COMPUTATIONAL MECHANICS 2022
37th conference with international participation
Srní
November 7 - 9, 2022

Active vibration suppression synthesis of mechanisms with tensegrity properties

T. Šindel, Z. Šika, J. Zavřel

Faculty of Mechanical Engineering, The Czech Technical University in Prague, Technická 4, 160 00 Praha, Czech Republic

1. Introduction

Only a relatively small number of projects is focused on tensegrity structures undergoing large structural deformations. The reason is a highly nonlinear dynamic behaviour complicating the analysis in many ways. In robotic locomotion, for example, the main task of the robot is to transport oneself relative to a global reference frame in terms of an untethered movement. The main advantage of using the tensegrity structures for locomotion is their robustness to the outside environment in terms of damage tolerance and the diffusive force distribution, which allows the structure to be less susceptible to failure when subjected to an unpredictable external disturbance, especially during highly dynamic motion [1]. During this highly dynamic movement, vibrations occur, and they must be eliminated in order to achieve precise movement. This aim applies for robotic manipulation as well.

There are three main types of vibration control: passive, semi-active and active. The passive type, still being the most conventional of the three, is based on inherent properties of the structure itself [3]. The dampers have inherent force-velocity characteristics, imprinted in them during the manufacturing process, and these stay the same if we neglect the temperature changes and the mechanical wear over time. Active and semi-active methods have shown themselves to be more universal, for they can be deliberately adjusted in real time to produce a desired response. Semi-active devices can only absorb energy from the interacting system, hence cannot destabilize it. The passive and semi-active methods essentially rely on their composing material and precision components. Active damping, on the other hand, offers an increased performance in a given control bandwidth while reducing the application cost and is a promising candidate for applications in tensegrity robotics [2].

2. Optimal placement of high-authority actuators

The optimal placement of actuators plays the key role especially for large spatial movements of the structure. The optimization objective is to find a suitable actuation vector c for a given set of contraction responses. Due to the nature of cables, the translational DOFs can be actuated only in one direction – the pulling direction. Thus, it is necessary to ensure the motion of the end-effector (task-space) DOFs in both directions. For this purpose, we rectify the response vectors in positive x^+ and negative x^- senses, respectively. The objective is to maximize the balanced sensitivity function S, which is a weighted sum of sensitivity magnitudes for all task-space DOFs (1)

$$S = 4\sum_{i=1}^{n_t} w_i S_i = \boldsymbol{c}^{\boldsymbol{T}}\boldsymbol{Q}\boldsymbol{c}; \quad \boldsymbol{Q} = \sum_{i=1}^{n_t} \boldsymbol{w\_i}\left(\left|\boldsymbol{x}_i\boldsymbol{x}_i^{\boldsymbol{T}}\right| - \boldsymbol{x}_i\boldsymbol{x}_i^{\boldsymbol{T}}\right). \tag{1}$$

The optimal actuator placement vector for a given number of actuators n_a is then

$$c_{opt} = \arg\max(\boldsymbol{c}^{\boldsymbol{T}}\boldsymbol{Q}\boldsymbol{c})\,; \quad ||\boldsymbol{c}||_1 = n_a\,. \tag{2}$$

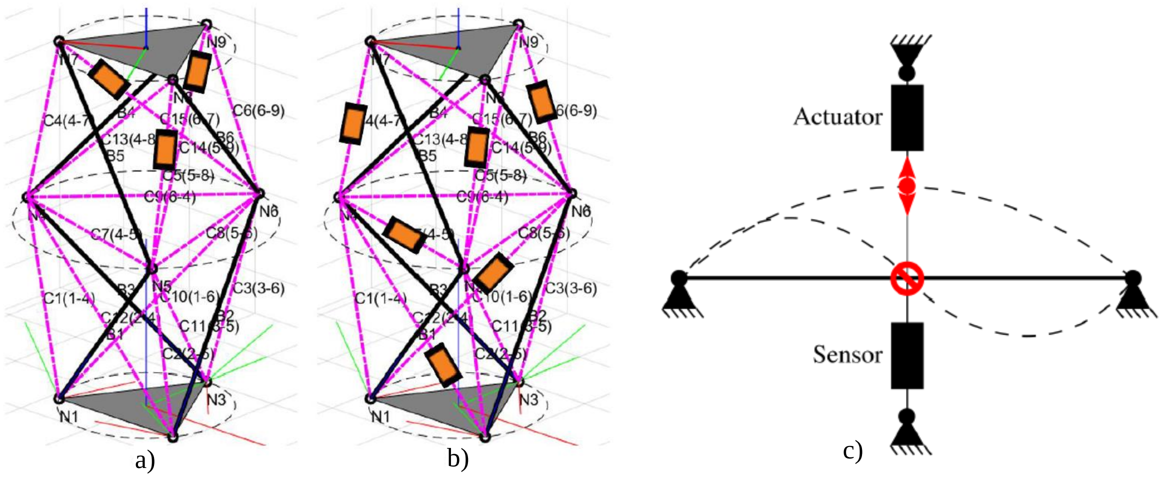


Fig. 1. Sensor placement for: a) 3 sensors, b) 6 sensors, c) modal shapes

3. Optimal placement of low-authority sensors and actuators

In active vibration suppression, a mere focus on the control algorithm with neglected consideration of a suitable sensor and actuator placement results in a sub-optimal solution. As illustrated on the example (Figs. 1a, b) of a simply supported beam in Fig. 1c, the collocated actuator/sensor pair is placed optimally for the first mode. However, the second mode, and all even modes for that matter, are uncontrollable and unobservable by the actuator, resulting in poorly damped vibrations of these modes. For this reason, it is of a substantial importance to address this issue early in the design process, so that the desired control performance is achieved. An optimal placement of sensors and actuators for a generic tensegrity structure is proposed. The optimization algorithm is based on the derived finite-element dynamic model.

For the actuator placement, a suitable objective is the minimization of control energy required to bring the system eigenmodes to the desired states after a certain time t. This can be expressed by the quadratic form

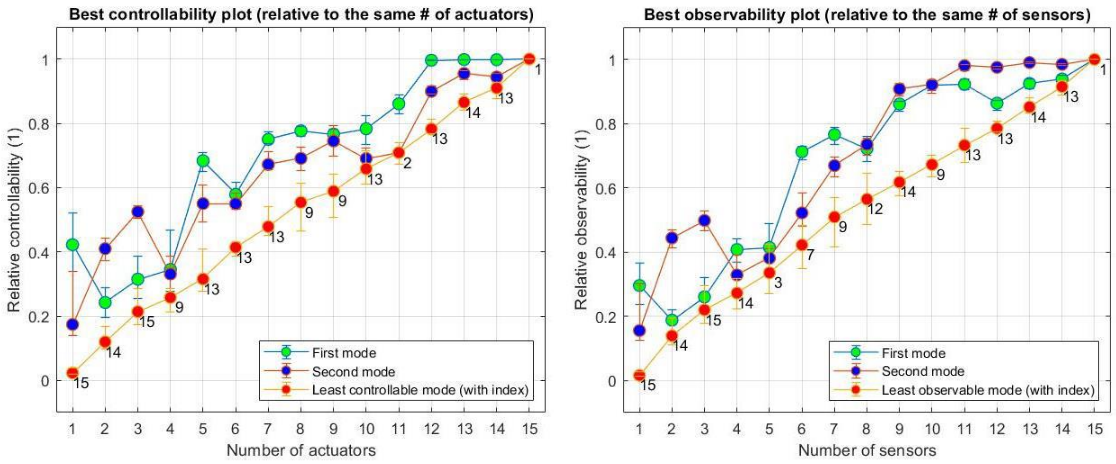
$$J_c = \int_0^t \boldsymbol{u}^{\boldsymbol{T}}(\tau)\boldsymbol{u}\,(\tau)dt\,. \tag{3}$$

For the placement of sensors, we seek an arrangement that maximizes the output energy of the system in the form

$$J_o = \int_0^\infty \boldsymbol{y}^{\boldsymbol{T}}(\tau)\boldsymbol{y}\,(\tau)dt \tag{4}$$

for the desired modes. To demonstrate this algorithm, a specific example of tensegrity structure was developed (Figs. 1a, b). It is a tensegrity tower with two stages of second order, which implies that two struts are connected at most within the structure. In our case the struts are connected in pairs with spherical joints between the stages. The nodes are fully connected with cables. We can divide the cables in three groups based on their orientation: vertical, horizontal, and diagonal.

Figs. 1a, b shows the geometrical model of the tower which was used in FEM modelling and the following optimization. The placement of sensors and actuators is considered in cables only. The model is has 18 DOF in total including the strut axial deformation and excluding the strut parasitic rotations. This consequently results in 18 modelled vibrational modes. The two objective functions used for optimization are the degrees of controllability and observability. Maximizing these scalar functions by genetic algorithm yields following results: quantitative and qualitative.



a) b)

Fig. 2. Best controllability/observability plot relative to a single actuator for each possible number of actuators. It is displayed for three different modes

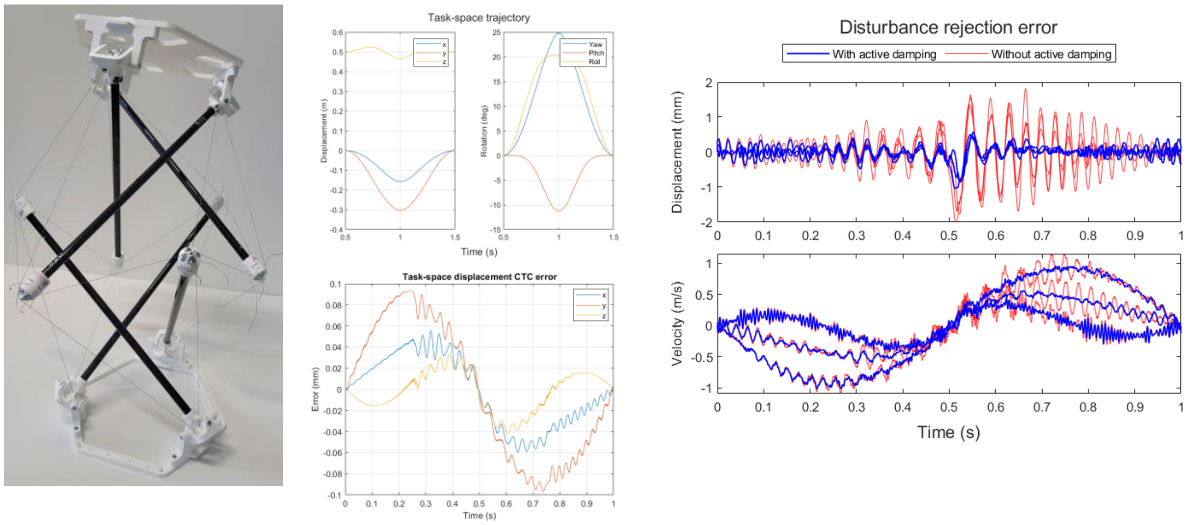
In Fig. 2a a DEGC (degree of controllability) for varying number of actuators is shown. It is displayed for three modes: first, second and the least controllable. Because DEGC is computed relative to the maximum value of controllability across all placements, the maximum value will be unity. In Fig. 2b the controllability relative to a single actuator is displayed. This plot has a significance for the decision-making purposes, where it serves as a useful tool to determine the used number of actuators for the application.

Qualitative results correspond to the best possible placement of sensors (actuators) for every number n_s (n_a) of them starting with one and ending with the total number of cables (when there are sensors/actuators present in each cable). These results are visualized in Fig. 2a and Fig. 2b.

4. Active vibration control synthesis and simulation

A two-stage tensegrity manipulator of type 1, which means that no two struts are connected, was constructed as shown in Fig. 3a. This demonstrator consists of two S3 tensegrity simplexes stacked on top of each other while being surrounded by two platforms – a bottom and a top platform. The bottom platform is considered fixed to the world frame and the top platform supports the end-effector, which is not shown in the figure. The platforms are attached to the struts by universal joints, eliminating parasitic rotations, otherwise present in spherical joints.

For simulation, control law synthesis, and testing, a specific bending movement pattern was chosen as shown in Fig. 3b. The figure shows the task-space coordinates of the top platform along the chosen trajectory performed by the manipulator. The control of large displacements of the manipulator was produced using the computed torque control (CTC) on which the IFF active vibration control was later superimposed. Fig. 3b displays the deviation of the real trajectory from the desired trajectory for the case when only CTC control is used. For practical testing of active vibration suppression, the disturbance signals are injected into the nonlinear simulation model. These signals are modelled in two ways: band-limited white noise injected to both the top and the bottom platform reference frames; and force impulse applied only to the top frame. The vibrational response of the structure is shown in Fig. 3c. It is clear that the response on the disturbance excitations has been attenuated for both the translational and the rotational degrees of freedom.



a) b) c)

Fig. 3. a) The physical demonstrator of tensegrity structure, b) displacement and rotation time plot of the top platform and a CTC task-space displacement error plot along the trajectory without disturbances, c) task-space displacement and velocity error with white noise disturbance

5. Conclusion

A complex simulation of the model is performed both in open-loop and closed-loop, both in presence and absence of external disturbances of distinct types. It is shown that the implemented method of active vibration suppression using collocated decentralized integral force feedback is highly effective for tensegrity structures. The suppression was successful for both cases of translational task-space vibrations, but to the lesser extent for the rotational vibrations, where the substantial damping is recorded for the former case only. This finding results in a realization that the pointing performance of controlled tensegrity manipulators needs to be addressed more deeply when kinematic excitations of the base frame are present [4].

Acknowledgements

The research is supported by the Czech Science Foundation project No GA20-21893S "Mechatronic Tensegrities for energy efficient light robots ".

References

[1] Iscen, A., Agogino, A., SunSpiral, V., Tumer, K., Learning to control complex tensegrity robots, in Proceedings of the 2013 international conference on Autonomous agents and multi-agent systems, 2013.
[2] Shah, D. S., Booth, J. W., Baines, R. L., et al., Tensegrity robotics, Soft robotics, 2021.
[3] Skelton, R. E., Adhikari, R., Pinaud, J.-P., et al., An introduction to the mechanics of tensegrity structures, in Proceedings of the 40th IEEE Conference on Decision and Control, Orlando, Florida, USA, 2001.
[4] Šindel, T., Tensegrity mechanisms with active vibration suppression, master thesis, CTU in Prague, 2022.