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Wire Robot Suspension Systems for Wind Tunnels

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1. Introduction

In the past decade, the main focus in ship hydrodynamic simulation was the computation of the viscous flow around a ship at constant speed and parallel inflow to the ship longitudinal axis. Meanwhile, the numerical methods developed by extensive research allow to simulate the viscous flow around a maneuvering vessel. Having these methods at hand, experimental data are required for the validation of the applied simulation models. These data can be obtained e.g. by wind tunnel experiments. Here, particularly the velocity distribution around the body and forces of the flow during a predefined motion are of interest.

The motion of the ship model can be realized by a superposition of longitudinal motion simulated through the inflow in the wind tunnel and a transverse or rotational motion of the ship realized by a suspension mechanism.

Mechanisms for guiding a ship model along a predefined trajectory are known e.g. from towing tank applications. However, the design criteria for these mechanisms are totally different from a wind tunnel suspension system. In the towing tank, the weight of the studied vessel is compensated by the buoyancy force. On the other hand, the required forces to move the model along a trajectory are much higher due to the higher density and mass of the water in comparison with air. In the wind tunnel application, the mass of the model leads to gravity and inertia forces which have to be compensated by the suspension system.

This chapter describes the development of a suspension system based on wire robot technology. Wire robots use wires for the suspension of their end effectors. In this application, this is very advantageous since wires have a relatively small aerodynamical footprint and allow for high loads. The system described within this chapter is installed at the Technical University Hamburg-Harburg, where ship models must be moved on defined trajectories within the wind tunnel, as described above (Sturm & Schramm, 2010). The application requires the motion of heavyweight payloads up to 100kg with a frequency of up to 0.5Hz for the translational degrees-of-freedom and up to 2.5Hz for the rotational degrees-of-freedom.

Within this chapter, at first a short historical review of the very active wire robot research within the last years is given in section 2. Afterwards, an appropriate design of the wire robot system is discussed in section 3. Due to the adaptability of the wire robot concept, different geometries are possible. Based upon the mechatronic development process according to VDI (2004), two designs are investigated in section 3. Therefore, virtual prototypes using mathematical models and numerical simulation are developed in sections 3.1 and 3.2. Based on the simulation results, the two designs are compared in section 3.3. Using numerical optimization approaches, the chosen design is adapted to the specific task, see section 4. In section 5, the mechatronic system design is described. Finally, conclusions and future steps are discussed.

2. History and state of the art

Wires are widely used to suspend models in wind tunnels (Alexeevich et al., 1977; Griffin, 1988). Usually, these wires are fixed and therefore, the model is installed at a statical pose. The idea of using a wire robot suspension system adds the capability for performing dynamic and repeatable maneuvers during the experiment.
This concept was already proposed by Lafourcade (Lafourcade, 2004; Lafourcade et al., October 3-4, 2002). The SACSO (SUSPENSION ACTIVE POUR SOUFFLERIE) robot made at CERT-ONERA is an active wire suspension for dynamic wind tunnel applications.
Recently, results are presented by chinese researchers (Yangwen et al., 2010; Zheng, 2006; Zheng et al., 2007; 2010), e.g. covering the aspects of load precalculation. The WDPSS (WIRE-DRIVEN PARALLEL SUSPENSION SYSTEM) (Zheng et al., 2007) was optimized for large attack angles. Note, that in these approaches, the mass of the prototypes was much less than in the application described here which defines new challenges and requirements as described above.
From a kinematical point of view, the wire robot suspension system described here belongs to the parallel kinematic machines. Generally, parallel kinematic machines have major advantages compared to serial manipulators in terms of precision, load distribution and stiffness. Contrary, classical parallel kinematic machines have a relatively small workspace compared to serial systems. In 1985, Landsberger (Landsberger & Sheridan, 1985) presented the concept of a parallel wire driven robot, also known as tendon-based parallel manipulator or parallel cable robot. These robots – in the following denoted as wire robots – share the basic concepts of classical parallel robots, but overcome some of their typical drawbacks:

- Flexible wires can be coiled on winches which allow larger strokes in the kinematical chain. Therefore, larger workspaces can be realized.
- No complicated joints are required. Instead, winches and deflection pulleys are used.
- Simple and fast actuators can be used. Ideally, winches integrating drives and sensors for the coiled wire length and the force acting onto each wire, respectively, are applied.

Wires can only transmit tension forces, thus at least $m = n + 1$ wires are needed to tense a system having n degrees-of-freedom (Ming & Higuchi, 1994a;b). From a kinematical point of view, this leads to redundancy. Taking into consideration that the wire robot must always be a fully tensed system to be stiff, the solution space of the wire force distribution has dimension $m - n$. Thus, for each pose of the platform within the workspace, there exists an unlimited number of wire force distributions which balance the load acting onto the platform. Contrarily, the wire forces are limited by lower and upper bounds to prevent slackness and wire breaks, respectively. From a control point of view, the force distributions must also be continuous while following a continuous trajectory through the workspace. This makes the force computation a complicated task, especially when the computation has to be performed in realtime, i.e. when a cyclic control system offers only a predefined time slot for all computations during run time.
Wire robots are subject to extensive research. At the University of Duisburg-Essen, the projects SEGESTA (SEILGETRIEBENE STEWART-PLATTFORMEN IN THEORIE UND ANWENDUNG, supported by the Germany Research Counsil DFG under HI 370/18, and ARTIST

(ARBEITSRAUMSYNTHESE SEILGETRIEBENER PARALLELKINEMATIKSTRUKTUREN, supported by the Germany Research Counsil DFG under HI370/24-1 and SCHR1176/1-2, focused on aspects of workspace calculation, design optimization and wire force calculation as well as on the realization of the SEGESTA testbed. Due to its acceleration capabilities, this testbed was successfully applied e.g. for the evaluation of inclinometers used within automotive electronic control units (ECU) (Bruckmann, Mikelsons, Brandt, Hiller & Schramm, 2008a;b; Fang, 2005; Hiller et al., 2005; Verhoeven, 2004).

Besides the acceleration potential, the large workspace of wire robots is advantageous which was addressed e.g. in the ROBOCRANE project (Albus et al., 1992; Bostelman et al., 2000) at the National Institute of Standards and Technology (NIST), USA. The CABLEV (CABLE LEVITATION) prototype at the University of Rostock, Germany (Woernle, 2000) was realized to investigate problems of control and oscillation cancellation (Heyden, 2006; Heyden et al., 2002; Maier, 2004). At the Institut national de recherche en informatique et en automatique (INRIA), Merlet achieved advances in workspace analysis of wire robots e.g. by applying interval analysis (Merlet, 1994a; 2004). Aspects of practical application and control are investigated in his project MARIONET which is referenced in section 3.

Tadokoro developed the wire robot WARP (WIREPULLER-ARM-DRIVEN REDUNDANT PARALLEL MANIPULATOR) for highly dynamical motions (Maeda et al., 1999; Tadokoro et al., 2002) and as a rescue system after earthquakes (Tadokoro & Kobayashi, 2002; Tadokoro et al., 1999; Takemura et al., 2006). The acceleration potential was also exploited in the project FALCON (FAST LOAD CONVEYANCE) by Kawamura (Kawamura et al., 1995; 2000).

At the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart (Germany), Pott focuses on the application of wire robots e.g. for handling of solar panels (Pott et al., 2009; 2010) and developed the prototypes IPANEMA and IPANEMA2. On the theoretical side, algorithms for fast workspace analysis are developed (Pott, 2008).

Several research groups investigate on the application of wire robots for the positioning of reflectors above a telescope (Su et al., 2001; Taghirad & Nahon, 2007a;b) which is challenging in terms of stiffness and kinematics.

At the Eidgenössische Technische Hochschule (ETH) in Zurich (Switzerland), the interaction of wire robots and humans is adressed. This includes e.g. a rowing simulator (Duschau-Wicke et al., 2010; von Zitzewitz et al., 2009; 2008) and haptical displays e.g. for tennis simulation. Additionally, sleep research has been investigated by using the SOMNOMAT setup .

Nowadays, the wire robot SKYCAM® by Winnercomm, Inc. (USA), is well known from sports television. The patent "'Suspension system for supporting and conveying equipment, such as a camera"' Brown (1987) was already applied in 1987. In Europe the system became very popular with the soccer championship UEFA EURO 2008™.

Wire robots using elastic springs instead of active drives were investigated by Ottaviano and Thomas Ottaviano & Ceccarelli (2006); Ottaviano et al. (April 18-22 2005); Thomas et al. (September 14-19, 2003). They propose passive wire robots for pose measurements of moving objects. In this case the forward kinematics problem has to be solved.

3. Topological design

Using the suspension system, a wide range of motions should be possible to realize arbitrary maneuvers. Two requirements have to be covered:

1. Generally, the maneuvers to be performed are not known a priori (which is contrary to robots and manipulators in many applications). Therefore, a generally large volume of the workspace is demanded to allow for a wide range of motion paths.

2. The system has to offer a wide range of motion dynamics. Again, generally the trajectories are not known which makes it hard to specify the power demands and force or torque requirements, respectively, for the drives and winches and to choose a geometry. As a design criterion, one example trajectory was chosen which is described later.

This leads to the problem of finding an adequate geometry design. Due to architectural limitations, the geometry of the supporting frame is fixed and forms a cuboid (see Fig. 1 and Tab. 1). A similar limitation holds for the moving end effector of the wire robot which is the ship model to be moved. Since a wire robot is used and a cuboid platform has to be moved within a cuboid frame on symmetrical paths, an intuitive decision in the topological design step is to use eight wires. Two different design concepts are developed and evaluated in the

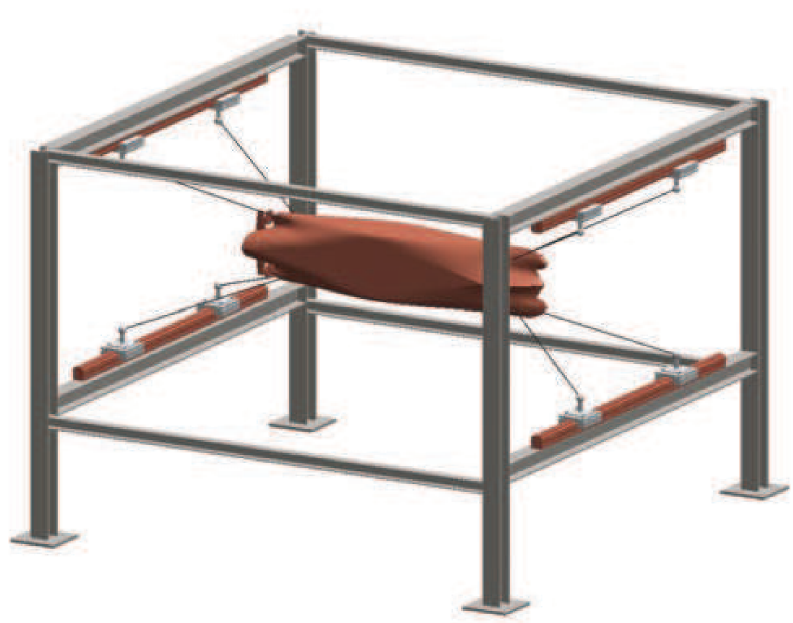

Fig. 1. Principle of application

following sections:

- The first approach uses a **rail-based system** with wires of constant length. The configuration of this mechanism is shown in Fig. 1. The wires are used as links of constant length, driven by a skid-rail system. Although each two skids share a common rail, every skid is separately operated by a DC motor via a drive belt. This equates to a linear drive. Linear drives for wire robots were introduced by Merlet (Merlet, 2008) who proposed this concept due to its enormous dynamic potential when coupled with pulley blocks. Application examples of the MARIONET robot can be found in Merlet (2010).
- The second concept – called **winch-based system** in the following – is based on classical wire robot approach using motorized winches. This principle used e.g. at the SEGESTA prototype of the University Duisburg-Essen in Duisburg, Germany (Fang, 2005), or at the IPANEMA prototypes of the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart, Germany (Pott et al., 2009; 2010).

In the following, both design approaches are compared to each other using mathematical models and simulation environments. This allows to evaluate the performance of the designs at a virtual stage and eliminates the need for expensive real prototypes.

3.1 Kinematical and dynamical modeling of the rail-based system

3.1.1 Kinematics

As a base for referencing all fixed points, an inertial frame $\mathbf{B}$ is introduced which may be located at an arbitrary point (see Fig. 2). Note, that it makes sense to choose a point which can be easily found on the real system, e.g. for the positioning of the deflection units or rails.
A similar approach is used for the definition of points which are attached to the end effector, i.e. which are measured with respect to the moving ship model. Therefore, a frame $\mathbf{P}$ is introduced.
Now the relation – or, in terms of kinematical analysis – the kinematical transformation between the coordinate systems $\mathbf{B}$ and $\mathbf{P}$ can be described: The vector $\mathbf{r}_p$ defines the position of $\mathbf{P}$ with respect to the inertial frame. The orientation of the end effector with respect to the inertial system is described by "roll-pitch-yaw" angles which are very common in nautical research. The local rotation around the x-axis is given by angle ψ, around the y-axis by angle θ and around the z-axis by angle φ. The end effector pose is therefore described by $\mathbf{X} = \begin{bmatrix} x \; y \; z \; \psi \; \theta \; \varphi \end{bmatrix}^T$. To represent the rotation between $\mathbf{B}$ and $\mathbf{P}$, the rotation matrix $\mathbf{R}$ is introduced.
This simple kinematic foundation can already be used to calculate the inverse kinematics which allows to compute the required linear drive positions for a predefined end effector pose (Sturm et al., 2011). Note, that this description is purely kinematic – thus, elastic effects which may have a major influence in wire robots are not taken into account. As for most parallel kinematic machines, the inverse kinematics calculation is simple. Given an end effector pose $\mathbf{X}$, the inverse kinematics for each driving unit of this robot can be calculated by an intersection between a sphere – representing the wire – and a straight line (see Fig. 2) which represents the rail. The sphere is described by

$$(\mathbf{b}_i - \mathbf{r}_{c_i})^2 - l_i^2 = 0, \quad 1 \leq i \leq 8, \tag{1}$$

where the vector $\mathbf{b}_i$ denotes the current position of the i^{th} skid and l_i is the constant length of the i^{th} wire. Now

$${}^B\mathbf{r}_{c_i} = {}^B\mathbf{r}_p + \mathbf{R}\,{}^P\mathbf{p}_i \tag{2}$$

describes the position of the i^{th} wire connection point $\mathbf{p}_i$ on the end effector, referred in the inertial frame $\mathbf{B}$.
The line can be described by

$$\mathbf{b}_i = \mathbf{r}_{S_i} + q_i \mathbf{n}_{R_i}, \quad 1 \leq i \leq 8 \tag{3}$$

where $\mathbf{r}_{S_i}$ is a known point on the i^{th} fixed rail axis, q_i the actuator degree of freedom – i.e. translation along the rail – and $\mathbf{n}_{R_i}$ a unit vector in direction of the length of the rail. In case of the proposed robot, $\mathbf{n}_{R_i}$ is equal to $\mathbf{e}_y$ for $i = 1 \leq i \leq 8$. The substitution of equation (1) into equation (3) leads to the equation

$$q_i = -\mathbf{c}_i \mathbf{n}_{R_i} \pm \sqrt{(\mathbf{c}_i \mathbf{n}_{R_i})^2 - \mathbf{c}_i^2 + l_i^2}, \tag{4}$$

where $\mathbf{c}_i = \mathbf{r}_{S_i} - \mathbf{r}_{c_i}$. Analytically, there exist two possible solutions for each actuator due to the quadratic equations. On the other hand, from a technical point of view, there are two skids per rail that cannot intersect each other. Thus, it is easy to derive a unique solution. In the case of the wire robot under consideration, it is assumed that the equation

$$q_i = -\mathbf{c}_i \mathbf{n}_{Ri} + (-1)^i \sqrt{(\mathbf{c}_i \mathbf{n}_{Ri})^2 - \mathbf{c}_i^2 + l_i^2} \tag{5}$$

shall hold for the actuator i. As already mentioned, these considerations only describe the

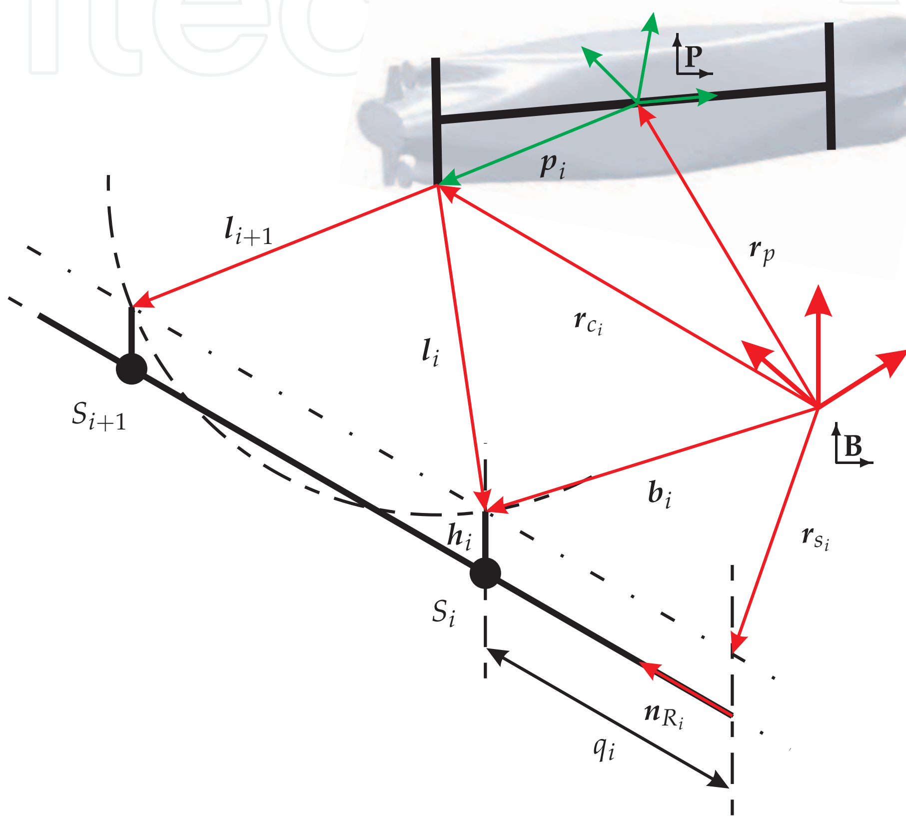

Fig. 2. Kinematic model

motion of the system without the influences of forces or torques. Therefore, also elastic effects are not covered by this model. Additionally, it is not possible to derive information regarding the required drive performance. The base for these calculations is the introduction of a dynamic model in the next section, describing the behaviour of the system under the influence of loads, forces and torques.

3.1.2 Dynamics

The dynamical equations of motion of the end effector can be described by

$$\underbrace{\underbrace{\begin{bmatrix} m_p\mathbf{E} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}}_{\mathbf{M}_p} \underbrace{\begin{bmatrix} \ddot{\mathbf{r}} \\ \dot{\omega} \end{bmatrix}}_{\ddot{\mathbf{x}}} + \underbrace{\begin{bmatrix} \mathbf{0} \\ \omega \times (\mathbf{I}\omega) \end{bmatrix}}_{\mathbf{g}_C} - \underbrace{\begin{bmatrix} \mathbf{f}_E \\ \tau_E \end{bmatrix}}_{\mathbf{g}_E}}_{-\mathbf{w}} = \mathbf{A}^T\mathbf{f} \tag{6}$$

with

$\mathbf{M}_p$	mass matrix of end effector,
$\mathbf{g}_C$	cartesian space vector of coriolis and centrifugal forces and torques,
$\mathbf{g}_E$	vector of generalized applied forces and torques.

Here $\mathbf{A}^T$ denotes the so-called structure matrix. This matrix describes the influence of the wire forces $\mathbf{f}$ acting onto the end effector (Ming & Higuchi, 1994a; Verhoeven, 2004).
The structure matrix can be derived by

$$\begin{bmatrix} \mathbf{v}_1 & \dots & \mathbf{v}_m \\ \mathbf{p}_1 \times \mathbf{v}_1 & \dots & \mathbf{p}_m \times \mathbf{v}_m \end{bmatrix} \begin{bmatrix} f_1 \\ \vdots \\ f_m \end{bmatrix} = \mathbf{A}^T \mathbf{f} = -\mathbf{w}, \tag{7}$$

where $\mathbf{l}_i = l_i \mathbf{v}_i$, i.e. $\mathbf{v}_i$ is the unit vector along the wires.
As already introduced in section 2, a wire robot has a redundant structure. Thus, for a body – in this case, the ship model – that moves freely in three translational and three rotational degrees of freedom at least seven wires are required. Due to symmetry and architectural considerations, in this application eight wires are applied. Accordingly, the robot is even twofold redundant.
This is also reflected by the structure matrix $\mathbf{A}^T$ which is element of $\mathbb{R}^{6\times 8}$. Accordingly, eq. 7 represents an under-determined system of linear equations. Therefore, the calculation of the wire force distribution is not straightforward and rather complicated. On the other hand, this offers a potential for optimizations. Considering that in this application fast motions of the heavy-weight end effector are desired, it is reasonable to reduce the motor power consumption and the applied load on the mechanical components.
Additionally, the unilateral properties of the wires have to be taken into account as introduced in section 2: On the one hand, wires have a limited breaking load, on the other hand, the wires need a defined minimum tension to avoid slackness.
Accordingly, the force distribution $\mathbf{f}$ can be formulated as a constrained nonlinear optimization problem (Bruckmann, Mikelsons, Brandt, Hiller & Schramm, 2008a) with

$$\begin{aligned} & minimize \, \|\mathbf{f}\|_2 = \sqrt[2]{\sum_{i=1}^{m} f_i^2} \\ & s.t. \quad \mathbf{f}_{min} \leq \mathbf{f} \leq \mathbf{f}_{max} \quad \wedge \quad \mathbf{A}^T \mathbf{f} + \mathbf{w} = \mathbf{0}. \end{aligned} \tag{8}$$

In this paper the function *lsqlin* from the `MATLAB`® `Optimization Toolbox`® has been used to solve the problem. Note, that this implementation cannot be used for realtime control since the worst-case run-time in each control cycle cannot be guaranteed a priori. Several approaches are known to handle this problem (Borgstrom et al., 2009; Bruckmann, Mikelsons, Brandt, Hiller & Schramm, 2008a;b; Bruckmann et al., 2007b; Bruckmann, Pott, Franitza & Hiller, 2006; Bruckmann, Pott & Hiller, 2006; Ebert-Uphoff & Voglewede, 2004; Fattah & Agrawal, 2005; Oh & Agrawal, 2005; Verhoeven, 2004). In this application, a force minimizing algorithm for realtime force distribution will be implemented, using a geometric approach (Bruckmann, 2010; Bruckmann et al., 2009; Mikelsons et al., 2008).
Each wire is driven by a combination of a skid and a DC motor. The dynamics of the skid subsystems can be modeled as

$$\mathbf{M}_s \ddot{\mathbf{q}} + \mathbf{D}_s \dot{\mathbf{q}} + \mathbf{f}_y = \mathbf{f}_s \tag{9}$$

with
$\mathbf{M}_s$ mass matrix of the skids
$\mathbf{D}_s$ diagonal matrix of coulomb friction between skids and rails,
$\mathbf{f}_y$ vector of wire force component in direction of skid movement
$\mathbf{f}_s$ skid driving force vector.

Motor and skid are connected by a gear belt, providing a linear drive. The elasticity of these belts – as well as the elasticity of the wires as already mentioned – are not taken into account. The dynamical equations of the DC motors can be described by

$$\mathbf{M}_m\ddot{\Theta} + \mathbf{D}_m\dot{\Theta} + \eta\mathbf{f}_s = \mathbf{u} \tag{10}$$

with
$\mathbf{M}_m$ inertia matrix of the drive units including crown gear and motor,
$\mathbf{D}_m$ diagonal matrix of coulomb friction at the crown gear bearing,
η radius of the crown gear,
Θ vector of motor shaft angles,
$\mathbf{u}$ electromechanical driving torque vector.

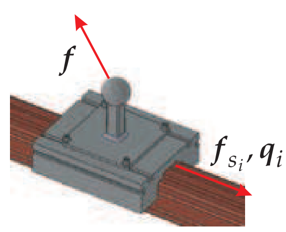

Fig. 3. Skid dynamics

3.2 Kinematical and dynamical modeling of the winch-based system

3.2.1 Kinematics

Wire driven parallel kinematic systems that use winches instead of rails are well studied as introduced in section 2. Therefore, only a very short description of the kinematics and dynamics is given here. The end effector properties are considered to be identical for both systems. By the use of fixed eyelets as exit points for the wires, the inverse kinematics approach can be calculated by

$$l_{w_i} = \|\mathbf{b}_{w_i} - \mathbf{r}_{c_i}\|_2\,, \quad i = 1 \leq i \leq 8. \tag{11}$$

In this case the vector $\mathbf{b}_{w_i}$ denotes the fixed position of the exit point of the i^{th} wire, while equation (2) is used for the transformation of the vectors $\mathbf{p}_i$ into the inertial coordinate system. Here, l_{w_i} describes the current length of the i^{th} wire.

3.2.2 Dynamics

The end effector dynamics, the structure matrix $\mathbf{A}^T$ and the minimum force distribution are calculated in the same way as presented in section 3.1.2. The significant difference between the rail-based and the winch-based system lies in the actuator dynamics. The winch dynamics including the motor can be modeled as

$$\mathbf{J}_w\ddot{\Theta}_w + \mathbf{D}_w\dot{\Theta}_w + \mu\mathbf{f}_t = \mathbf{u}_w \tag{12}$$

with

$\mathbf{J}_w$	inertia matrix of the drive units including winch and motor,
$\mathbf{D}_w$	diagonal matrix of coulomb friction at the winch bearing,
$\mathbf{f}_t$	vector of wire forces,
μ	radius of the winch,
Θ_w	vector of motor shaft angles,
$\mathbf{u}_w$	electromechanical driving torque vector.

3.3 Comparison of rail- and winch-based system

The concepts described in section 3 are both capable to move the ship model within the wind tunnel, but based on the different actuation principles, relevant differences in terms of

- workspace volume,
- peak forces in the wires and
- required peak motor power

are expected. Based on the introduced models, virtual prototypes within a `MATLAB/Simulink`® simulation environment can be derived and investigated and their suitability for the application addressed here can be evaluated.

First, preliminary design parameters have to be set. In Tab. 1, a review of the dimensions of the testbed as well as of the ship models to be moved is given. Some of the further assumptions are specific to the proposed designs:

- For the winch-based system the eyelets are considered to be attached at the corners of a cube.
- For the rail-based system, the rails are considered to be mounted at the front and back side of the cube (see Fig. 1). During the design phase, a length of $l = 1.8$m for each wire has been empirically determined.

	testbed	model
length [m]	5.25	3.2
width [m]	3.7	0.5
height [m]	2.4	0.5
mass [kg]	–	100

Table 1. Robot parameters

In order to compare and evaluate the two design concepts, two criteria were specified from the user's point of view as introduced in section 3:

- The achievable workspace under a predefined orientation range should be as large as possible. This allows a wide range of paths. To compute the workspace volume, the cuboid volume of the test bed has been discretized along the three translational degrees of freedom by 100 grid points in each direction. Each point in this volume has been examined to ensure the desired orientation capabilities for the end effector at each grid point. Therefore, orientations of $\psi = \pm 30°$, $\theta = \pm 5°$ and $\varphi = \pm 5°$ have been defined.
- Additionally, the peak power consumption of each motor is of interest (Sturm et al., 2011). Especially the required peak power per drive has a major influence on the costs of the overall system since the motors and winches must be designed to provide this mechanical

peak power. For the power consumption analysis a reference trajectory according to Fig. 4 has been defined: The end effector performs a translational ascending and descending movement with a frequency of 0.5Hz combined with an oscillating rotation of 2.5Hz around the body-fixed x-axis. This trajectory is typical for the maneuvres to be tested in the application example.

The minimum wire force distribution was calculated according to Eq. 8. The wire force boundaries were set to $100N \leq f_i \leq 2000N$. In Fig. 5 and Fig. 6 the power consumptions

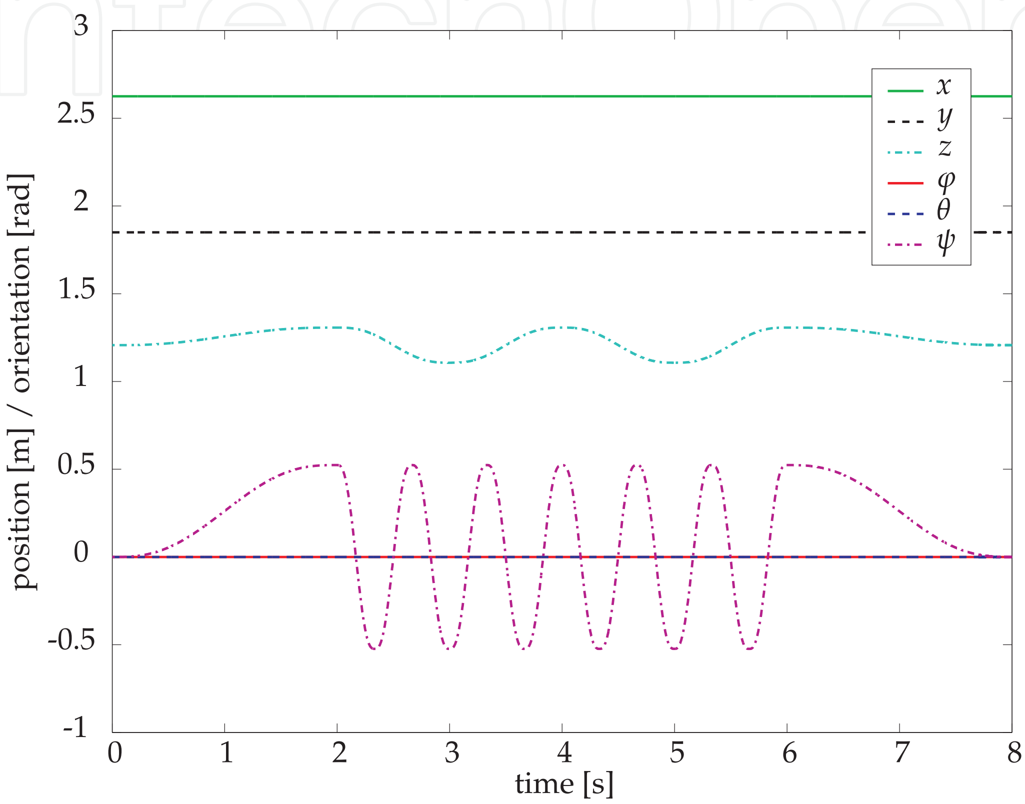

Fig. 4. Time History of the Reference Trajectory

of both the systems are shown. It is obvious that the required peak actuator power of the winch-based system is about four times higher than that of the rail-based system. This disadvantageous distribution of the required mechanical power demands for very powerful and expensive drives which should be avoided. In Fig. 7 the workspace of the winch-based system is shown. The blue colored dots define the positions of the wire deflection points. In Fig. 8 the workspace with identical properties of the rail-based system is shown. Here the four blue colored bars define the positions of the rails. Obviously, the rail-based system has a workspace which is remarkably smaller than the winch-based approach has. Nevertheless, the rail-based concept provides an acceptable volume ratio of the testbed cuboid. According to the lesser power requirements the rail-based design concept has been chosen for the realization of the wind tunnel suspension system.

3.4 Further optimization potential

In the last sections, the approach of using wires of constant length was chosen for realization. Thus, one of the most outstanding properties of wires – the variable length – is not exploited and a conventional parallel kinematic machine of type *PRR* (Merlet, 2006) should be

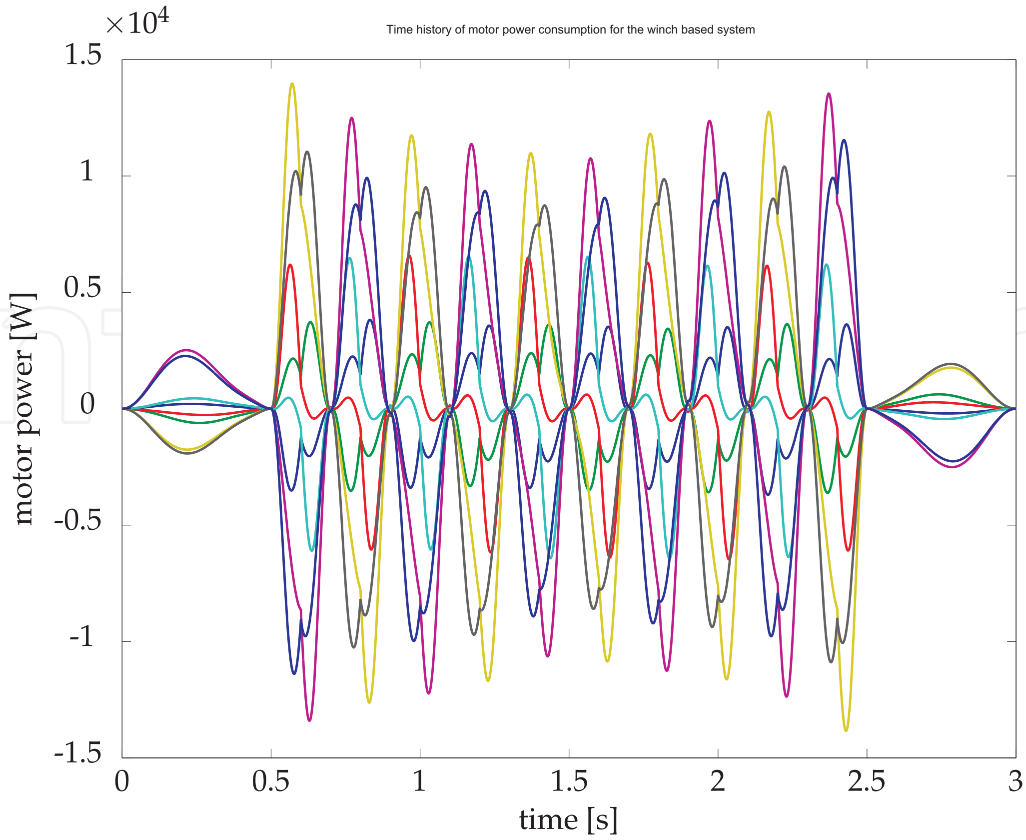

Fig. 5. Time history of the motor power consumption of the winch-based system

applicable. On the other hand, conventional parallel kinematics use very stiff and therefore massive components for legs, drives and joints to withstand both tensile and compressive forces which causes massive turbulences within the air flow. Nevertheless, applying again a redundant structure allows to control the inner tension of the system. This can be very useful as it allows to set the forces which the favorably thin links and joints have to withstand. For thin links, the Euler's second buckling mode should be avoided as the following example shows (Bruckmann, 2010; Bruckmann et al., 2010):
It is assumed that the links are realized using Rankine (Ashley & Landahl, 1985) profiles which are similar to ellipses. The ratio of the length L_A and the width L_B of the ellipse should be a compromise between a high geometrical moment of inertia I and an optimal aerodynamical shape. In this example, it is set to

$$\frac{L_A}{L_B} = 4 \tag{13}$$

The collapse load F_K for a buckling length s, a modulus of elasticity E and a geometrical moment of inertia I is defined as

$$F_K = \pi^2 \frac{EI}{ks^2}, \tag{14}$$

where Euler's second buckling mode – i.e. both ends of the link are hinged – defines $k = 1$.
Assuming that modern fiber material can be applied to realize the links, the lightweight, but very tensile carbon fiber reinforced plastic (CFRP) is chosen. The properties of CFRP are listed in Tab. 2.

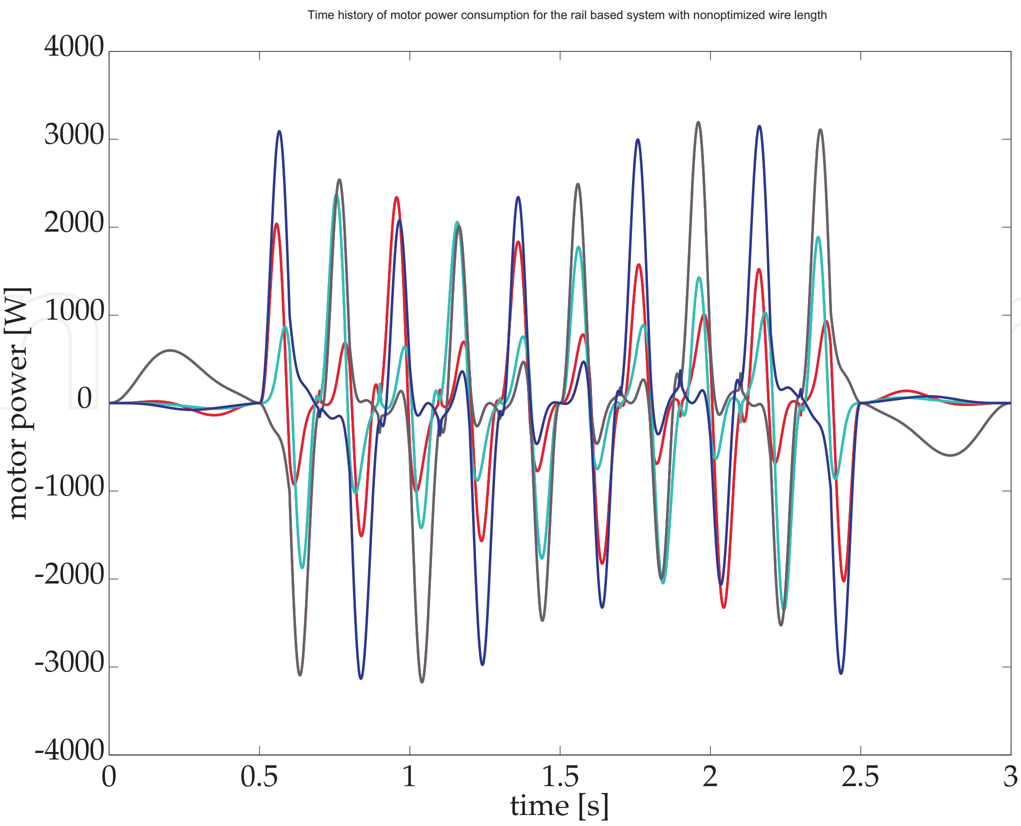

Fig. 6. Time history of the motor power consumption of the rail-based system

fiber material	carbon fiber HT
matrix	epoxy polymer
fiber volume percentage	60%
tensile strength (in direction of fibers) $R_{\parallel}^{+}$	$2000\mathrm{N/mm}^2$
modulus of elasticity $E_{\parallel}$	$140000\mathrm{N/mm}^2$

Table 2. Material properties of the carbon fiber reinforced plastic (CFRP)

The ellipsoid and solid link profile choosing $L_A = 40$mm and $L_B = 10$mm has a length of $l = 2500$mm. Thus, the smaller geometrical moment of inertia is

$$I_A = \frac{\pi}{4} L_A L_B^3 = 31415.92\mathrm{mm}^4. \tag{15}$$

Using the buckling lengh $s = l = 2500$ mm and the CFRP proposed,

$$F_K = \pi^2 \frac{E_{\parallel} I_A}{l^2} = 6945.40\mathrm{N} \tag{16}$$

holds. Contrarily, a collapse of the link due to pure compressive forces can be computed, using a tensile strength R and a cross section of the ellipsoid profile A as

$$F_Z = RA. \tag{17}$$

This results in

$$F_Z = R_{\parallel}^{+} \frac{\pi L_A L_B}{4} = 2513274.12\mathrm{N}. \tag{18}$$

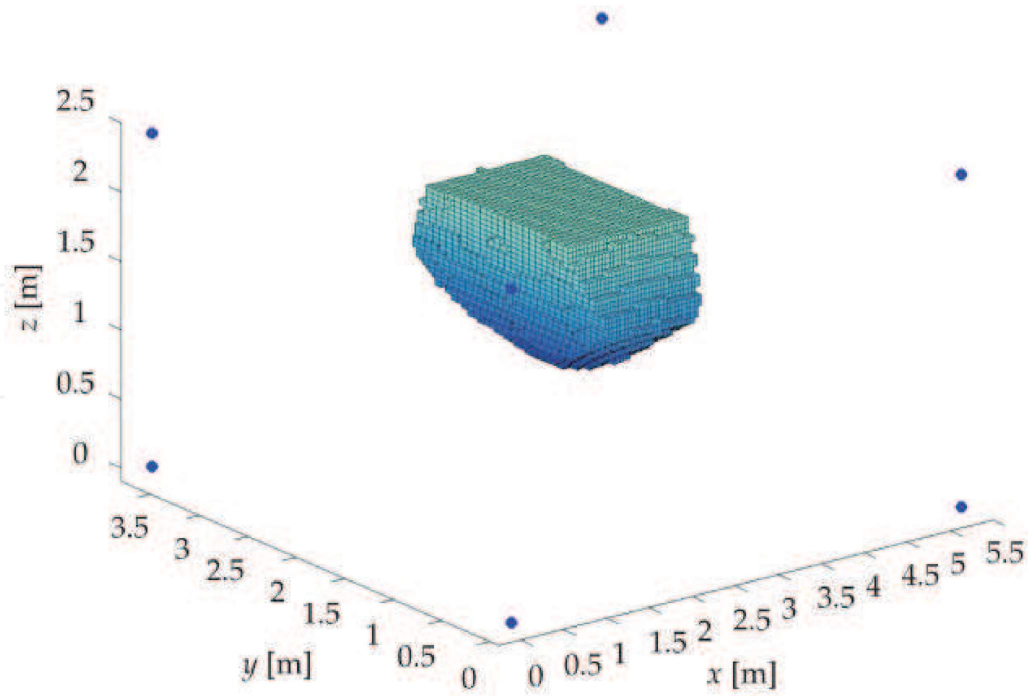

Fig. 7. Workspace of the winch-based system

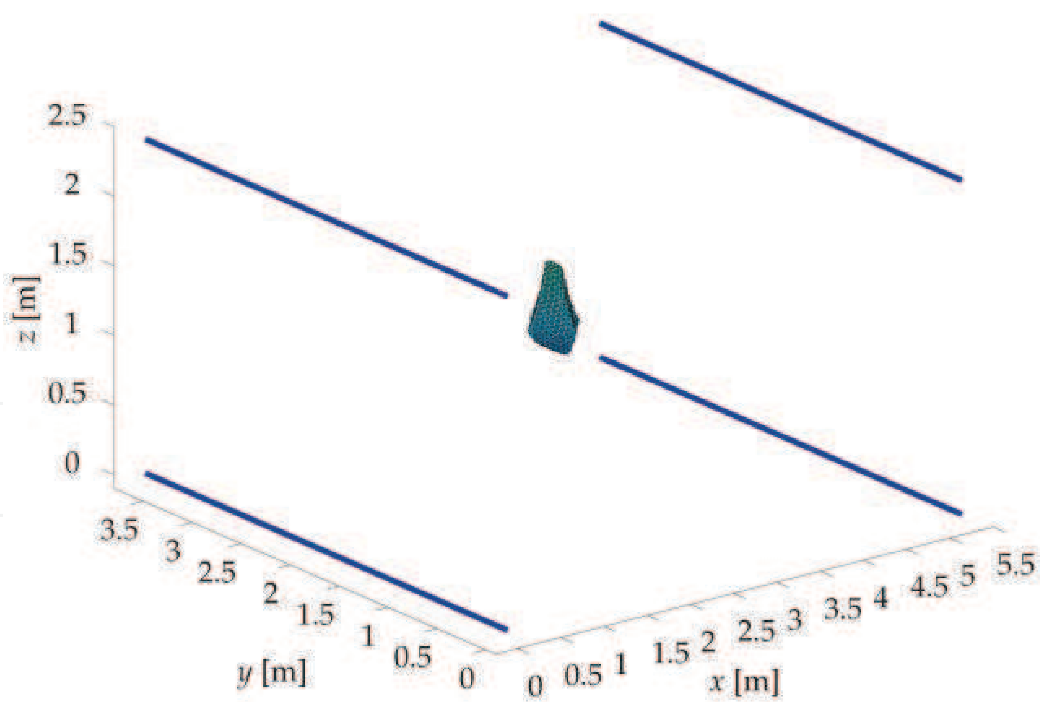

Fig. 8. Workspace of the rail-based system with $l_i = 1.8m$

The huge ratio of $F_Z/F_K \approx 360$ shows the potential of a tensile system. Now the application of solid links of constant length also offers the possibility to transfer small (!) and controlled

compressive forces using a force control system: While in the case of using wires of constant length the required positive tension in the lower links increases the tension in the upper links, this need vanishes for links made of solid material. Additionally, high tensions in the upper links coincide with high velocities in the respective drives. Therefore, high power peaks occur during the benchmark trajectories. At the same time some of the lower drives run at comparably low velocities while their links have advantageous angles of attack regarding the load compensation. These advantageous angles of attack could be used to support the upper links very effectively (Bruckmann et al., 2010).
These considerations are subject to current research. For the time being, they are not applied in the project described here.

4. Optimization of wire lengths

For the rail-based approach, the position and the length of the rails are fixed parameters due to the limited available architectural space within the wind tunnel test facility. Nevertheless, the concept uses wires as links of constant length. This fixed length can be set during the experiment design phase, considering that the wire length has an influence onto the peak forces in the wires on a predefined trajectory.
The robot can be subject to two different optimizations which resemble the requirements during the topological design phase:

- The first criterion is a maximum available workspace with predefined orientation ranges. This is investigated in section 4.1.
- The second criterion is to minimize the maximum motor power required along a predefined trajectory in order to reduce the required actuator peak power. This is analyzed in section 4.2.

Therefore, two different optimization routines are employed and their results are discussed.

4.1 Workspace criterion

Analyzing the application-specific requirements, the rotational degrees-of-freedom of the end effector are of much more interest than the translational ones. This is due to the fact that the trajectory to be performed may be located at an arbitrary domain of the workspace as long as the model stays within the parallel inflow.
Due to this aspect, the workspace has to provide possible rotations of $\psi = \pm 30°$, $\theta = \pm 5°$ and $\varphi = \pm 5°$ in a volume as large as possible as already introduced in section 3.3. Again, the basic discretization approach for this optimization routine is applied and at each point, the kinematical constraints (e.g. the prismatic joint limits) and force limits are checked. Accordingly, a minimum force distribution for predefined loads onto the end effector is calculated for each grid point and platform orientation in order to ensure that the wire forces are within the limits. The optimization algorithm was implemented in MATLAB®, employing a combination of an evolutionary and a gradient-based approach. Discretization approaches are also proposed in Hay & Snyman (2004; 2005).
Advanced approaches base on the continuous analysis and verification of the workspace as described in Bruckmann et al. (2007a); Gouttefarde et al. (2011; 2008; 2007). The application of those methods is subject to future work.
The task of optimizing can be formulated as follows: Let $A = \{a_i\}$ define the set of the discretized points and $g : A \mapsto \mathcal{R}; \mathbf{l} \mapsto n$ the function that maps a set of wire lengths onto a natural number n, where n is the number of points $a_i \in A$ that lie in the desired workspace.

Then the optimization task is to maximize the function g. Fig. 8 shows the workspace of the proposed robot with an identical length of $l = 1.8m$ for each wire. Fig. 9 shows the workspace after the optimization process. The results for the optimized wire length are listed in Tab. 3.

	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
length [m]	1.80	1.80	1.83	1.83	1.60	1.60	1.66	1.66

Table 3. Wire lengths for maximum workspace volume

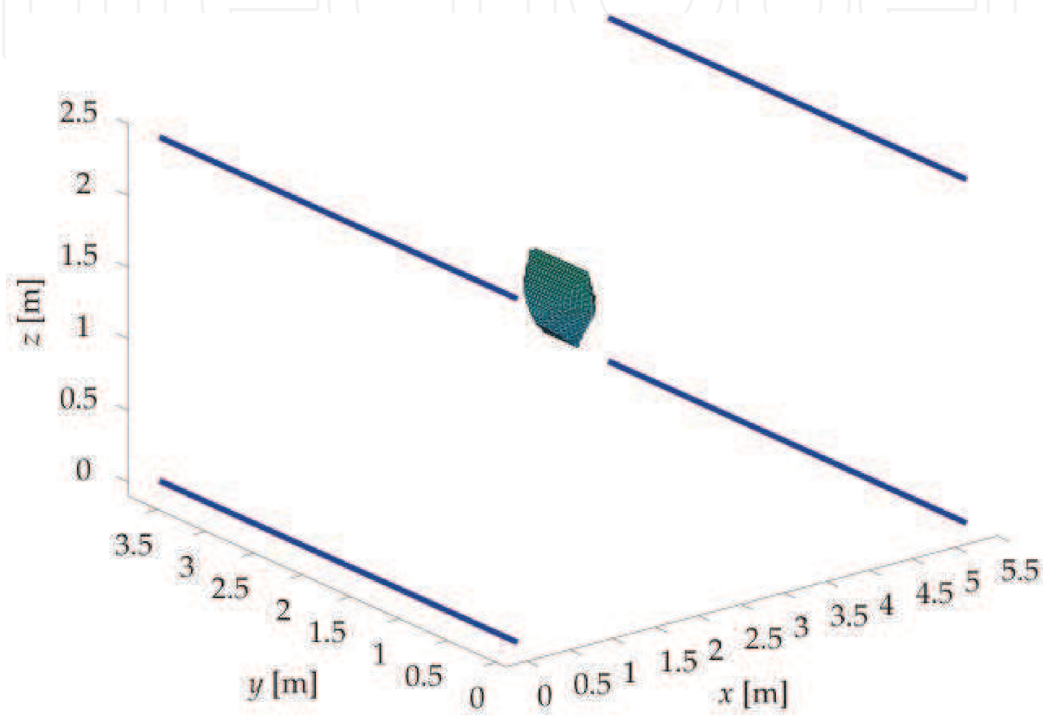

Fig. 9. Workspace using optimized wire lengths

By the comparison of the workspace calculations of both approaches it is clear that the optimization process led to an increased reachable workspace by 136% that has been therefore more than doubled.

4.2 Drive power criterion

The second optimization approach attempts to minimize the peak power consumption of the drives for a given trajectory. It is clear that in upper regions of the workspace, the angles of attack of the wires become very disadvantageous which leads to high wire forces. An additional effect is that with these disadvantageous angles also that part of the reaction forces increases which is exerted onto the skids. Since this is related to the wire length, the goal is to find an optimized length that leads to a minimum peak power consumption of the motors for a given trajectory. Again this analysis was performed based on a discrete sampling of the trajectory. Advanced continuous approaches are known (Bruckmann, Mikelsons & Hiller, 2008; Merlet, 1994b) and subject to future work.

According to this goal the optimization task can be formulated as follows: Let b define a real scalar that represents maximum power per motor along a given trajectory. Let $h : \mathbf{l} \mapsto b$ be the

function that maps a set of wire lengths onto that real number b. Then the optimization task is to minimize the function h.
Again, the reference trajectory shown in Fig. 4 has been used. The results of the wire length for an optimized power consumption are listed in Tab. 4.

	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8
length [m]	2.00	2.00	2.00	2.00	1.83	1.70	1.81	1.70

Table 4. Wire lengths for minimum power consumption

Note the reduced peak power consumption shown in Fig. 10. By using the optimized wire lengths a peak power reduction from 3194kW (compare Fig. 6) to 3061kW could be achieved. Concluding these results, the system has to be adapted to different requirements since the

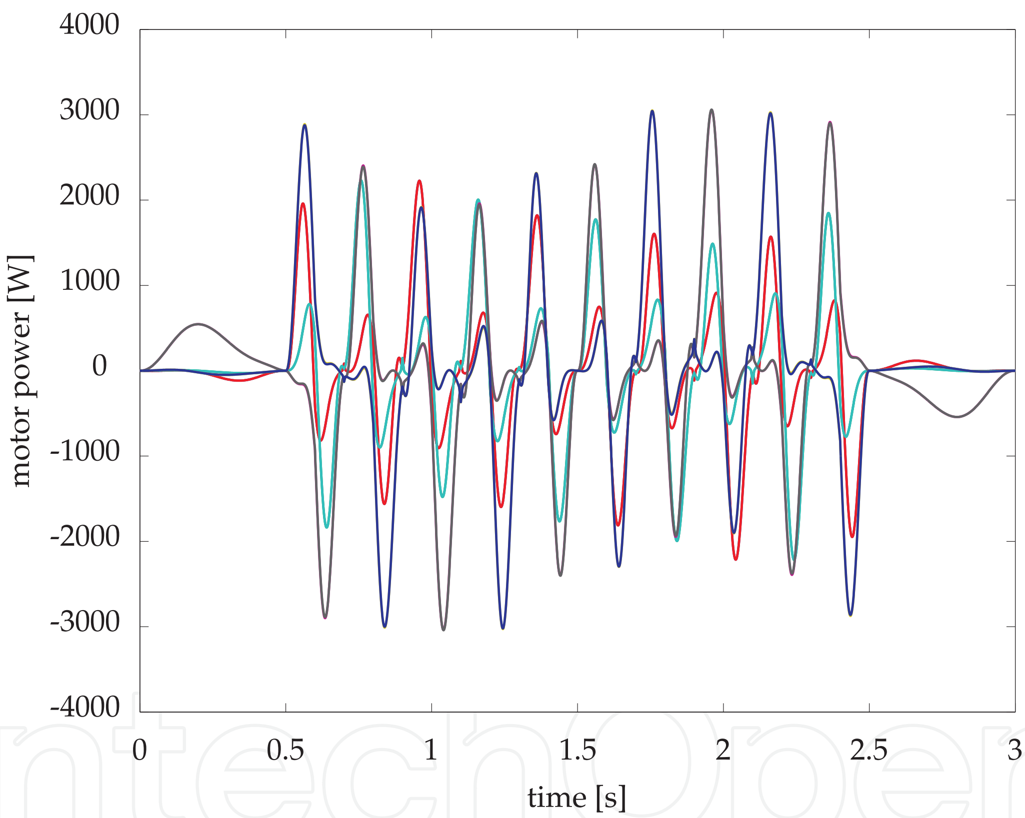

Fig. 10. Motor power consumption over time with optimized wire lengths

optimized parameters differ considerably. It depends on the specific experiment if workspace or drive power are critically, but using exchangeable wires, the adaption of the system to defined trajectories is easy and can be done quickly.

5. Mechatronic system design

Besides the geometrical design problem, the question of components, interfaces and control system architecture had to be solved. To guarantee a maximum flexibility, a modular controller system by dSPACE GmbH (Paderborn/Germany) was chosen for the hardware realization (Fig. 11):

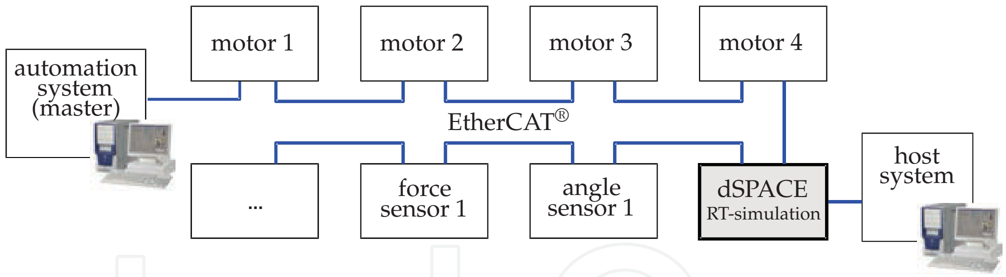

Fig. 11. EtherCAT® communication system

- **Control System:** The dSPACE DS1006 (Quadcore AMD Opteron Board, 2.8 GHz) is the CPU of the modular dSPACE hardware. This system can be programmed using `MATLAB/Simulink`® and is a very powerful base for data aquisition and numerically extensive computations.
- **Communication System:** A number of values has to be measured. This includes skid positions, wire forces and the state of safety systems. Due to the overall size of the wind tunnel suspension system, the distances between the different components are comparably far. As a consequence, the Ethernet-based field bus system EtherCAT® was chosen for communication. It combines robustness against electromagnetic disturbances, integrated error diagnosis and a broad bandwidth of 100MBit/s. This allows to completely process all communication (i.e. sensor values, motor commands) via one single bus system.
- **Sensors:** During testing, the skid positions and the tendon forces are monitored. All sensors have interfaces to the EtherCAT® bus.
- **Skid-Rail System:** The skids are driven by DC motors manufactured by SEW Eurodrive (Bruchsal, Germany). These motors use smart power amplifiers and can be commanded by desired torque, velocity or position. Also those power amplifiers are connected to the EtherCAT® bus which allows easy and reliable commanding and monitoring.

6. Conclusions

In this paper, the application of a wire robot as a wind tunnel suspension system is described. Starting with an overview of the state of the art, topological variants are described. The decision for the optimal system was based on a modeling and simulation approach which allowed to study different systems by using virtual prototypes. Additionally, the usage of solid links in a redundant structure was discussed. The chosen architecture was optimized for the application by using numerical approaches. The optimization goal was to achieve either a large workspace or a low peak motor power to limit the costs for the mechanical components and especially the motors.
Finally, a short overview of the mechatronic system design is given. Presently, the system is installed and prepared for first test runs.

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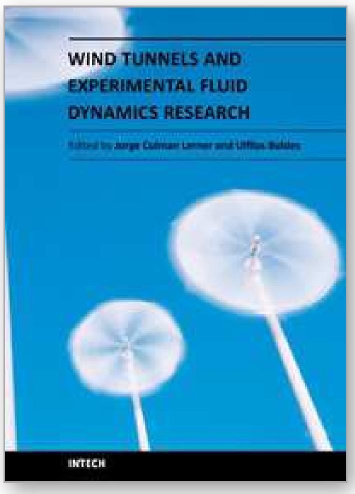

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The book â€œWind Tunnels and Experimental Fluid Dynamics Researchâ€ is comprised of 33 chapters divided in five sections. The first 12 chapters discuss wind tunnel facilities and experiments in incompressible flow, while the next seven chapters deal with building dynamics, flow control and fluid mechanics. Third section of the book is dedicated to chapters discussing aerodynamic field measurements and real full scale analysis (chapters 20-22). Chapters in the last two sections deal with turbulent structure analysis (chapters 23-25) and wind tunnels in compressible flow (chapters 26-33). Contributions from a large number of international experts make this publication a highly valuable resource in wind tunnels and fluid dynamics field of research.

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