotation angles $\beta_i$ and $\beta_{i+1}$ of both inclined cylinders in each link (Fig. 2). The $\beta_i$ and $\beta_{i+1}$ angles are the rotation angles of the motors multiplied by the overall gear ratio, $N = 22$.

$\theta_i$ and $\theta_{i+1}$ are given by

$$\theta_i = x(\cos(\beta_i) - \cos(\beta_{i+1}))$$ (6)

$$\theta_{i+1} = x(\sin(\beta_i) - \sin(\beta_{i+1}))$$ (7)

where $x$ is the inclination angle of the rotating inclined cylinders ($x = 11.25$ deg), $\beta_i$ is the rotation angle of the lower inclined cylinder, and $\beta_{i+1}$ is the rotation angle of the upper inclined cylinder. The bending angles of the universal joints for both of its perpendicular revolute joints can be extracted from Eqs. (6) and (7). These angles are plotted in Fig. 11 for a fixed lower cylinder.
rotation motions independently, as a function of each cylinder (or motor) of the full length of the arm, should define these two different
inclination angle (between 0 and 22.5 deg). In Fig. 13, we set $\beta_1 = 0$ and kept $\beta_2 = \beta_1$ during rotation, and as can be seen in Fig. 14, $\beta_1 = 0$ while $\beta_2$ is changing and reaching an amplitude of 22.5 deg in both directions (magnitude of inclination).

The set of kinematics transformations presented are the inverse kinematics solution of a link. This means that once a set of $\theta$ angles are determined using an inverse kinematics solution for the entire arm, the local $\beta_1$ and $\beta_2$ angles for each link can be determined resulting in motor commands if the overall gear ratio is known. It is worth mentioning that once the inverse kinematics of a single link is solved one needs to solve inverse kinematics of the entire arm. This issue has been the scope of many works related to robotics. It is even of a greater interest and complexity when referring to hyper-redundant mechanisms as in the current case. The inverse kinematics of the entire arm is not within the scope of this paper. It will, however, be reported in a future publication.

4 Inverse Kinematics of Link

The inclined cylinder design and the way they are actuated define a kinematics dependency between the orientation of the inclination plane and the magnitude of inclination (angle) of the upper cylinder relative to the lower one.

Figure 12 shows a top view of a link, which can be regarded as a polar arrow, where the orientation of the arrow refers to the orientation of the inclination plane of the link (between 0 and 360 deg), while the length of the arrow refers to the magnitude of the inclination angle (between 0 and 22.5 deg).

The inverse kinematics solution, as a means for path planning of the full length of the arm, should define these two different motions independently, as a function of each cylinder (or motor) rotation $\beta_1$ and $\beta_{i+1}$.

In order to choose the orientation of the inclination plane, one must rotate both $\beta_1$ and $\beta_2$ at the same speed, meaning keeping $\beta_2 - \beta_1 = \text{constant}$, where this constant is a measure of the magnitude of inclination. In Fig. 13, we set $\beta_2 = \beta_1 + 180$, meaning an initial full inclination of 22.5 deg and rotation of both cylinders in the same direction a full revolution of 360 deg. As can be seen, $\beta_2$ follows $\beta_1$ by 90 deg, reaching the same amplitude (magnitude of inclination angle).

In order to keep the orientation of the inclination plane constant while changing the magnitude of inclination, one must rotate both $\beta_1$ and $\beta_2$ at the same speed but in opposite directions, meaning $\beta_2 + \beta_1 = \text{constant}$, where this constant now determines the direction of inclination. In Fig. 14, we set $\beta_1 = 0$ and kept $\beta_2 = \beta_1$ during rotation, and as can be seen in Fig. 14, $\beta_1 = 0$ while $\beta_2$ is changing and reaching an amplitude of 22.5 deg in both directions (magnitude of inclination).

5 Conclusions

In this report, we describe the mechanical structure and kinematics analysis of a novel hyper-redundant robotic arm. The arm is composed of 16 rotational degrees of freedom and is design to achieve high rigidity and accuracy. The arm is composed of two concentric skeletons: internal and external. The internal skeleton is responsible for the kinematics of the arm and serves as a backbone, whereas the external skeleton serves as a mechanical “exoskeleton” carrying the self-weight of the arm and the external loads.

The forward kinematics of the mechanism are not straight-forward, that is, the bending angles of the arm are not directly related to motor angle. We, therefore, derived the inverse kinematics transformation for a link by deriving the kinematic linkage between the arm tilt angles and motor angles.

There are many daily applications where such an arm may be useful given its high precision and strength. For example, this type of hyper-redundant arm can be very useful for search and rescue applications when it is mounted on a mobile platform with a camera mounted on its end-effector, to be used to look for survivors trapped inside collapsed rubble. This use will lower the risk of rescue workers finding themselves trapped due to secondary collapse of structures [14]. Another application for such an arm is remote bomb disposal. The arm allows for a large workspace combined with delicate and stable maneuvers via its gripper, unlike some of the current robots which have an arm moving in a vertical plane. Currently, with these platforms, the operator is obliged to manipulate the mobile platform in order to reach out of plane. The presented inclined links hyper-redundant design can better suit these applications over other HRR designs, due to its relative lightweight, long reach and high number of DOF, which
does not prevent it from lifting larger payloads, such as the case of the current design.

References


