Application challenges of large-scale wire robots in agricultural plants

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Abstract: The paper presents an efficient approach for the modelling of wire robots kinematic and dynamics considering the effects of structural elasticity. Using the simulation and animation system several potential applications in agriculture have been simulated and analysed. The paper discusses possible robot configurations, system dynamic constraints and limits, as well as reachable performance for typical large-span wire robot applications in agriculture.

Keywords: Cable driven parallel robots, wire-robots, agriculture automation, work-space analysis.

1. INTRODUCTION

Recently there is an ever increasing awareness of the necessity to develop and apply robotic systems in the novel fields of agriculture, forestry, green houses, horticulture etc. (Belforte et al. 2006, Gay et al. 2008, Mcintosch 2012). Fundamental challenges of these applications include large working areas (on the order of hectare), irregular surface structures, minimal soil loads (precluding use of wheeled vehicles), positioning of various sensors and tools (e.g. with the accuracy of 50 mm or less), low operational costs, easy reconfiguration and migration etc.

Contrary to industrial applications which are almost well-specified and known a priori, an agricultural robot must deal with an unstructured, uncertain and varying environment which cannot be predetermined. Many agricultural activities that include tedious and repetitive operations, such as precise fertilization and spraying, plant inspection and disease detection, optimal irrigation, spraying and selective harvesting etc. could be automatized and performed by robots. Since agricultural works often require many decisions based on worker's experience and specific environmental conditions, there are considerable constraints on the full automation (Ibanez-Guzman, 1994). Current alternatives to applicable technical systems such as aerostats, rotorcrafts, cranes or aerial robots are limited due to costs or payload inefficiency. A quite promising option to cope with large-area applications in agriculture is the so-called *cable-driven parallel robots* (CDPR, term also used *wire-robots*).

Wire-robots have been recently addressed in numerous researches (Bruckmann and Pott, 2013) focusing on their advantages for implementing large spans, fast moving, lightweight and heavy-duty active spatial mechanisms. In comparison to a more general class of cable robots (e.g. spatial advanced robotized crane systems), the wires robots offer benefits to apply and control wire over-tension by wire pulling forces and thus to perform more precise and robust pose and motion control in spite of the external dynamic perturbations and excitations (e.g. wind, inertia etc.). Taking into account their relatively simple and light-weight structures (essential components of wire robots are winches that may be mounted on various carriers, mobile towers, pillars etc.), the wire robots may become especially attractive for a wide spectrum of agricultural applications.

The NIST RoboCrane represents one of the first large wire-robot prototypes (with the 6m span) developed for various applications (Albus et al. 1992, Bostelman et al. 1994). The initial RoboCrane development was funded by DARPA to stabilize loads suspended by conventional cranes. The RoboCrane consists of a platform suspended by six cables connected to three base point on a mobile or fixed carrier. This so called *under constrained wire-robot configuration* (with six or less cables) are more popular in the literature due to their relative simplicity and larger workspace availability. In order to realize free-space motion with 6 DOF and ensure cable-tension, the wire-robots needs at least seven wires (so called *over-constrained* CDPR structures).

Outstanding examples of under-constrained cable-array robot are the SkyCam (Cone, 1985) and SpiderCam (www.spidercam.tv/en) systems used in many sporting arenas around the world. These systems provide computer-controlled, stabilized, cable-suspended camera transporters. The systems are manoeuvred through three dimensional space with a set of four computer controlled winches. Both static and dynamic active stabilizations of camera carriers that ensure proper camera orientation are included in the real time control system.

The Large Adaptive Reflector (LAR) is a large orientable radiotelescope positioned by a cable-driven parallel robot kept under tension by an aerostat filled by helium (Bouchard and Gosselin, 2006). The LAR is planned to carry 4 metric tone of payload and provides up to 500 m length. Takemura et al. (2005) have proposed a balloon-cable driven system for information collection from sky at crushed structures at landside caused by huge earthquake.

The largest wire robot currently under development is the Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) (Lu et al. 2006, Tang et al 2012). The manipulator structure is based on a cable-driven Stewart-Platform (similar to the RoboCrane) that realizes a large-space coarse motion, while the rigid Stewart-Manipulator attached to the suspended trolley is responsible for fine manipulation. Due to very large dimensions and high payload the applied cables must be real elastic and weighty wires, which considerably complicate the system modelling.

One of the first efforts to introduce the wire robots in agriculture represents the LOMAF (Large-Area Overhead Manipulator for Access of Fields) (White and Bostelman, 2011). This flexible six DOF manipulator was developed at NIST and Arid Land Agricultural Research Center (ALARC). The investigations on LOMAF performance for large area applications is based on several mockups with and without stabilizing downhaul cables.

However, the analysis of CDPR applications in a large workspace requires complex dynamic computations and examinations. The motion planning of wire-robots cannot be similar to that of the convenient industrial robots performed separately from system dynamics i.e. quasi-static analysis (Verhoven et al., 1998). The wire-robots planning requires analysis of so called *wrench feasible working space* in which the wire tension must be ensured for various payloads and perturbation forces. Due to the relatively large dimensions and inevitable elasticity inherent in robot cables, the wire robots are prone to vibrations (Diao and Ma, 2009). Thereby the common platform can perform complex coupled 6D oscillations, particularly in case of abrupt motion changes. Therefore, elastodynamic analysis of wire robots becomes essential in trajectory planning, as well as during system design and control development. Especially in the large-span systems, the elastic deformations and vibrations may be characterized by relatively low frequencies and high amplitudes causing undesirable behaviour.

This paper presents an efficient approach for the modelling of wire robots kinematic and dynamics considering the effects of structural elasticity. Using the simulation and animation system several potential applications in agriculture have been simulated and analysed. The paper discusses possible robot configurations, system dynamic constraints and limits, as well as reachable performance for typical large wire robot applications. The maximum reachable working space for the given maximum/minimum wire forces has been computed. The paper also considers coupled 6D deformations of the common wire-robot platform in both over- and under-constrained wire robot structures.

2. MATERIAL AND METHODS

2.1 Wire robots modelling

Here a brief overview of wire robots-models used in the analysis will be given. More details are given in (Surdilovic et al. 2013).

Kinematic scheme of a general agricultural wire robot (Fig. 1) with n-wires (i=1,…,n) is given in (Fig. 2). Using the notion from (Fig. 2), the loop closure condition for the i-th wire platform attachment point B_i is defined by

$$\mathbf{p}_i = \mathbf{a}_i + \mathbf{L}_i = \mathbf{p} + \mathbf{b}_i \tag{1}$$

where $\mathbf{a}_i$ and $\mathbf{b}_i$ are position vectors of pulley and platform attachment points A_i and B_i wrt. base and local platform frames respectively, $\mathbf{p}$ is the position vector of the platform reference frame and

$$\mathbf{L}_i = \overrightarrow{A_i C_i} + \overrightarrow{C_i T_i} + \mathbf{l}_i \tag{2}$$

where $\mathbf{l}_i$ is the wire-length vector, while C_i and T_i denote centre of the pulley and wire tangent points(Fig. 2). After differentiation of (1) and projection of velocities vectors into wire-length vector direction, defined by unit vector $\mathbf{l}_{i0} = \mathbf{l}_i / l_i$, i.e. scalar multiplication of these equations by $\mathbf{l}_{i0}$ yields the magnitudes of wire linear relative velocity defining the cable length variations (by winch rotation)

$$\overset{*}{l}_i = [\mathbf{l}_{i0}^T \quad -\mathbf{l}_{i0}^T \underline{\underline{\mathbf{b}_i}}]\mathbf{t}_p \tag{3}$$

where $\mathbf{t}_p = [\mathbf{v}_p^T \quad \boldsymbol{\omega}_p^T]^T$ is the platform twist vector, while $\underline{\underline{\mathbf{b}_i}}$ denotes *skew-symmetric* 3x3 matrix formed from the elements of the vector $\mathbf{b}_i$ in order to represent the vector product in the matrix form.

$$\overset{*}{\mathbf{l}} = \mathbf{J}\mathbf{t}_p \tag{4}$$

where $\overset{*}{\mathbf{l}} = [\overset{*}{l}_1 \ldots \overset{*}{l}_i \ldots \overset{*}{l}_n]^T$ and Jacobian matrix $\mathbf{J} \in \Re^{nx6}$ is defined by

$$\mathbf{J}^T = \begin{bmatrix} \mathbf{l}_{10} & \cdots & \mathbf{l}_{i0} & \cdots & \mathbf{l}_{n0} \\ \underline{\underline{\mathbf{b}_1}}\mathbf{l}_{10} & \cdots & \underline{\underline{\mathbf{b}_i}}\mathbf{l}_{i0} & \cdots & \underline{\underline{\mathbf{b}_n}}\mathbf{l}_{n0} \end{bmatrix} \tag{5}$$

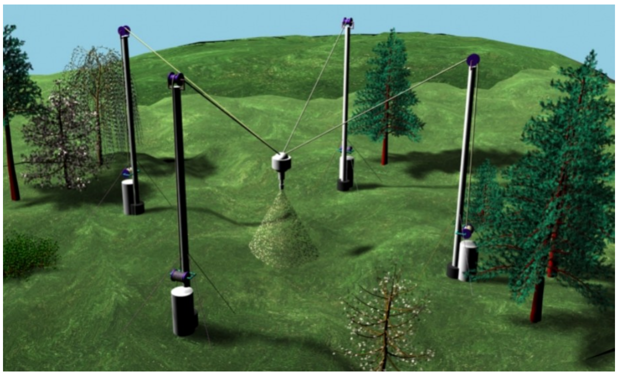

Fig. 1. A possible wire-robot structure for applications in agriculture.

The mapping between internal wire tension forces, grouped in the wire tension vector $\mathbf{f} = [\mathrm{f}_1 \ldots \mathrm{f}_i \ldots \mathrm{f}_n]^T$ with elemental forces acting along $\mathbf{l}_{i0}$ (i=1,…,n), and Cartesian wrench (involving external force and moment vectors acting on the platform) is also defined by the wire-robot Jacobian

$$\mathbf{w} = \mathbf{J}^T \mathbf{f} \tag{6}$$

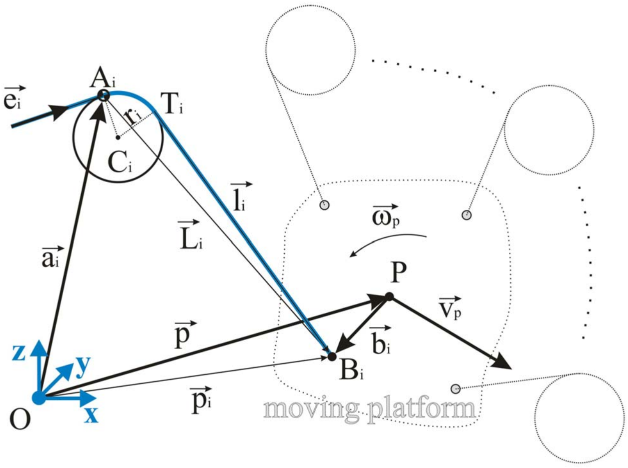

Fig.2. Wire-robot kinematic scheme.

As is well known, in an over-constrained wire-robot structure (with *n>6* wires) we can realize for the same external wrench various wire tensions utilizing Jacobian null-space and inverse force transformation

$$\mathbf{f} = \mathbf{J}^{\#T}\mathbf{w} + \mathbf{N}\boldsymbol{\lambda} \tag{7}$$

where $\mathbf{N}$ denotes *nx(n-6)* dimensional null-space (kernel) of $\mathbf{J}^T$ and $\boldsymbol{\lambda} \in \Re^{(n-6)x1}$ represents arbitrary wire tension scaling factors. The reachable tension range of the internal wire forces defines *wrench-feasible* or *wrench-closure* wire-robot workspace where arbitrary external wrenches may be realized within some minimum-maximum tension interval $\mathbf{f}_{\min} \le \mathbf{f} \le \mathbf{f}_{\max}$. The tension coefficients $\boldsymbol{\lambda}$ are then obtained as solutions of linear inequalities

$$\mathbf{f}_{\min} - \mathbf{J}^{\#T}\mathbf{w} \le \mathbf{N}\boldsymbol{\lambda} \le \mathbf{f}_{\max} - \mathbf{J}^{\#T}\mathbf{w} \tag{8}$$

The vector $\boldsymbol{\lambda}$ that ensures minimum tension represents the solution of the optimum linear programming problem with the constraints (8). For the considered wire-robot with *n*=8 wires, the tension coefficients are determined within a convex polygon (Fig. 3) representing the solution of the system of linear inequalities (8).

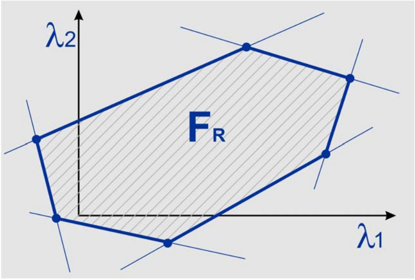

Fig.3. Determination of wire tension in the Null-space of $\mathbf{J}^T$ *for n=8 wires.*

The structural stiffness matrix plays the key role in the deformation analysis of the wire-robots. The Cartesian spatial stiffness matrix relates the variations of applied forces and moments (*wrench*) to the corresponding spatial displacements (*twist*) rates of change

$$\delta\mathbf{w} = \mathbf{K}\delta\mathbf{t}$$

$$[\delta\mathbf{F}^T \quad \delta\mathbf{M}^T]^T = \begin{bmatrix} K_{xx} & K_{xo} \\ K_{xo} & K_{oo} \end{bmatrix} [\delta\mathbf{x}^T \quad \delta\mathbf{o}^T]^T \tag{9}$$

where $\mathbf{w}$ and $\mathbf{t}$ are wrench and twist screw vectors, $\delta\mathbf{F}$ and $\delta\mathbf{M}$ are variations of Cartesian forces and moments acting on the common platform and $\delta\mathbf{x}$ and $\delta\mathbf{o}$ are corresponding relative translational and rotational displacements compatible with the constraints. The differentiation of (6) gives external-wrench/wire-tension relationship in the variational form

$$\delta\mathbf{w} = \mathbf{J}^T\delta\mathbf{f} + \delta\mathbf{J}^T\mathbf{f} \tag{10}$$

where the variation of the Jacobian describes the structural changes during deformation. Based on elastic wire models and Jacobian derivations (Surdilovic et al. 2013), the total stiffness matrix may be expressed as sum of the structural $\mathbf{K}_s$ and geometric $\mathbf{K}_g$ stiffness matrices

$$\mathbf{K} = \mathbf{K}_s + \mathbf{K}_g = \bar{k}\mathbf{J}^T\bar{\mathbf{L}}\mathbf{J} + \sum_{i=1}^{n} \underline{\mathbf{J}_i^T} \mathrm{f}_i \tag{11}$$

where $\bar{\mathbf{L}} = diag(1/l_i) \in \Re^{nxn}$, $\bar{k}$ is the specific wire cable axial stiffness for unit length $\bar{k} = EA$, E is Young's module and A the cable cross-section (for the sake of simplicity the same elastic characteristics have been adopted for each wire), while *6x6* block matrices $\underline{\mathbf{J}_i^T}$ is given in (Surdilovic et al. 2013).

Finally, the dynamic model of the wire robots describes the motion of the platform in the space under action of inertial, wire and external forces (wrench $\mathbf{w}_e$)

$$\mathbf{M}(\mathbf{x})\dot{\mathbf{t}}_p + \mathbf{t}_p \otimes \mathbf{C}(\mathbf{x})\mathbf{t}_p + \mathbf{G}(\mathbf{x}) = {}^P\mathbf{J}_E^{-T}\mathbf{w}_e + \mathbf{J}^T\mathbf{f} \tag{12}$$

where $\mathbf{M}(\mathbf{x})$, $\mathbf{C}(\mathbf{x})$ and $\mathbf{G}(\mathbf{x})$ are matrices of platform inertia, Coriolis and centrifugal matrix, and vector of gravitational forces respectively, while ${}^P\mathbf{J}_E^{-T}$ is Jacobian transformation from the acting point of external forces (E) to the centre of the platform (P). In conjunction with (11) the model (12) describes elastodynamic oscillations along a trajectory.

2.2 Considered robots structures

The above models were applied for the analysis of two wire-robots structures (Fig.4-5). The first robot is an under-actuated manipulator with *n*=4 wires with the structure similar to the SkyCam (Cone, 1985). The wires are attached to the 4 pillars with the height of 25 m which span an area of 100x100 m (Fig. 4). The adopted platform mass is 20 kg.

Since this structure includes non-controllable DOFs, the perturbation forces (e.g. wind) can cause undesired platform motion such as orientation errors that may be compensated for by means of additional DOF at the platform which should ensure the desired vertical altitude.

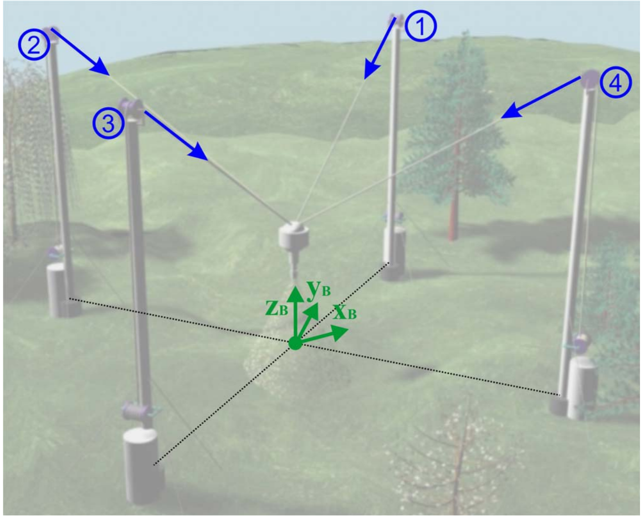

Fig.4. 4-wires robot structure.

In order to ensure stable platform position and elevation, a modified structure with downhaul wires (Fig 5) may be applied. In order to realize a reconfigurable and portable system the pillars may be mounted on mobile platform with supporting stabilizing legs (Fig. 6).

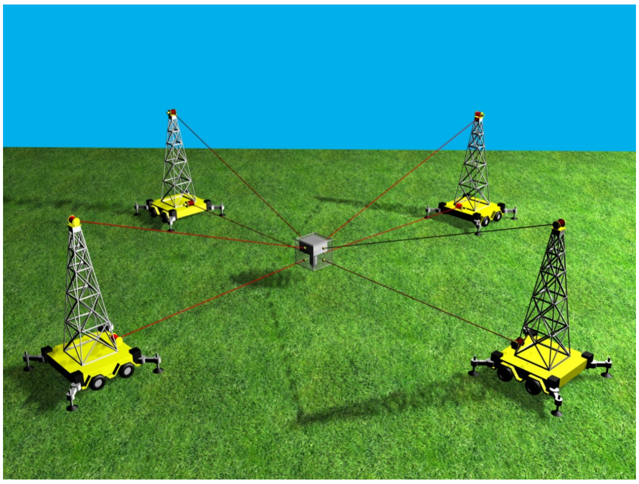

Fig5. Over-constrained configuration with n=8 wires.

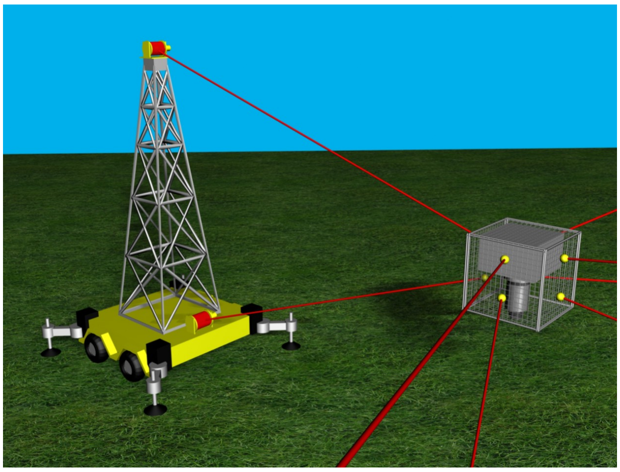

Fig.6. Conceptual design of a mobile pillar.

3. RESULTS AND DISCUSSION

The real-time simulation has been implemented in MATLAB/SIMULINK and rapid-control prototyping environment dSPACE enabling real-time dynamic model simulation. For the real-time motion animation the Motion-Desk dSPACE system (Fig. 6) has been applied. In the following only few typical results are presented.

The working space analysis of the robot with 4 wires (Fig. 4) is presented in (Fig. 7). As can be seen a relatively large area (ca. 80x80 m) and applicable heights up to 5 m may be realized with relatively low wire tensions (up to 200 N). Obviously, the tension feasible workspace for limited wire internal forces (determined by maximum wire loads (1000 N in considered case) is smaller than the kinematic workspace.

Larger working area and considerable improved stabilization of the platform may be realized by over-constrained robot (Fig. 8), however the required tension forces become also higher.

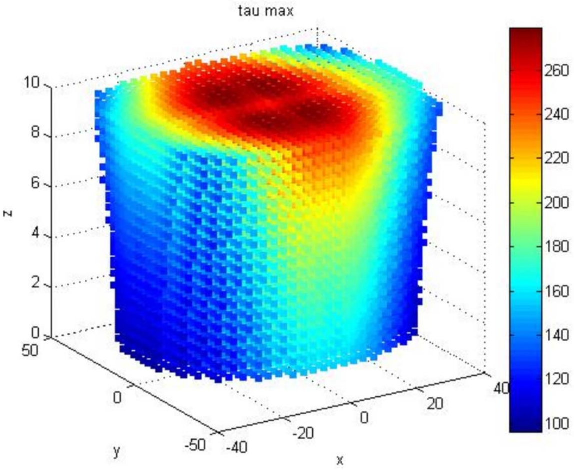

Fig7. Working space of the under-constrained configuration.

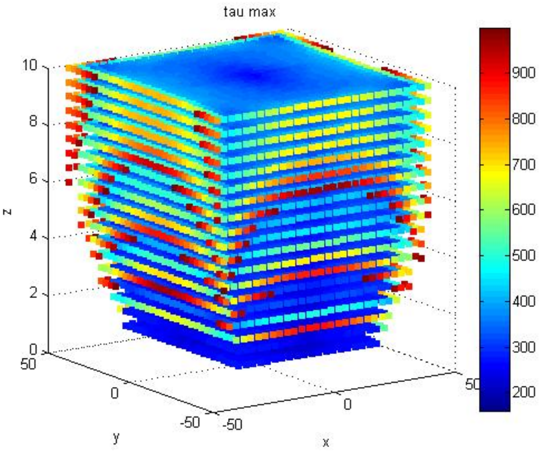

Fig 8. Working space of the over-constrained robot.

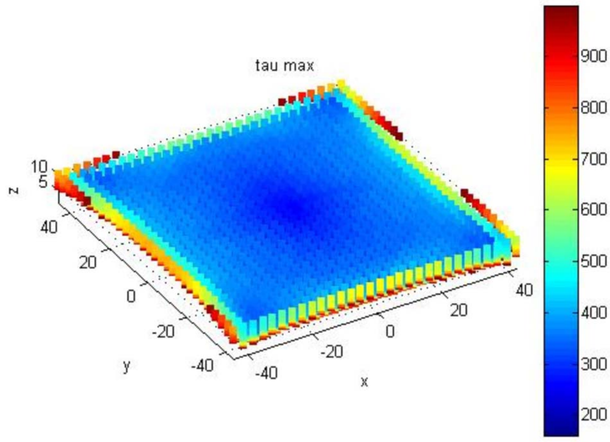

Fig 9. Tension forces of the over-constrained robot.

The larger tension forces cause higher loads on the pillars and carriers. The maximum torques on the mobile platform are presented in (Fig. 10) in the entire working space. The maximum tilt torques within area of interest amounts up to ca. 10000 Nm causing the loads on the stabilizing legs of approximately 2500N (assuming the transporter radius of 2m).

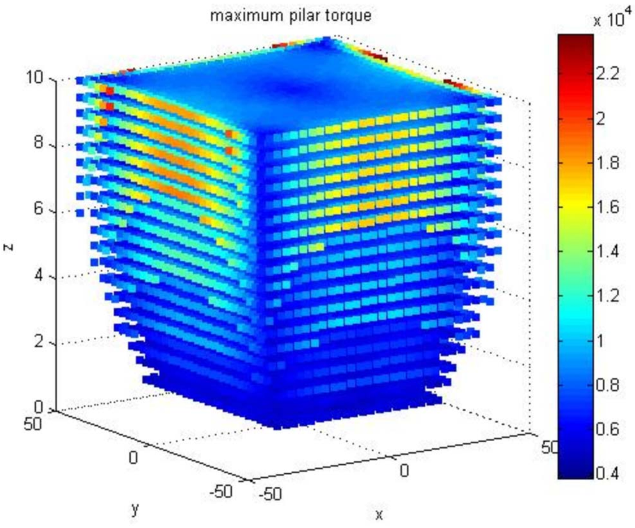

Fig 10. Maximum tilt torques acting on the transporter.

To illustrate the stiffness of the robot the vibration of the platform after a short perturbation action of a force F=100 N in y-direction has been illustrated. As can be remarked the platform perform damped oscillations with relatively law frequency of 1-2 Hz and maximum amplitudes of 0,03 m (Fig. 11). This frequency can cause resonant effects with the oscillations of pillars that should be made stiff as possible (e.g. using a grid structure).

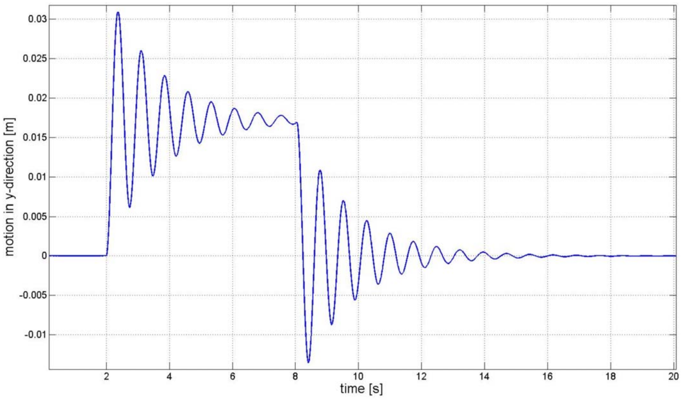

Fig 11 Platform vibrations response to an external impulse force.

4. CONCLUDING REMARKS

The goal of agricultural robots is not to apply robotics technology on the field of agriculture but also to use agricultural challenges to develop new technique and systems.

The wire-robot large spans and light-weight structure characteristics offer promising performance for various agricultural applications. The planning and programming of these applications however require efficient dynamic analysis taking into account maximum wire tension and oscillation behaviour. An efficient real-time environment for simulation the wire-robot application has been presented in the paper.

The considered prototypes structures provide usable cable tensions, work volume and mobile transporter loads.

The under-constrained robot structures are simpler to realize and cost efficient, however, the additional stabilization of the working platform must be realized that complicates the system structure and control considerably. The over-constrained wire-robots provide improved stabilization and stiffness for various applications. The reconfigurable and portable structures may be mounted on mobile transporters that include automatized commissioning of the robots utilizing attachable platforms. The real systems may be build at relatively low costs in comparison to alternative systems.

The on-going work relates the methods for robot commissioning including field calibration using GPS and novel inertia motion units (IMUs), as well as development of first mock-ups for experimental analysis and validations.

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