A Compliant Lightweight Universal Joint Cascadable to a Multi-joint Kinematics - Tripedale Alternanzkaskade, TAK -

Ivo Boblan*, Andreas Schulz*, Alexej Tuchscherer*,
Ivan Perfilov* and Björn Bertrand**
*Control System Group, TU Berlin, Berlin, Germany
{boblan, schulz, tuchscherer, perfilov}@control.tu-berlin.de
**Weißensee Kunsthochschule Berlin, Berlin, Germany
bjoernbertrand@gmx.net

1 Motivation

In the development of robotic assistance systems with safe human-robot interaction for flexible personal and industrial applications size, weight, redundancy and compliance play an important role. For a redundant multi-joint kinematics with long range, high payload and variable resilience the elephant's trunk is the ideal biological role model. The elephant's trunk is a continuous kinematics which has no traditional joints of bones. It is a muscular hydrostat which can multiple bend in different directions over the entire length by longitudinally disposed muscle packets.

2 State of the Art

Present industrial articulated robots are manipulators, which are rigid multi-body systems with revolute joints driven by inherent stiff electric motors. The simple dynamics is bought with heavy weight and large construction space [1-2].

Under the heading trunk, worm, snake or more generally continuous or hyper-redundant kinematics many solutions are known. Some developments from the past named continuum robots [3-6] begin to make use of the operating principle of the elephant's trunk [7-11] and some show first technical applications up to commercial products [12-13]. The field of application is limited generally to the conduct of a tool or a camera in an inaccessible object.

The continuum manipulator OctArm replaces the serial chain of rigid links in conventional manipulators with smooth, continuous, and flexible links. OctArm generally based on the principle of a trunk driven by antagonistic pneumatic muscles, but is more of a hook than a manipulator [14-16]. The Rice and Clemson Universities have developed a trunk like kinematics based on a centrally located rubber backbone which acts as counterforce to a cable actuation system driven by electric motors [17-19]. The also tendon driven Air-Octor furthermore regulates its stiffness by pneumatic pressure [20].

The British company OCRobotics has developed snake-arm robots based on a skeleton with cable as a commercial product.

The nearly simultaneously developed trunk kinematics "Serielle Modularkinematik" SMK from the German Fraunhofer Gesellschaft IFF is equipped with local electric motors and thus not inherently compliant, can only bend to about 60 degrees, move only a few 100 grams payload and the motion speed is limited by screw jacks [21-22]. The snake like robot from the Carnegie Mellon University [23] and the redundant chain robot HRCR from the Bernstein Center for Computational Neuroscience [24] are also more suitable for inspection tasks than for manipulation of payload.

By closer look all approaches have an articulated basic structure. This is clearly visible in approaches with servo motors such as the great manipulator EMMA from GreyPilgrim [25] used in nuclear power plants. By the rigid elements with servo motors except the high number of degrees of freedom is retained none of the above advantages of the trunk kinematics.

The outstanding trunk kinematics "Bionic Handling Assistant" from the German company Festo is a demonstrator for lightweight by additive manufacturing and compliance but is not designed for precision and payload [26].

A continuum manipulator inspired by real properties of an elephant's trunk like radius of action, payload, compliance and speed of motion does not exist.

3 Contribution

The idea presented here is to combine a 3 fluidic muscle driven universal joint with lightweight construction by new materials. By the special design this joint can be connected not only in series but also alternate cascaded into each other to save manipulator length at the same amount of flexion. It can be stated that the more lightweight the single joint is built and the stronger the further up joints are designed, the more can be cascaded to a continuous manipulator.

Our modular joint named segment consist of two parts named bones which are connected via a universal joint with each other and are tilted by three fluidic muscle actuators against each other. The lower bone of a segment is the upper bone of next distal segment and so on. This cascading leads to a smaller manipulator length with the same number of degrees of freedom.

The lever arms of the bones for the connecting muscle actuators are made of polyamide 12 (PA12) [27] in the laser sintering process (SLS) [28] and strengthen with spring steel reinforcements similar to ferroconcrete [29]. The upper side of the arms is additionally reinforced by a tension belt made from carbon and the shape of the lower side is optimized for notch stress free [30] (Figure 1).

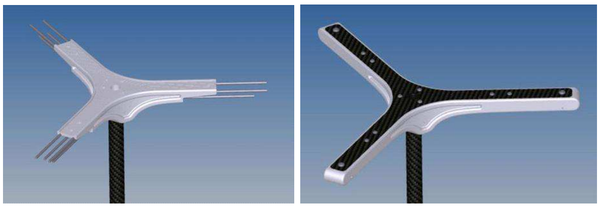

Figure1 Build-up of a bone with spring steel reinforcements (left) and with an upper carbon tension belt and lower optimized shape (right).

Not only is the lower side of the lever arms (Figure 1) optimized for notch stresses, but also the complete lever arm is analyzes for von Mises stress (Figure 2).

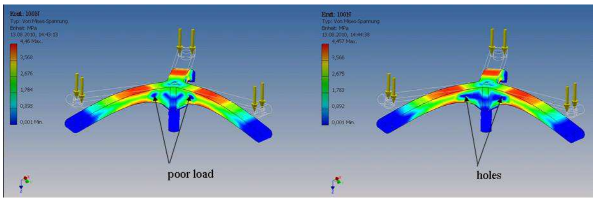

Figure2 Stress analysis where blue regions have poor load (left) and can be used to e.g. mounting holes (right).

The areas with stress peaks are marked in red and have to be reinforced. The blue marked regions are minor stress areas which do not contribute to the rigidity. In principle, these areas can be removed to save weight or to use for mounting holes to hold cables, circuit boards or sensors.

Each configuration with and without inner reinforcements, with or without tension belt and combinations is tested for break. By a fluidic muscle, the tension force on the outer lever arm is continuously increased up to 1000 N, and is measured by a force sensor (Table 1 and Figure 3).

Table 1: Specification of the pulling actuator and the force sensor used in the breaking test stand

	Name	Company	Force	Length
Actuator	DMSP-20	Festo AG	1600 N	400 mm
Sensor	KD 9363s	ME-Meßsys.	500 kg	61 mm

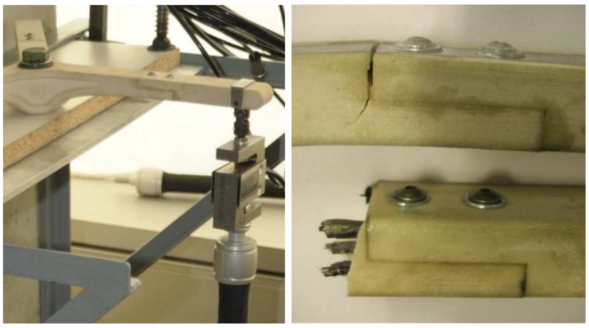

Figure3 Breaking test stand with pulling actuator, force sensor and to test lever arm (left) and breaking test example (right).

The breaking test results presented here show that the lever arm of the big star equipped with a 2 mm carbon tension belt without any reinforcements breaks at about 600 N pulling force. This is the force that can be hold solely by the polyamide 12. When equipped with 4 times 1.5 mm carbon reinforcements the breaking force increased up to about 850 N. If the arm equipped with 4 times 2.5 mm carbon reinforcements the material does not break up to a pulling force of 1000 N (Figure 4). This is the estimated maximum force that can be occurring in the segment. In our configuration we use 4 times 2.5 mm spring steel reinforcements, so we also have fail-save feature. In case of fault the kinematics bends first before it breaks and collapses.

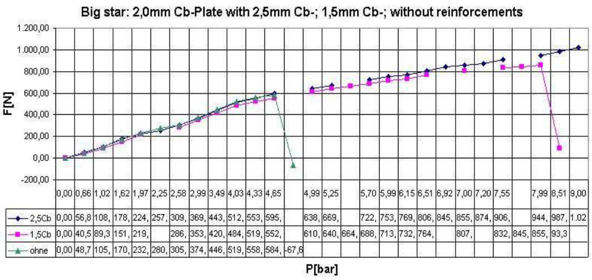

Figure4 Breaking test results of a lever arm of the big star without reinforcements (green), with 4 times 1.5 mm (magenta) and 4 times 2.5 mm carbon reinforcements (blue).

Each segment has a modular design and can be fitted with different types of muscles. In the trunk kinematics “Tripedale Alternanzkaskade” TAK version 3, both the fluidic muscles DMSP-10 from the company Festo with the maximum force of 630 N as well as DMSP-20 with the maximum force of 1500N are fitted. The nest state (start not ground position) of a segment with antagonistic connected muscles all muscles are contracted about 50 % of the maximum contraction of the resting length. Only the joint can be moved, when muscles shorten and in return other muscles extend. The case that more than one muscle pulls on the lever arm with its maximum force never occurs by design.

All electronic components of each modular joint are located around the central carbon compression strut of the dorsal bone of the segment. The complete electronics are located on three printed circuit boards, which are arranged in a triangle around the strut. Two redundant designed boards containing the ARM microcontroller STM32F107R, which are supplied from the third board with voltage. The microcontrollers enable transparent segment addressing, communication with other segments via CAN bus and a logging or emergency communication via Ethernet bus. The proprietary operating system on the controllers is implemented in C/C++ and includes a dynamic and segmented memory management, semaphores for process synchronization, shared memory of the processes on a microcontroller, interrupt-driven collision detection in real-time and sensor fusion between redundant sensors. Each segment gets its target angles, joint stiffness, controller structure and control parameters from an external path planning via CAN bus. The segments operate independently from each other, but the control parameters take into account the respective position in the chain.

The current version 3 is equipped with both muscle types DMDP-20 and DMSP-10. The bulky muscles DMSP-20 of the upper 4 segments are driven by proportional valves in order to realize a good positioning accuracy and low noise. The smaller muscles DMSP-10 of the lower 4 segments are driven by light switching valves in order to realize a wide range of motion and sufficient payload. The following Table 2 shows the main differences of the two valve types.

Table 2: Characteristics of the two used valve types

	proportional	switching
Name	PVQ	MH1
Manufacturer	SMC	Festo
Muscle type	DMSP-20	DMSP-10
Noise emission	low	high
Valve function	2/2	3/2
Nominal flow rate	100 l/min	10 l/min
Weight	80 g	10 g
Hysteresis	10 %	-
Cut-off frequency	no information	20 Hz
Control	0-180 mA	PWM
Dead zone	±54 mA (≈30%)	±1.2 V (≈5%)

Each segment requires only 5 V for electronics, 24 V for the pneumatic valves and compressed air from the outside to be able to work autonomously and independently.

All construction details together lead to a very lightweight, but stable and sufficiently rigid kinematics that can withstand the high tensile force of the fluidic muscle actuators of approximately 1000 N (Figure 5).

Figure5 Part of the biomimetic trunk kinematics "Tripedale Alternanzkaskade" TAK as CAD drawing of two segments (left) and photograph of a segment in the chain (right).

The main performance parameters of the current version 3 of the TAK consist of 8 segments and 16 degrees of freedom can be found in Table 3.

Table 3: Performance parameters of the TAK v3

Target speed normal/max.	250 mm/sec	1000 mm/sec
Position-/repeat accuracy	±15 mm	±5 mm
Handling/max. payload	500 g	2000 g
Power stand-by/operation	10 W	50W+air

4 Discussion

Robotic systems are rated according to their capabilities such as motion speed, payload, positioning accuracy as well as energy consumption and costs. These properties are primarily determined by the used **materials and structures** as well as actuators. Light in the fast laser sintering process produced solids (e.g. polyamide) combined with selected materials with special mechanical properties (e.g. spring steel) positioned in the right places in the solid (e.g. in the distribution of forces) can not only reduce production costs but also open up new fields of application. The better the requirements can be quantified, the better the kinematics can be aligned and optimized in that effect.

The changing of the **joint stiffness** can be achieved in certain areas independent of the joint position by the simultaneous actuation of all muscles (co-contraction). Thus, the impedance can be adjusted over the entire length of the trunk to the surrounding environment.

When multiple segments are connected to a redundant kinematics, the supernumerary **degrees of freedom** for the path planning objectives as an energy-optimal position in space can be used. The maximum achievable angle over the entire length of the trunk can be optimized over the degree of cascading of the segments, the position of the universal joint along the central compression strut and the length of the lever arms. With currently 8 segments, the

TAK bend to about 135 degrees. The present combination of materials and the thus achieved weight per segment allows a maximum cascading into each other of up to about 12 segments.

By design, the **positioning accuracy** depends only on the stiffness of the central pressurized components and not of the lever arms of the muscles. A potential in lightweight unavoidable bending of the lever arms of the muscles only leads to a reduction in the effectiveness of muscle contraction. By function, the positioning accuracy depends mainly on the minimum adjustment of the used valves and the resolution of the sensors.

A redundant trunk kinematics is a **multivariable control system** with couplings. These couplings have to be modeled, so that the controllers of each segment can take into account e.g. the appropriate weight per lever arm.

The trunk kinematics TAK is designed for use both in the automated assembly as well as in households.

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