Kinematic calibration of a 2-DOF flexure-based manipulator

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Flexure-based mechanisms enable high dynamic performance, repeatability and accuracy in high precision applications due to the absence of friction, hysteresis and backlash. Usually the mechanism's motion is captured by means of sensors that measure the actuators' displacement or rotation. Hence in order to achieve true end-effector accuracy the relation between actuator and end-effector motion has to be known. Such kinematic and inverse kinematic relations can be derived from models that account for the complicated non-linear behaviour of the deforming compliant joints. For real-time applications simplified expressions are required that can be evaluated much faster. In [1] we showed that polynomial relations offer the combination of sufficient accuracy and required computational speed for a 6-DOF flexure-based parallel manipulator. Unfortunately, the experimental verification for this system didn't yield the expected accuracy, most likely due to hysteresis and friction in the actuators.

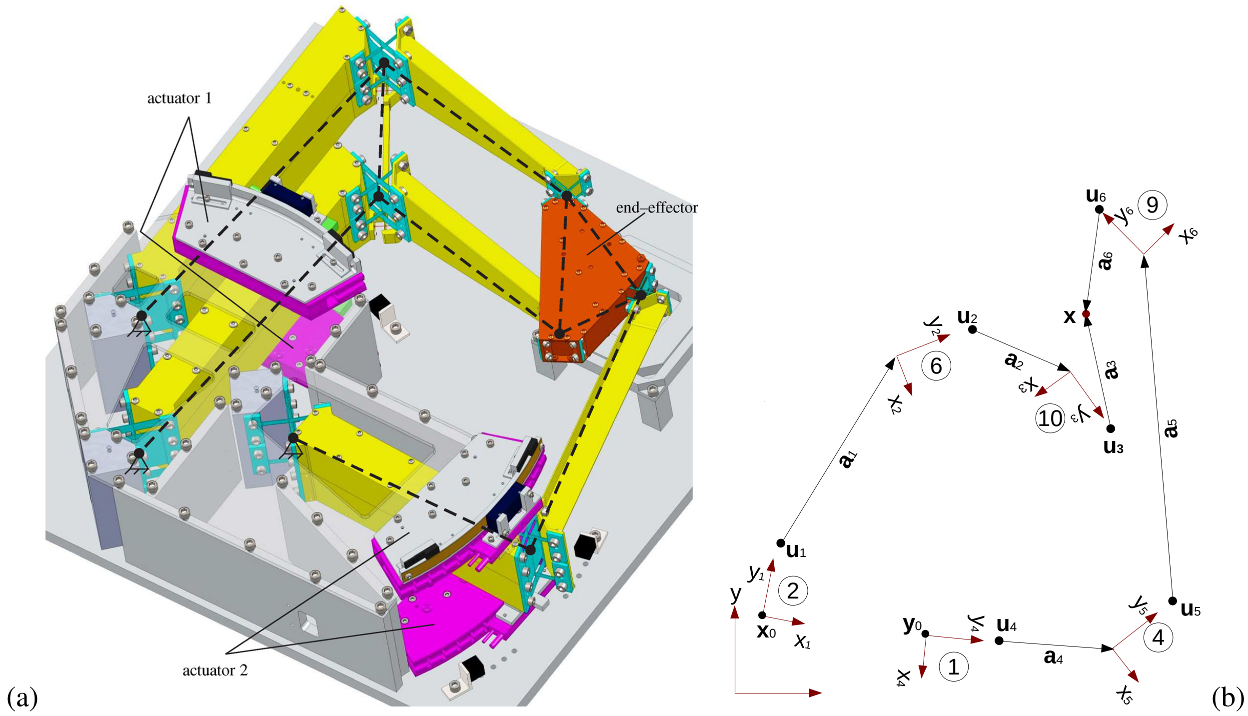

Fig. 1: (a) Two-DOF mechanism with two base mounted actuators and eleven cross-flexure hinges allowing motion of the end-effector in two translational directions (from [2]). (b) Schematic overview for the kinematic analysis (from[3]).

In the present paper we would like to avoid this non-ideal behaviour by investigating the kinematic relations of the fully flexure-based 2-DOF manipulator shown in Fig. 1(a) [4]. All eleven joints in this manipulator are cross-flexure hinges. Hence there are no apparent sources of hysteresis due to play or friction, although some disturbances may be expected e.g. from the wired connection of the actuators and hinges.

At first the deformation of a single cross-flexure hinge as shown in Fig. 2(a) is analysed. Analytical solutions are known since the pioneering work of Haringx [5] and numerical solutions have been given by various authors. We used our SPACAR software package of which the non-linear beam model is well-suited to evaluate the shape of the sheet flexures in the hinge when deformed and possibly loaded. The motion of an arm connected to the hinge is simulated as a function of the rotation angle θ of the hinge. More specifically, the coordinates u_x and u_y

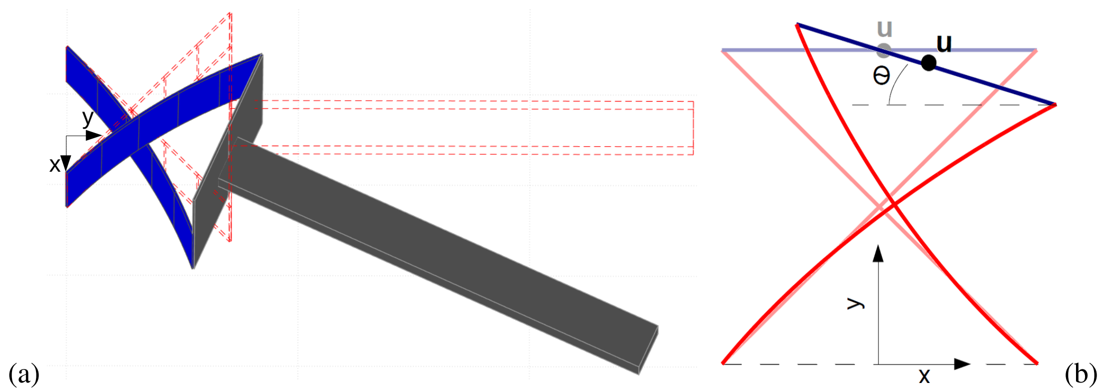

Fig. 2: (a) Single cross-flexure hinge with simulated deformation and (b) the definition of point **u** to describe the joint kinematics (modified from [3]).

of a point **u** on the connection between arm and hinge as illustrated in Fig. 2(b) are considered. It appeared that relatively simple polynomials offer already a sub-micron accuracy for cross-flexure hinges with typical dimensions of about 20–50 mm. Due to symmetry only odd or even terms remain and for this accuracy only up to four orders are required, i.e.

$$\begin{aligned} u_x(\theta) &= a_{x1}\theta + a_{y3}\theta^3, \\ u_y(\theta) &= a_{y0} + a_{y2}\theta^2 + a_{y4}\theta^4. \end{aligned} \tag{1}$$

The coefficients a_{xi} and a_{yi} are obtained from a straightforward fit to the simulated joint motion.

Next the hinge models are combined into a kinematic model for the complete manipulator, see Fig. 1(b). The cross-flexure hinges are numbered 2, 6, 10, 1, 4 and 9. The kinematic hinge relations are expressed in a local coordinate system for each hinge. The point **u** previously defined for each hinge is connected with a rigid link denoted $\mathbf{a_j}$ to the origin of the local coordinate system of the next hinge or to the end-effector. Parameters are used to model possible inaccuracies in the set-up such as encoder offsets, inaccurate position of the base points and errors in the dimensions of the links between the hinges. As this easily results in a model in which not all parameters are independent, a singular value decomposition (SVD) is used to determine a base parameter vector. This vectors includes only independent parameters that can be identified from combined measurements of the Cartesian end-effector position and the encoder readings. A simulation showed that using position data with 5 μm noise results in a vector with 10 parameters that could be identified and gives a kinematic model of which the accuracy is consistent with the noise level.

In the paper to be presented at the conference we plan to include an experimental validation as well and evaluate the practical usability of the proposed method.

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References

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