A Novel Approach to Mechanical Design of Articulated Fingers for Robotic Hands

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Abstract

The paper first discusses the reasons why simplified solutions for the mechanical structure of fingers in robotic hands should be considered a worthy design goal. After a brief discussion about the mechanical solutions proposed so far for robotic fingers, a different design approach is proposed. It considers finger structures made of rigid links connected by flexural hinges, with joint actuation obtained by means of flexures that can be guided inside each finger according to different patterns. A simplified model of one of these structures is then presented, together with preliminary results of simulation, in order to evaluate the feasibility of the concept. Examples of technological implementation are finally presented and the perspective and problems of application are briefly discussed.

1. Introduction

In the development of anthropomorphic robotic hands, that are devices mimicking the human hand as to shape, size and internal mobility, on one side there is a trend to increase dexterity, on the other a growing need of simpler and more practical and applicable devices. A good recent review of many aspects of dexterous hands evolution can be found in [1]. As to the mechanical aspects, the hands proposed so far exhibit a wide range of design solutions, concerning the overall kinematical configuration, the actuation scheme, the adopted technological solutions and the sensory integration. Most of existing solutions however are too complex, bulky, not really suitable for hosting a distributed sensory equipment and, last but not least, too expensive for a large-scale diffusion of such robotic end-effectors.

Aim of the present work is to develop and test different design concepts, focusing on the development of simplified structures based on “compliant mechanisms” [2], that means articulated structures with joints made with flexible hinges and motion provided by guided flexures. The reason of this approach comes from the consideration that mechanical design of robotic hands is many times unsatisfactory: priority is given to solve joint, structure, actuation and transmission problems, while other basic needs, like to host a distributed sensory system and to get well-shaped and compliant contact pads, are not considered with the same level of priority. Few robotic hands can be considered good examples of design according to concurrent engineering rules. In particular, traditional design solutions lead to a poor exploitation of the available space inside the finger, that is mainly used to host articulations and transmissions or, sometimes, direct-drive joint actuation. The lack of space for locating sensors, wires and compliant pads dramatically increases whenever pulleys are used to route tendons across the joints. Pulleys help overcoming many problems related to tendon transmission, but introduce severe design restrictions, because their diameter cannot be too small and they occupy most of the finger cross section. An example of this traditional approach is sketched in Figure 1, showing how difficult it can be to host the other necessary things like sensors, wires and skin pads within the finger.

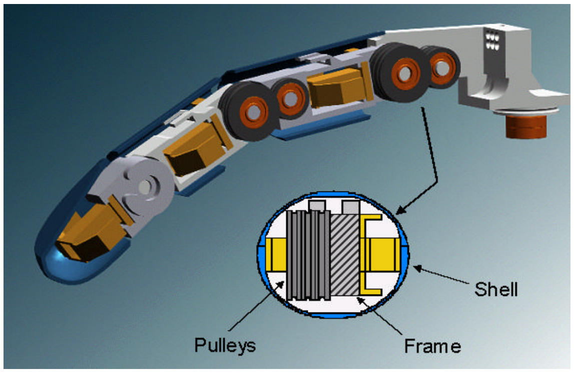


Figure 1: *Pulley-based finger design (U.B.Hand II [3])*

In the usual approach, inspired to the exoskeletal model, the material of the link is distributed around the internal hollow (that hosts the tendon transmission), with a shape mainly oriented to closed cross sections, with a good ratio between stiffness and weight but with low capability to host other equipment. Most times only a thin rubber layer can be applied on intermediate phalanges, just in order to increase contact friction and the use compliant pads is possible only on the fingertips. Several examples of this design approach can be found in the literature.

A different approach, that mimics the human hand model, is based on the endoskeletal model and shows a functional distinction between an inner stiff framework (the “bones”) and an outer compliant layer (the “flesh”). The actuators are usually remote and transmission is achieved by sheath-guided tendons, so that a large part of the cross section of the finger is available for other functions. The design concept is quite different, because actuation, sensors and wiring are not placed *inside* an articulated structure, but *around* it. This biomorphic approach is much more difficult to be implemented as far as technological solutions are concerned, but seems a promising way to the development of new generation robotic hands. Significant contributions along this direction have been proposed recently [4], [5]; they witness the need of upgrading the level of mechanical solutions used so far, not adequate if related to the evolution of other robotic technologies, like sensing and control.

2. Alternative structures for robotic fingers

Articulated finger structures can be obtained using joints quite different from the classical revolute pairs based on pin-and-bearing design: alternative solutions can be found according to different concepts, often suggested by nature itself.

Two main classes of solutions can be identified:

- joints in which the relative motion between adjacent rigid links is obtained by means of kinematical pairs (that means contact surfaces between the two links and a discontinuity of material);
- joints in which the relative motion is allowed by the deformation of a compliant part of the structure that permanently connects the two rigid links; in this case the connecting compliant part can be made of a different material (e.g. rubber or steel spring) or simply obtained by introducing structural compliance inside a continuous structure (compliant mechanism).

In the first class of solutions some biomorphic articulation models can be found, capable of one or more degrees of freedom, with two basic patterns:

- sliding-contact pairs (Figure 2a), in which the relative rotation between the two links is mainly due to sliding between two fitting surfaces, convex and concave respectively, with eventual interposition of low-friction layers;
- rolling-contact pairs (Figure 2b, 2c) in which the relative rotation is the consequence of rolling between two conjugated profiles, both convex or forming a concave-convex couple.

In both cases, the kinematical pairs need to be integrated with ligaments, able to create a sort of continuity in the structure, because the pairs themselves can resist loads only in one sense [6].

The second class of solutions, that use compliant parts acting as joints, aims to simplify structure design, obtaining articulated structures with a reduced number of parts, easy to be manufactured and assembled, cheap, yet fully efficient and compatible with the required functions. Different kinds of compliant articulations can be defined, based on deformation of properly sized flexural (Figure 2d) or torsional hinges. This approach, that exhibits however severe design problems, has been adopted so far in different cases for small-displacement manipulators. The major goal was to develop articulations with no friction and no backlash and to use such design solutions in manipulators or end effectors dedicated to high-precision tasks [7]. Detailed contributions to hinge design can be found in [8], [9], [10], [11], [12].

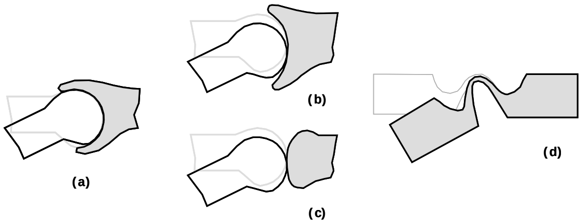


Figure 2: *Alternative design concepts for finger joints*

In spite of many problems connected with its design and implementation, the compliant mechanism concept shows some attractive features that are:

- no ligaments are necessary, phalanges can be directly connected so that the finger skeleton can be imagined as a one-piece structure to be obtained with a suitable technology and contact problems between surfaces are avoided;
- the stiffness of the hinges can be exploited in order to simplify the actuation system, because a single action (e.g. by mean of a tendon) can be used to bend a joint pulling in opposition to the hinge stiffness; furthermore, the presence of concentrated elastic joints along the finger structure can allow under-actuated configurations.

Against these attractive features several drawbacks and severe design problems arise.

Some of them are due to the kinematical properties of such joints that can behave quite differently with respect to a revolute joint. A structural hinge (Figure 3) usually does not displace simply like a revolute pair with a rotational spring inside, because the position of its centre can change and translation in addition to rotation can occur. A generalized model could be defined as sketched in Figure 3a, where each hinge is substituted by a prismatic pair with axial stiffness, connected to the finger links by means of two revolute pairs with internal rotary springs; to add further complexity to the problem, non linear behaviour of all internal springs should probably be considered. A simplified model can be defined as in Figure 3b, assuming the axial stiffness of the hinge very high and its change in length negligible, or as Figure 3c assuming that, even in case of large displacements, the position of the centre of relative rotation between the two links does not significantly change. This assumption can be justified whenever the pseudo-rigid body model proposed by Howell [2] can be applied.

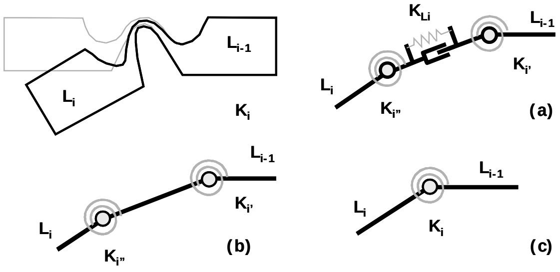


***Figure 3**: Kinetostatic models of the hinge*

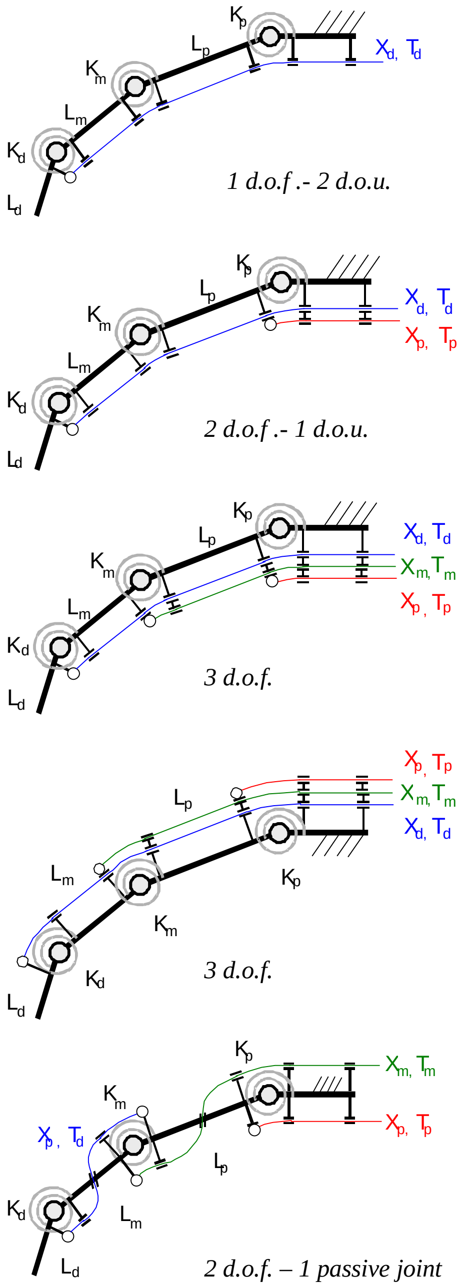
The second family of problems concerns the optimal design of hinges: differently from previous small displacement applications, inside a robotic finger large deflections are needed: at least 90 degree rotations should be achieved for mimicking human finger mobility. A proper choice of shape and material becomes a key factor for practical feasibility as it determines stiffness, fatigue resistance and manufacturability. On one side, a low-stiffness hinge can reduce the amount of energy needed to bend the finger and reduce the forces required from actuators; on the other side it will reduce the system bandwidth and increase the position errors due to hinge deformation. In general it will make more difficult to manage the model of the system and to get a good control of it.

For its attractive features however the hinge-based structure seems a very interesting concept for robotic fingers design that encourages the development of novel mechanical architectures.

3. Design of compliant finger structures

Despite its apparent simplicity, the implementation of the compliant mechanism concept into a robot finger involves many practical and theoretical problems of relevant complexity. The main activities in design development are the choice of the actuation pattern, that can be helped by preliminary kinetostatic analysis of the finger model, the choice of the manufacturing technology, the final design optimisation and characterization.

As to the actuation pattern, different configurations can be defined, depending on the number of actuating elements and their location with respect to the elastic hinges. In Figure 4 some of the examined configurations are sketched, adopting the simplified hinge model of Fig. 3c.



1 d.o.f .- 2 d.o.u.

2 d.o.f .- 1 d.o.u.

3 d.o.f.

3 d.o.f.

2 d.o.f. – 1 passive joint

***Figure 4**: Actuation patterns*

They mainly differ for the number of actuating elements and their path with respect to joints, which results in a different number of achievable degrees of freedom (d.o.f.) and eventual degrees of under-actuation (d.o.u.), and in a different behaviour of flexures (single acting with tension loads or double acting with tension-compression loads).

Because our goal was to achieve at least 2 degrees of freedom in order to perform variable approach trajectories and hopefully to implement object manipulation strategies, suitable configurations with a minimum of two double-acting tendons have been considered. An evaluation procedure has compared the different solutions: the configuration 4b was tried first, but the solution sketched in Fig. 4e was later preferred.

For what concerns the technological implementation, available solutions can differ depending on the choice of materials and assembly concepts. Basically three main possibilities have been considered, that are:

- the integral one-piece design (hinges, phalanges and tendons made of the same material);
- the one-piece structure with added tendons (e.g. phalanges and hinges in moulded plastic, tendons made of steel flexures);
- the assembled solution where phalanges, hinges and tendons can be made of three different materials and parts are separately manufactured and then assembled or permanently joined.

As to the material itself, it must be mentioned that the achievement of high strain without overcoming the yield strength requires a material with a high S_y/E ratio. As it is shown in Tab.I, to this respect some plastic materials, like polypropylene or PTFE, offer very interesting chances and strongly support the adoption of the one-piece concept.

Tab. I

MATERIAL	*Young's modulus E (MPa)*	*Yield strength Sy (MPa)*	*Sy/E x 1000*
Teflon (PTFE)	345	23	66,7
Delrin	2068	69	33,4
Nylon (type 6)	2620	81	30,9
E-glass (73,3vol%) in epoxy	56000	1640	29,3
Polyprolypene	1400	34	24,3
Polyethylene (HDPE)	1400	28	20,0
Steel (Sandvik 11R15)	186000	1950	10,5
Titanium Ti-13 heat treated	114000	1170	10,3
Aluminum 7075 heat treated	71100	503	7,1

Very low cost structures can be imagined in this perspective and the continuity of the finger structure can lead to imagine very interesting solutions, like wiring distributed sensors by means flexible circuits printed along the finger structure itself.

On the other side, hinges and tendons made with high-strength steel flexures can provide more predictable fatigue behaviour, higher buckling resistance and, in general, more controllable sliding conditions for guided tendons.

A definitive choice can be made only considering all the design goals and their weight in defining the overall design quality. At present the one-piece, one material solution has been preferred for early prototype implementation, but different possibilities are not abandoned.

In Figure 5 a view of the latest-design finger prototype is presented, as it comes out of the machine tool (a) and after insertion of flexures into their guides (b). It has been made of machined PTFE and has three elastic hinges plus two active and one passive flexures. The undeformed configuration of hinges corresponds to an angle of 45 degrees between adjacent links, so that a total angular excursion of 90 degrees is obtained moving from 45 deg. upwards to 45 deg. downwards.

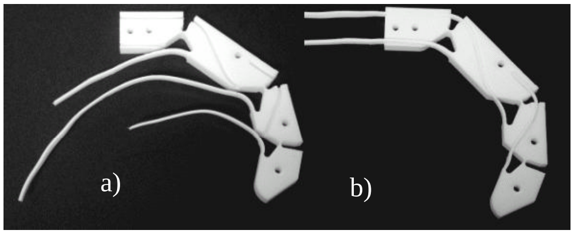


Figure 5: *The latest finger prototype*

For any considered actuation pattern and structural design, a preliminary kinetostatic analysis of a finger model was performed, in order verify its kinematical behaviour and evaluate the intensity of loads required on actuating elements. In the case of the structure of Fig.5, the three hinges were designed with the same stiffness (a linear behaviour of the joint has been estimated, with K= 0,7 Nmm/deg). The flexures exhibit the same bending stiffness and are able to transmit both tension and compression loads, while phalange masses and friction between flexures and guides have been considered negligible.

During the kinetostatic analysis, internal actions generated by imposed bending of flexures are evaluated as a function of angular displacement between joints.

Some results from numerical computation have been plotted in Figure 6, showing first the finger workspace, then the angular displacement of proximal (PJ), medial (MJ) and distal (DJ) joints during a circular trajectory of the fingertip, finally the correspondent axial loads Tp, Tm and Td acting on the proximal, medial and distal flexures respectively, together with the required displacements Xp, Xm of the two active flexures. It can be clearly observed that negative values of Tp, Tm and Td can occur, that means compression loads acting on the flexures, with consequent risk of flexure buckling.

Reduction of the hinge stiffness can generally reduce the intensity of loads acting on the flexures during free motion, and consequently can reduce the bending stiffness required to avoid buckling on flexures. In the adopted configuration compression loads occur only when the finger structure is bending outward with respect to the unstrained reference configuration, while only tension loads are present when the finger bends inward or resists contact forces applied on its internal surfaces.

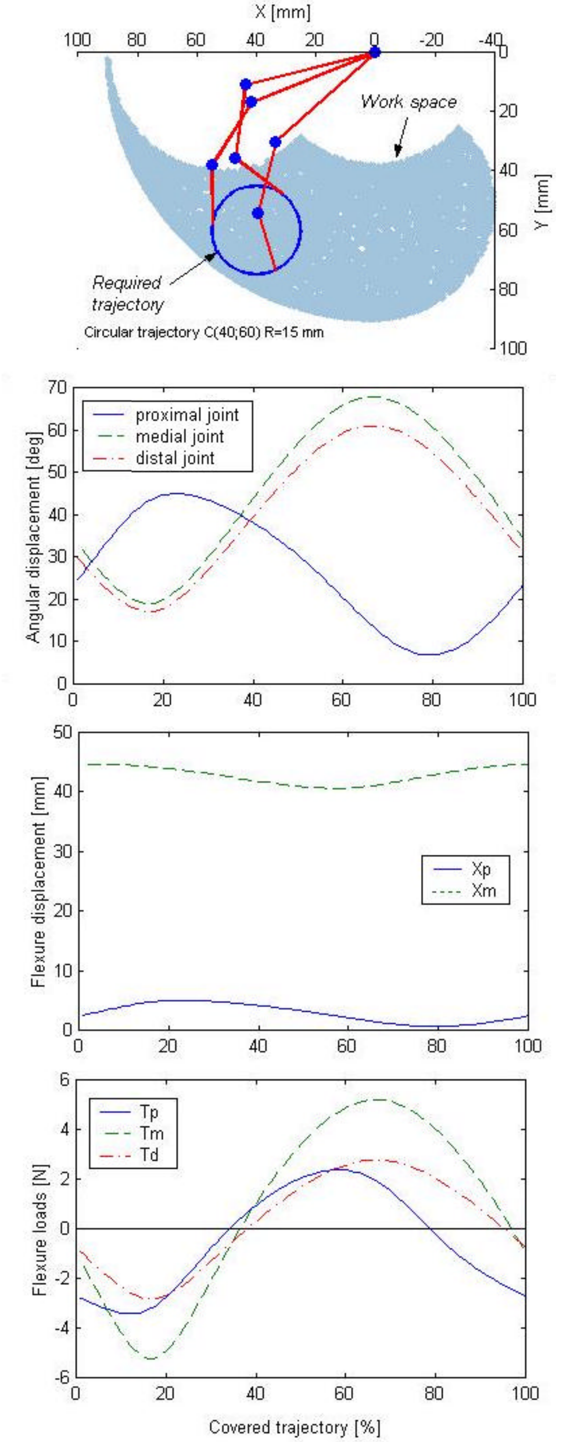


Figure 6: *Trajectory related displacements and forces*

4. Prototype implementation and early results

This paper reports the work to develop one-piece finger structures, where integrated flexures are made of the same material as hinges and phalanges. Several prototype fingers, with different actuation patterns, and hinge design have been built and tested, in parallel with the analysis and optimisation work.

PTFE is the material currently adopted in the finger structure, for its good mechanical properties (see Tab. I), manufacturability, low friction and wear resistance. Plates of this material were milled by CNC machine in order to obtain different finger structures with integrated flexures: two examples are shown in Figure 7.

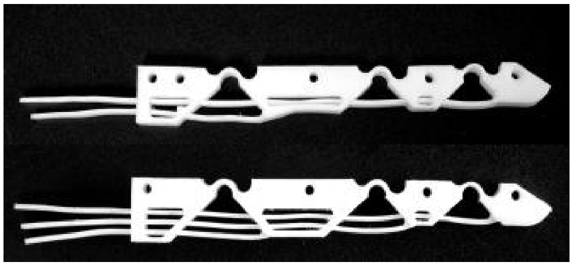


Figure 7: *Prototypes with different actuation patterns*

Finger prototypes are tested by means of a purposely-designed laboratory equipment, (Figure 8) where double-acting actuators can generate controlled linear motion of the active flexures. Position and force control can be provided; experiments aim to characterization of the structural behaviour and to evaluation of the achievable performance, in terms of trajectory accuracy and repeatability.

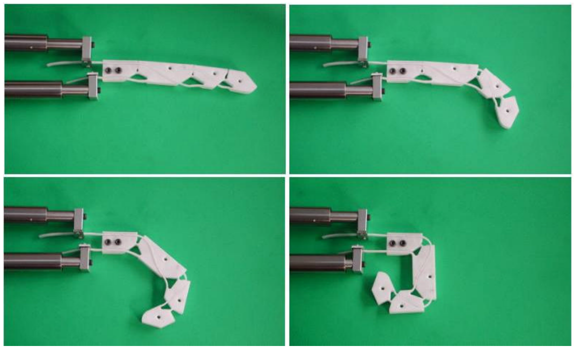


Figure 8: *The finger during bending tests*

Early qualitative results show that the concept works fairly well, even if trajectory errors due to modelling approximation and structural deformation under load are not negligible in the present implementation: further design improvement seems to be necessary to this purpose.

5. Work in progress

Besides the necessary optimisation work, the design of the compliant articulated structure is being developed in order to achieve two important additional goals, that are the location of a fourth hinge for adduction-abduction movement and the integration of an angular position sensor within each joint in order to obtain more accurate trajectory control.

The structure developed so far is a basic component of the finger, but does not represent the whole system, because the skeleton must be covered with a compliant layer to reproduce the function of soft tissues, possibly including distributed touch sensors.

To this purpose design work is in progress in order to integrate the one-piece finger skeleton with a continuous external shell, made of polyurethane gel, with variable thickness, in order to reproduce pulps as well as skin bends over joints [13]. Technogel®, a polyurethane gel by Bayer, was adopted for its visco-elastic behaviour and is currently tested according to several design patterns. A sketch of a possible shape of the gel finger cover can be seen in Fig. 9.

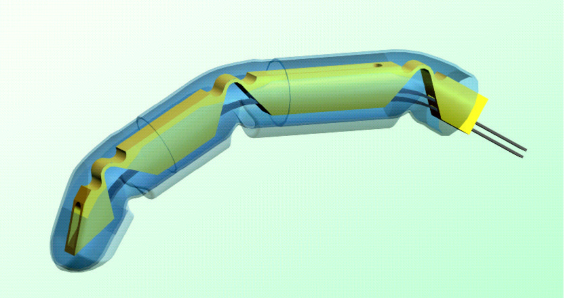


Figure 9: *A sketch of the finger with gel pulps*

6. Conclusions

Unconventional design of robotic devices, as far as mechanical structures and materials are concerned, can help overcoming some limits presented by more traditional approaches.

In the specific case of robotic hands great benefits can be expected from structural simplification, provided that it does not mean a reduction of functional capacity, but, on the contrary, a way to help solving some critical problems still present in hand design.

The design refinement work and the experimental tests conducted so far proved that the compliant mechanism concept can be profitably introduced into the design of articulated robotic fingers, with very interesting and stimulating perspectives, but showed, at the same time, that the search of an optimal solution is a very complicated matter, with many ways to be explored and a lot of work still to be done in order to go deep into general design criteria and specific structural and control problems as well.

On the base of the achieved results the authors do believe that the effort in developing the discussed design concepts is however worthy to be continued.

7. Acknowledgements

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