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NEW CABLE MANIPULATORS

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Summary: *The paper deals with the analysis of different cable manipulators. The cable manipulators are analysed from the point of the size of the working space and especially of the transfer of the forces between drives and end-effector. The existing cable manipulators either require the cable access from all sides or have unfavourable transfer of the forces in the case of tendon manipulators. It is described new variants of cable manipulators that overcome these drawbacks and posses really very good and especially uniform ratios of force transfer with cable access just from one side.*

1. Introduction

The cable manipulators are very attractive alternative to the traditional manipulators because they can achieve very low moving inertia and can require very small construction space. It is based on the fact that the actuators can be placed at the frame outside the manipulator, the transmission of the driving forces is very light and small. The natural and limiting condition is that the cables must be always under tension and that they can exert only one dimensional force.

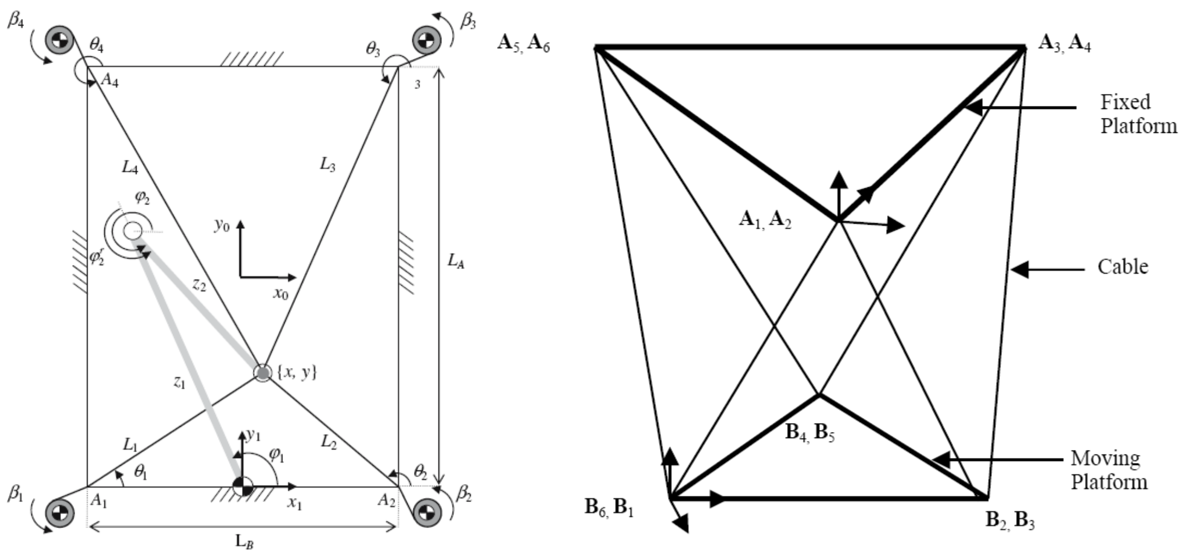

Fig. 1 The cable driven manipulators with cable access from all sides

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Three classes of cable manipulators have been proposed and designed. The first class consists of the manipulators that use for the guaranteed tension of the cables some external force like gravity or lift force by a balloon. The examples of such manipulators are even traditional cranes, draglines but especially crane manipulators, e.g. (Kittnar & Valasek 2004). The second class of such manipulators is based on the cable access to the end effector from all sides. Examples from (Trevisani et al. 2006) and (Joshi & Surianarayan 2003) are in Fig. 1. The third class uses tendons based on bionic motivation. An example from (Ou & Tsai 2002) and (Lafourcade et al. 2002) is in Fig. 2. The great advantage is that for *n* DOFs only *n*+1 tendons are necessary. All these manipulators suffer from serious drawbacks. The first class requires the external force. The second class cannot reach an object just from one side. The third class has unfavourable transfer of the forces between the drives and the end-effector.

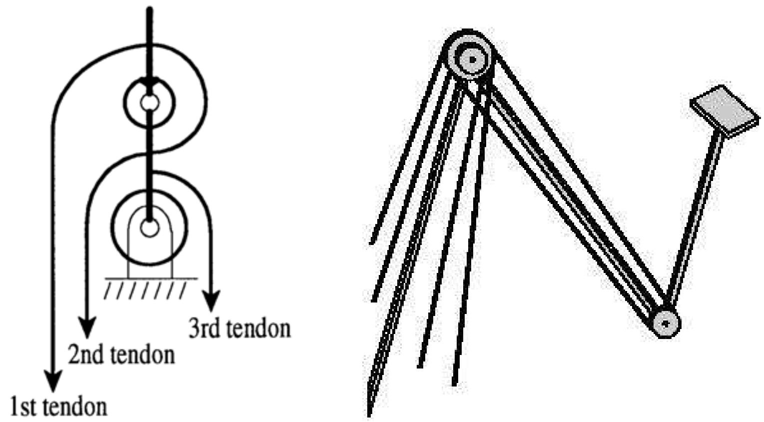

Fig. 2 The cable driven manipulators based on tendons

The objective of the study described in this paper is to develop a concept of cable driven manipulators that do not require an external force that enable the access to the manipulated object just from one side and that have favourable transfer of the forces. Two approaches can be distinguished. One approach (Chan 2005) is based on the parallel kinematic structures where a platform with the end-effector is suspended on the spine central link and stabilized by the cables (Fig. 3). The problem is again the reduced manipulability as the end-effector E must be directly accessible from the frame S and not the whole half-plane is accessible. The other approach tries to avoid this necessary assumption and to develop a true cable analogy to the traditional serial manipulators without the unfavourable transfer of the forces realized by tendons (Fig. 4).

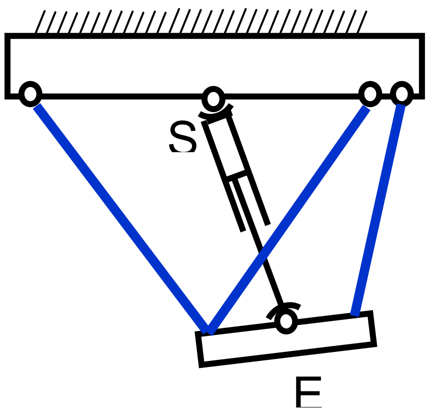

Fig. 3 Parallel kinematical structure with spine

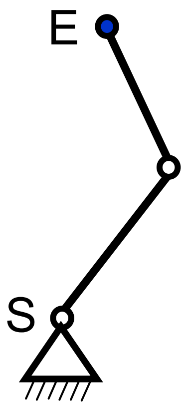

Fig. 4 The required kinematical concept

2. Initial concepts of cable manipulators

The possible concepts of cable manipulators were based on the principle of redundant actuation (Valasek 2004) and its consequences for anti-backlash control (Florian & Valasek 2006). The links of the serial kinematical structure were always attached to the frame by two cables. Based on that the first concept of cable manipulator was proposed (Fig. 5). It was required that such manipulator could operate within the whole half-plane. But this is not possible as the manipulator under the cable actuation would collapse at the right (red) position in the Fig. 5.

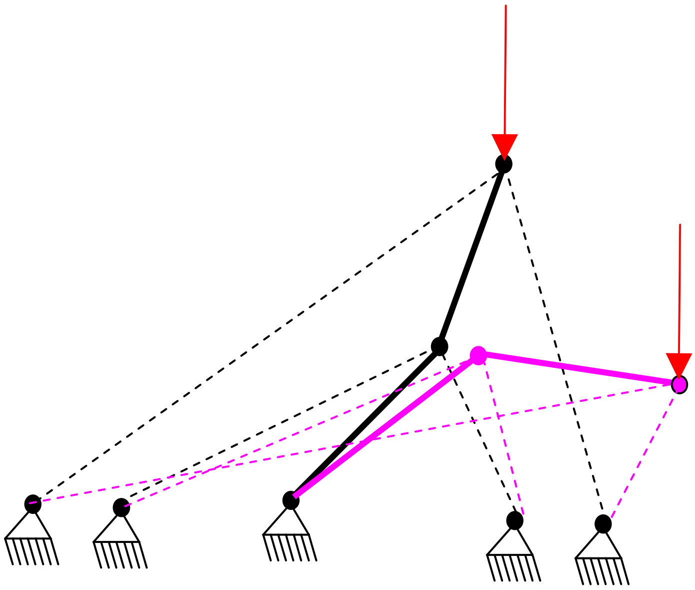

Fig. 5 The first concept of cable manipulator

Therefore the second concept of cable manipulator was proposed (Fig. 6). This concept is fulfilling the requirements in the whole half-plane until one of the link reaches the dividing straight line (Fig. 7). The manipulator is then not capable to carry the load.

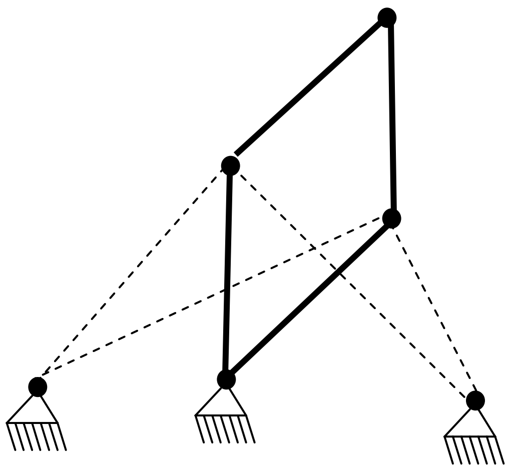

Fig. 6 The second concept of cable manipulator

However both the first two concepts demonstrate that the problem is just with the actuation of the second link. The first link connected by the revolute joint directly to the frame can move almost in the whole half-plane without problems. This fact is the starting point for the proposition of the third concept. It is based on the usage of the same mechanism for the actuation of both links.

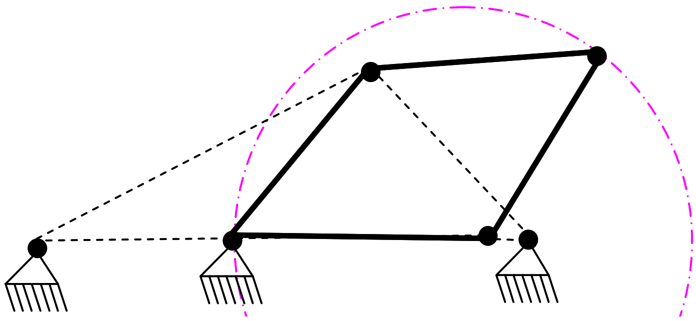

Fig. 7 The force transfer problem of the second concept of cable manipulator

3. Proposed concept of cable manipulators

The new concept is in Fig. 8. Four cables are used in order to achieve the uniform transfer of the forces. They are attached at the circle with the center S and the radius r1. The attachment points E1, E2 are under the line C1C2 at the middle position of the link SE (Fig. 8). The positions of the point E1, E2 with the respect to the radius r1 are further optimized.

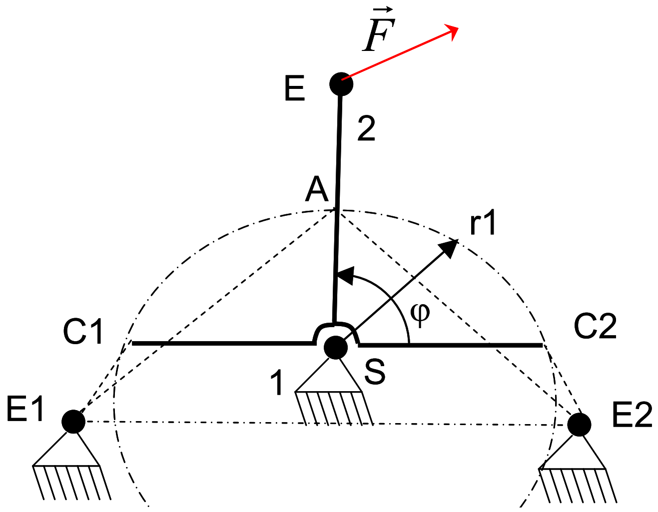

Fig. 8 The new concept for the single rotational link with cable actuation

The necessary condition of the tension of the cables are analysed straightforward for each position of the angle φ as follows. The forces in the cables are introduced according to the Fig. 8 as F_{AE1}, F_{C1E1}, F_{AE2}, F_{C2E2}, the reaction force in the rotational joint S as F_S. Then the condition of equilibrium can be written

$$\begin{aligned}
&\vec{F} + \vec{F}_S + \vec{F}_{AE1} + \vec{F}_{C1E1} + \vec{F}_{AE2} + \vec{F}_{C2E2} = \vec{0} \\
&\vec{r}_{ES} \times \vec{F} + \vec{r}_{AS} \times \vec{F}_{AE1} + \vec{r}_{AS} \times \vec{F}_{AE2} + \vec{r}_{C1S} \times \vec{F}_{C1E1} + \vec{r}_{C2S} \times \vec{F}_{C2E2} = \vec{0}
\end{aligned} \tag{1}$$

where generally F_{XY} and r_{XY} are the acting forces and radius vectors between the points X and Y. The condition of the cable tension is introduced by the rules:

(i) The cable forces F_{AE1}, F_{C1E1}, F_{AE2}, F_{C2E2} can be only positive.

(ii) From the forces F_{AE1}, F_{C1E1}, F_{AE2}, F_{C2E2} only one force is nonzero, i.e. only one cable is active. However, then four forces will be applied in order to be all cables under tension.

Then there are 4 possibilities of acting forces (F_{AE1}, F_{C1E1}, F_{AE2}, F_{C2E2}). Each combination is introduced into the equations (1) by the way that the other cable forces are set to zero. The resulting equations are solved. If the result is that the considered cable force from the forces F_{AE1}, F_{C1E1}, F_{AE2}, F_{C2E2} is positive then the solution is admissible. Among all admissible solutions the optimization was carried out in order to find minimal solution. It has been done for all positions of angle φ from 0 to 180 degrees. On top of this solution of optimal cable forces the optimization of the position of the points E1, E2 was provided again with the goal of minimization of the cable force.

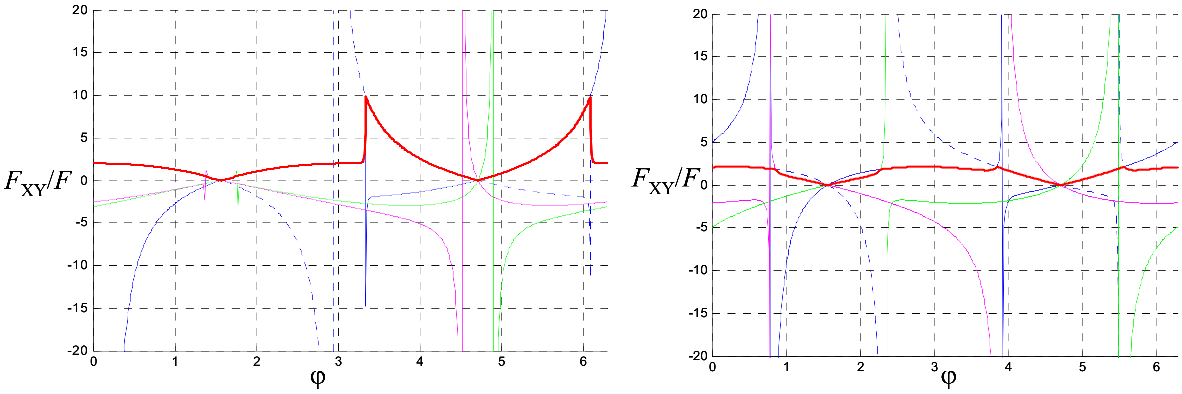

Fig. 9 Force transfer for initial and optimized position of the points E1, E2

The example of the results of the optimization is in Fig. 9. The left figure is the dependence of the cable forces F_{XY} on the acting force F=[0,1]N for the position of the points E1=[-0.5, -0.1], E2=[0.5, -0.1] and the right figure is the optimized dependence for the optimized position of the points E1=[-0.385, -0.385], E2=[0.385, -0.385] where the radius r1 was r1=0.5 and the length of the link was 1m. The required cable forces were decreased four times. The other three optimal dependences were computed for the acting forces F=[1,0]N, F=[0,-1]N, F=[-1,0]N.

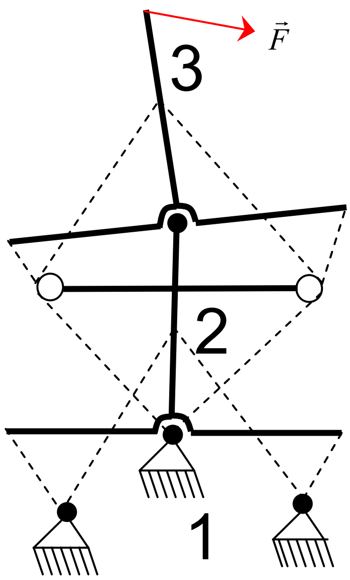

Fig. 10 The third concept of cable manipulator

Based on this design and optimization the third concept of the whole planar cable manipulator was proposed (Fig. 10). It enables to build a sequence of rotational joints each with the motion extent of at least 180 degrees.

The required forces for the exerting the forces at the end-effector of the two-link manipulator in Fig. 10 have been computed by the same optimization approach as above for one link. The results are in Fig.11. The left figure represents the maximum required force T1 at the cable actuators on the first link and the right figure represents the maximum required force T2 at the cable actuators on the second link.

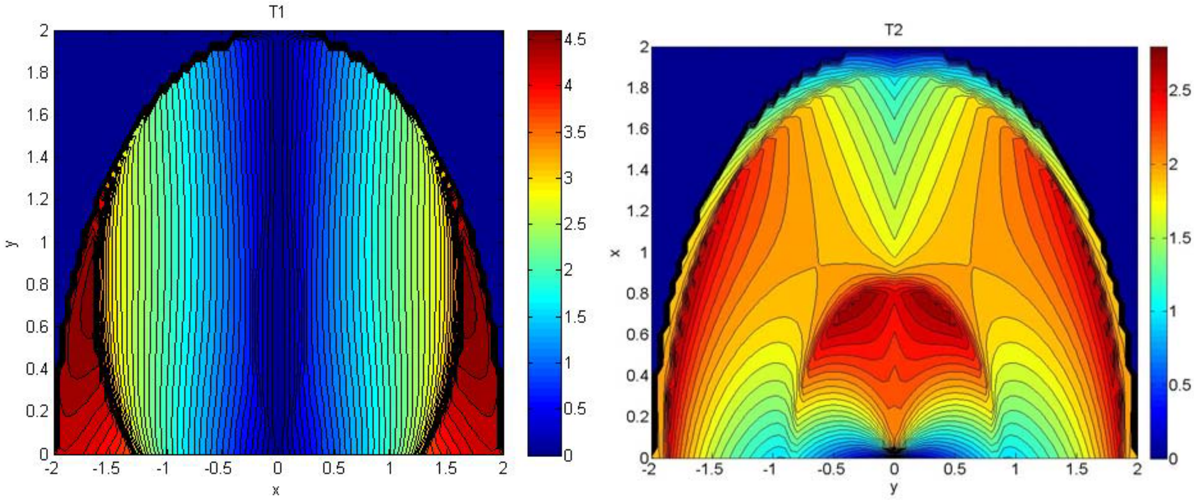

Fig. 11 The required cable forces the two-link manipulator

4. Comparison of tendon and new cable manipulators

Finally the comparison of the developed cable manipulator actuation was carried out with the traditional tendon actuation and the new cable one. One rotational link of a manipulator with the tendon actuation and with the new cable actuation are in Fig. 12.

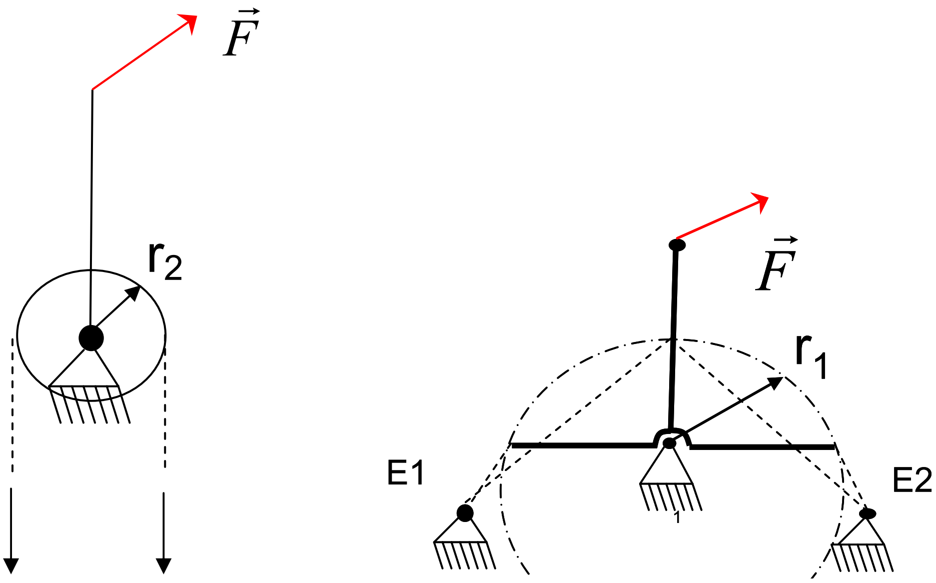

Fig. 12 Compared manipulator link of tendon and new cable actuation

For both cases it was computed the required actuation force F_{XY} for the equilibrium with the acting force F. Their ratio in the dependence on the angle φ (as in the Fig. 8) is in Fig. 13 for the equal radiuses r1=r2. Their ratio for different radiuses r1=4*r2 is in Fig. 14. The tendon actuation can hardly increase the radius of the pulley, but the new cable driven mechanism can enlarge the radius r1 by moving the cable attachement point and by the enlargement of the orthogonal lever. It demonstrates the advantages of the developed actuation mechanism.

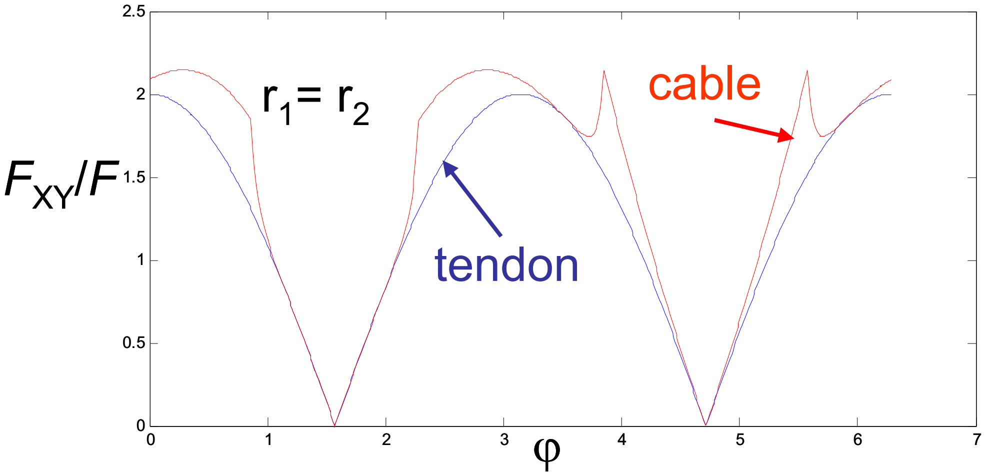

Fig. 13 The ratio of actuation and acting forces for equal radiuses

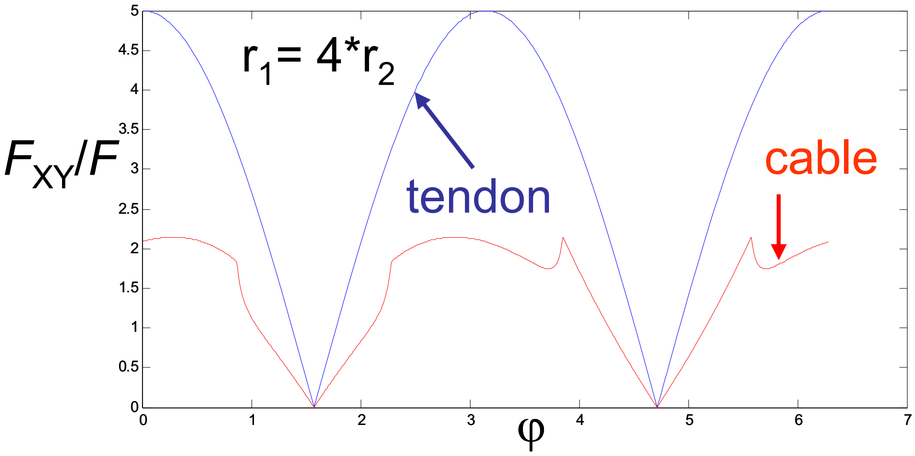

Fig. 14 The ratio of actuation and acting forces for different radiuses

5. Conclusion

The cable driven actuation is a promising approach because the moving inertia and the required construction space are very small compared to traditional approaches. However, the ratio between the required drive force and the exerted force in the manipulator is a challenge. The proposed new cable actuation reaches very moderate. This actuation can be used for the design of cable manipulators with the traditional serial kinematical structures.

6. Acknowledgement

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