Design of the new modular tendon-driven manipulator TENDRIM

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Abstract— **This paper presents a concept for the design of hyper-redundant manipulators utilizing stages of spatial links with remote tendon actuation. This methodology is illustrated by the prototype of a new tendon-driven modular manipulator (TENDRIM). The TENDRIM is composed of three stages of completely restrained, tendon-driven parallel mechanisms featuring two rotatory DOF each. A workspace analysis for a single stage and the resulting TENDRIM is given. This prototype demonstrates the potential of the proposed concept and the derived family of light-weight manipulators allowing for high maneuverability, which is desirable for assembly applications.**

I. Introduction

Conventional manipulators in production are typically used in strongly structured environments, performing predescribed tasks and guaranteeing a required precision. To keep the moved masses in a standard serial robotic manipulator reasonably low, the number of actuated joints is usually limited to the required minimum for the demanded task. Consequently this restricts the reachable workspace in the presence of obstacles. Tasks for which an obstacle-free working environment cannot be asserted have been largely exempt from thorough automation. One important example is the assembly process in the automobile industry, where the grade of automation is typically below 30% [1]. Many assembly tasks have to be performed inside the vehicle body, mostly not accessible for conventional robotic arms from the outside of the car without collision. The high cost percentage of the manual labor triggers today's significant efforts towards the exploration of new automation strategies making those tasks accessible to automation.

To enhance maneuverability and flexibility of motions, additional axes of motion can be introduced. Manipulators in which the number of actuated joints exceeds the degrees of freedom of the end-effector are consequently referred to as redundant manipulators. The kinematic redundancy can be utilized to avoid obstacles in the workspace [2]. Additionally if one joint reaches a mechanical limit a redundant joint may still allow the execution of the desired end-effector motion [3].

There are examples of biological systems with a large number of joints (tongues, trunks, and tentacles). Inspired by these biological existence proofs, a special class of redundant manipulators, known as hyper-redundant manipulators, was developed, with a large number of actuable joints, far exceeding the numbers of DOF of the end-effectors [4]. Two main strategies to achieve kinematic hyper-redundancy derived from nature are utilized with these robots: (I) the rigid-link approach, as seen in snakes or an elephant's trunk, employing a discrete backbone comprising a large number of small links and (II) a continuous backbone allowing for bending at any point [5].

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Besides using conventional gearhead or direct drives, a wide range of actuation technologies has been proposed for experimental demonstrators. A biologically inspired approach is the choice of an artificial muscle or a tendon drive for actuation. Diverse artificial muscles have been proposed utilizing electro- or magnetostrictive polymers, elastomers or gels, SMA materials or fluidic actuators [6]-[8]. Tendon-driven mechanisms in particular have received a great attention in robotics due to their promising advantages and unique features [9]-[11].

Our research is focused on the development of a robot design, which allows constructing kinematically redundant manipulators for assembling applications with following capability characteristics:

- light-weight mechanical structure, resulting in low moment of inertia, high speed motion, low energy consumption and higher payload-to-weight ratio
- modular and cascadable structure, resulting in high maneuverability and large reachable workspace

In this paper a concept for the construction of hyper-redundant manipulators is presented. The special features of the proposed design are the utilization of stages of spatial parallel mechanisms and the careful tendon routing for remote actuation. The modular structure allows an extension by an appropriate number of stages in order to achieve kinematic redundancy.

II. Concept for a tendon-driven modular Manipulator Design

A. Conceptual Issues of the Design

Kinematic hyper-redundancy: A discrete backbone design was chosen, as it provides the manipulator with dexterity and versatility in its motion by a kinematic hyper-redundancy. Thus, the bending occurs at distinct and well-defined points of the mechanism, with the effect of hyper-redundancy coming from the large number of joints. The major advantage of rigid-link hyper-redundant designs is a simple extension of traditional industrial manipulator counterparts. Therefore, traditional kinematic analysis (Denavit-Hartenberg-approach, manipulator Jacobian) is applicable.

Actuation: The next central question of the design concept is the determination of the effective actuation technology for the manipulator under development. Two strategies are conceivable: intrinsic and remote actuation. Intrinsic actuation, as featured in [12], while conceptually simple, has several major disadvantages. Using conventional robot drives for a hyper-redundant serial manipulator would result in high moved masses and the prospect of packaging and moving a large number of such actuators distributed through the robot is unattractive. The use of alternative types of actuators, such as pneumatic or new classes of artificial muscles for intrinsic actuation (as found in the biological equivalents) is an interesting possibility [13]. However at the present time, it seems that no specific muscle technology has found large scale application, at least for industrial manipulators.

In contrast tendons provide a simple way of transmitting power through the structure, allowing manipulators to be fairly light, as the actuators themselves are remote. This allows the construction of versatile light-weight manipulators [10], [11]. For the above reasons, the remote tendon drive approach was chosen to actuate our device.

Number of tendons and degrees of freedom: A large number of degrees of freedom (n) for the backbone module of the manipulator would result in a high maneuverability. On the other hand this would consequently lead to a large number of drive tendons (m) and, as easy to suppose, to difficulties in physical routing of the tendons through the robot's structure. As an advantageous solution the degrees of freedoms of a single module were limited to only two and the module was developed as a tendon-driven parallel mechanism. Since all tendons must be in tension at any working configuration to be fully controllable, the redundant actuation principle of completely restrained mechanisms ($m = n + 1$) or redundantly restrained mechanisms ($m > n + 1$) can be used [14]. Additionally the redundant actuation allows to suppress vibration problems and to increase stiffness of the mechanism [15]. In the majority of cases $2n$ is applied as upper limit for the number of tendons in order to control n degrees of freedom. Otherwise there will be too many redundant tendons in the mechanism, which burdens the control scheme [16]. Hence, the most effective number of tendons to drive the 2-DOF backbone module of the manipulator is from three to four. A completely restrained concept was implemented by using three tendon drives for each manipulator module.

B. Design of the Module

A key question is how to constrain the module motion so that it can be efficiently driven by the defined set of tendons. This phase of the design procedure is closely interrelated with the next one - the physical routing of the tendons through the robot's structure, which is the most essential issue in remotely tendon-actuated devices. It should be noted that the final design for the manipulator module and the physical routing of the tendons, as a result, was obtained after several iterations between these two design phases.

The principal idea to endow the manipulator module with structural stiffness is to compose triangles from rods and tetrahedrons from triangles. Structures based on n-simplexes become very rigid in the n-dimensional space. Their links are stressed only by longitudinal forces (tension and compression), if the links allow shared centers of rotation in the nodes. For example, planar structures based on polygons with more sides than three (such as squares and hexagons) and with joints in their corners will not be rigid.

A module of the developed manipulator was created by removing three links of a regular tetrahedron and adding two mirror symmetrical tetrahedrons connected together by a triangle, see Fig. 1. The remaining triangular face of the regular tetrahedron $A_iB_iO_i$ forms the module's moving platform. The pairs of bearings R_{11_i}, R_{12_i} and R_{21_i}, R_{22_i} form two joints (J_{1_i} and J_{2_i}), which allow two rotatory DOF for this mechanism. Note, that the composition of these two joints forms one universal joint for the module's moving platform. Due to the tetrahedron structure the proposed module possesses structural stiffness and the rod construction makes the module light-weighted.

Relations in a regular tetrahedron allow the determination of the module's link lengths, if the tetrahedron's edge length l_i is known, see Tab. I. Two specific angles of the regular tetrahedron are significant for these computations: the angle between two faces $\alpha_0 = \arccos\frac{1}{3} \approx 70.5°$ and the angle between an edge and a face $\beta_0 = \arccos\frac{1}{\sqrt{3}} \approx 54.7°$.

C. Routing of Module's Drive-Tendons

The main principle utilized for the routing of drive-tendons in this module design is to locate the motion plane of the tendon, which drives the module, so that it is orthogonal with respect to the rotation axis of a driven joint. The considerable advantage of this principle is the use of fixed instead of movable pulley bearings. A detailed design of the module with the drive-tendon routing is shown in Fig. 1.

Two tendons (a_i and b_i) are attached to the corners (A_i and B_i) of the triangular module's moving platform $A_iB_iO_i$ and drive the rotation about the axis of joint J_{2_i}, which passes through the height of the regular tetrahedron. The third tendon c_i is attached to the end of the extension link behind the axis of joint J_{1_i} (point C_i). The tendon c_i will be termed "pitch tendon" in this paper and tendons a_i and b_i - "roll tendons", although these two tendons also have an effect on the pitching about the axis of joint J_{1_i}. The return pulleys of both roll tendons $Pa_{1_i} \dots Pa_{3_i}, Pb_{1_i} \dots Pb_{3_i}$ are fixed to those module's parts, that can rotate only with respect to the rotation axis of joint J_{1_i}.

TABLE I

THE LINK LENGTHS OF MODULE i

Link	Definition
l_{x_i}	$\frac{1}{2\sqrt{3}}l_{i-1}$
l_{R_i}	$\frac{1}{\sqrt{3}}l_i$
l_{B_i}	$\frac{1}{2}\sqrt{(l_{i-1}-l_i)^2+3l_i^2}$
l_{C_i}	$\frac{1}{2}\sqrt{l_{i-1}^2+4l_{x_i}^2}$
l_{H_i}	$\sqrt{\left(\sqrt{\frac{2}{3}}l_i+l_{x_i}\right)^2+R_i^2}$

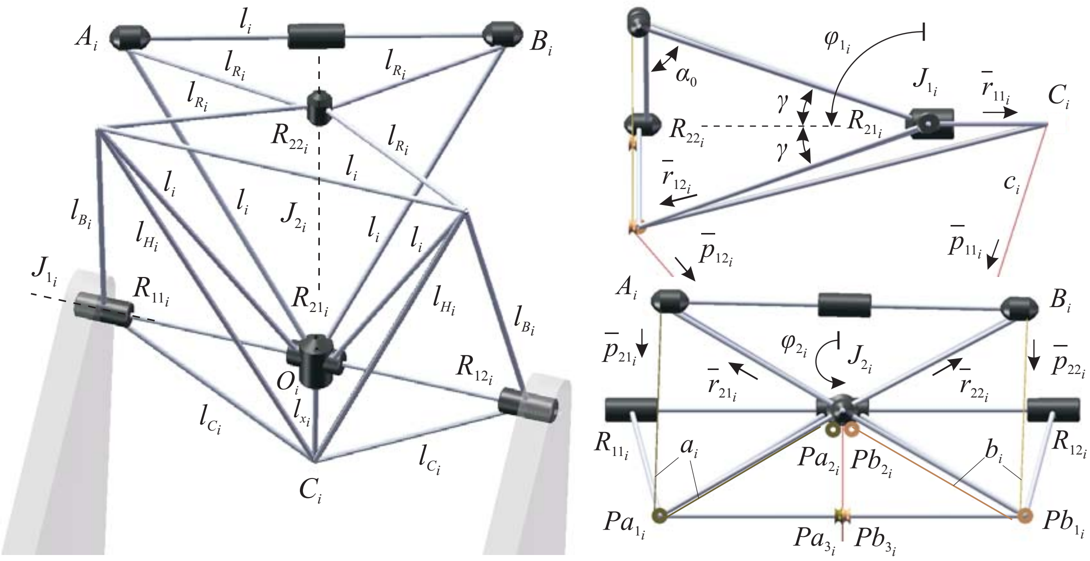

Fig. 1. Significant denotations (left) and routing of drive-tendons (right) in a single module.

D. Boundaries of a Module's Workspace

The effective workspace is the most essential property of an optimal kinematic design of any mechanism. For tendon-driven parallel mechanisms, this is even more meaningful since their workspace is generally rather limited. The critical constraints of these mechanisms are the limits of joint motion and the fundamental requirement to provide for the force-closure tension. The last is the necessity to maintain a positive tendon tension at any time (assuming a positive tendon force representing a tension). For the design of modular robots with a large number of tendon-driven modules, some additional workspace constraints must be taken into account, which avoid collisions of the module's parts.

Verification of the Force Closure Condition: A motion around a joint J_{j_i} ($j \in \{1,2\}$) of module i can be regarded as being caused by two tendon forces: the rolling motion by the two roll tendons' forces within plane $\langle \varphi_{2_i} \rangle$, whereas the pitching motion in plane $\langle \varphi_{1_i} \rangle$ is driven by the force of the pitch tendon and the resulting force of the roll tendons in that plane. Due to the orthogonality of the motion planes, the compliance with the force closure condition for the whole module simplifies into the verification of the condition for each motion within plane $\langle \varphi_{1_i} \rangle$ and $\langle \varphi_{2_i} \rangle$ separately. The force closure for joint J_{j_i} is ensured only if the tendon forces have the same sign at the torque equilibrium. This results in the condition $\sin\angle\left(\overrightarrow{rj2_i}, \overrightarrow{pj2_i}\right) \cdot \sin\angle\left(\overrightarrow{rj1_i}, \overrightarrow{pj1_i}\right) > 0$, with $\overrightarrow{rjk_i}$ being the vector from joint J_{j_i} to the attachment point of one of the tendons k ($k \in \{1,2\}$) in plane $\langle \varphi_{j_i} \rangle$ and $\overrightarrow{pjk_i}$ the vector pointing along tendon k from this attachment point. Accordingly same sign tendon forces are provided, as long as both tendons are directed towards the same side of the contour formed by connecting both tendon's attachment points via the respective joint within plane $\langle \varphi_{j_i} \rangle$. Since both tendons are redirected at points on the motion platform of the previous module, this limits the theoretical possible range of the angles to $0° < \varphi_{1_i} < 180° - \gamma$ and $-90° < \varphi_{2_i} < 90°$, with γ being $90° - \alpha_0$.

Reachable range of the joint angles: The roll motion of the module's moving platform is limited to an angle of $\pm 60°$ by placing the return pulleys Pa_{1_i} and Pb_{1_i} as shown in Fig. 1. The effective working range for a pitch angle of this module design amounts to $120°$, although kinematically a pitch angle up to $160°$ is allowed. With too large pitch angles though, the tendons will not be able to create sufficient tension forces to achieve kinetostatic equilibrium of the moving platform, in order to withstand external moments about axis of J_{1_i}.

It will be shown later that the limits found in this way also provide for a collision free modular manipulator design.

E. Design of modular structures

The designed module allows to construct discrete backbone manipulator structures with kinematic hyper-redundancy by mounting of the 2-DOF modules in a serial configuration. Fig. 2 shows the manipulator structure with two modules.

The following two practically relevant recommendations can be made regarding geometric relations between the neighbor modules of this design, which will provide a larger collision free workspace. First, in order to avoid a collision (within the defined range of the joint angles) between the bearing R_{22_i} of the joint J_{2_i} and the extension of the tetrahedron's height $l_{x_{i+1}}$ of the next module $i+1$, the length of $l_{x_{i+1}}$ must not be larger than an inscribed circle's radius of the triangular tetrahedron's face $A_iB_iO_i$ of the module i. And the second recommendation is, for the reason given above, that the tetrahedron's edge length l_{i+1} of the module $i+1$ have to be smaller than the height of the triangular face $A_iB_iO_i$ of the module i. Therefore, a sufficient factor to scale down modules is $\frac{\sqrt{3}}{2}$, so that $l_{i+1} = l_i \frac{\sqrt{3}}{2}$. As a result, the manipulator module located at the base will be larger than the end module used for tool manipulation. This scaling has

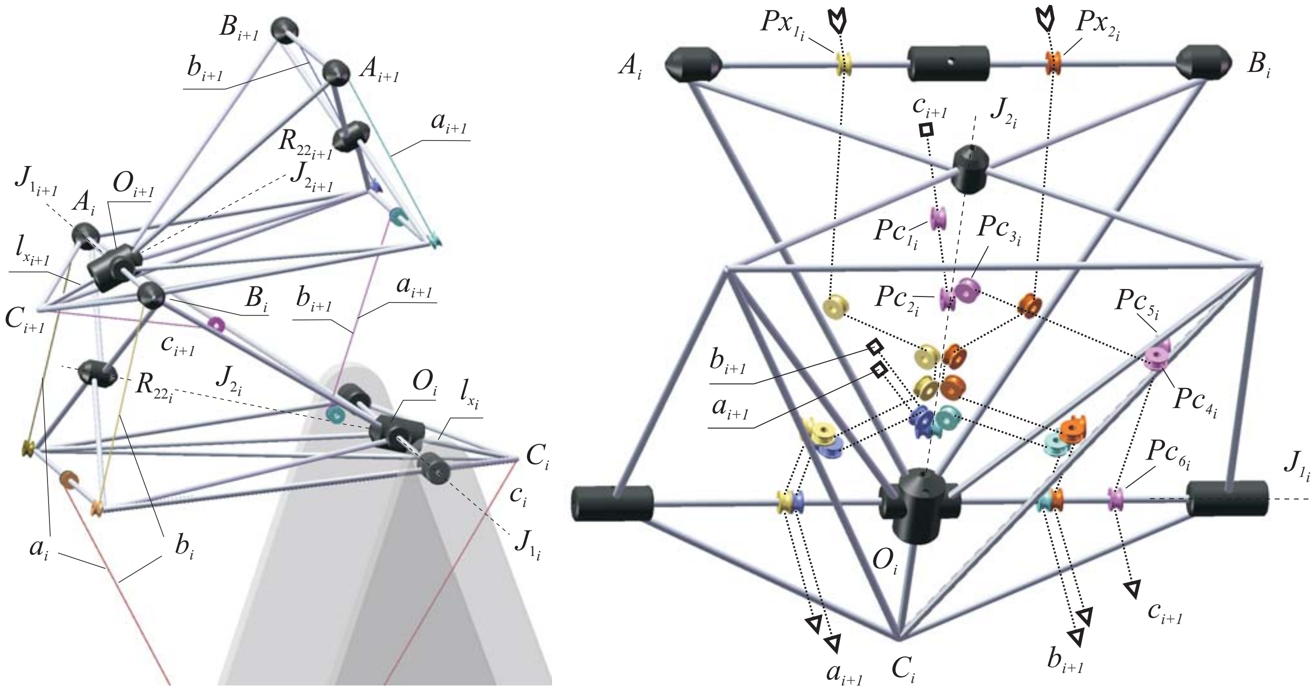

Fig. 2. Two module manipulator structure with drive-tendons (left) and routing of passing tendons (right).

other advantages apart from increasing the workspace. For a larger number of modules in a manipulator structure, it allows each module to be designed according to the mass it is required to displace and lesser powerful actuators will be necessary. Using this relation and expressions for module's link lengths from Tab. I all constructional parameters of a modular manipulator structure of this design are determined by predefining the number of modules N and the length of either the base link l_0 or the tetrahedron's edge l_N for the last module.

F. Routing of passing Tendons

There are two sets of tendons passing through a module i in the designed modular structures. The first set is formed by two roll tendons (a_{i+1} and b_{i+1}) and one pitch tendon (c_{i+1}) of the module $i+1$. The second set includes all rest tendons coming from other modules. The tendons of the first group move the module $i+1$ relative to the moving platform of the module i. Hence they have to exert drive forces upon the platform. To eliminate unwanted interaction torques between the moving elements of the module i and the passing tendons of both groups, the length of the passing tendons may not be changed, while these elements are moving. This can be achieved by redirecting the passing tendons by pulleys, which are located on the relevant rotation axes of the module i. Fig. 2 shows the detailed routing of tendons passing through the module i to the module $i-1$.

The tendon c_{i+1} of the first group, for instance, comes from the neighbor module to the return pulley Pc_{1_i}, which is fixed to the module's moving platform $A_iB_iO_i$ and exerts drive forces upon it. Then the tendon is forwarded to the return pulley Pc_{2_i}, which is placed on the rotation axis of J_{2_i} and fixed to the module's moving platform, too. The return pulley Pc_{3_i} is also placed on the rotation axis of J_{2_i}, but fixed to those module's parts, that can rotate only with respect to the axis of J_{1_i}. So the last pair of pulleys fulfills the above-mentioned tendon's routing principle to eliminate the interaction between passing tendons and the moving elements of the module. The following three return pulleys $Pc_{4_i} \dots Pc_{6_i}$ redirect the tendon towards the rotation axis of J_{1_i} and pass it over to the next module. Unfortunately it is quite difficult to fix two redirection pulleys in close proximity to this axis. Therefore interaction torques between passing tendons and the joint J_{1_i} will be produced, but for small enough pulley radii their values will be very small in comparison to the module's drive torques. The same holds for the tendons a_{i+1} and b_{i+1}.

The routing of passing tendons from the second above defined group is similar to tendons of the first group. The difference is only that tendons, for instance x_{1_i} or x_{2_i}, come from the return pulleys Px_{1_i} and Px_{2_i}, which are also fixed to the moving platform $A_iB_iO_i$.

The routing of tendons inside the module constrains the rotation of the module's moving platform about the axis of J_{2_i} to the angle of $\pm 60°$, thus providing the working range of $120°$ established above. A larger angle of rotation would cause collisions between one of the links (A_iO_i or B_iO_i) of the moving platform with the tendons.

III. Kinematic Modeling

Due to the modular structure of the composed manipulator, its kinematic equations can be derived by analysis of one of the modules. Subsequently these equations can be connected to describe the kinematics of the resulting robot in all degrees of freedom.

The kinematic analysis is restricted to the mechanical skeleton of the robot and neglects the tendons of the structure. As pointed out earlier, the presence of the tendons only restricts the range of the joint angles, which is treated separately. For the sake of simplicity the triangular structure of the links is replaced by a single rods, which are equivalent from kinematic point of view.

A. Kinematics of a module

The geometric properties of one module of the manipulator are presented in Fig. 3. It consists of two joints (J_{1_i} and J_{2_i}) and two links with the lengths $k_i = 0$ and $h_i = l_i \frac{\sqrt{3}}{2}$, respectively. The pitch angle φ_{1_i} is the angle from the extension line of h_{i-1} to link k_i and the roll angle φ_{2_i} is the angle between the plane spanned by h_{i-1} and k_i and the link h_i. Thus they are defined as follows:

$$\begin{aligned}\varphi_{1_i} &= \angle\left(h_{i-1}, k_i\right)\\ \varphi_{2_i} &= \angle\left(\operatorname{span}\left(h_{i-1}, k_i\right), h_i\right)\end{aligned}$$

The axis of joint J_{1_i} is perpendicular to the plane $\langle\varphi_{1_i}\rangle$, whereas the axis of joint J_{2_i} is along the line k_i.

The problem of direct kinematics is solved by homogeneous transformations using the Denavit-Hartenberg (DH) convention. Fig. 3 shows the coordinate systems that result from the selected approach for one module. The geometric properties of the module yield the DH parameters. For a base coordinate system located in joint J_{1_1} the resulting DH parameters listed in Tab. II allow the calculation of the transformation matrices.

Due to a tilting angle $\gamma \neq 0$ a module spans a curved surface in x, y, z coordinates, see Fig. 4. Additionally, the effect of constrains on the workspace is illustrated. Within

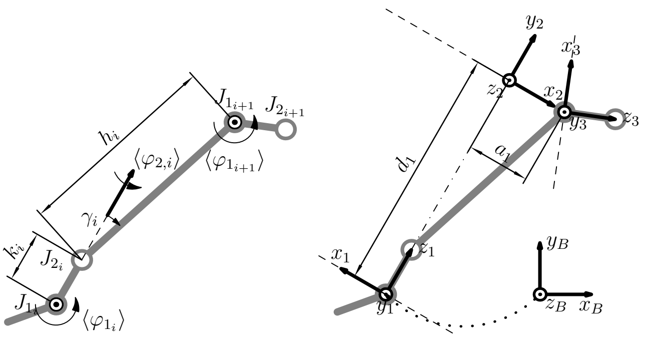

Fig. 3. Geometric properties of one module (left) and module's coordinate systems following the Denavit-Hartenberg convention (right).

TABLE II

DH PARAMETERS OF THE FIRST MODULE W.R.T. FIG. 3

	Displacement		Angle	
$B \rightarrow 1$	d:	0	α:	$\pi/2$
	a:	0	θ:	$\pi/2 + \varphi_{1_1}$
$1 \rightarrow 2$	d:	$k_1 + h_1 \cos\gamma$	α:	$\pi/2$
	a:	$h_1 \sin\gamma$	θ:	$\pi/2 + \varphi_{2_1}$

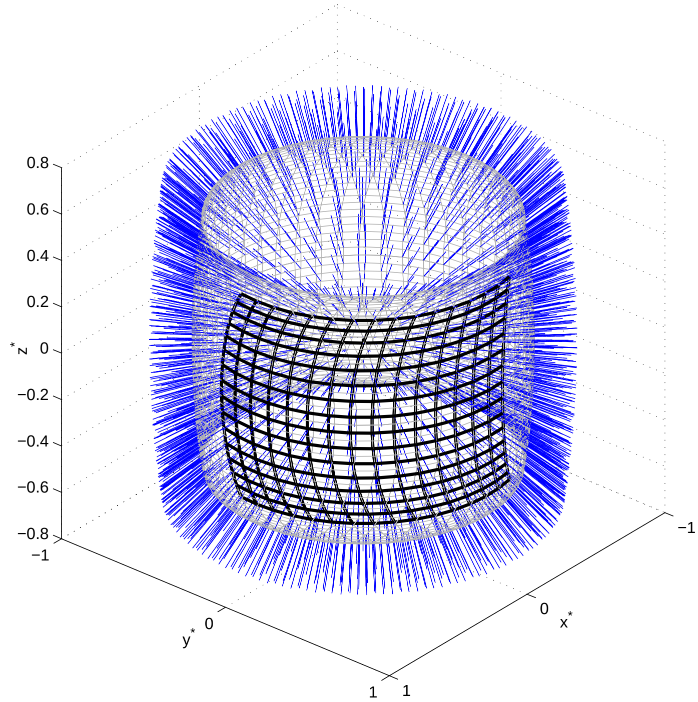

Fig. 4. Workspace of one module normalized with regard to l_i (the bold mesh indicates the workspace with constrains and arrows indicate the orientation of the last link).

the constrains, the ratio between joint and Cartesian coordinates is nearly constant.

B. Composed Structure

A composed manipulator structure is built by connecting several of the modules described earlier. Because of the iterative approach, the kinematics of the composed manipulator arise from consecutive application of the DH-transformation. The table of DH parameters can be extended by defining the transformation between two modules, with the base system from Tab. II. Its DH parameter θ needs to be adjusted according to Fig. 3. The complete table of N modules is presented in Tab. III.

To guarantee an closed workspace, the composing has to meet two main requirements when using identical geometrical properties for each pair of modules:

- each module has two DOF and its workspace forms a contiguous hull

TABLE III

DH PARAMETERS OF COMPOSED MANIPULATOR

	Displacement		Angle	
$B \rightarrow 1$	d:	0	α:	$\pi/2$
	a:	0	θ:	$\pi/2 + \varphi_{1_1}$
...			...	
$1_i \rightarrow 2_i$	d:	$k_i + h_i \cos\gamma$	α:	$\pi/2$
	a:	$h_i \sin\gamma$	θ:	$\pi/2 + \varphi_{2_i}$
$2_i \rightarrow 1_{i+1}$	d:	0	α:	$\pi/2$
	a:	0	θ:	$\pi/2 + \varphi_{1_{i+1}} - \gamma$
...			...	

- its end-effector orientation indicated by the last link must be parallel to the hull normal, see Fig. 4.

This guarantees that after the extension with additional modules the interior of the hull of the former is reachable.

IV. Composition of the TENDRIM prototype

In order to verify the proposed manipulator design concept of utilizing spatial parallel mechanisms as modules with remote tendon actuation, the prototype of a new tendon-driven modular manipulator (TENDRIM) was developed. The TENDRIM is composed of a serial stack of three modules, with $l_1 = 275mm$, $l_2 = 238mm$ and $l_3 = 206mm$. Each of these is a completely restrained, tendon-driven parallel mechanism with two rotatory DOF. This prototype allows 6-DOF-manipulation and, while just having few modules, illustrates the potential of the new design and the derived family of light-weight, tendon-driven manipulators with a high maneuverability and a large workspace. With the chosen tetrahedron design and the defined range of the module's joint angles the resulting manipulator is able to fold into a stack, see Fig. 5. It can be noted that for heavy duty lift-majority manipulations a hanging configuration will be more suitable. In this case the two roll tendons together will counteract gravity, in contrast to just the one pitch tendon in the standing configuration. This manipulator can be extended by an appropriate number of modules in order to provide for kinematic redundancy.

V. Conclusion and future work

In this paper a concept for the design of modular and highly maneuverable manipulators for assembly applications is presented. In order to achieve a light-weight construction and highly dynamic motions, a remote actuation approach and parallel spatial mechanisms were chosen for the single backbone modules. The remote actuation was enabled by careful tendon routing with regard to the minimization of interaction torques and to allow the use of fixed pulley bearings. The workspace of a single module, formed by a 2 DOF parallel mechanism, was presented as well as its underlying kinematic equations. The single modules can be composed in a serial manner to derive a family of dextrous robotic manipulators. A non-redundant member of this family consisting of three modules is presented under the name of TENDRIM. It constitutes a limit case with 6-DOF at the end-effector with the same number of tendon-actuable joints. From this limit case the manipulator can be extended by an appropriate number of modules in order to achieve kinematic redundancy.

To be used in an application-related field, more work should be completed, e.g., to optimize the mechanical components with regard to the expected performance parameters and develop a high-performance control strategy, etc.

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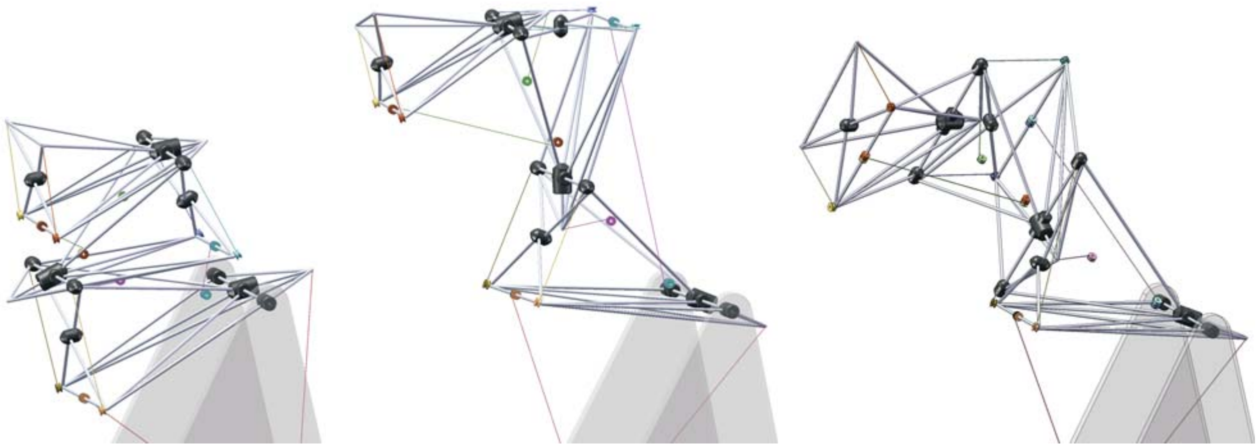

Fig. 5. The TENDRIM prototype in different poses (for better visibility only the drive-tendons are displayed).