Use of Passively Guided Deflection Units and Energy-Storing Elements to Increase the Application Range of Wire Robots

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Abstract Since few years, wire robots are making their way into industrial application. Besides the continuation of research in the fields of kinematics and dynamics modeling, control, workspace analysis, and design, new challenges like robustness, energy efficiency and maturity arise due to practical requirements. This holds especially true for the actuation and deflection components of the system. In the past, a wide range of actuation and deflection concepts were presented. Within this contribution, at first known ideas of deflection concepts are reviewed and compared. In the following, a new deflection concept using passively guided skids is presented which homogenizes the load capabilities of a wire robot over its workspace. Subsequently, new approaches optimizing the energy consumption based on the installation of counterweights and pre-stressed springs are discussed. Using those passive elements, not only static pre-tension can be generated but, in the case of using springs, also dynamic motions can be boosted by using the eigenmotions of the oscillator consisting of the end effector and the attached springs. The paper describes both

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the theoretical background as well as simulation results for eigenmotion utilization showing that the concept is capable of drastically reducing wire forces generated by the active components, i.e. the motors, for a given task.

1 Introduction

Wire robotics is a re-emerging research field in robotics: A large number of prototypes was presented in the last decade of the past century. Apparently, only a small number of these prototypes have made their way to practical applications. Possible reasons are manifold, reaching from the difficult controllability up to the comparably low precision induced by the uni-laterally constraining and inherently elastic wires, which replace the stiff conventional robot arms.

During the last five to eight years, a renaissance of practical applications can be found, most of which were proceeded by an extensive theoretical preparative work. In more recent research projects, the focus is increasingly put on a major advantage of wire robots: their easy reconfigurability. This property emerges from the modular usability of the three main components of a wire robot: the actuation unit, the deflection unit, and the wire.

A large variety of these three components has been presented in the literature, wherein especially the deflection units are mainly used as modular components. These units, which guide the wire from the actuation unit into the workspace, are no longer considered as units mounted to a fixed position, meaning, that the robot has a permanent configuration. Rather, their number as well as their position have become adaptable in order to configure the robot for different tasks [1, 2]. The proper robot configuration (i.e., the arrangement of the deflection units and the platform connection points) influences the workspace size as well as the achievable end-effector dynamics and wrench considerably.

These two parameters, workspace size and end-effector wrench, depend on a second variable: the dimensioning of the actuation unit. In contrast to rigid-linked robots, an increase in actuator power does not only influence the producible end-effector wrench but also the workspace size: This property emerges from the fact that, in case of fully constrained, over-actuated wire robots, a minimum pre-tension has to be maintained in all wires. At the borders of the workspace, the maintenance of this pre-tension in certain wires requires high counter forces in other wires which is often the main limitation of the workspace.

Within this paper, extended concepts for the modular use of the two above-mentioned components, actuation units and deflection units, are elaborated while investigations on proper wires are subject to future research. For the deflection units, a review on their different utilization in known wire robots is presented. Subsequently, a new concept is presented which is supposed to close a gap in wire robotics as it allows to keep the wire forces homogeneous over large workspace areas.

The concept for the robot actuation is extended to passive units which are used to relieve the active units, i.e. the motors. After summarizing a recent application

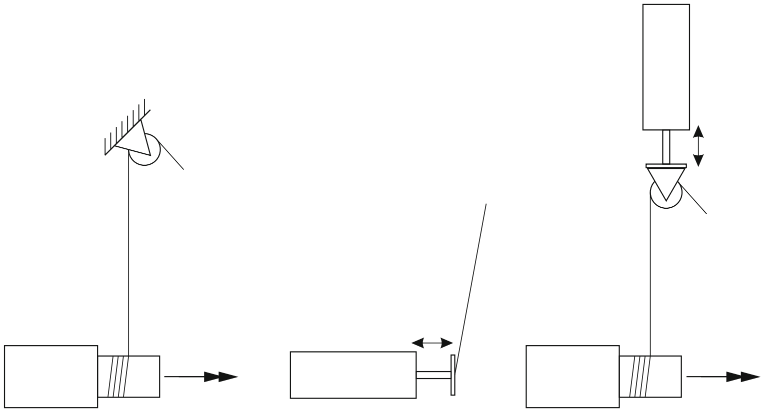


Fig. 1 Current concepts for deflection units: actuated drum and fixed deflection unit (*left*); linear actuation unit and wire with constant length (*middle*); actuated drum and actuated deflection unit (*right*)

involving counterweights, new concepts for the integration of springs are presented. These springs can either be used to relieve the motors in general or their characteristics are optimized for single tasks or trajectories.

Both concepts remarkably increase the usability of wire robots and, thereby, extend their applicability for new groups of applications.

2 Use of Deflection Units: Review and New Concept

In the following sections, the term *deflection unit* is referring to the device which guides the wire into the workspace.

Various designs for deflection units has been presented in the literature: simple rings or holes (made from low friction materials, e.g. ceramics) [3, 4] guiding the wires into the workspace are preferred to facilitate kinematic calculations, but they bare the disadvantage of higher friction and, as a consequence, increased wear compared to other solutions. Swivel castors are the logical option to overcome this problem; they are implemented in several wire robots, e.g. the IPAnema [5]. Their geometrical description can be found in the literature [6]. Further designs involving static pulleys and/or rollers have been presented over the past years [7, 8].

However, the following section will not focus on design issues of the proper deflection unit. Rather, the different use of deflection units within the actuation concept of wire robots, independent of their design, will be discussed, as this aspect has a major influence on the properties and capabilities of the robots.

2.1 Fixed Deflection Units

In most cases, deflection units are mounted to a fixed point (Fig. 1, left). They guide the wire from this point into the workspace where its free end is connected to the end effector. In certain concepts, the position of the deflection unit can be freely chosen along the frame structure of the wire robot in order to make the robot more versatile and adaptable to different tasks [1, 2].

This concept is the mechanically most simple and probably the best investigated solution. A major disadvantage is the limited workspace with heterogeneous, pose dependent load capabilities.

2.2 Actuated Deflection Units with Constant Wire Lengths

In a concept presented by Maeda et al. [9], reinterpreted by Bruckmann et al. [10], actuation units changing the wire lengths are completely omitted. Instead, wires with constant lengths are connected to linear actuators (Fig. 1, middle).

Also this concept has the advantage of mechanical simplicity, especially concerning the wire guidance. Furthermore, this arrangement turned out to be more energy efficient compared to rotary actuators with drums, as the actuation units only have to exert the component of the wire force tangential to the linear unit [10]. However, the required linear drives are often mechanically complex modules. They introduce large friction—potentially leading to control problems—and the choice of commercially available types is much smaller compared to rotary motors. As a further disadvantage, the highly limited workspace of this option has to be mentioned.

2.3 Actuated Deflection Units

Normally, the change of the wire lengths or the position of the deflection points determine the pose of the end effector. However, also the combination of both has been applied in one project [4] to manoeuver a tablet horizontally in space: In order to fully define the pose of an inertial body hanging on wires, at least six wires are required. When omitting wires, the body's position is no longer fully defined unless other actuated degrees of freedom are integrated. In the application mentioned before, the drive trains enables both the change of wire length by actuated winch units and the active positioning of the deflection unit. As this solution requires less wires, collision with other wires and objects inside the workspace become less probable.

A similar concept has been applied recently to address the collision problem [2]: In an interactive application with a human user standing inside the robot's workspace, the free ends of two actuated wires (variable lengths l_1 and l_2) were connected to a third wire with a constant length l_3 at the point **P** (Fig. 2). The free end of the third

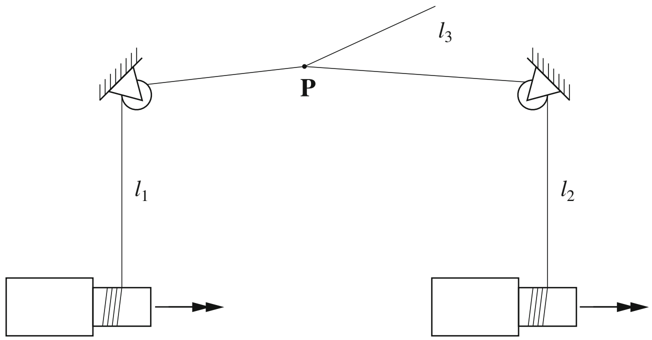


Fig. 2 Two actuated wires manipulating the deflection point of a third wire

wire was connected to the end effector grasped by a human subject. The change of the two active wire lengths resulted in a movement of **P**. This movement was used to avoid collision between the third wire and the subject. The point **P** could be interpreted as an actuated deflection point with a more complex movement range. Alternatively, a pulley could be mounted at the end of one active wire, deflecting the second wire.

The concept of movable deflection points could also be applied to an over-actuated wire robot in order to increase the workspace size of the robot. However, this solution is the mechanically most complex version compared to the other concepts presented above.

2.4 New Concept: Passively Guided Deflection Units

All concepts mentioned above have one clear disadvantage: their load capabilities vary strongly depending on the end-effector pose inside the workspace. This results from the increasingly inhomogeneous distribution of wire force vectors when the end effector is moved away from its central pose towards the outer workspace zones. This disadvantage can be compensated by actuated deflection points as they were presented in Sect. 2.3, but this solution is costly due to its high mechanical complexity.

We suggest a new concept where the deflection units are neither fixed nor actuated; instead, they move passively, while being connected to each other, and potentially subjected to additional passive constraints.

In an exemplary planar case, a single force vector acts on a moving attachment point at an object or human W (Fig. 3). Two winches are used, and two deflection units (pulleys) are combined and constitute a trolley running on a linear guide. To minimize the mass m_T of this trolley, given that distances between deflection units could be large, the units can be mounted on two separate carts that are connected by a cable. This is possible because the force between carts will always be tensile. A single

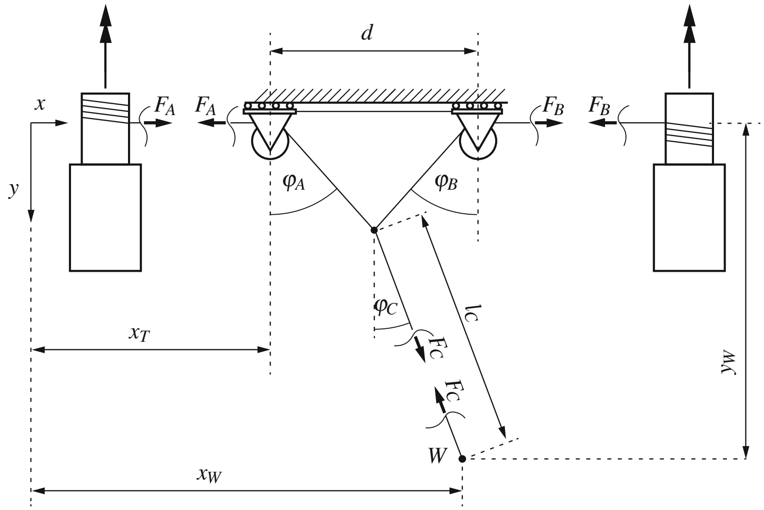


Fig. 3 Inter-connected passive deflection units enlarge the achievable workspace; the object or human subject is connected at point W

wire of length l_C connects the node to the attachment point W on the moving object or human. A configuration similar to this, but extended to the three-dimensional case, is currently being realized in an overhead support device for gait training.

We now assume that the endpoint W moves along a given trajectory $\mathbf{w} = (x_W, y_W)^T$, with $y_W > 0$, and that the force acting on W is to be controlled. This force is defined by its magnitude F_C and the angle φ_C. In the chosen Cartesian coordinate system, y points downward and x points to the right, in direction of the rail.

Geometry defines how the wire angles φ_A, φ_B, φ_C, and the trolley position x_T are related:

$$(y_W - l_C \cos\varphi_C)\tan\varphi_A + l_C \sin\varphi_C = x_W - x_T \tag{1}$$

$$(y_W - l_C \cos\varphi_C)(\tan\varphi_A + \tan\varphi_B) = d. \tag{2}$$

Force equilibrium on the node defines the relationships between the wire forces F_A, F_B, F_C, and the angles:

$$-F_A \sin\varphi_A + F_B \sin\varphi_B = -F_C \sin\varphi_C. \tag{3}$$

$$F_A \cos\varphi_A + F_B \cos\varphi_B = F_C \cos\varphi_C \tag{4}$$

Given a current trolley position x_T and wire forces F_A and F_B, the algebraic Eqs. (1–4) define the magnitude F_C and the angle φ_C of the output force vector (as well as the angles φ_A and φ_B).

The inverse problem, as necessary for control purposes, is to find appropriate reference wire forces $\hat{F}_A$ and $\hat{F}_B$ in function of a reference force $\hat{F}_C$ at the endpoint, and a reference angle $\hat{\varphi}_C$. The winches can then be used to track the desired wire forces $\hat{F}_A$ and $\hat{F}_B$.

If the deflection units were fixed, as in classical configurations, the solution would be found easily using the same equations, but the direction of the realizable output force would be constrained by the relationship

$$x_W - x_T - d < y_W \tan \hat{\varphi}_C < x_W - x_T \tag{5}$$

with fixed x_T. The range of possible angles thus depends strongly on the position of W and on the distance d between deflection units. Increasing the workspace by increasing d would automatically lead to higher wire forces F_A and F_B, which is undesirable.

The movable deflection units solve this issue and allow almost arbitrary positions x_W of the endpoint along the x direction, only constrained by space limitations in the building or by maximum allowable wire length. However, the control task of commanding appropriate wire forces is less straightforward, because of the under-actuated nature of the system. The trolley moves under the influence of the wire forces, according to the equation of motion:

$$m_T \ddot{x}_T = -F_A + F_B + F_C \sin \varphi_C. \tag{6}$$

One simple solution, which is efficient for low trolley mass, is to control based on static equilibrium: For constant wire forces F_A and F_B, the trolley will approach its equilibrium position, defined by the left side of (6) being equal to zero. Then, an additional algebraic relationship for the reference forces results:

$$\hat{F}_A - \hat{F}_B = \hat{F}_C \sin \hat{\varphi}_C. \tag{7}$$

This equation, combined with (1–4), with forces replaced by reference forces, allows the realization of a simple controller without static error: The system of five algebraic equations can be solved for $\hat{F}_A$ and $\hat{F}_B$ (and angles, and trolley position), given only $\hat{F}_C$ and $\hat{\varphi}_C$. For the equations to be solvable with non-negative forces, the commanded angle can theoretically take any value within the interval $-\pi/2 < \hat{\varphi}_C < \pi/2$. The smaller the mass of the movable deflection units is, the faster the trolley will approach its static equilibrium.

3 Combining Motors and Passive, Energy-Storing Elements

Apart from the deflection concept, the way how the wires are tensed has a considerable influence on the capabilities of a wire robot. In common wire robots, the wire tension is applied by all sorts of actuators. The most common type of actuators are electrical motors of both, rotary and linear type.

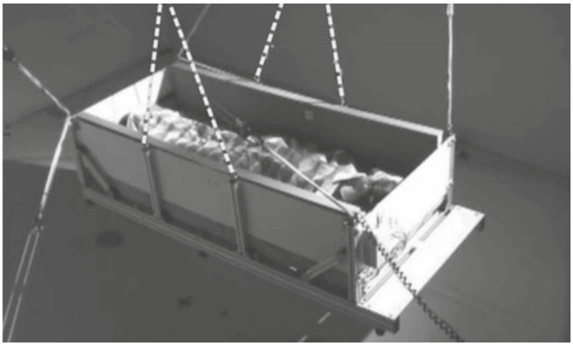


Fig. 4 The SOMNOMAT, an actuated bed platform for sleep research: Counterweights on additional wires (highlighted as *dashed lines*) partially compensate the high platform weight

Independent from the actuation concept, the active unit always exerts unidirectional torques or forces, as wires represent unilateral constraints. As a consequence, only half of the actuator's power spectrum is utilized in common wire robots.

This section presents possibilities how to overcome these shortcomings and how to increase the wrench of wire robots by using passive energy-storing elements.

3.1 Use of Single Springs or Counterweights

The minimum requirement for an end effector to work in n degrees of freedom without end-effector wrenches is to have at least $n + 1$ wires attached to it [11, 12]. However, one of these wires could be tensed by a passive energy-storing element. In the literature, applications can be found where an active actuation unit is replaced by a spring [13, 14]. The pre-tension of this spring determines the producible end-effector wrench.

A further challenge in robotic handling applications is the often high gravitational load induced by the proper robot structure as well as the end-effector load. While the structural load is usually negligible in wire robots, the end-effector load can significantly limit the robot's range of motion.

An example is the SOMNOMAT, a tendon-driven platform with six degrees of freedom used for sleep research [15]. In the SOMNOMAT, motorized drums were used as actuation units. These motorized drums are parts of a modular wire-robot concepts [2] and were by far too small-dimensioned to lift or even move the total platform weight of 140 kg. By attaching wires connected to counterweights which partially compensate the high platform weight, the application became realizable with the minimal number of seven actuation units (Fig. 4).

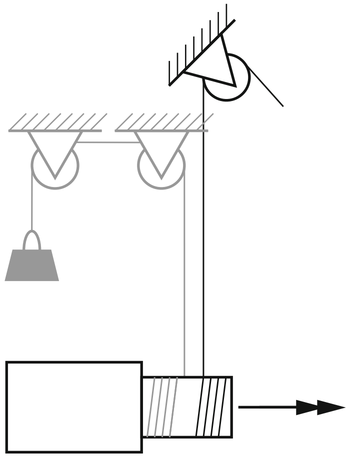


Fig. 5 Pre-tensing of the actuation unit with an inertial mass directly connected to the drum

3.2 Constant Pre-Tension of Actuation Units

As pointed out in the introduction of this section, the power spectrum of actuators is not fully exploited in wire robots, because the actuators only pull on the wires. In addition, the actuation units have to produce a minimum pre-tension F_{pre} in each wire when the system is over-actuated. This pre-tension does not contribute to any force or torque at the end-effector and, therefore, further diminishes the robot's wrench for a given actuator size.

This shortcoming can be compensated by pre-tensing the actuator—and therefore the wire—with the force:

$$F_{pre,const} = F_{pre} + F_{act,max} \tag{8}$$

with $F_{act,max}$ as the maximum static force the actuator can produce. Due to this pre-tension, the static load capabilities of the actuator is more than doubled. An option to realize this pre-tension is to attach a passive, energy-storing element directly to the actuated drum (Fig. 5). The drum length hardly has to be extended for this, as one wire is unwound when the other one is wound on.

To minimize the maximal motor torques, $F_{pre,const}$ could also be set to a value between the minimal and the maximal actuator torque required for a specific task on each actuator:

$$F_{pre,const} = F_{task,min} + \frac{F_{task,max} - F_{task,min}}{2} \tag{9}$$

3.3 Energy Minimization—Utilization of Eigenmotions

In the preceding sections, passive elements were used to increase the overall load capacities of wire robots. In the following section, we want to highlight how the dimensioning of these elements can be further fine-tuned dependent on the task to be realized.

3.3.1 Idea

An approach to minimize the energy consumption of a robot is to add passive elements to the robotic structure such that the eigenmotion of the robotic structure is close to the desired task-specific trajectory. The utilization of eigenmotions of course implies that the robot is transformed into an oscillator by adding elastic elements such as springs to the structure. Examples in the literature have shown that the integration of roughly-dimensioned springs can already release active units for tasks within a specific frequency spectrum [16].

The idea of utilizing the robot's eigenmotions has been presented by Uemura et al. [17]. They present the idea of attaching springs with adjustable stiffness to the axes of a serial robot. The spring stiffness and its equilibrium angle were adjusted such that the robot's eigenmotions were close to a previously specified trajectory describing a periodic movement. This idea is transferred herein to wire robots in the following paragraphs.

A cyclic trajectory of the robot's end effector in task space coordinates is described by the n-dimensional vector $\mathbf{x}(t)$. When neglecting frictional effects and the motor inertia, the following wrench has to be produced by the actuators to move an end effector along $\mathbf{x}(t)$:

$$\mathbf{w}_{EE} = \mathbf{M} \cdot \ddot{\mathbf{x}} \tag{10}$$

with $\mathbf{M}$ as the n-dimensional inertia matrix of the end effector.

Assuming that a number of $m \in \mathbb{N}$ springs with adjustable spring constant k_i and the initial length $l_{0,i}$, $i = 1, 2, \dots, m$, are attached serially to the actuation unit, the wrench $\mathbf{w}_s$ produced by these springs can be described by

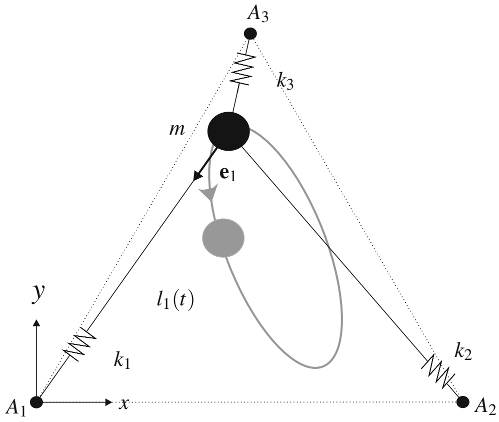
$$\mathbf{w}_s = \mathbf{A}^T \cdot [k_1 \cdot (l_1 - l_{0,1}) \dots k_m \cdot (l_m - l_{0,m})]^T \tag{11}$$

with $\mathbf{A}$ as the pose-dependent structure matrix of the wire robot and with l_i, k_i, and $l_{0,i}$ as the actual length, the spring constant, and the unloaded length of the i-th spring, respectively.

Under the given assumptions, the actuator has to produce the following wrench $\mathbf{w}_a$ to move the end effector along $\mathbf{x}$:

$$\mathbf{w}_a = \mathbf{w}_{EE} - \mathbf{w}_s \tag{12}$$

Fig. 6 Assembly of a planar wire robot with deflection points $A_{1...3}$ and point mass m moving along a cyclic trajectory (*grey*)



The goal is to tense the springs in such a way that the required actuator power is minimized for the given task. In other words, the oscillator consisting of the end effector and the springs should be dimensioned such that the eigenmotion of the end effector supports the desired cyclic movement optimally. Knowing the trajectory in advance, this dimensioning can be done off-line and is not critical concerning calculation time. According to [17], this is reached by minimizing the following expression

$$J(\mathbf{k}, \mathbf{l_0}) = \int_{i \cdot T}^{(i+1)\cdot T} \mathbf{w}_a^T \mathbf{w}_a dt \tag{13}$$

with $k = [k_1, k_2, \ldots, k_m]$ and $l_0 = [l_{0,1}, l_{0,2}, \ldots, l_{0,m}]$.

3.3.2 Example

The utilization of the eigenmotions in a wire robot will be demonstrated on a planar wire robot (Fig. 6).

Three wires are attached to a point-shaped end effector with a mass of $m = 1$ kg. The deflection points of the wires, A_1, A_2, A_3, form an equilateral triangle. The position vectors of these points are denoted by $\mathbf{a}_1 = [0, 0]$, $\mathbf{a}_2 = [10, 0]$, and $\mathbf{a}_3 = [5, 8.66]$. The coordinate system is located in A_1.

In a first step, the purely passive spring system is considered. Therefore, the wires are replaced by springs with adjustable stiffnesses k_1, k_2, k_3 and relaxed spring lengths $l_{0,1}, l_{0,2}, l_{0,3}$. Practically, this can be realized by a clock spring tensing a winch which coils the wires. The sum vector of wire forces caused by the springs is $\mathbf{F}_{pre} = F_{pre_1}\mathbf{e}_1 + \cdots + F_{pre_m}\mathbf{e}_m$ with an absolute value of F_{pre} and e_i, $i = 1, 2, \cdots, m$, as the unit vectors in direction of the wires.

Now, k_i and $l_{0,i}$ should be chosen such that the springs optimally support an end-effector movement along a predefined cyclic trajectory, meaning that (13) is minimized. The following trajectory definition was chosen, describing a periodic movement, consisting of two superimposed movements: A basic elliptic movement with a frequency f_1 and amplitudes a and b, and a second superimposed oscillation with the eightfold frequency f_2 and an amplitude of 1 % of a:

$$\mathbf{x}(t) = \begin{bmatrix} a_0 + a\cos(\phi)\cos(2\pi f_1 t) - b\sin(\phi)\sin(2\pi f_1 t) + \frac{a}{100}\cos(\phi)\cos(2\pi f_2 t) \\ b_0 + a\sin(\phi)\cos(2\pi f_1 t) + b\cos(\phi)\sin(2\pi f_1 t) + \frac{a}{100}\sin(\phi)\cos(2\pi f_2 t). \end{bmatrix} \tag{14}$$

The basic elliptic trajectory is rotated by ϕ. The center point of the equilateral triangle formed by deflection points A_i, $i = 1, 2, 3$, does not coincide with the center point $[a_0, b_0]$ of the ellipse. In this example, the following parameters are used: $f_1 = 0.5\,\text{Hz}$, $f_2 = 4\,\text{Hz}$, $a_0 = 5.7\,\text{m}$, $b_0 = 3.5\,\text{m}$, $a = 3\,\text{m}$, $b = 1.2\,\text{m}$, $\phi = 14.5\,\text{deg}$.

Neglecting frictional effects and the inertia of the drums and motors, $\mathbf{w}_a$ can be calculated for this system as follows:

$$\mathbf{w}_a(t) = \underbrace{m\ddot{\mathbf{x}}(t)}_{\mathbf{w}_{EE}} - \underbrace{\mathbf{A}^T(\mathbf{x}(t))[\,k_1(l_1(t) - l_{0,1})\;k_2(l_2(t) - l_{0,2})\;k_3(l_3(t) - l_{0,3})\,]^T}_{\mathbf{w}_S} \tag{15}$$

where m and $\ddot{\mathbf{x}}(t)$ are given and the structure matrix $\mathbf{A}^T$ can be calculated by

$$\mathbf{A}^T(\mathbf{x}(t)) = [\mathbf{e}_1(t)\,\mathbf{e}_2(t)\,\mathbf{e}_3(t)] \tag{16}$$

with

$$\mathbf{v}_i(t) = \mathbf{a}_i - \mathbf{x}(t) \quad \text{vector of the wire } i$$
$$l_i(t) = \|\mathbf{v}_i(t)\|_2 \quad \text{length of the wire } i$$
$$\mathbf{e}_i(t) = \frac{\mathbf{v}_i(t)}{l_i(t)} \quad \text{unit vector of the wire } i$$

for $i = 1, \ldots, 3$.

For the evaluation of (13), the expression $\mathbf{w}_a^T\mathbf{w}_a(t)$ can be calculated as

$$\mathbf{w}_a^T\mathbf{w}_a(t) = s_1(t) - 2ms_2(t) + s_3(t) \tag{17}$$

with

$$s_1(t) = m^2\,\|\ddot{\mathbf{x}}(t)\|_2^2$$
$$s_2(t) = \sum_{i=1}^{3} \ddot{\mathbf{x}}(t)^T\mathbf{e}_i(t)\,\underbrace{k_i(l_i(t) - l_{0,i})}_{:=F_{pre_i}(t)} \tag{18}$$

$$s_3(t) = \sum_{i=1}^{3}\left[\left(\mathbf{e}_i(t)^T\begin{bmatrix}F_{pre_i}(t)\\0\end{bmatrix}\right)^2 + \left(\mathbf{e}_i(t)^T\begin{bmatrix}0\\F_{pre_i}(t)\end{bmatrix}\right)^2\right]$$
$$+2[\mathbf{e}_1(t)^T\mathbf{e}_2(t) + \mathbf{e}_1(t)^T\mathbf{e}_3(t) + \mathbf{e}_2(t)^T\mathbf{e}_3(t)]$$

where only the passive system is assumed.

Discretizing t with a sampling rate of 0.001 s the value of $J(\mathbf{k}, \mathbf{l_0})$ for the evaluation of (13) can be calculated e.g. by using trapezium rule with $iT = 0$ and $iT + T = 2$. The objective function of the optimization is defined by $J(\mathbf{k}, \mathbf{l_0})$.

The optimization of the spring parameters k_i and $l_{0,i}$, $i = 1, 2, 3$, can be performed by minimizing $J(\mathbf{k}, \mathbf{l}_0)$, e.g. with the MATLAB® function `fmincon` given the following boundary conditions:

$$\begin{aligned} 0 \le k_i &\le \infty, \quad i = 1, 2, 3 \\ 1 \le l_{0,i} &\le \min_{0\le t\le 2}(l_i(t)), \quad i = 1, 2, 3 \\ F_{pre_i}(t) &\ge 5 \quad i = 1, 2, 3 \end{aligned} \tag{19}$$

ensuring only positive spring constants, positive spring forces defined by a positive difference $(li(t) - l_{i,0})$ for any $0 \le t \le 2$, a minimal spring length of 1m, and a predefined minimum wire force of 5 N at any time. The optimization is started using the initial value $\mathbf{x}_0 = [1.5\ 4.8\ 16\ 2\ 2\ 2]$ for $\mathbf{k}$ and $\mathbf{l}_0$ fulfilling the defined boundary conditions. It converges delivering the following parameters

$$\mathbf{k}_{opt} = [k_{opt_1} k_{opt_2} k_{opt_3}] = [2.68\ 2.91\ 4.38] \tag{20}$$

$$\mathbf{l}_{0_{opt}} = [l_{opt_{0,1}} l_{opt_{0,2}} l_{opt_{0,3}}] = [1.91\ 1\ 1]. \tag{21}$$

Using these values, the forces of the hereby defined springs can be calculated as

$$\mathbf{F}_{pre,opt}(t) = \sum_{i=1}^{3} F_{pre,opt_i}(t)\mathbf{e}_i(t) \tag{22}$$

with

$$F_{pre,opt_i}(t) = k_{i_{opt}}(l_i(t) - l_{0,i_{opt}}), i = 1, 2, 3. \tag{23}$$

Looking at the magnitude of the spring forces F_{pre,opt_i} for each spring over one cycle (Fig. 7), it can be observed that the prescribed minimal wire force is maintained in all wires.

The resulting force produced by the just dimensioned springs $\mathbf{F}_{pre,opt}$ counteract the inertial forces caused by the low frequent platform movement while the high frequent inertial forces cannot be compensated (Fig. 8).

To discuss the quality of the optimization result, first a purely active system is modeled where only actuators have to keep the platform on the desired cyclic

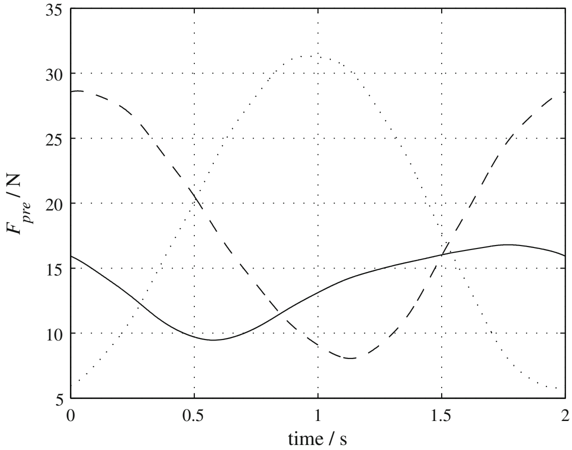


Fig. 7 Forces produced by the optimized springs (*solid*: spring 1; *dashed*: spring 2, *dotted*: spring 3

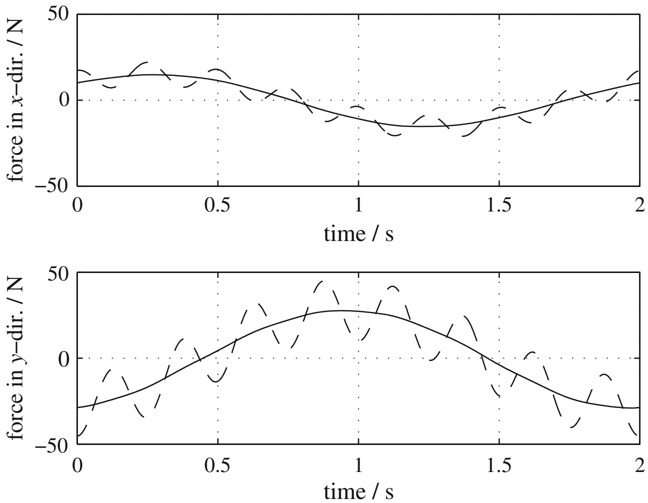


Fig. 8 Inertial force of the platform (*dashed line*) and inverted sum of forces produced by the springs (*solid line*) in x- and y-direction

trajectory. The following equation describes the dynamic system neglecting friction and actuator masses:

$$\mathbf{A}^T(\mathbf{x}(t))\mathbf{F}_{act}(t) = m\ddot{\mathbf{x}}(t). \tag{24}$$

Here, the unknown forces $\mathbf{F}_{act}$ have to be determined for any $t \in [0, 2]$. Since this system is underdetermined but has to maintain the wire force limits, again an optimization problem with boundary conditions can be specified. A quadratic opti-

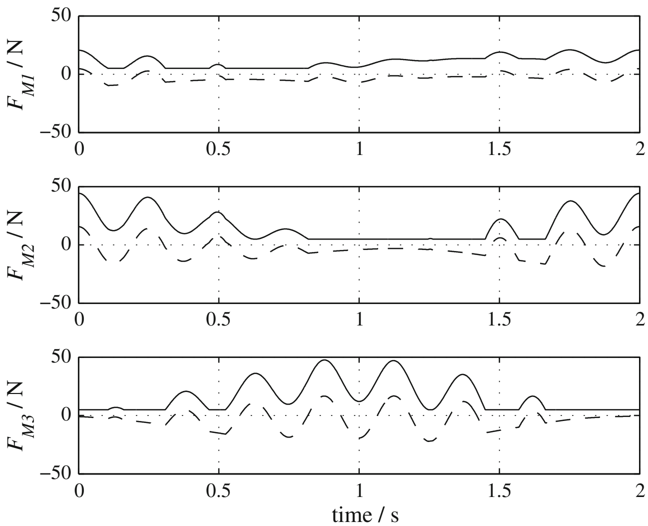


Fig. 9 Required actuator force without springs (*solid line*) and with springs (*dashed line*) (F_{Mi}: force produced by the motor placed at point A_i, $i = 1 \ldots 3$)

mization criterion is chosen which warrants continuity of the single wire forces [12]:

$$\min \|\mathbf{F}_{act}\|_2$$

subject to

$$\begin{aligned} \mathbf{A}^T\ \mathbf{F}_{act} &= m\ddot{\mathbf{x}}(t) \\ \mathrm{F}_{min} \leq \mathbf{F}_{act} &\leq \mathrm{F}_{max} \end{aligned} \tag{25}$$

where $\mathbf{F}_{act} \in \mathbb{R}^m$ denotes the m tendon forces to be optimized. As for the springs, the minimal wire force F_{min} was set to 5 N, an upper bound F_{max} was not set.

Finally, the hybrid system combining the springs and the active system is modeled and allows the evaluation of the effects of the springs. Therefore, the required actuator forces of the purely active system $\mathbf{F}_{act}$ are compared to the actuator forces of the hybrid system $\mathbf{F}_{diff}$ which can be calculated by

$$\mathbf{F}_{diff}(t) = \mathbf{F}_{act}(t) - \mathbf{F}_{pre,opt} \tag{26}$$

It can be observed that the springs considerably reduce the amount of required actuator force by factors between 2.8 (motor 2) and 4.4 (motor 1) (Fig. 9). In the hybrid system, all motors apply positive and negative forces.

4 Conclusion and Outlook

Wire robots are probably the most suitable robotic subgroup to be used as modular, reconfigurable systems. The advantage of this modularity is the relatively simple adaptability to other tasks. This advantage can be further increased by utilizing different kinds of deflection concepts as well as the integration of passive elements in parallel or serial to the actuators.

Regarding the choice of the deflection concept for a given task, clear design rules can hardly be given. If a task cannot be realized with the minimum number of wires required for the given number of degrees of freedom, the increase of the number of used wires might already be sufficient, while the deficits of certain concepts disqualify them in advance for other tasks. The herein presented approach of using passively guided deflection units nicely demonstrates these aspects: The given task could probably be realized with other deflection concepts. However, these concepts would require more powerful actuation units and/or a larger frame, e.g. in case of fixed deflection units, which might not be feasible under given circumstances.

As for the wire deflection, several approaches exist to extend the actuation concepts and, thereby, the range of realizable applications. For example, the use of passive, energy-storing elements in the actuation concept does not only compensate in certain cases for the disadvantageous use of uni-directionally loaded motors in classical wire robots. Furthermore, these elements can relieve the motors from static and dynamic end-effector load. Simple applications have already proven the feasibility and advantages of using counterweights or springs in wire robots. The more sophisticated, task-specific methods such as the eigenmotion approach presented in this paper have a large impact on the energy consumption and load capabilities of a robot. In the presented example, we had to add a secondary, high-frequent oscillation to the basic elliptic movement to be able to demonstrate the effects of the additional springs: Despite the arbitrary position of the trajectory in the workspace, the oscillator, i.e. the combination of the springs and the end effector, could almost optimally follow the cyclic trajectory without any interference of the motors. In a next step, the load induced by the proper motor inertia and frictional effects will be integrated into the eigenmotion approach.

The third basic component of wire robots has not been discussed within this paper: The proper wire. In the literature, its choice is commonly explained with the need for types with a maximum load-to-weight ratio. Model-based compensation is normally applied to deal with unavoidable effects like elongation due to elasticity. In contrast, the utilization e.g. of these elastic effects for different control modes has not been discussed yet. In this context, over-actuated wire robots are a unique robotic subgroup: The adjustable pre-tension of wire robots allows to change the properties of the robot in a wide range, from an elastic to a comparatively stiff structure. This adaptability does not require any hardware adaptation but might allow to operate a given wire robot in different, complementary control modes, from sensitive force control to precise position control. This research field, combined with the presented options for deflection units and actuation units might considerably widen the task spectrum for wire robots and, thus, allow to occupy some of the numerous application niches where rigid-link robotics comes to its limits.

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