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METROLOGICAL CHARACTERIZATION OF A HEXAPOD FOR A MULTI-COMPONENT CALIBRATION DEVICE

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Abstract – A newly developed measuring device [1] allows the generation and measurement of arbitrarily directed forces and moments. This device consists of a driving unit for generating the loads and a measuring unit for the accurate measurement of the acting components. Both units are realized as hexapod structures with the same geometry but mirrored arrangement. This paper describes the metrological characterization of the hexapods of this multi-component measuring device.

Keywords: multi-component calibration, force and moment measurement.

1. INTRODUCTION

The widely used calibration devices for force and torque have in general a certain direction of the quantity to be generated. Very rare are special multi-component calibration devices for the measurement of arbitrarily directed forces and/or moments. Multiple force generating systems like weight stacks, ropes and pulleys are used in these machines to superimpose single force and/or moment components.

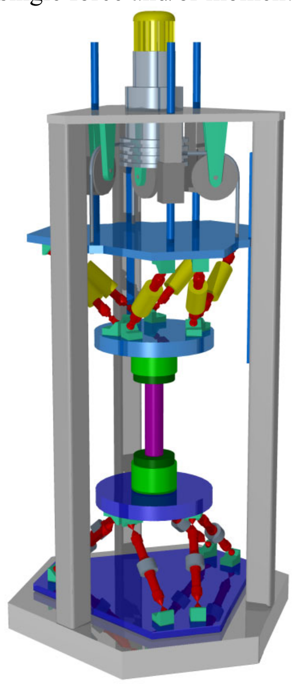


Fig. 1. Design of the multi-component calibration device (PTB and GTM - Gassmann Theiss Messtechnik GmbH)

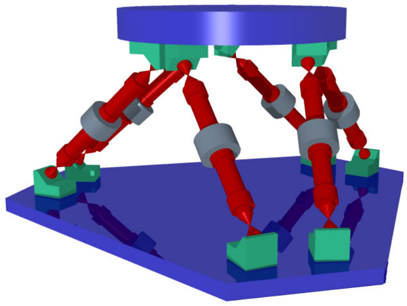
The device described here (Figure 1, forces: up to 10 kN, moments: up to 1 kN·m, overall height about 4 m) is an attempt to realize the multi-component principle without weights and pulleys. A set of six electrical drives is used for the load generation, the measuring system is represented by a set of six force transducers. Both sets are implemented as hexapod structures. The theoretical basics of these arrangements have been published in [1], the consideration of different types of joints is the subject of [2]. The given paper deals with the metrological investigation of the multi-component calibration device, in particular with the requirements for the geometry of the hexapods. This multi-component calibration device will be used for the calibration of special sensors for the monitoring of buildings and constructions.

2. METROLOGICAL PROBLEMS

From the mathematical point of view the two hexapods realized in the machine can be described by the positions of the turning points of the joints at the ends of the links. Two each of the 12 turning points of a hexapod constitute a pair with a fixed distance of $2{\cdot}f$ or $2{\cdot}g$. The centres of these pairs lie on two horizontal and concentric circles with radii r_{u} and r_{o}, wiht a vertical distance h between them, at 120° angles on the circumference of the circles. The positions of these centres differ by 60° between upper and lower circle. The attack angle of the links (inclination against the horizontal), but also the angles of the link projections in the horizontal plane, result from the five parameters given above.

The hexapod links in the lower part of the machine contain force transducers which are able to measure the link forces (Figure 2 shows a more detailed view of this measuring hexapod and its geometrical parameters, Figure 3 shows a single link), in the upper hexapod there are drives for the generation of the load components. Different joint geometries are used in the two hexapods, but the geometrical dimensions are the same on both sides.

In reality this theoretical description will only apply approximately. Due to manufacturing tolerances all length measures will differ from the desired values to a greater or lesser extent and a "real" geometry will result. The joints used at the ends of the links are weak against bending and allow the measurement of the angles to be avoided. During the construction of the machine the real lengths and distances will lead to the appropriate angles as the result of a self-adjusting process. These angles can also be calculated from the known length values and can be used in the theoretical description of the machine.



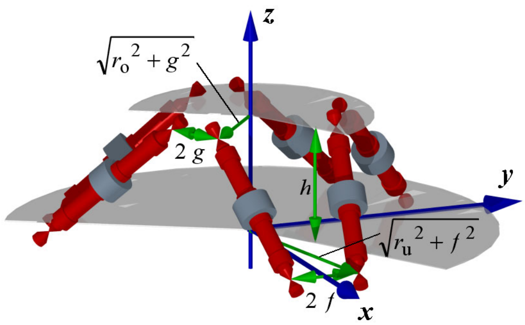


Fig. 2. Drawing of the measuring hexapod (above) and length measures defining the geometry (below)

It was now the task to investigate the influence of the manufacturing tolerances and the transducer properties on the uncertainty of measurement of the machine. The results can be proved in future by measuring calibrated force, torque or multicomponent transducers and by comparing the indicated signals with the calculated values. The deviations should be within the measurement uncertainty of the machine.

3. SOLUTION

3.1. Theoretical Considerations

The calculation of the decomposition of the forces and moments to be generated into the six link forces can be found in [1]. For the idealized geometry assumed, a set of six equations had to be solved and a computer algebra software was used. By varying the parameters and comparing the results for the different components more or less optimal values of the parameters were found. They are given in Table 1.

Table 1. Caculated hexapod parameters

parameter	r_u	r_o	$2{\cdot}f$	$2{\cdot}g$	h
value in mm	500	230	180	180	348,4

In order to estimate the influence of the tolerances it is possible to repeat the calculation of the link forces for the different force and moment components with slightly altered values of the parameters given in Table 1. The results are link forces which deviate from those for the unchanged parameters.

The differences between corresponding forces are a measure for the influence of the geomtrical deviations of the structure on the measurement uncertainty of the machine. On the other hand, the actual values of the parameters found in measurements, for example, on a co-ordinate measuring machine can be used in the theoretical description, i. e. in the set of equations for the composition which is necessary for the calculation of the acting forces and moments from the measured link forces.

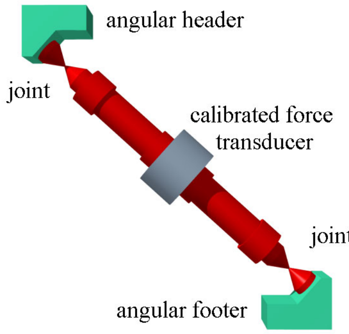


Fig. 3. Measuring link with force transducer (centre), joints at both ends, angular header and footer

Calculations for the investigation and application of multi-component techniques are mostly always very time consuming, but due to the symmetry of the hexapod structure it is possible to compare the different resulting forces for one link only. Nevertheless, a complete solution requires that all possible values and directions in space of the two (external for the hexapod) vectors force or moment be considered. A compromise was found by taking the maximum value for the two quantities (10 kN force and 1 kN·m moment) and by dividing the ranges for the azimuth angle φ ($0° \leq \varphi \leq 360°$) into 36 and for the height angle ψ ($-90° \leq \psi \leq 90°$) into 18 equal intervals of 10° resulting in $19{\cdot}36 = 684$ directions of each of the two vectors (some of them coincide for the directions with $\psi = 90°$ or $\psi = -90°$).

Now each of the parameters r_u, r_o, f and g was taken with the value from Table 1 increased by 0,1 mm. The attack angle α of the links (cf. (2) in [1]) containing the information about h was increased by 0,01°, corresponding to 0,12 mm change in h. Then the link forces were calculated for every single parameter and all the directions of each of the two load vectors using the same formulae as for the hexapod optimization.

For the visualization of the different directions in space the surface of the sphere described by a vector rotating in two dimensions was mapped on a rectangular area. Figure 4 shows the link forces (in N) in the links 1 (upper part) and 2 (lower part) for a maximum external force of 10 kN and all its possible directions. The diagram for the other links look very similar and due to the different direction of each of the links (projected to the x-y plane) there is a shift of the curves in the φ direction, as can be seen in the two parts of Figure 4.

Figure 5 shows the link forces (in N) in the link 1 (upper part) and link 2 (lower part) for a maximum external moment of 1 kN·m (the reference distance for the moment is 0,35 m) and all the possible directions. Here were can see that the second part of the diagram can be generated by shifting and reflecting the first part. And again the diagrams for the other links are similar to that shown in Figure 5 including a certain shift and, if necessary, a reflection.

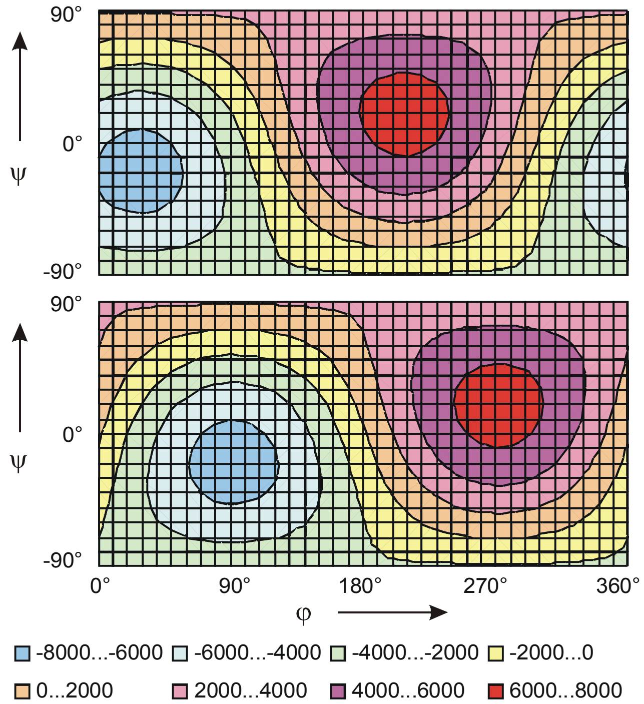


Fig. 4. Link forces (in N) in link 1 (above) and link 2 (below) for a 10 kN external force with direction (φ, ψ)

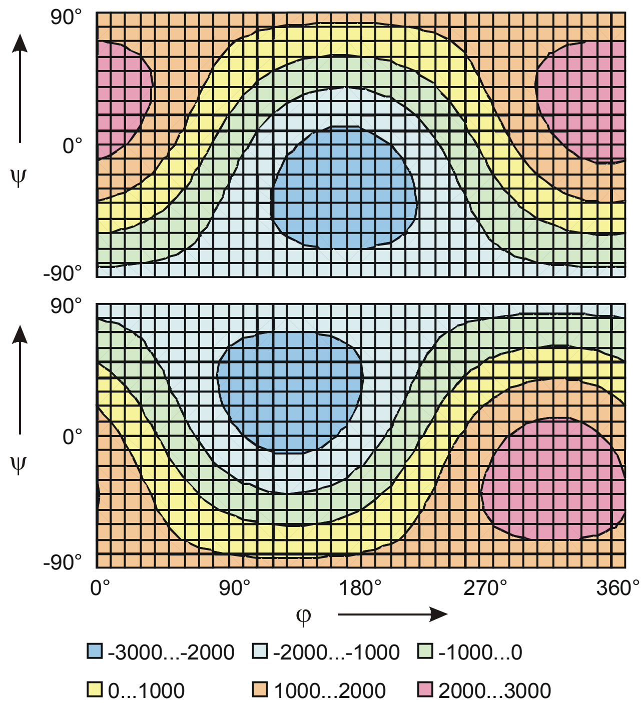


Fig. 5. Link forces (in N) in link 1 (above) and link 2 (below) for a 1 kN·m external moment with direction (φ, ψ)

The diagrams show that we can consider only one link on condition that we take all possible directions of the force and moment vectors. The aim now was to determine the variations of the link forces for small deviations of each of the above defined parameters.

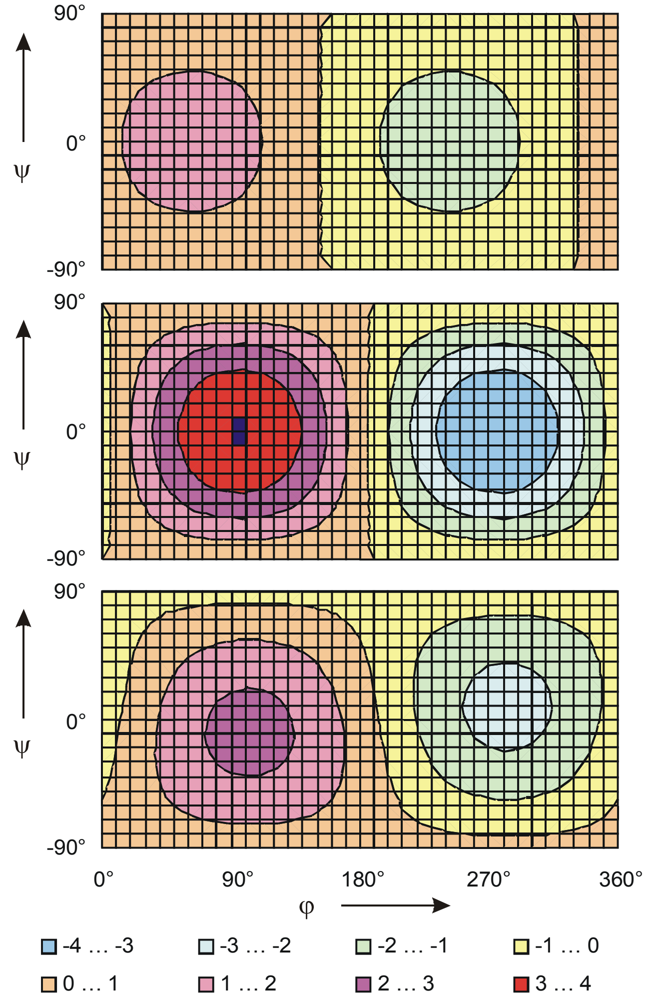


Fig. 6. Link force variations (in N) in link 1 for an increase of 0,1 mm in the parameters: Δg (above), Δr_o (middle) and Δh (below) for a 10 kN external force with direction (φ, ψ)

Figure 6 shows some of these results for the case of an external force. The link force variations for Δr_u are much smaller than those for the other parameters, because r_u has the highest value of all the parameters and so the smallest relative deviation of 0,1 mm/500 mm = 0,02%. The variations for Δf are in the range of those for Δg. Therefore the results for the two parameters Δr_u and Δf are not included in the diagrams.

Figure 7 shows the same results for the case of an external moment. The link force variations for Δr_u are again much smaller than those for the other parameters. The variations for Δf are now about 50% higher in comparison with those for Δg. The dependence on Δh is a little less strong than in the case of the force. Therefore, Figure 7 contains only the results for the parameters Δf, Δg and Δr_o.

All the results are shown in Table 2. Comparing the values it must be kept in mind that the link forces for the maximum external force are about two and a half times higher than those for the maximum external moment. In addition, the calculations were carried out with 10° steps for each of the angles. But on the other hand, the surfaces described by the resulting vectors are smooth enough without sharp peaks, so that the results are very close to the unknown link forces and their variations.

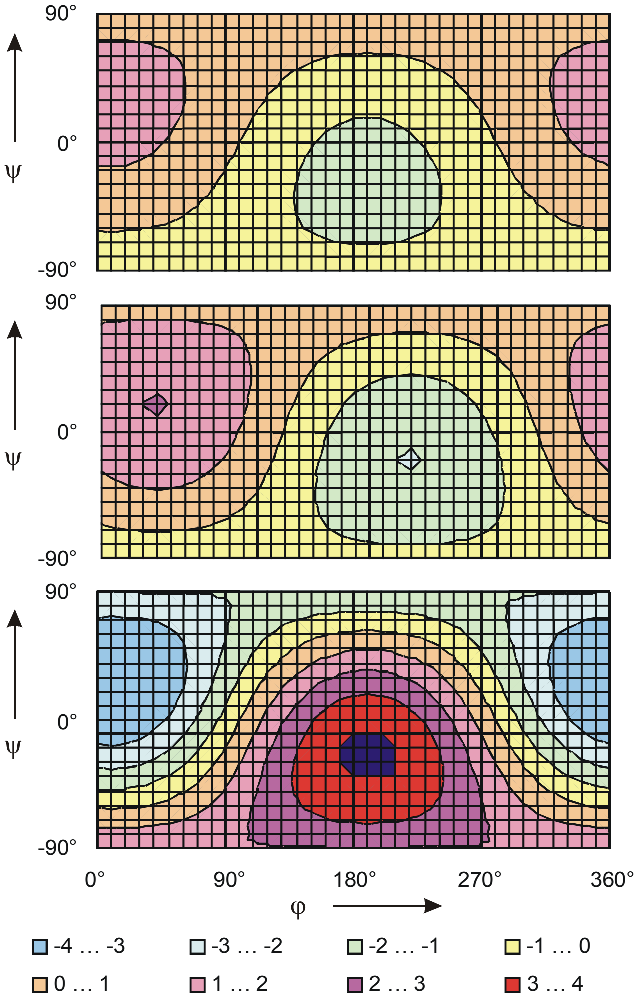


Fig. 7. Link force variations (in N) in link 1 for an increase of 0,1 mm in the parameters: Δg (above), Δf (middle) and Δr_o (below) for a 1 kN·m external moment with direction (φ, ψ)

Table 2. Calculated link force variations

parameter	r_u	r_o	f	g	h
value in mm	500	230	180	180	348,4
variation in mm	0,1	0,1	0,1	0,1	0,1
	for an external force of 10 kN				
max. link force in N	6843,10				
max. variation in N	0,35	4,09	1,67	1,52	2,33
	for an external moment of 1 kN·m				
max. link force in N	2693,23				
max. variation in N	0,21	2,14	1,01	0,70	0,45

A rough estimate of the force variation effect resulting from deviations in the geometry using the data given in Table 2 shows that the geometry of the hexapod should be known with a small absolute uncertainty not exceeding 0,01 mm. Especially for the parameter r_o the uncertainty should be even below this value. The manufacture of the parts and components with such small tolerances is possible, but to be sure about the real geometry the measurement of the parameters is the better choice.

3.2. Practical Considerations

The idea was now to determine the geometry of the hexapod on a co-ordinate measuring machine. Unfortunately, the hexapod has quite a complex structure combined with relatively large dimensions and weight. Therefore the measurement of the single components was considered.

The base and the cover plates of the two hexapods are manufactured by grinding with small tolerances for evenness. They have centring holes for the link feet (footers and headers) and one reference hole in the middle. The position of the centres of these boreholes relative to each other must be measured for each of the plates.

The links are connected to the base and cover plates by special angular footers and headers (see Figure 3). These parts also have centring holes in order to guarantee precise positioning during assembly. The links are designed in such a way that their joint centres have a given vertical distance to the nearest plate and their projection should lie in the middle of the centring holes. It is necessary to measure the position of the joint centres and the centring holes for all the six measuring and the six drive links.

The final information needed to describe the hexapod is the length of each of the links defined as the distance between their joint centres. The joints are the "weak" points of the hexapod where the greatest deformation will take place. Very important is the self-adjusting process during assembly of the hexapod. Here the constant preload of about 2,5 kN introduced by the weight of the upper plate must be taken into consideration. The stiffness of the links was defined during the calibration of the force transducers. The preload acts on the links and generates link forces which can be recorded. The shortening of the links can then be derived from the known stiffness and the resulting geometry can be calculated.

The measuring procedure is now specified in a more detailed way. First of all a reference plane must be defined on the top (bottom) surface of the base (cover) plate. Then the local area where the footer (header) will be placed must be measured with respect to the coplanarity. If there are larger deviations then the joint centre will not lie on the perpendicular of the reference plane erected in middle of the centring hole. Afterwards the positions of the centres of these boreholes must be determined.

The same must be done for the links: a reference plane must be defined on the horizontal bottom (top) surface of the angular footer (header). Now the position of the centring boreholes ("reference points") can be measured in this plane. After that the centre of the joint must be defined as the centre of the smallest cross section of the joint (the pivot) and the position of this point in space must be measured in relation to the reference plane and the reference point. This procedure has to be carried out for the link footer and the link header.

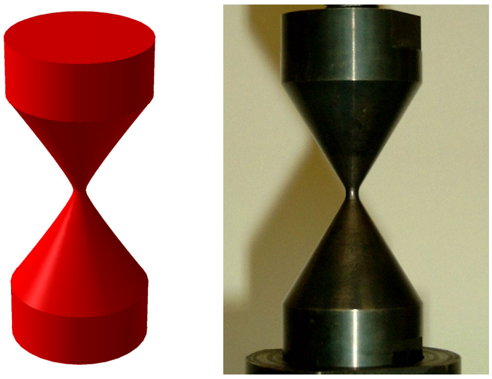


Fig. 8. Rotationally symmetrical joint

Rotationally symmetrical joints (Figure 8) are integrated in the measuring links, whereas the driving links are equipped with universal joints (Figure 9). For the first ones it is no problem to define the pivot. The latter have two cross-sections with minimum area at an angle of 90° and representing the pivots for two possible bending movements which are perpendicular to each other.

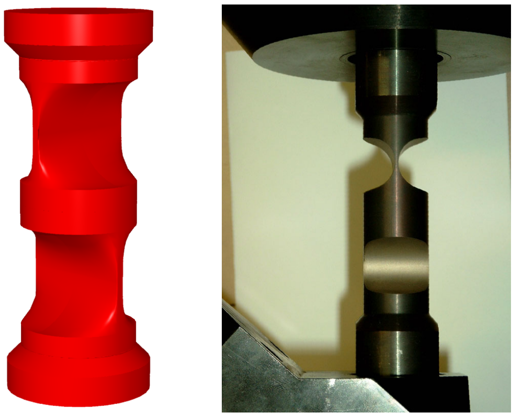


Fig. 9. Universal joint

On the drive side there is no need to know the geometry with very high accuracy. It is intended to use the machine in a countinuous calibration regime and therefore it should be sufficient to establish a given load (force and/or moment vector) with an uncertainty of a few percent. More important is the precise measurement of the load state reached during the calibration process. Thus for simplicity the centre of the two pivots for the bending was taken as the reference point. It can be found from the measured position of the two pivots by calculation. The result is the position of the pivots with respect to the above-defined reference plane and the reference point.

The link length as the distance between the centres of the joints can be easily measured for the links on the measuring side. For the drive links the pivots should be taken - as just explained - as the centres of the pivots for the two bending directions. Then the length can be calculated from the position of the pivots on both ends of the link.

The practical considerations described above are now being applied to the real measurements and calculations. The results will be reported later.

4. CONCLUSIONS

The measurement uncertainty of the multi-component calibration device depends on different influence quantities, the most important are: the hexapod geometry, the force measurement in the force transducers and the distance from the measuring hexapod to the transducer which is to be calibrated. The paper deals with the first of the three topics, namely the characterization of the hexapod. It was shown that the geometry must be measured with an uncertainty of 0,01 mm or even less. A procedure for the co-ordinate measurement of the hexapod components is proposed and will be realized. Knowing the uncertainty contributions from all of the quantities mentioned above the measurement uncertainty of the device can be calculated.

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