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MULTI-LEVEL CABLE MECHANISMS WITH ADDED ACTIVE STRUCTURES

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Abstract: *The multi-level mechanisms including superimposed active structures can significantly improve the positioning accuracy and operational speed of the end-effectors with respect to pure cable-driven parallel mechanisms. The objective of the paper is description of the current state of the ongoing research project concerning complex research of active structures superimposed to cable-driven mechanisms. Different possible architectures of active structures have been investigated by simulation as well as by preliminary experiments on primary demonstrator. The complex simulation model has been prepared using identified dynamical models.*

Keywords: Multi-level mechanism, superimposed active structure, parallel mechanism, cable-driven mechanism, hierarchical motion control.

1. Introduction

Parallel kinematic mechanisms (PKM) proved their supremacy over serial structures in many mechanical parameters including dynamics and stiffness. On the other hand the ratio between the effective workspace and installation space is usually worse. The cable-driven variants of the PKM have the further advantages, namely the light-weight, large range of motion, possibility of anti-backlash property (Valášek & Karásek, 2009) and easy reconfiguration. Their application area ranges from the cargo handling (Patel & George, 2012) and astronomic applications (Zi, et al., 2011), (Meunier, et al., 2009) to humanoid-arm manipulators (Chen, et al., 2013) and snakelike manipulators (Taherifar, et al., 2013). The typical disadvantages of the cable-driven PKM are the relatively narrow frequency bandwidth of their feedback motion control and the problems with the accurate positioning of the end-effector. In (Merlet, 2015) it is stated that the over-constrained 6 DOF cable-driven parallel manipulator is always in configuration where at most 6 cables are under tension. The reason is that the cable coiling mechanism is SISO system and therefore it is not possible to control both cable length and tension simultaneously and hence the redundant cables become slack. The second reason should be that discrete time controllers are not capable to ensure the precise cable length with all cables under tension at all time (Merlet, 2014). However the results of our experiments show, that this opinion is problematic. The promising research direction for solution of weaknesses of cable-driven mechanisms comes from the concept of multi-level mechanisms with the hierarchical structure composed from the parallel cable-driven mechanism for large and slow motions and the active structure for the small and high frequency motions (Duan, et al., 2011).

Consequently the ongoing research project „Multi-Level Light Mechanisms with Active Structures“ has the following objectives: 1) To investigate possible architectures of the active structures superimposed to the end-effectors of cable-driven parallel mechanisms. 2) To investigate influence of vibrational phenomenas of the cable manipulated end-effector to the control strategies and their stability. 3) To investigate different possible strategies of the control of active structures in order to improve end-effector positioning accuracy. Some topics of the first year of project solution are described within the presented paper.

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2. Variants of active structures superimposed to end-effectors of cable-driven mechanisms

The important part of the research is the investigation of possible types of multi-level mechanisms. The recently developed cable-driven parallel mechanisms with high tilting capability are the main light structures taken into consideration. The cable-driven parallel manipulators can be classified with respect to different characteristics, namely the number of DOF (spatial, spherical, planar), the mounting of cables (cables) with respect to gravity (suspended, general) and some others (Beneš, et al., 2015). As the range of the active structure motion is small, the kinematic analysis in terms of the reachable workspace, the dexterity and possible collisions within the workspace is focused especially on the cable-driven part of mechanism. The main limitation that must be respected is that cables are either under tension or slack. We cannot exert the pushing force by cables. The total stiffness of the system is influenced by the type of applied control. The mixed position-tension control enables the tension in redundant number of cables in spite of statements in (Merlet, 2014) and (Merlet, 2015). The most general variant of the cable-driven and consequently the multi-level mechanisms is the system with 6 DOF positioned platform (Svatoš, et al., 2015). The typical example with 6 DOFs and 8 driven cables is in Fig. 1. This structure was the target of optimization. Besides the 6 DOF cable-driven structures, also the newly rebuilt 3 DOF cable-driven tilting mechanisms (Fig. 2.) developed within the project „Tilting Mechanisms Based on Cable Parallel Kinematical Structure with Antibacklash Control" (Procházka, et al., 2016), (Skopec, et al., 2015) are considered as the base for the multi-level mechanisms. The current project follows the results of the previous project in order to widening the servo control bandwidth and consequently to improve feedback position control of cable-driven mechanisms by the superimposed active structures.

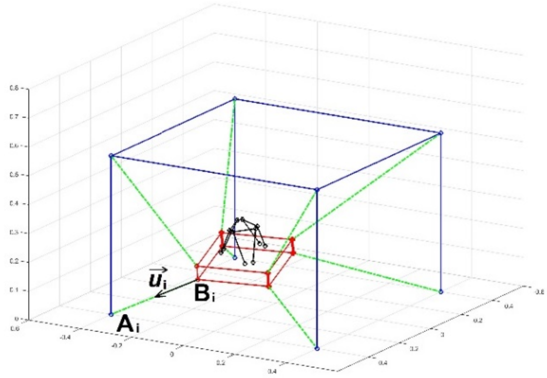


Fig. 1: Over-constrained multi-level mechanism with 6 DOF.

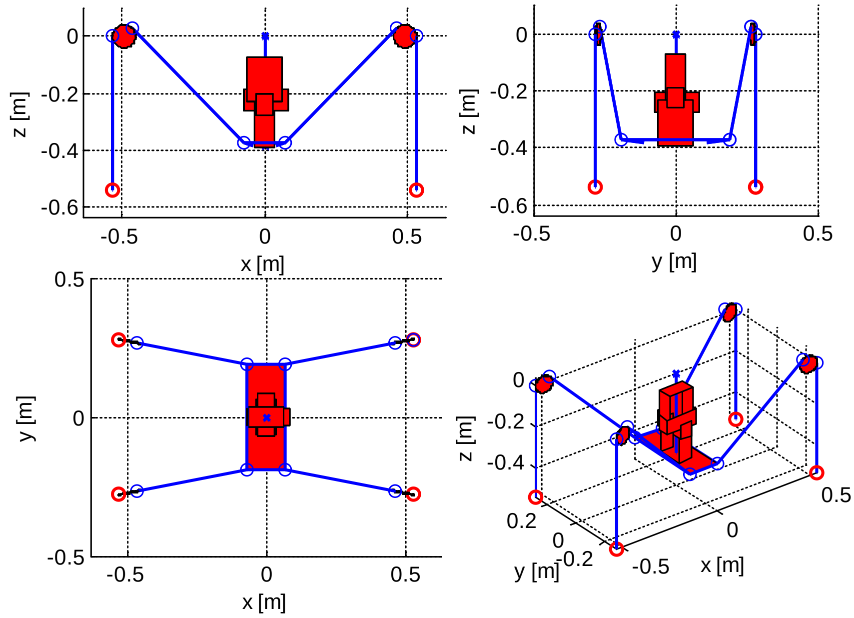
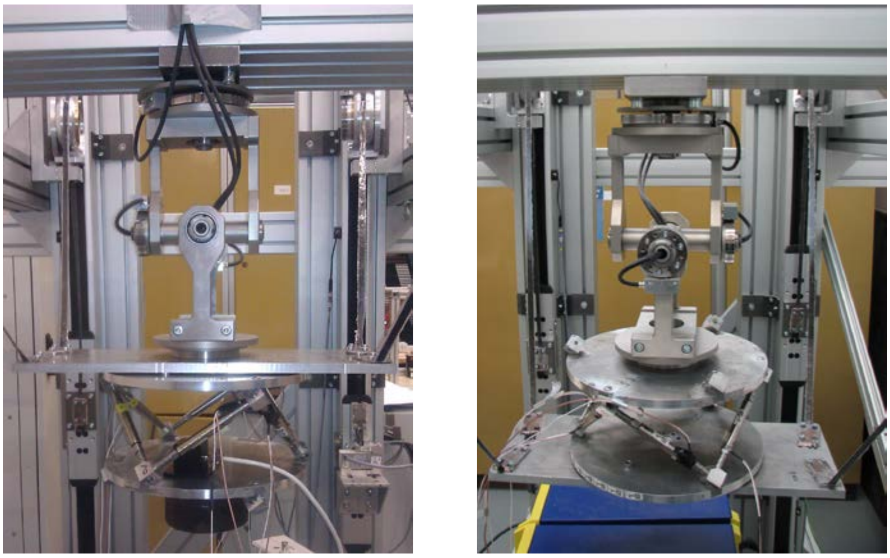


Fig. 2: Cable-driven tilting mechanism QuadroSphere with 3 DOF and angular position measurements.

The dynamical properties of the different concepts of attached active structures have been investigated not only by simulation and mathematical modelling, but also using the primary experiments

(Svatoš, et al., 2015). The demonstrator with the cable driven tilting platform has been reassembled and the piezoactuators available from the earlier times have been used for the setup of active platform (Fig. 3). The cubic architecture of 6 piezoactuators has been used. The parameters of the piezoactuators (stiffness, lengthening range, frequency range, etc.) used for these preliminary experiments are certainly given and their optimality in tested mechanism isn't guaranteed. The final specification (type and parameters) of appropriate actuators will be the result of ongoing optimization with complex model during the second project year.



a) external placement of active structure *b) internal placement of active structure*

Fig. 3: Two tested variants of active structure placement in stand with cable mechanism.

The external variant in Fig. 3 a) according to concept in Fig. 2 a) has the active structure outside the main kinematic loops created by cables and positioned tilting platform. The cubic architecture piezohexapod has been assembled below the cable-positioned platform. The principle of acting in this configuration is in fact the 6 DOF active vibration absorber. The response level and the eigenfrequencies of the system can be influenced by the mass added to the lower desk of active absorber (the results are for 4 kg). The system was excited by the chirp signal 10÷140 V with the frequency up to 100 Hz and time length 60 s that was applied to particular piezoactuators P1-P6. The position of tilting platform was measured by three incremental revolute sensors (Fig. 4). The results for excitation by piezoactuator P4 are in Fig. 5 a).

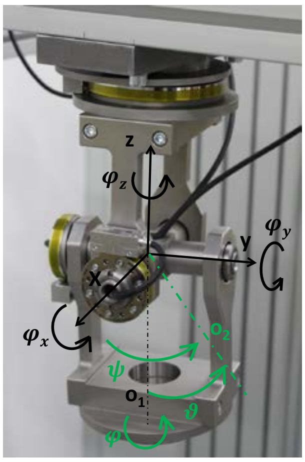
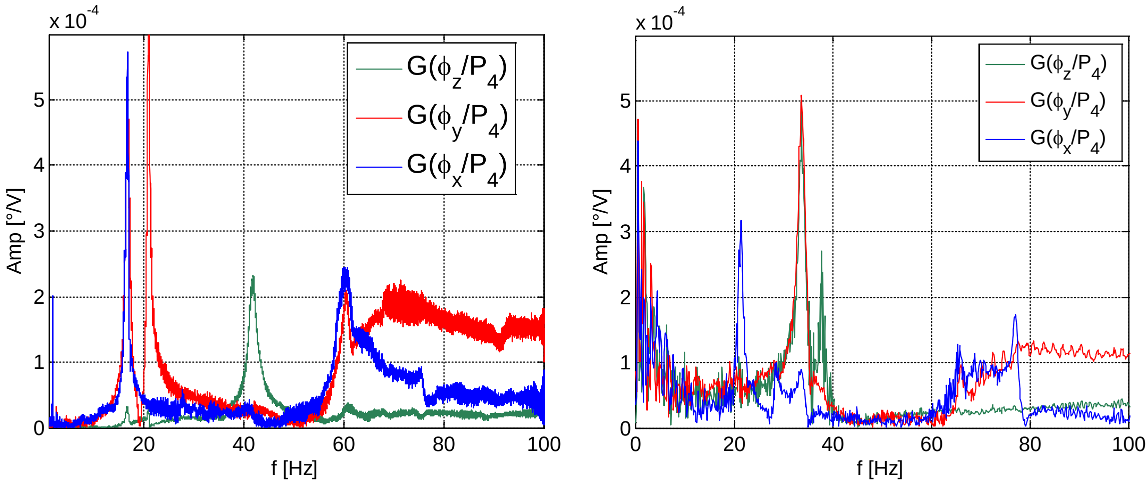


Fig. 4: Revolute incremental sensors and corresponding coordinates

The internal variant in Fig. 3 b) according to concept in Fig. 2 b) has the active structure inside the main kinematic loops created by cables and positioned tilting platform. The same type of excitations by particular piezoactuators P1-P6 have been applied. The results for excitation by piezoactuator P4 are in

Fig. 5 b). The experiments prove that the internal active structure inside the mechanism kinematical loops has significantly higher influence in the low frequency range (Svatoš, et al., 2015), nevertheless both variants are further investigated. The early experimental identification of the system variants is useful despite the fact, that the currently used piezoactuators are available from the earlier times and haven't been optimized for the given platform. Besides this the measured network of transfer functions for both variants has been the input for the state space model identification (Fig. 7) and is currently used for the control law synthesis.



a) external placement of active structure *b) internal placement of active structure*

*Fig. 5: Measured transfer functions from piezoactuator **P4** to platform position sensors.*

3. Investigation of nonlinear dynamic behaviour of cables for manipulation of end-effector and superimposed active structure

During the first year of the project solution, different approaches to cable modelling were studied and compared. The main viewpoint of the models is their robustness and capability to be suitable for further usage, particularly for the mechanism control.

The first approach used is based on a continuous model of a cable described by following governing equation

$$\rho \frac{d^2 \boldsymbol{r}(s,t)}{dt^2} = \frac{\partial}{\partial s}[EA\varepsilon(s,t)\boldsymbol{b}(s,t)] + \boldsymbol{a}(s,t) \qquad (1)$$

This equation is spatially discretized by difference method in absolute coordinate system. Used symbols have following significance ρ is linear density, E is Young's modulus, A is cross-sectional area of the cable, $\boldsymbol{b}(s,t)$ is unit tangent vector to the cable curve at point given by length coordinate s, $\boldsymbol{a}(s,t)$ is external force acting per unit length, $\varepsilon(s,t)$ is axial strain in cable, $\boldsymbol{r}(s,t)$ is position vector of an arbitrary point P at cable given by s. The range of the model (in sense of number of degrees of freedom) depends on the number of considered discretization points. This approach showed very numerically unstable behaviour and has been neglected for further considerations.

The second approach is based on variations of total energy of the system and uses Galerkin's a collocation methods with 6-th degree polynomial approximation for cable displacement. In both cases their application leads to the system of strongly nonlinear algebraic equations whose solution has to be submitted to various rearrangements to achieve numerical convergence of applied methods. Numerical implementation of the mathematical model and developed methodology was performed in computational system MATLAB. Following basic case studies have been solved and debugged.

1) Static equilibrium determination of individual cables. In spite of existence of chainsaw analytical solution taking into account a dynamic solution in future two approximate numerical methods were developed. Their outputs are in very good agreement with analytical solution.

2) Static equilibrium determination of end effector – EF (considered as a mass point) and adjoining cables by means of presented methods in 2D space. Here, the 6-th degree polynomial approximation for cable displacement was used.

3) Dynamic behaviour investigation of EF and adjoining cables by means of presented methods in 2D space. The 6-th degree polynomial approximation for cable dynamic displacement was used again. It is supposed that motion of pulleys with deployed cables is prescribed. The application of approximating function leads to the system of nonlinear ordinary differential equations whose solution corresponds to time functions for dynamic displacement approximations individual of cables end EF motion (Dupal & Byrtus, 2015).

The first analysis of the dynamic interactions between the cable-driven mechanism and the selected variant of the active structures has been done using this second type of cable model, the experimental identification of the second (internal) variant of the active structure placement, and the setup of first complex dynamical model (Fig. 3 a), Fig. 5 a)) (Svatoš, et al., 2015).

The third approach of modelling is based on so called Absolute Nodal Coordinate Formulation (ANSF) which allows to consider detailed interaction of a cable and a pulley (Fig. 6) including its nonlinear dynamic behaviour (Hajžman, et al., 2015). Global position $\boldsymbol{r} = [r_x, r_y]^T \mathrm{r} = [\mathrm{r_x}, \mathrm{r_y}]^\mathrm{T}$ of and arbitrary beam point determined by parameter p can be written as

$$\boldsymbol{r}(p) = \boldsymbol{S}(p)\boldsymbol{e}, \quad \boldsymbol{e} = [e_1, e_2, \dots e_8]^T, \tag{2}$$

where $\boldsymbol{S}$ is a global shape function matrix, $\boldsymbol{e}$ is a vector of element nodal coordinates and $p \in (\,0, l\,)$ is a parameter of a curve. The complete model of a cable-pulley system based on the ANCF planar beam element is of the form

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{B}(\dot{\boldsymbol{q}}, \boldsymbol{q})\dot{\boldsymbol{q}} + \boldsymbol{K}(\boldsymbol{q})\boldsymbol{q} = \boldsymbol{Q}_k, \tag{3}$$

where $\boldsymbol{q}$ is the vector of all elastic coordinates of the cable. This model can be combined with the models of other flexible or rigid bodies and with model of kinematic joints using a standard ways.

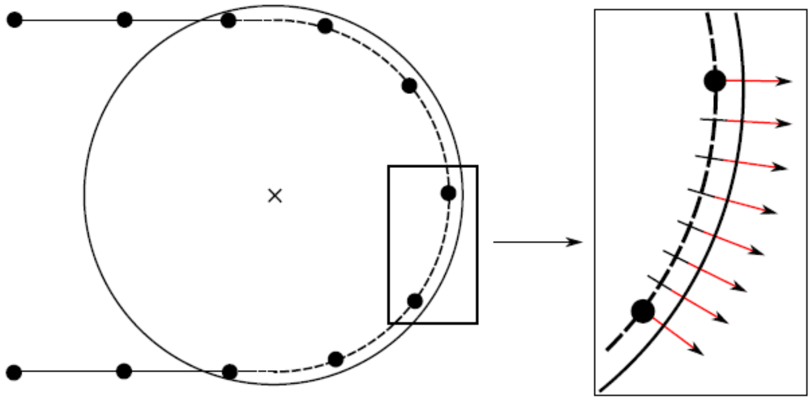


Fig. 6: Interaction of a cable and a pulley

The ANCF approach can employ cable-pulley interaction in the sense of circumferential contact forces between cable and pulley. The contact can be described i.e. by Hertz contact model. The behaviour of the cable-pulley system was modeled also using standard multibody simulation tool Alaska, where different models of velocity dependent stiffness and damping of the cable were investigated. Simultaneously, the stiffness and damping coefficients were analyzed based on records of experimental measurement and simulation results (Polach & Hajžman, 2015).

4. Development of complex dynamical models of multi-level mechanism

The models of multi-level mechanisms corresponding to the experimental demonstrator in external as well as internal variants (Fig. 3 a), Fig. 3 b)) have been used as the first modelling targets. Active structure with six piezoactuators is integrated between or on the top of the end-effector platform suspended and moved by four cables. The piezoactuators are mounted in the cubic configuration. The physical modelling have been combined with the experimental identification. Especially the experimentally identified transfer functions from the piezoactuators **P1**-**P6** to the platform position sensors (Fig. 4) are of special interest because of their importance for the platform controllability by piezoactuators or other added micro-actuators. The core project idea is the collaborative control of platform motion. The experimental identification has been successful as demonstrated by the example in

Fig. 7. The presented result corresponds to the external variant (Fig. 3 a)) and the response of incremental sensor ϕ_x (Fig. 4) for the chirp input excitation from the piezoactuator **P3**.The developed models are devoted to the optimization and control synthesis usage. The concept of a complex simulation dynamical model has been fixed during the first year of the project solution. The model integrates cable-driven mechanism and active structures, taken into account the advanced models of cables. The research consists in finding proper and suitable approach integrating the above mentioned parts from the model complexity point of view. The complexity of the model determines its usability especially from the computational time point of view and its potential employment in real-time simulations.

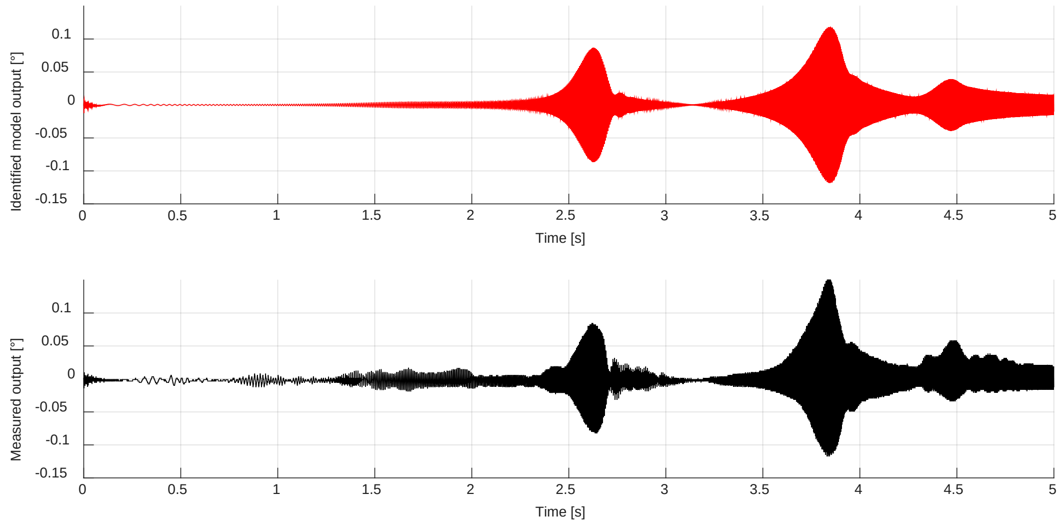


*Fig. 7: Comparison of experimental and model response of multi-level platform (piezo **P3** to ϕ_x sensor)*

5. Conclusions

The target of this paper was to present some results of the first year of solution of Czech Science Foundation research project „Multi-Level Light Mechanisms with Active Structures“. Firstly the variants of active structures superimposed to end-effectors of different cable-driven mechanisms have been analyzed by simulation. The planar, spherical as well as fully spatial variants have been taken into account. The most general variant of spatial cable-driven mechanisms has been optimized for 6 DOF and 8 driven cables. The demonstrator of 3 DOF cable-driven tilting mechanism has been newly rebuilt and considered as the base for the tilting variant of multi-level mechanisms. The piezoactuators available from the earlier times have been used for the setup of preliminary active platform. The cubic architecture with 6 piezoactuators has been reassembled and included to the system. The internal as well as external (from the point of view of kinematical loops) placement of the piezo-platform has been tested. The experiments prove that the internal active structure inside the mechanism kinematical loops has significantly higher influence in the low frequency range, nevertheless both variants are further investigated. The measured network of transfer functions from piezoactuators to revolute incremental sensors has been used for the successful state space model identification. The second important topic has been the investigation of several variants of modelling of nonlinear dynamic behaviour of cables. Three main variants of modelling have been tested. The first approach is based on a continuous model of a cable spatially discretized by difference method in absolute coordinate system. This approach showed very numerically unstable behaviour and has been neglected for further considerations. The second approach is based on variations of total energy of the system and uses Galerkin’s a collocation methods with 6-th degree polynomial approximation for cable displacement. The third approach of modelling is based on so called Absolute Nodal Coordinate Formulation which allows to consider detailed interaction of a cable and a pulley including its nonlinear dynamic behaviour. The problem of third formulation is very high computational complexity. The most promising seems to be the second variant of formulation. The further steps of the project will be finalization of complex simulation models and consequently the investigation of different possible strategies of the control of active structures superimposed to the end-effector of cable-driven mechanism in order to improve end-effector positioning accuracy and operational speed.

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