New design of soft robot arm for infrastructure inspection

Ilija Stevanović, Aleksandar Rodić

Abstract— **This paper presents new, inspired by nature design of soft robot arm for infrastructure inspection. The robot arm is hyper redundant, under actuated, with 20 DOFs and with gripper as end effector. Robot arm is powered by only 9 servo-motors. The power transmission from the actuators to robot links and further to the end-effector is realized intra structurally by wires. Controllability and dexterity of the soft robotic arm is verified by model simulation before implementing control algorithms to the robot controller. For the purpose of simulation the algorithms of the inverse kinematics are realized. Mechanical prototype in its' early phase of integration is shown in this paper, too.**

Index Terms— **Hyper-redundant robot arm, continuum robots, under actuated mechanism, flexible robots, soft robots.**

I. Introduction

Current industrial robots are mechanical structures inspired by human arm anatomy as system for manipulation with segments lined up in the row. Application of this kind of robots are limited to industrial environments where workplace and tasks are predefined and adapted for each robot arm system. The conventional industrial robot arms are rigid and heavy and because of that for safety reasons they are placed in controlled environment and human restricted workspace. However, there are specific tasks when robots and humans must work in same workspace, not only that they also must work in interaction with each other, i.e. coming into a direct contact. Next advanced steps for industrial robots are ability to maneuver in narrow and curved spaces, and to adapt to disturbances in interaction with the physical environment. To improve the robot's flexibility and versatility, recently interests have increased for development of the so-called "soft" robots.

Hyper-redundant, multi-segment robots are mechanisms with sequential kinematic chains having a significantly higher number of mechanical degrees of freedom than is normally required to perform the task. Typically, six degrees of freedom structure is sufficient to execute any robotic tasks in the three-dimensional workspace where the manipulating final device (gripper) requires movement of the three translations and three rotations around these coordinate directions. These movements include translation in the longitudinal (X), lateral (Y) and vertical direction (Z), and the corresponding rotations about the X-axis (twisting), the Y-axis (flexion) and about the Z axis (turning).

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Due to a low weight, large number of segments in the kinematic chain and elastic structure, these types of robots have a relatively small payload, limited robustness to external disturbances and high complexity of motion control. A large number of segments in the kinematic chain need a large number of servo-motors, increasing complexity of the mechanical design and total device cost. For this reason, certain modified design approach is required with a less number of drive motors then the number of degrees of freedom. Such mechanisms are called "under-actuated" mechanisms. As it is already noted, the redundant robotic structures, even considerably more complicated to control, provide better maneuverability and significantly increase the working area. These structures also can continue to work even if some servo-motor fails to work, meaning that other motor drives can take over role and the system will continue to operate at a reduced capacity but not stop.

The paper is organized into several sections. In the introductory Section 1, the research objectives are set and the basic terms that will be used in the paper are defined. The Section 2 provides a brief survey of the recent results in the area. The Section 3 presents the innovative mechanical design and robot kinematics in brief. The Section 4 presents some early control and the simulation results priory to experimental verification. The paper terminates with the bibliography.

II. State-of-the-Art

The hyper-redundant multi-link soft robots were investigated for a long time in numerous applications that benefit of an increased dexterity and high capacity to avoid obstacles [1], [2]. A Hyper-redundant multi-links flexible robot has a similar structure to the snake skeleton, octopus' arm, elephant's trunk, mammal's tongue, etc. The typical structure of a hyper-redundant multi-links flexible robot is a series of links, such as the ACM-Rx developed by S. Hirose [4], or the Omni Tread serpentine robot developed by J. Borenstein [5]. These links are articulated by the joint and each joint is actuated independently. The flexibility comes from the motion of the many joints. However, it is difficult for them to follow an arbitrary trajectory regardless of the large number of degrees of freedom (DOF). Because of the high number of DOFs, the efficient resolution for the inverse kinematics was one of the main theoretical problems that have delayed their use. Chirikjan and Burdick [3] solved this problem by using the variation calculation methods. Lu and

Proceedings of 4th International Conference on Electrical, Electronics and Computing Engineering, IcETRAN 2017, Kladovo, Serbia, June 05-08, ISBN 978-86-7466-692-0 pp. ROI2.2.1-4

Du [6] have analyzed multi-segmented robot as a multi-section flexible robot. Each section is treated as a link with 3 DOFs. For the calculation kinematics of the each section the geometry method is used. For solving inverse kinematics they proposed uniform bending scheme in which closed form inverse kinematics can be solved. The Walker, et al. are developed a modified Denavit-Hartneberg (D-H) method for continuum robots [7] and pro-posed a closed-form inverse solution for multi-section continuum robots [8]. In this method, besides the distal end position, the length of each section needs to be known.

III. MECHANICAL DESIGN AND KINEMATICS

Hyper-redundant robot arm consists of: a) a base of the robot (Fig. 1), b) a set of 9 cylindrical segments connected by the universal joints and linear springs, c) a wrist and d) a gripper (Fig. 2a). The fundament of the robot is a metal frame in the shape of a truncated heptagonal base pyramid (Fig. 1) which is intended to be placed on a rotational platform, thus allowing revolution around the vertical axis of the robot, as shown in the kinematic model scheme (Fig. 2b). Power motors are dislocated from the robot joints and mounted into the fundament (Fig. 2c). They drive the multi-segment robotic arm, rotate the hand around the longitudinal axis and tighten/release the robot gripper. The anchor with two pulleys with a diameter of 48 mm is mounted to the motor shaft. Two steel strings of diameter 1.2 mm are reeled up in the opposite directions to drive the individual rows (column-1, column-2 and -3) of the kinematic chain of the robot mechanism composed of three equal sections (Fig. 1a). In such a way, the segments are moved under the antagonistic effect of strain wrapped on the pulleys (how much of one strain is wrapped on the other side second strain for as many is unwrapped). The strings that depart from the corresponding servo-motor for bending and turning particular segment, ending on the third segment of each of these sequences (column-1, -2, -3). The springs are pre-stressed to ensure constant tension of the strings. Loosing of the stains is not desirable in the system in order to ensure regular movement all the times. At the end of the kinematic chain is the wrist segment (Fig. 2a). It is also driven by its servo-motor and the corresponding pair of strings. Linear movements of the strings are transferred to the rotational movement around the twisting axis of the wrist, using a pair of conical gears, which are located within a segment of the wrist. In this way, it is avoided to mount the motor into the wrist joint and total weight of the system is reduced as well as better dynamic characteristics of the robotic system is achieved. The strings inside the internal structure of the robot arm are freely moved through the Teflon tubes with a low friction coefficient. For this purpose inexpensive standard break bike ropes are used. An extra motor is also reserved for the gripper tightening.

Presented structure can achieve the desired movement or the robot arm i.e. reliable control of 20 mechanical degrees of freedom. Motion is provided by 9 servo-motors. Single motor preserve rotation of the fundament of the whole system. Another 6 motors of the type Faulhaber 3863H024C R [10] control successive three series of robot links with three segments every (column-1, column-2 and column-3) in two orthogonal directions - bending and tilting. Each of the mechanism joint can achieve a rotation of 20 degrees in both directions – right-left or up-down. Corresponding neighborhood segments are connected by the universal joint and by the linear springs which are pre-stressed according to the design. This segmented robotic system is similar to spine type system of the mammals giving the desired strength of the structure and robustness to stretching and deformation of the kinematic structure. The springs provide string tensions, partially affect the compensation of gravity moment at joint mechanism and give certain elasticity in terms of structure and desirable compliance. For these mentioned reasons, the structure of the robotic mechanism can be considered as "soft structure". Presented structure of the hyper-redundant robot can be considered as an under-actuated system because this robot has 20 degrees of freedom that are driven by only 9 power drives. The advantage of the presented structure is that it has reduced the overall mass of the robot system and consumes less energy for overall motion. On the other hand, the robot motion control is significantly more complex because there are numerous of couplings between particular segments and kinematic structure is high redundant.

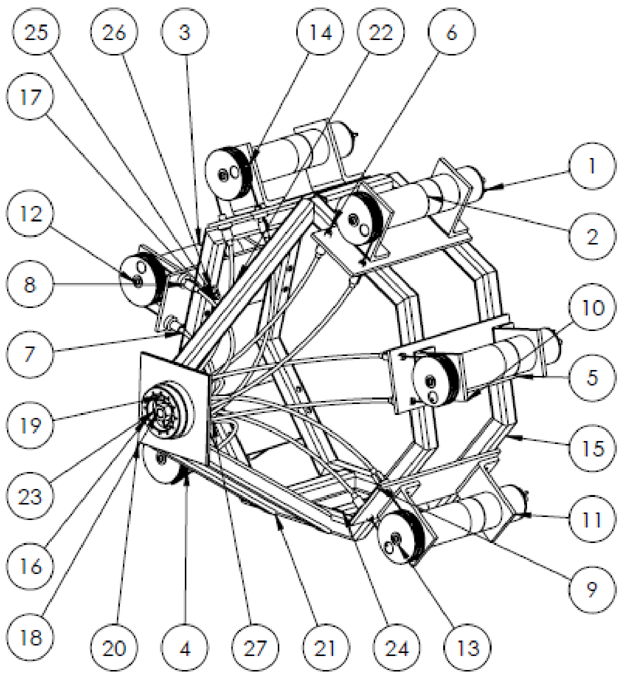
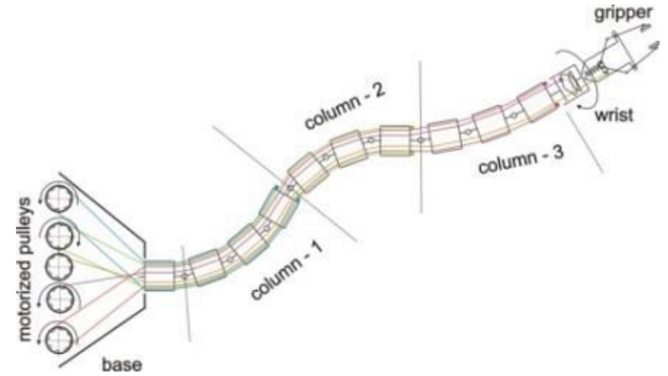
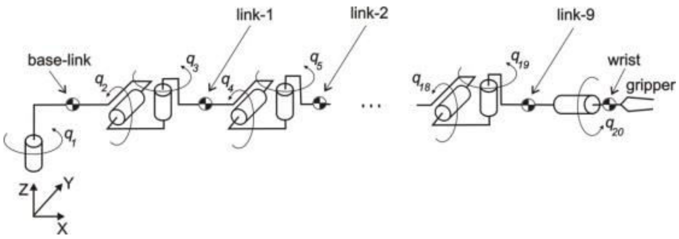


Fig. 1. Base of the robot with servomotors, pulleys and wires.



a)



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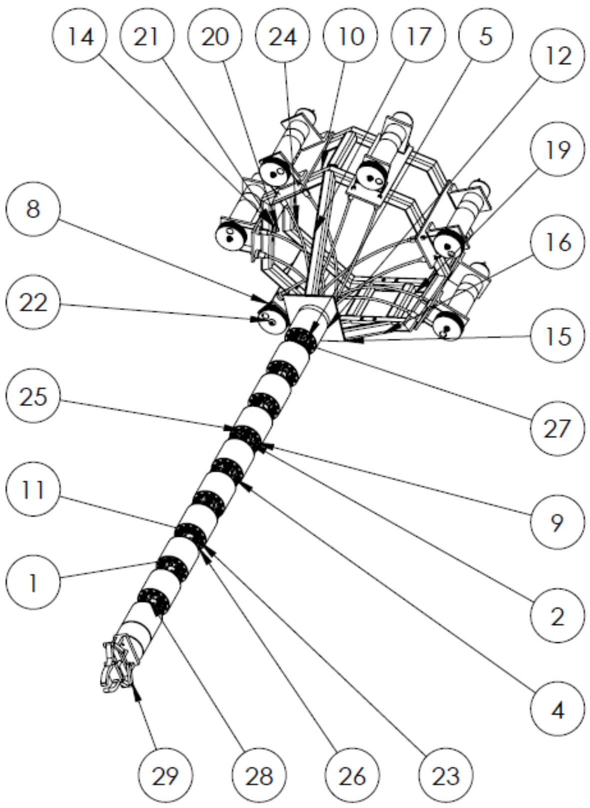

c)

Fig. 2. a) 2D scheme of the robot arm actuation; b) Kinematic scheme of the hyper-redundant under-actuated 20 DOFs robot-arm with end-effector c) 3D model of robot arm.

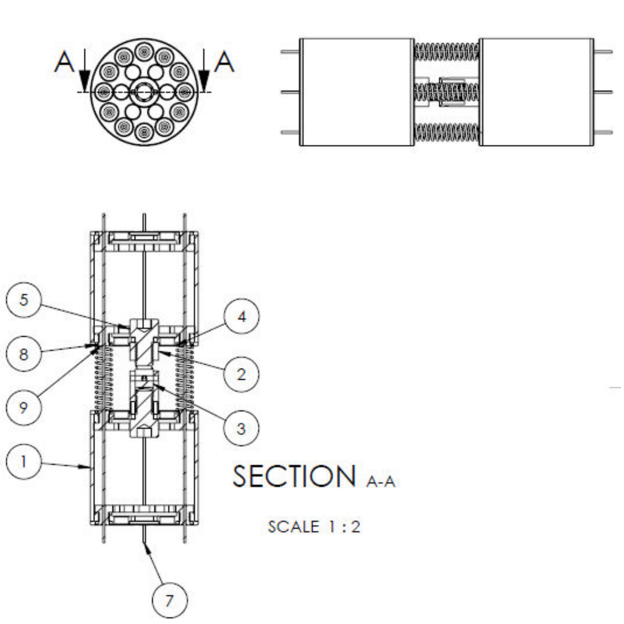

Fig. 3. Cross-section of segments of the kinematic pair of robot arm.

Presented mechanical structure of the robot is hollow inside. Each segment on its' front side and the back side has a drilled cylindrical plate (Cross section A-A, Fig. 3a) that providing passing the stings and electrical cables for sensors, LED lamp and micro camera mounted to the robot end-device. Sensors system includes incremental encoders and tension meters which measure the tension force in the strings and angular position of the joints. The acquired sensor-data are collected by the robot controller that plans motion and task realization including trajectory tracking and gripper manipulation.

IV. Control System and Simulation Example

Path planning, inverse kinematics calculation and robot trajectory tracking control of a hyper-redundant robot is rather complex task [9]. A closed-loop system simulation with kinematic and dynamic model of robot mechanism is tested priory to the experimental verification of the controller with real prototype in order to tune control parameters in advance. Standard PD control algorithm is applied for testing controller.

The control algorithm includes inverse kinematics solving as well as calculation of the direct dynamics for an imposed trajectory in task space. For the purpose of simulation and testing control performances of the soft robot arm, the trajectory was introduced in the task space XYZ (Fig. 4). The corresponding joint angles, i.e. coordinates in the robot joint space, are generated by controller – the inverse kinematics software module. Corresponding joint speeds are presented in Fig. 5

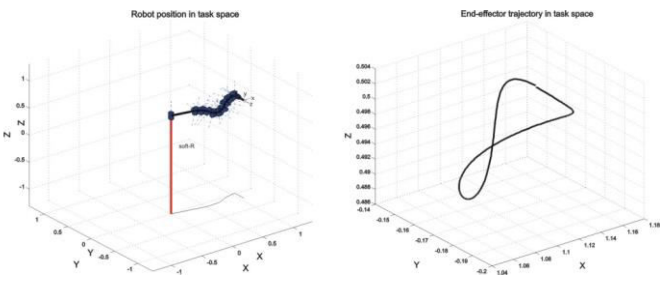

Fig. 4. End-effector trajectory and a robot arm position along the path.

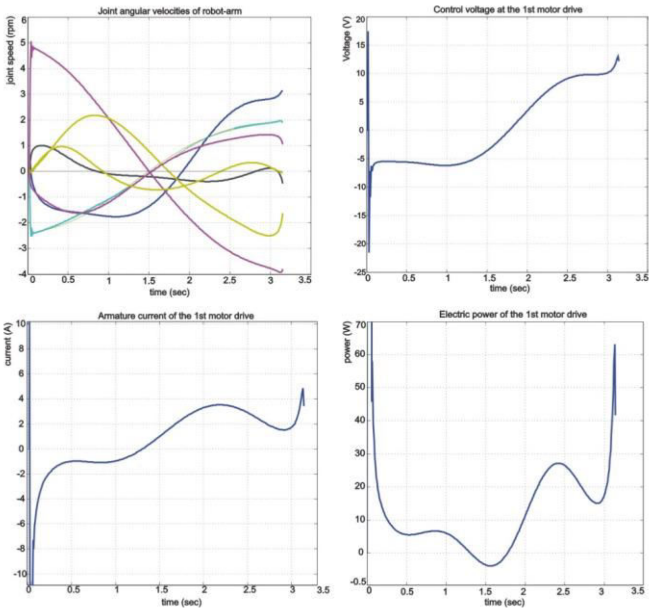

Fig. 5. Joint angular velocities of the soft robot-arm; Control voltage, armature current and electric power at the 1st motor drive.

V. CONCLUSION

In this paper the new design of soft robot with 20 DOFs is presented. Controllability and dexterity of the soft robotic arm is verified by model simulation before implementing control algorithms to the robot controller. For the purpose of simulation the algorithms of the inverse kinematics are realized.

The next phase in development of the soft robot-arm will be experimental evaluation of different configuration of the system and testing of position repeatability.

ACKNOWLEDGMENT

The paper is funded by the Ministry of science of Republic Serbia under contract TR-35003 and partially by the Alexander von Humboldt Foundation (Germany), contract no. 3.4-IP-DEU/112623, 2015-2017. The authors of this paper are inventors on a patent application Π-2017/0151 that covers design and associated software.

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