The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

A DOF State Controllable & Driving Shared Solution for Building a Hyper-Redundant Chain Robot

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Abstract—**This paper puts forward a novel design solution for building a 3D hyper-redundant chain robot (HRCR) system, which consists of linked, identical modules and one base module. All the joints of this HRCR are passive and state controllable, and share common inputs introduced by wire-driven control, no matter how many degrees of freedom (DOF) are implemented using different numbers of modules. The prototype developed here, named *3D-Trunk*, is used as a proof of concept. We will present here its concept, mechanical and embedded controller design and the implementation.**

I. Introduction

The study on hyper-redundant chain robot (HRCR) systems is always an important field, because such robots offer many independent degrees of freedom (DOF). Elephant trunk robots, snake robots, serpentine robots, etc, are all representative cases [1-10, etc]. The related literature is substantial, and many groups exist who build different HRCRs pursuing theoretical and application driven research.

The most popular approach to build a hyper-redundant robot is by connecting several rigid links via an actuated revolute joint in a chain. Another popular design approach utilizes parallel mechanisms to connect several links together [1-2]. The interest in building modular robots is also increasing [3-4]. The realization of an HRCR raises various mechanical design issues. There are many tradeoffs between different restrictions [5] which have to be considered and wider efforts have been made to reduce the mass/volume of the links. A good review of the prior work had been presented in [5]. There exist some other interesting HRCRs, which present different mechanical solutions [6-10].

Paap et al used cylindric rubber pieces to construct snake robot joints [6]. There were four motors mounted in a segment, and these motors were used to wind and unwind wires to compress cylindric rubber pieces in different directions for rotation.

Ananiev et al present a new method for driving a hyper-redundant robot [7]. Their method comprises a flexible shaft, which transports the rotation from only one irreversible motor to the mechanisms inside all multiple modules of the robot by means of several clutches to distribute selectively the torque/rotation of the motor independently to any of the robot modules [7].

Clemson University developed an elephant trunk robot [8]. Of the possible 32-DOF, the hybrid cable and spring servo system creates a manipulator with 8-DOF that are user controllable and 24-DOF that are coupled to the controllable DOFs [8].

Ohno and Hirose presented a slime robot, which is constituted of many slime robot modules [9]. Each module is a 3-DOF pneumatic module with pneumatic actuators, valves, sensors and a microprocessor in its body.

The Autonomous Systems Laboratory of EPFL presents the development of a bio-mimetic spine for the humanoid robot, Robota [10]. This spine is composed of four vertebrae parts, linked through spherical bearings. There are distributed hydraulic pumps and springs to drive these vertebrae parts and bend the spine.

In this paper, we present a novel concept for building an HRCR, which consists of passive and state controllable joints, and shares a common wire-driven input. The remainder of this article is organized as follows. In Section 2, the concept is presented. The original prototype design and some implementation issues are described in detail in Section 3. Section 4 describes the distributed control architecture of our prototype, and some issues related to electronics. Feasibility experiment results of our primary 3D-Trunk prototype are presented in Section 5. Finally, conclusions and application potential are presented in Section 6.

II. Concept Of The Novel Hyper-Redundant Chain Robot

A. Passive Joint with State Control

Figure 1(a) shows a general 3D hyper-redundant chain mechanism schematics described in this paper. It consists of a set of links serially connected by passive revolute joints in a chain. Each revolute joint has one DOF. The angle between

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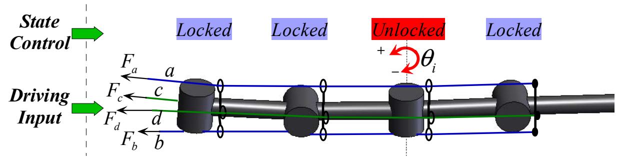
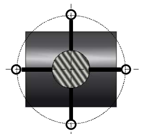
two neighboring joint axes is arbitrary.



(a)



(b)

Fig. 1. A 3D hyper-redundant serial-link mechanism schematics. All the revolute joints are passive and with binary-state control. They can only be in locked and unlocked states.

There are two pairs of driving-wires (*a* and *b*, *c* and *d*) drive this hyper-redundant serial kinematic chain. As shown in Fig.1 (b), there are four "rings" symmetrically distributed and fixed in each link. These rings are used for turning and to guide the wires. Two opposite rings are coplanar with the joint's axis; and the other two are perpendicular to them. These rings are located very close to the joint. As shown in Fig.1 (a), two pairs of wires are routed along the chain via many such rings.

If we lock some of the revolute joints, then the locked joints will not be rotatable and the DOF of the whole chain has essentially degenerated. In the case shown in Fig.1 (a), only joint i is in the unlocked state, external force or torque introduced by the routed wires will rotate it.

With this concept, we can control any one joint's motion step by step; then by altering the loading configuration change the whole chain's shape according to our expectation.

B. DOF State Controllable & Driving Shared

Recently some novel wire-driven robots had been reported

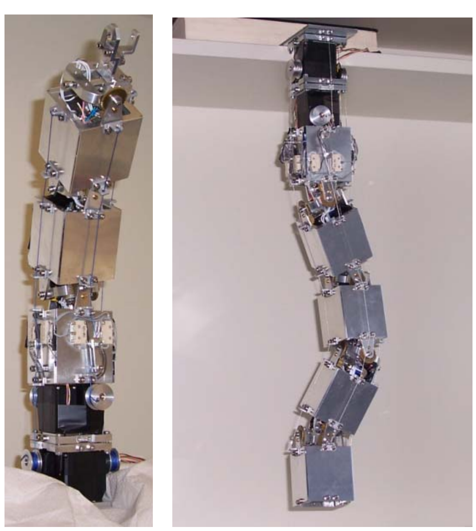


Fig. 2. The original 3D-Trunk prototype. The left one is with 4-DOF; the right 8-DOF one is the extension version. This wire-driven system is a closed-loop control system with multiple Micro-Controllers distributed and embedded.

[e.g., 11-16], with some advantages. In this study, wire-driven is also an easy and effective approach to drive our passive hyper-redundant serial kinematic chain. All the passive joints of the whole chain share the driving effect introduced by wires. All driving-wires need to be in a taut status, because wires can only impose unidirectional constraints.

For this kind of HRCR, every unlocked joint is differentially driven by a pair of wires. Driving these wires by windlasses is an easy and suitable approach. In the situation shown in Fig.1 (a), only joint *i* is unlocked, the wires' traction will not affect the locked joints. If wire *c* is wound and wire *d* is unwound, joint *i* will rotate positively, and vice versa. The pulling caused by wires *a* and *b* will have very limited effect on joint *i*, due to the torque they generate which is mostly perpendicular to the axis of joint *i*. As this effect is small we have abstained from this, though. So, for the unlocked of joint *i*, wires *c* and *d* are the effective pair of wires.

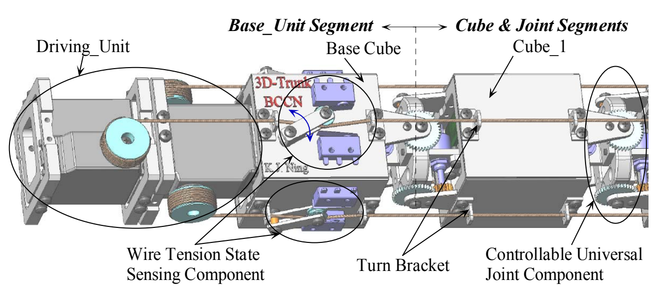
Based on this concept we could make all passive links lighter, equipping the joint with a strong binary-state locking mechanism. Using a powerful wire-driven base segment, the whole chain robot, thus, is lighter and much stronger than many conventional architectures, offering wider application fields.

III. 3D-Trunk, a Design Paradigm Based on This Concept

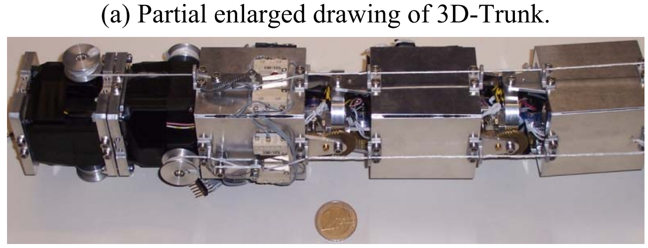
A. Introduction of 3D-Trunk's Mechanical Design

Figure 2 shows our original prototype system called "3D-Trunk". All electronics components and micro-controllers were embedded inside.

Figure 3 shows some key implementation details of 3D-Trunk. Based on the segments' function partition, the chain comprises a "Base_Unit" and many identical



(a) Partial enlarged drawing of 3D-Trunk.



(b) The key structure of the completed prototype.

Fig. 3. The key structure of 3D-Trunk. The chain comprises a Base_Unit, many identical modularized Cubes and Controllable Universal Joint Components. The Wire Tension State Sensing Component is a key for closed-loop wire-driven control.

modularized "Cube & Joint" segments. The Base_Unit is the power segment of the whole chain, for housing four DC Reduced Motors and motor control boards, as well as providing the interface components for mechanical mounting to some other structures.

As shown in Fig.3, in the Cube & Joint Segments, the same Cubes and Joints components are linked with each other. The Cubes are used for positioning the joints, housing distributed electronics boards, and routing cables inside. They are the movable segments of this HRCR. There are four Windlasses, actuated by the four DC Reduced Motors, driving the four Driving-Wires.

For the original prototype, these Reduced Motors were reconfigured starting from off-the-shelf servos. We removed their original circuits and spacer pins, just left the gears, motor and housing parts and drive them now by the new circuit boards we developed. In this way, we can achieve better and more suitable actuation performance. At present, each Reduced Motor can generate a maximal torque near 1Nm, and a maximal rotational speed (at no load) of approximately 20rpm.

As shown in Fig.3, there are some Turn Brackets mounted outside of the cubes (Base Cube, Cube_1,…, Cube_n). They work as simplified pulleys for positioning and guiding the Driving-Wires (same function as the rings shown in Fig. 1(a)).

As shown in Fig.3, there are four Wire Tension State Sensing Components (WTSSC) symmetrically distributed on the four outer faces of the Base Cube. Each Driving-Wire is routed along a small pulley inside of one WTSSC. Each WTSSC is pulled by a spring, and triggers a pair of micro-switches at the respective and predetermined positions. In this way, we can acquire all tensile state of the four Driving-Wires by these WTSSCs in real time.

The actual pulling force from the Driving-Wire can be deduced from the WTSSC's design [17]. By adjusting the related design parameters, we can obtain suitable 3-state outputs (i.e., Loose, Mid-state, and Tense). In fact, this is a discrete solution for deducing the pulling force of a wire with resilience capability. The WTSSC's design is the foundation to control this wire-driven system [17].

For example, similar to the case shown in Fig.1 (a), to achieve a positive rotation of joint *i*, wire *c* can be wound by its motor utilizing various driving strategies and its WTSSC will always be in tense state. The motors for driving wires *d*, *a*, and *b*, need to be self-adjusting to keep their respective WTSSC's state changing between loose and mid-state. This is the easiest way to ensure the stability of this wire-driven robot (overcoming the coupling problems of this non-linear system) and to reduce the power dissipation.

The solution presented in Fig.3 is simple and very practical, with very low controller resource requirements.

Figure 4 (a) shows more details of the inner mechanism of the Cube and Joint component. As mentioned in Section 1, for constructing practical hyper-redundant robots, the joint is the main mechanical design challenge. For our requirements, a strong enough binary-state locking component is the key for implementing our new concepts. Fig.4 discloses our solution for constructing an effective and compact "clutch" for this new conceptual HRCR.

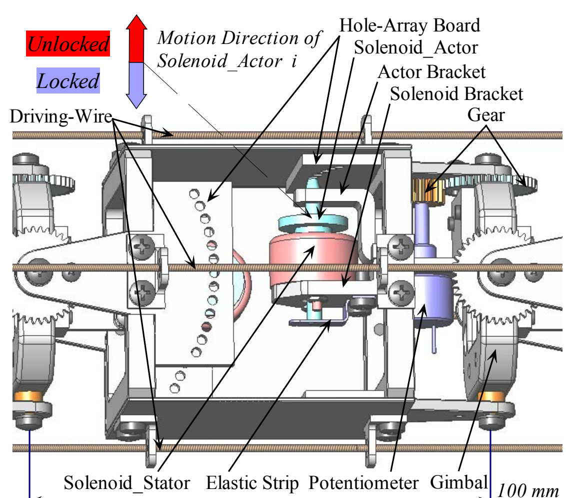
B. Design of 3D-Trunk's Controllable Universal Joint Component

Generally speaking, a clutch is a suitable device to control the revolute joint's binary-state (locked and unlocked). But off-the-shelf products are not suitable for our requirements. For building a chain-like robot, we have to consider tradeoffs between many issues [5].

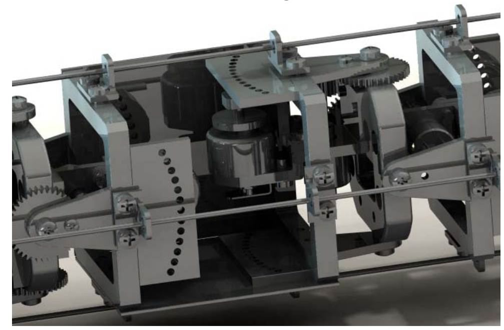
We designed a different compact locking-clutch for 3D-trunk. This design achieves much higher locking torque in a very compact and light implementation, and it provides joint angle feedback information.

The device called "Controllable Universal Joint Component" (CUJC) shown in Fig.3, is a special and compact component designed for 3D-Trunk. It contains a Gimbal in Fig.4 (a), whose two perpendicular axes coincide at each joint. Some key parts of this design are mounted on the Gimbal. One CUJC is used to bridge two neighboring Cubes to provide 2-way independent clutches, and to house 2-way joint angle sensors.

As shown in Fig.4, a linear solenoid (pull type) driving



(a) The inner mechanism design of the Cube and Joint.



(b) The design's rendering picture.

Fig. 4. Explanation of 3D-Trunk's mechanical design.

mechanism was employed to construct a practical and compact binary-state clutch for 3D-trunk. Linear solenoids are ideal for high force, short stroke applications.

In Fig.4 (a), the Solenoid_Stator encapsulates coil and sliding bearing, mounted on the Solenoid Bracket. The Solenoid_Actor is the moveable iron core, acting as a moving "pin". The Hole-Array Board provides arrayed holes to plug into. They are the key parts of the controllable binary-state locking mechanism of this design. The Solenoid_Actor has a pointy tip for easy plugging into the holes distributed in the Hole-Array Board.

For each Hole-Array Board, the holes are circularly and evenly distributed. The angle space between two neighboring holes depends on the diameter of the "pin", the radius of the hole-array, strength of material, components' size constraints, etc. For our original prototype, one joint's working range is from -27° to $+27^{\circ}$, with 4.5° resolution.

In Fig.4 (a), if the solenoid is not powered, the Elastic Strip will push the Solenoid_Actor into a plug. If it is just coaxial with a hole in the Hole-Array Board, then the plugging action will be successful. If there is no hole in the right place, the joint will continue to move until a neighboring hole is met allowing locking.

In this design, pull type linear solenoids were employed, and the joint's locked state is identical with solenoid's unpowered state. In this way, power consumption of the whole HRCR is reduced greatly.

As show in Fig.4 (a), if the solenoid is powered, the Solenoid_Stator will pull the Solenoid_Actor by an electro-magnetic force. If this effect is strong enough, the Solenoid_Actor will be unplugged from the Hole-Array Board. The Actor Bracket is used for positioning the Solenoid_Actor (together with the sliding bearing of Solenoid_Stator) and enhancing the locking stiffness of CUJC.

In order to increase the reliability of such locking action, the Elastic Strip should be stiffer. Sequentially, the solenoid needs to offer enough pulling force to against the elasticity of Elastic Strip and the sliding friction between its stator and actor.

For increasing the maximum pulling force, a pulse-width modulation (PWM) controlled current is used to power the solenoid. By powering the solenoid with higher voltage and low duty cycle, we can obtain much higher pull force and the solenoid will not burn out.

As shown in Fig.4 (a), this solution can also provide joint angle feedback information. A potentiometer is used to sense a joint's absolute angle. A pair of gears is employed to transmit motion. As the bigger gear is fixed to the cube, the obtained reduction ratio increases the potentiometer's effective resolution. Small plastic conductive potentiometers were employed in our prototype, for getting low electrical noise, high linearity and long life. The angle feedback is not only used to measure a joint's real rotation, but also to deduce plugging positions or check the result of a locking (plugging) action.

This type of "clutch" implementation is compact and can achieve much higher locking torque than a friction based approach, because the available shearing force between "pin" and "hole" is much stronger. The current locking mechanism design provides 7NM as its allowable maximal locking torque.

This solution, however, also has some disadvantages. The pin's plugging and unplugging actions are relatively slow and the locking angle steps of each joint are discrete and predetermined.

IV. Controller Architecture of 3D-Trunk

A distributed control architecture is a suitable approach for the HRCR. Fig.5 shows a distributed control architecture scheme for such HRCR. For 3D-Trunk, all power, driving cables and communication twisted pairs were routed along and inside the Cubes. The communication between the master and the distributed slave control systems are via a RS-485 serial bus. An RS-485 serial bus was employed because of its

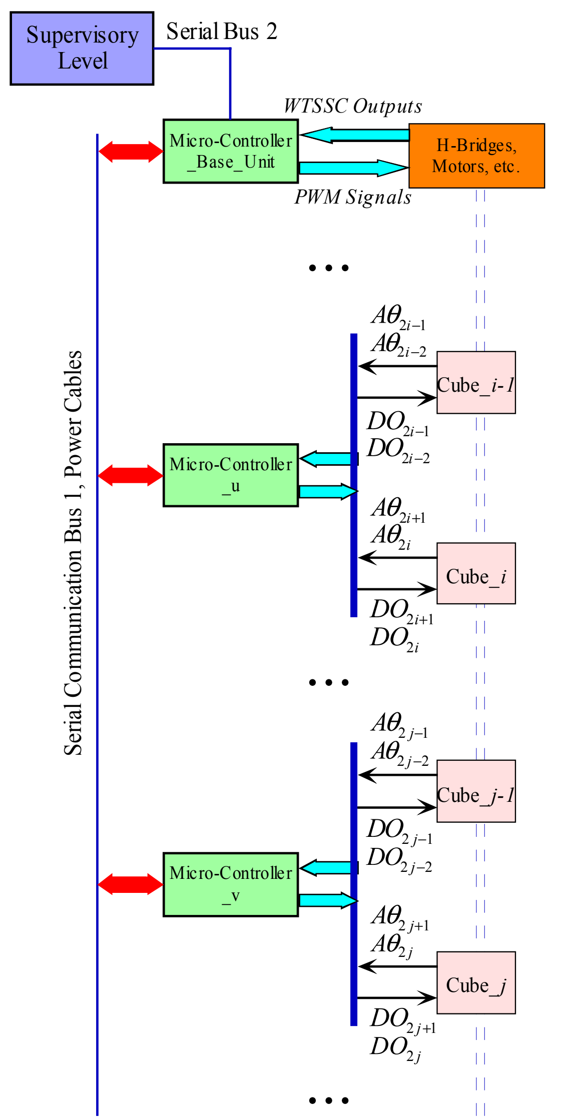


Fig. 5. A distributed control architecture scheme for such HRCR.

high immunity to noise and ability to drive large distances with high data rates. Solenoids are powered by PWM current, and each peak current is about 1.6A. Thus, they could be stronger interference sources. Since the RS-485 is differential, however, it resists electromagnetic interference from distributed solenoids and driving cables.

We developed specific embedded control boards for 3D-Trunk. These modularized boards are distributed only in some Cubes of the whole HRCR. A set of distributed slave control modules consists of a controller board and a MOSFET-array board. Such a separate design is for reducing interference and for better housing them in their Cubes.

The distributed slave control modules are based on an ATMEGA16 micro-controller (AVR core, from ATMEL). For the distributed slave control modules, the internal peripheral Timer/Counters of ATMEGA16 generate the PWM signals (for the solenoids), and the programmable I/O ports drive MOSFET-array boards for actuating the solenoids.

The motor control boards were encased in the Base Cube (see Fig.3). As shown in Fig.5, they share the communication bus (RS-485), gather WTSSCs' outputs, and drive the four motors.

The developed communication protocol is simple as it just transfers commands and data between the distributed controllers (identified by the exclusive addresses), and coordinates the behavior of the distributed locking mechanisms and the four motors, etc. Because the RS-485 is a half-duplex bus it avoids transfer conflicts and this has been considered in the related firmware code.

This controller architecture, as shown in Fig.5, is open and extendable. We can access and operate the whole HRCR by connecting a supervisory level controller. The supervisory level controller could be a PC or embedded system, depending on the actual application. A Command Set was implemented in the firmware of the Base_Unit Controller. At present, we access and control 3D-Trunk's inner resources and status by an RS-232 port of a PC, without prior knowledge about the low level implementation details of the whole mechatronic system. As the ATMEGA16 has only one hardware UART (Universal Asynchronous Receiver Transmitter), an extended, software-driven UART was independently implemented by us. This architecture design shown in Fig.5 facilitates debugging and possible future extensions.

At present, there are some autonomous functions implemented in the embedded controllers of 3D-Trunk, for example, overtime protection, self-triggering to adjust all Driving-Wires' tension states, autonomous escaping from a possible "stuck" situation, self test, etc.

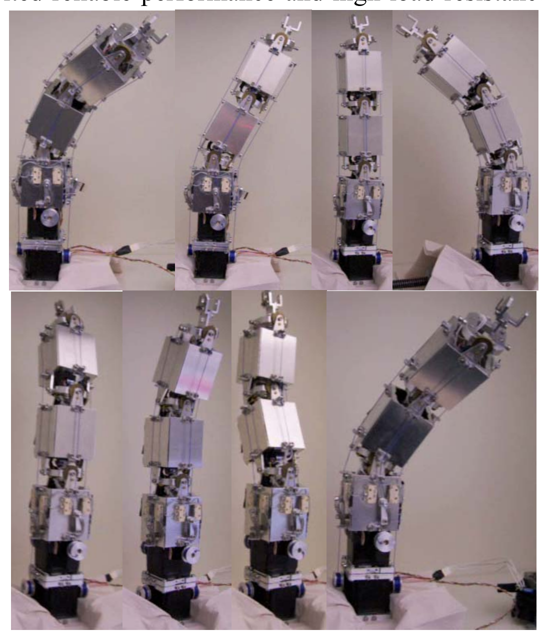
So far, it is clear, that the computational burden of the distributed controllers is low. In other words, such a robot offers a very high potential for extensions. We can mount various sensors and mechanical effectors, and port their signals to the remaining controller resources for further research and application works.

V. Experiments

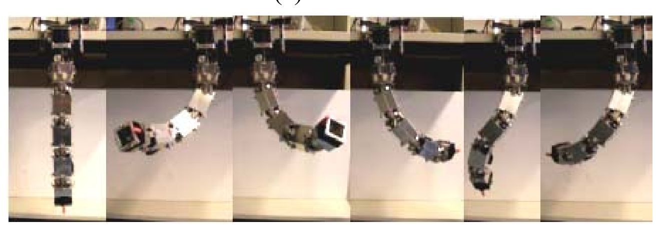
For our 3D-Trunk prototype, the weight of each Cube is 119 gram, for the CUJC it is 130 gram, and for the end cube is 103 gram (not including cables and controller boards).

Figure 6 (a) is a feasibility demonstration experiment of our primary 3D-Trunk prototype (4-DOF). Fig.6 (b) is the extension version of 3D-Trunk (8-DOF). These snapshots were taken during the experiments. Fig.6 (c) shows the experiment for testing the locking mechanism of the 8-DOF robot.

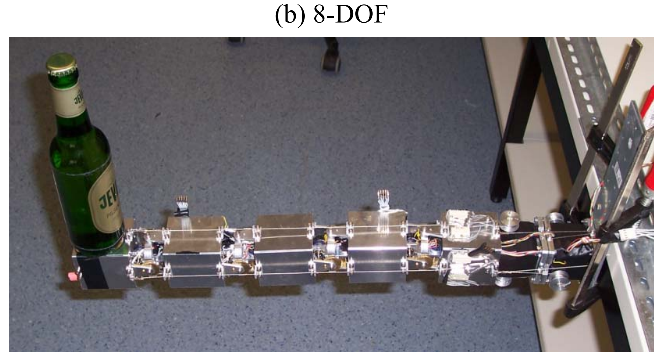
The experiments also disclosed some problems. The present controllable binary-state locking mechanism has exhibited reliable performance and high-load resistance. By



(a) 4-DOF



(b) 8-DOF



(c) Testing the locking mechanism of 3D-Trunk (8-DOF), in cantilevered pose.

Fig. 6. Snapshot and photo from experiments.

contrast, at present, the employed four driving motors are too slow for this system. The Turn Bracket design shown in Fig.3 and Fig.4 is too simple and we get rather large friction during an intensely bended pose. Neither of these problems, however, is fundamental and they can be resolved by small changes in a redesign. More details about this concept are presented in [17].

VI. Conclusions and Application Potential

In this paper, we presented a novel design concept for building a 3D HRCR. The implemented prototype system "3D-Trunk" is used as a development paradigm for introducing more details. At present, our original prototype design and experiments could verify the novel concepts presented in this paper in a satisfactory way.

The main drawback of such robot is its long action cycle, for the all passive joints sharing the common driving input. We have to operate these joints one by one. Thus, any redesign needs to focus on speeding up these processes.

On the other hand, our design also offers some clear advantages. Because joints are passive and the locking mechanism is very strong, the whole system is lighter than others with the same DOFs. Just several small actuators are required to drive the whole system. This concept and the present system level design offer an advantage for a wide range of applications.

In principle we can build different kinds of elephant trunk or snake style robots, new multiple-DOF pan-tilts, etc. Equipped with cameras, such a chain robot on a mobile platform may be capable of inspection and surveillance.

Furthermore this system seems especially well suited to be used as shape-changeable, rigid manipulators or positioners due to the fact it can own many highly accurate, predefined configurations. The principles shown here should be transferable to the robustness requirements of industry without too many problems.

Acknowledgement

The work was supported by PACO_PLUS from the European Commission and by the BMBF BCCN W3-project.

We would like to thank our university's machine workshop for their nice manufacturing work.

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