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MOTION DESCRIPTION OF MECHATRONIC FLEXIBLE JOINT

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Key words: Flexible joint, mechatronic flexible joint, motion description, modeling, redundant measurement, calibration.

Summary: *The paper deals with the description of motion of mechatronic flexible joint and its calibration. Flexible joints are used in compliant mechanisms. If they are actuated they are called mechatronic flexible joints. The answered questions are how many parameters are necessary for exact description of motion of mechatronic flexible joint, how to develop efficient description of motion of mechatronic flexible joint, how to identify (calibrate) such model by efficient approaches.*

1 INTRODUCTION

The paper deals with the description of motion of mechatronic flexible joint. Flexible joints are used in compliant mechanisms. If they are actuated they are called mechatronic flexible joint. However, the examples are compliant arms of traditional robots (Fig. 1) as well as inflatable robotic end-effectors [2] (Fig. 2) or inflated/deflated smart structures for manipulators [1] (Fig. 3) or traditional compliant mechanisms from hyperelastic materials (Fig. 4) with traditional as well as non-traditional actuators.

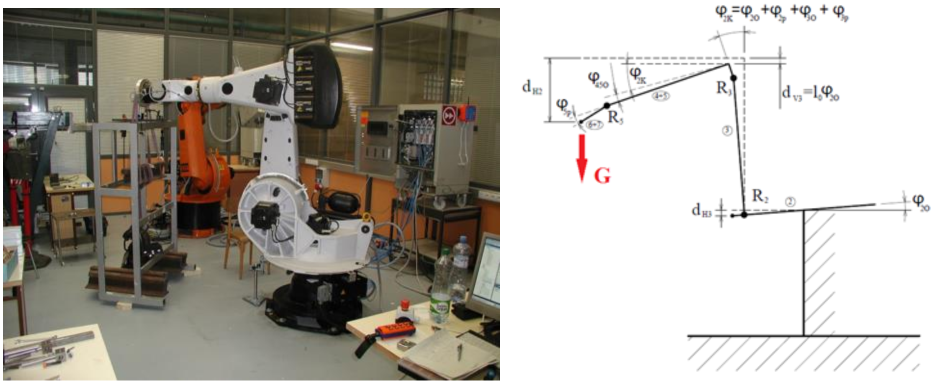


Fig. 1 Flexible mechatronic joint in a traditional robot and scheme of its deformation

The ultimate challenge is the development of methods using computation and efficient measurement for determination of kinematic transformation of the mechatronic flexible joint in order to enable its precise position control under real operation condition (especially loading).

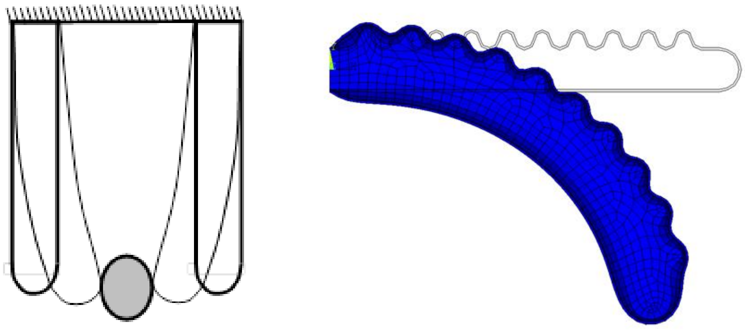


Fig. 2 Concept of inflatable robotic end-effector as flexible mechatronic joint

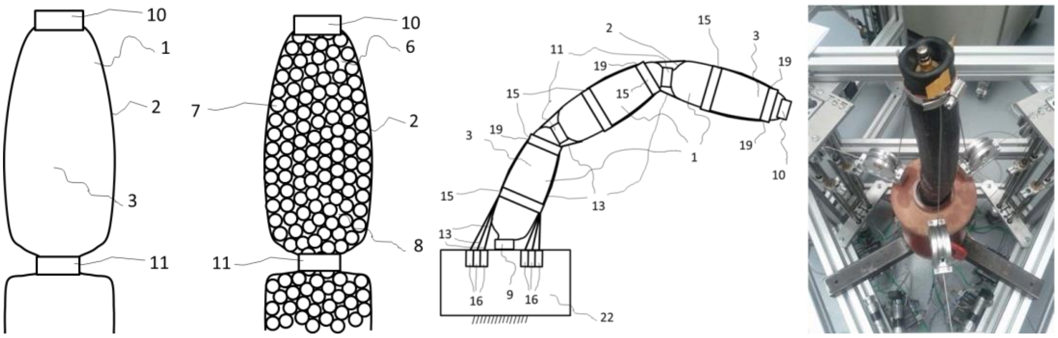


Fig. 3 Robot from inflated/deflated links as mechatronic flexible joints from patent [1]

Fig. 4 Traditional compliant mechanism from web

The open problem of basic research is the methods for description and calibration of kinematical transformation of mechatronic flexible joint without simplifications in similar way as it is realized for traditional joints of mechanisms (revolute, translational). The open problem is the transition from fully compliant FEM model into some equivalence of rigid mechanisms. How the traditional geometrical variables of kinematics of rigid mechanisms originate from the compliant FEM description?

The paper includes both the theoretical development and the simulation of examples of mechatronic flexible joints.

2 PROBLEM FORMULATION

It has been analyzed many compliant mechanisms that include the examples described in the introduction.

One of the first problems was to define the flexible joint. After several discussions it was agreed that the flexible joint is a compliant body fulfilling the function of movable connection of other bodies. The mechatronic flexible joint is a flexible joint that is actuated and measured (Fig. 5). According to these definitions the mechatronic flexible joints in Fig. 1 for example consists of robot links actuated by drives in the robot joints and by the gravity forces of links or robot loads. The inflatable robotic end-effector in Fig. 2 consists of inflatable bodies actuated by the fluid pressure and by the gravity of the load. The robot in Fig. 3 consists of inflated/deflated bodies 1 actuated by cables 13. The flexible joint alone depicted in Fig. 5 is the connection by the flexible body between the flanges. Its description means the relationship between the loading Fx, Fy, M on the flange, the forces Fa1 and Fa2 of the actuators and the position of the flange x, y, φ. Two actuators Fa1 and Fa2 are integrated into the flexible body.

The paper answers positively these questions and describes the solution for two challenging questions:

(1) Could be mechatronic flexible joint precisely described by finite number of parameters? Under which conditions is it possible? Could be done joint by joint of for overall compliant mechanism only?

(2) Could be mechatronic flexible joint calibrated based on redundant measurement as mechanisms with traditional joints? Could be possible the self-calibration procedure for mechatronic flexible joint/compliant mechanism?

In particular the paper proves that the mechatronic flexible joint can be characterized by finite number of parameters equal to number of degrees of freedom of equivalent mechanisms and the number of actuators, its motion can be efficiently described by LOLIMOT approach for description of nonlinear systems and it can be self-calibrated using redundant measurements.

3 DESCRIPTION BY FINITE NUMBER OF PARAMETERS

The problem is how to describe the movable connection by concise description similarly as transformation matrix in kinematics of rigid bodies.

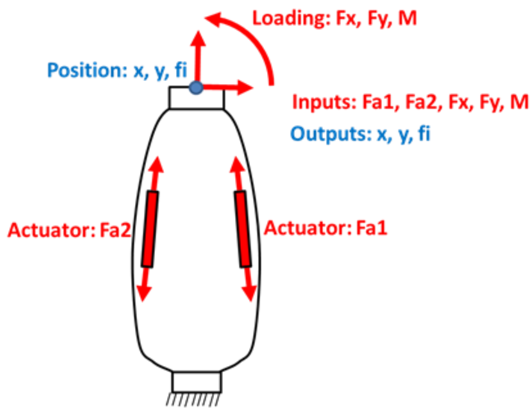


Fig. 5 Input-output relationship of mechatronic flexible joint

In order to achieve the description of flexible joint by finite number of parameters it is necessary to fulfill the Saint-Venant principle. Therefore the existence of rigid flanges on both ends of flexible body that creates the flexible joint is important (Fig. 5). There are loading the forces Fx, Fy, M. It is supposed that the application of actuator forces Fa1 and Fa2 is within the applicability of Saint-Venant principle. This is also supported by the approving the patent [1] with many variants of mechatronic flexible joint.

The simulation of the motion of mechatronic flexible joint was carried out. The basic model was the corresponding FEM model. The motion is a nonlinear large deformation of the flexible body with geometric nonlinearity. One of important questions that was clarified was the possible dependence of final deformation (position of mechatronic flexible joint) on loading path (loading history). If the dependence occurred then the precise description of motion of mechatronic flexible joint would not be possible. It was proven on the example in Fig. 6 that the final deformation does not depend on loading path. Its numerical demonstration is in Fig. 7 where the results of two different loading paths are compared.

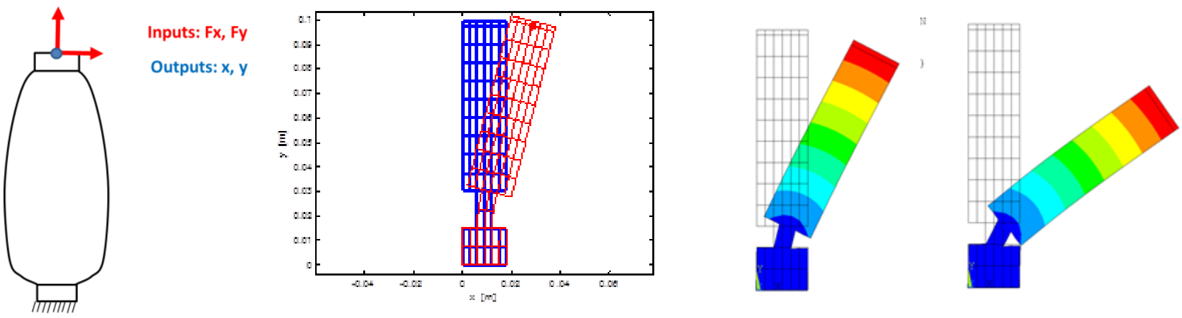


Fig. 6 Mechatronic flexible joint and its FEM model during its motion

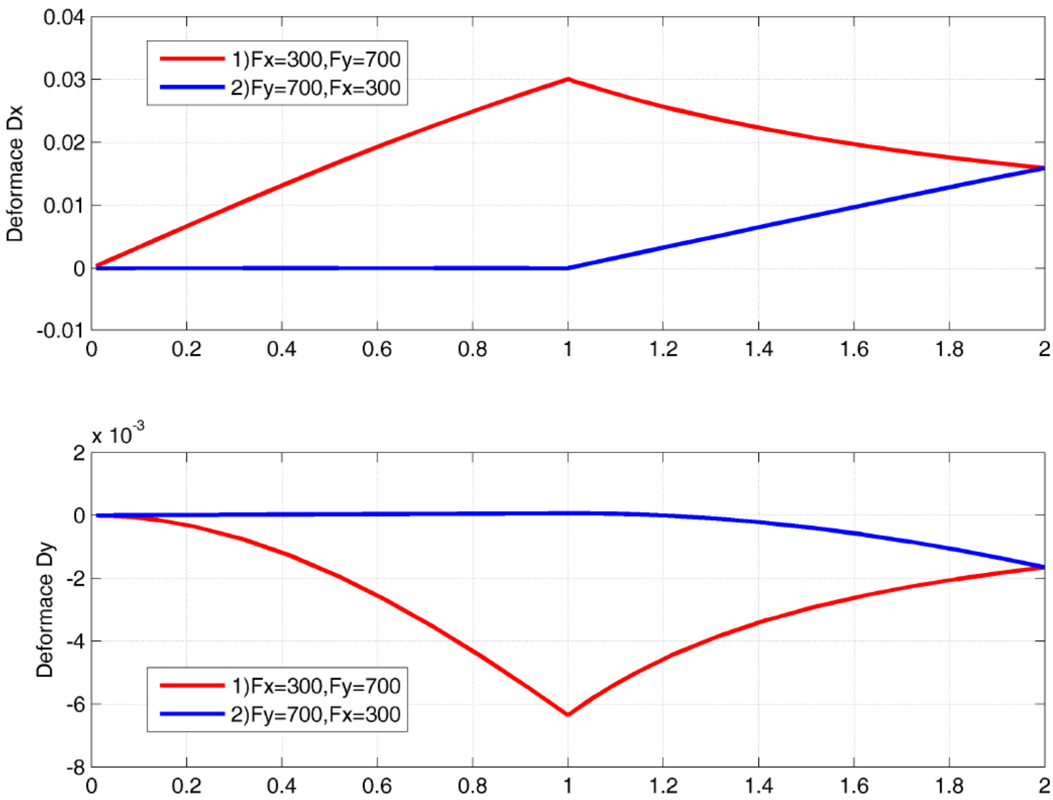


Fig. 7 Independence of loading path on final deformation – position

The FEM model has large number of degrees of freedom and it represents infinite number of degrees of freedom of real body. Due to the application of Saint-Venant principle the FEM model is loaded by forces (actuators, gravity and external loading) that are described by finite number of values. The motion of mechatronic flexible joint is characterized by the relative position and orientation of rigid flanges on both ends of flexible body of mechatronic flexible joint. Therefore the motion of mechatronic flexible joint can be described by this finite number of parameters – force elements, position and orientation.

4 EFFICIENT MOTION DESCRIPTION

The next problem is the investigation of suitable efficient description of motion of mechatronic flexible joint. The investigation of suitable methods of reduction of FEM models has continued the approach [3]. The suitable and efficient reduction of FEM models especially parametrized is still a challenge. However, for the final description it was applied the approach used for efficient approximation of nonlinear functions. The reduced models were approximated by LOLIMOT method.

It is an adaptive nonlinear description of input-output relation of a nonlinear system [3]. The output **y** is described as a function of input **u** by summation of linear models with coefficients **w** and weighting Gaussian functions **Φ**

$$\hat{y} = \sum_{i=1}^{M} \hat{y}_i \Phi_i(\mathbf{u}) = \sum_{i=1}^{M} (w_{i,0} + w_{i,1}u_1(k) + w_{i,2}u_1(k-1) + w_{i,n_1+1}u_1(k-n_1) + w_{i,n_1+2}u_2(k) + w_{i,n_1+3}u_2(k-1) + \ldots$$
$$+ w_{i,n_1+n_2+2}u_2(k-n_2) + w_{i,n_1+\ldots+n_{p-1}+p}u_p(k) + w_{i,n_1+\ldots+n_p+p}u_p(k-n_p) + w_{i,n_1+\ldots+n_p+p+1}y(k-1) + w_{i,n_1+\ldots+n_p+p+n_y}y(k-n_y))\Phi_i(\mathbf{u}) \quad (1)$$

The overall nonlinear function is replaced by local linear functions that are smoothened by Gaussian functions **Φ** in weighted sum.

By this approach the results from simulation of motion of mechatronic flexible joint (Fig. 6) was processed and compared with the original simulations. The example of FEM simulation of motion from Fig. 6 is in Fig. 8 and its LOLIMOT description is in Fig. 9. This approximation reaches very high value of accuracy. This was published in [4].

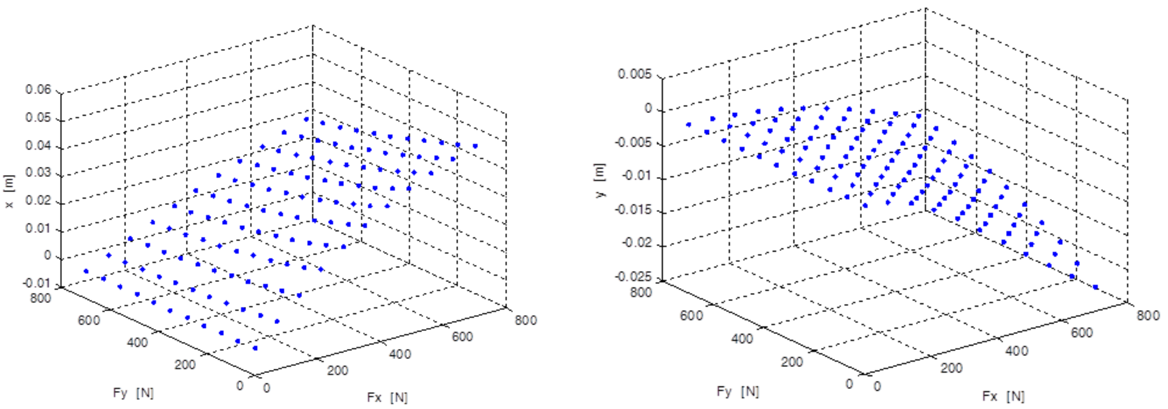


Fig. 8 Example of motion of mechatronic flexible joint from FEM simulation

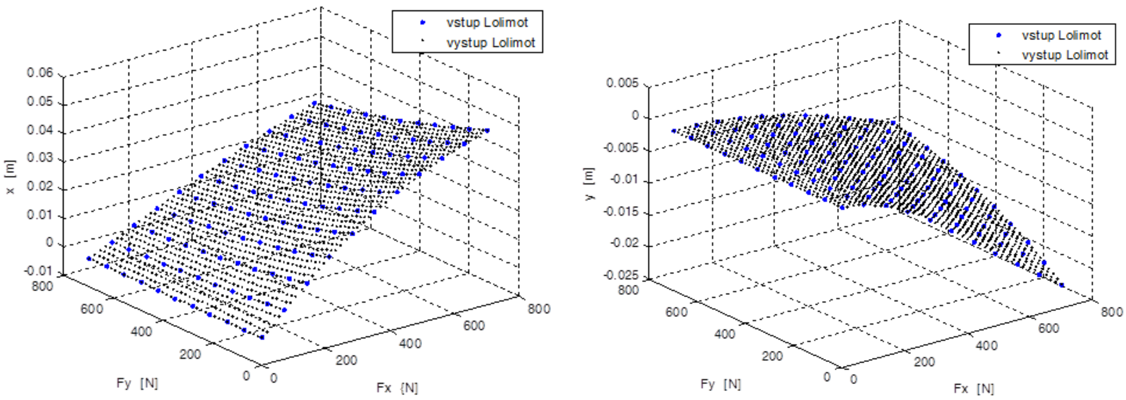


Fig. 9 The motion of mechatronic flexible joint from Fig. 8 described by LOLIMOT approach

6 CALIBRATIONS

After the solution of efficient description of motion of mechatronic flexible joint the next challenging problem is the calibration of mechatronic flexible joint with possible self-calibration. Three different approaches of the calibration problem have been investigated. The details are discussed in [5]. The basic principle that has been applied in order to enable the self-calibration was the usage of redundant number of sensors (measurements).

6.1 Approach of rigid body

The motion of the upper flange with respect to the lower flange (Fig. 5) is the general planar motion of the upper flange. The description and calibration problem is to resolve such general description. The proposed principal approach for this planar case is in Fig. 10. The necessary measurements are 3, there are 4 measurements in each position and the calibration index is 4-3 = 1. The calibration index i_C is defined

$$i_C = i_S - i_{DOF} \tag{2}$$

where i_S is the number of sensors (measurements) and i_{DOF} is the number of degrees of freedom. Therefore the self-calibration is possible and for calibration no external measurements are necessary (the usage of external measurements is usual current approach). The problem is that the calibration ration that is the number of redundant measurements per one kinematic loop is only 1/3 (1 redundant measurement and 3 independent kinematic loops). The calibration ratio r_C is

$$r_C = \frac{i_C}{i_L} \tag{3}$$

where i_L is the number of kinematic loops inside the calibrated multibody system.

This is too low. The experience from calibration of parallel kinematic structures [6, 7] is the necessity of this ratio larger than 0.5. (The maximum value for multibody systems consisting from rigid bodies in plane is 3 and in space is 6.)

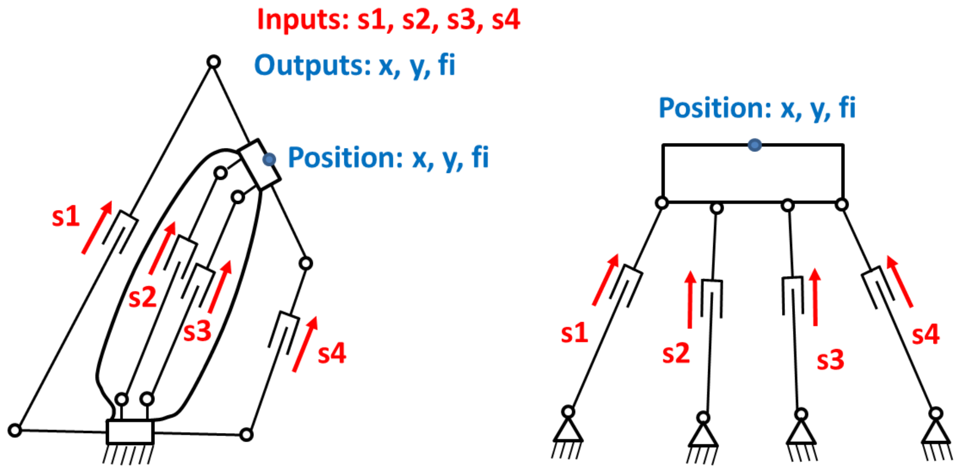


Fig. 10 Mechatronic flexible joint as rigid body motion

Therefore the schemes in Fig. 11 have been proposed. Adding the angular measurements increases the number of redundant measurements per one kinematic loop to 3/2 in Fig. 11a and 6/2=3 in Fig. 11b. The calibration properties of this approach are similar to the advantageous properties of parallel kinematic structures like RedCaM, Sliding Star etc. However, the instrumentation of many sensors outside the flexible body is not easy especially due to the possible collisions of links. Therefore another approach using the sensors mounted inside the flexible body is searched.

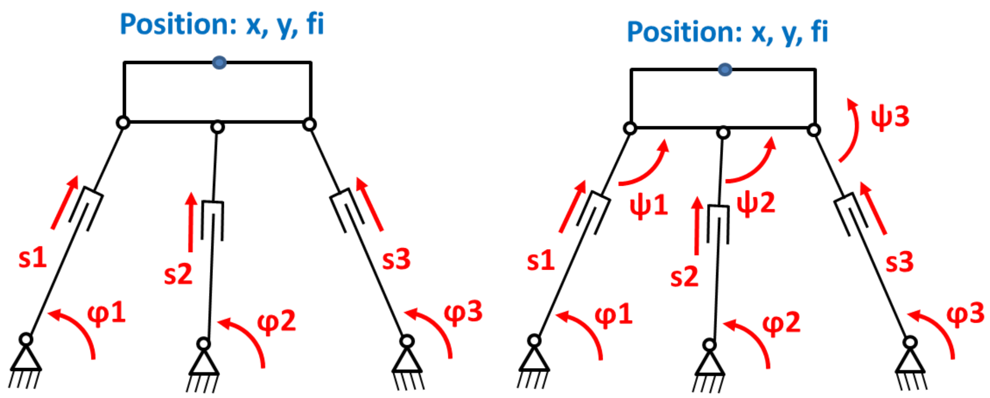


Fig. 11 Mechatronic flexible joint as rigid body motion with improved calibrability

In case of inflated structures the feasible measurement approach for spatial mechatronic flexible joints based on rigid body approach with sensors inside the flexible body from patent [1] is in Fig. 12. However, it requires laser interferometers.

6.2 Approach of sensor network

The second approach is based on the usage of multiple sensors mounted in the flexible body of the mechatronic flexible joint and forming in fact the closed connection from one flange to another one (Fig. 13). Each point of the network is connected to at least three previous points with links that include deformation sensors. This can be feasible by strain gauges. However, if one such cell is analyzed in details (Fig. 14) then the calibrability is bad as the number of redundant measurements per one kinematic loop is low. Each point is in fact a small body. The number of redundant measurements per one kinematic loop is in Fig. 14 equal 1/3 (the same as in Fig. 10). The improvement is proposed in Fig. 15 where the number of redundant measurements per one kinematic loop is 5/3 and 3. However, such solutions require many sensors and therefore are not feasible.

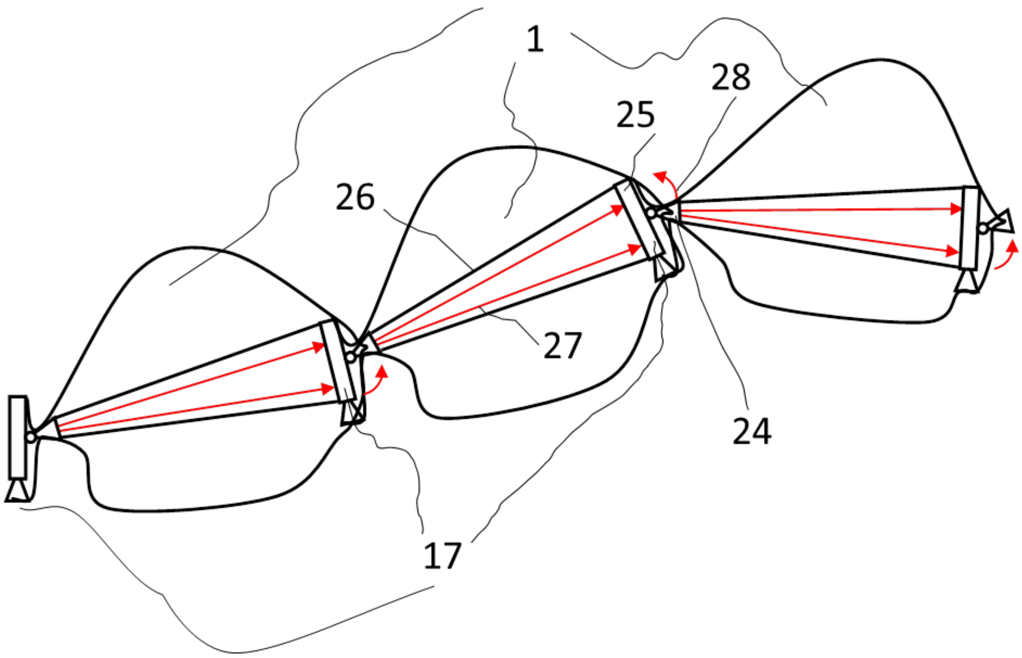
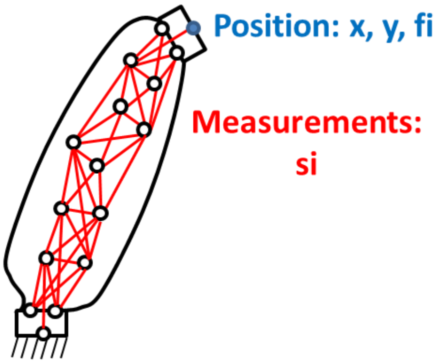


Fig. 12 Measurement of motion of mechatronic flexible joints from patent [1]



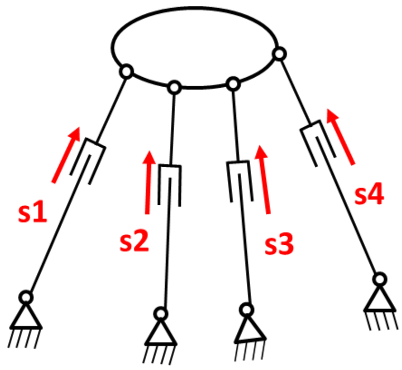


Fig. 13 Mechatronic flexible joint as network of sensors Fig. 14 Detailed analysis of one cell

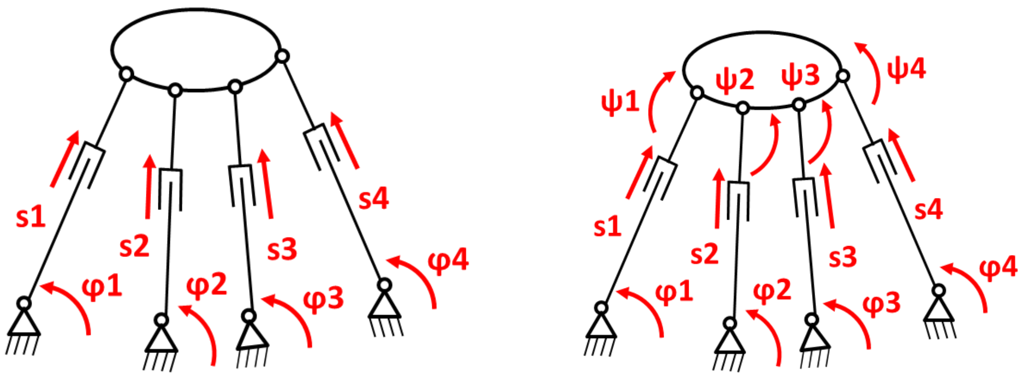


Fig. 15 One measurement cell with improved calibrability

6.3 Approach of redundant regression

The third approach uses the concept of self-calibration. It is supposed that on the flexible body of the mechatronic flexible joint there are mounted a set of sensors s1j that enable to describe the position of the upper flange with respect to the lower flange. It is supposed that there is mounted at least another such set of sensors s2j (Fig. 16). If the regression expression is applied then it holds for the description of the position [x, y, φ] of the upper flange

$$
\begin{aligned}
x &= \sum_i a_{1xi} b_i(s_{1j}) \\
y &= \sum_i a_{1yi} b_i(s_{1j}) \\
\varphi &= \sum_i a_{1\varphi i} b_i(s_{1j})
\end{aligned}
\tag{4}
$$

where a1xi, a1yi, a1ϕi are regression coefficients for the base regression functions bi(s1j) in measured values s1j. The base functions can be polynomials or members of Fourier series.

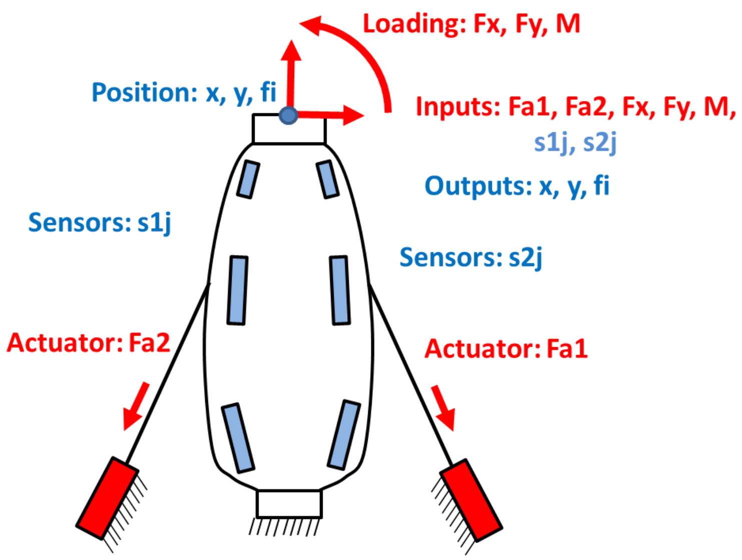


Fig. 16 Mechatronic flexible joint as rigid body motion as redundant regression

Similarly for the other set of sensors

$$
\begin{aligned}
x &= \sum_i a_{2xi} b_i(s_{2j}) \\
y &= \sum_i a_{2yi} b_i(s_{2j}) \\
\varphi &= \sum_i a_{2\varphi i} b_i(s_{2j})
\end{aligned}
\tag{5}
$$

Comparing both set of equations (4) and (5) the following equations for calibration regression can be derived

$$
\begin{aligned}
\sum_i a_{1xi} b_i(s_{1j}) &= \sum_i a_{2xi} b_i(s_{2j}) \\
\sum_i a_{1yi} b_i(s_{1j}) &= \sum_i a_{2yi} b_i(s_{2j}) \\
\sum_i a_{1\varphi i} b_i(s_{1j}) &= \sum_i a_{2\varphi i} b_i(s_{2j})
\end{aligned}
\tag{6}
$$

The equations (6) can be solved by regression for the unknown coefficients under the important assumption that within the measurements (sensors) some lengths are included, otherwise some external measurement of absolute positions is necessary. The application is currently being simulated.

Nevertheless the calibration and self-calibration under these wide conditions is possible. The calibration index i_C must be redefined

$$
i_C = i_S - i_{PAR} \tag{7}
$$

where i_{PAR} is the number of parameters that fully characterizes the mechatronic flexible joint. It is the generalization of degrees of freedom for multibody systems but taking into account the number of inputs as discussed in the solution of first project objective in the previous year. The calibration ratio r_C must be also redefined

$$
r_C = \frac{i_C}{i_{SL}} \tag{8}
$$

where i_{SL} is the number of sensor loops the mechatronic flexible joint, i.e. the number of measurement sets s_{kj} minus 1. In the above described case it is 2-1=1. For the example in Fig. 16 it is i_{PAR} =5, i_S =6, i_C=1, i_{SL}=1, r_C=1. The number of sensors is in the case of mechatronic flexible joint in principle not limited. Therefore the calibration ratio can be larger than in the case of rigid multibody systems. However, the conclusions from the thesis [6] about the influence of multiple redundancy and the experience of necessary values of r_C for good and accurate results must be investigated and confirmed.

7 CONCLUSIONS

The paper has described the basic principles for efficient description of motion of mechatronic flexible joint. The described approach enables also efficient identification of the description. By this way the motion description of mechatronic flexible joint achieved the same complexity as traditional kinematic description.

Acknowledgment.

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