Methods for calibration and testing of flexible arm measuring devices

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Abstract

The most important characteristic of measuring devices is the measuring uncertainty. To achieve and confirm high accuracy performances of flexible arm measuring devices, related test methods and appropriate equipment are needed. After a general discussion of this problem and presentation of some existing methods for calibration and testing of flexible arm measuring devices, a new approach of such measuring device is presented. As a result of this research work, a high precision measuring equipment "MOLLI" for testing and calibration of devices with rotational axes has been developed. In the paper we discuss the design and construction of this equipment, provide a theoretical calculation of measuring accuracy level and carry out some preliminary measurements to confirm the theoretical hypotheses.

1 Introduction

Portable 3D measuring devices with rotational axes found their place in many industrial areas. The main areas of their use are in automotive, aerospace, heavy, railway and energy industry. A robot-like, manually driven, multi joint, flexible arm device connected with a computer allows the users to achieve measuring tasks during maintenance, assembly, quality assurance, inspection, replication of complex models into 3-D data, or in measuring of free formed surfaces and curved pipe lines. Another application field is in connection with industrial robots1. The configuration of the Coordinate Measuring Machine (CMM) with rotational axes is not new. There exist some manually driven devices in
anthropoidic and SCARA configurations. To carry out the measuring tasks in the manufacturing industry, the measuring device uncertainty of measurement is one of the most important device requirements. The fact is that an open kinematic chain with more axes does not assure high rigidity and accuracy of mechanical structure respectively. On the other hand, the structure compactness, law weight, good flexibility, portability and good dexterity allow such devices completely new application areas. A quick survey of the existing device performances shows that the accuracy characteristics and the cost category of such devices are both below the Coordinate Measuring Machines (CMMs) level\(^5\). Only SCARA measuring machine ScanMax\(^3\) has currently the expected accuracy for the measurement in the mechanical manufacturing technology. It is obvious, that the use of special materials and the choice of the right construction can offer the possibility of solving this problem and to achieve relatively good repeatability performances of the devices with the open chain of kinematic structure\(^4\).

The experiments on the existing anthropoidic measuring device show that the remaining sources of errors have mostly a systematical character\(^5\). With an appropriate kinematic model it is possible to consider a great number of these errors. In this way the device accuracy characteristics can be improved through calibration and compensation by software. Many authors have considered and tested such calibration and compensation procedures \(^3,7,8,9\). The experiments in robotics show that it is possible to improve the absolute accuracy nearly up to the repeatability limitation. Critical points of these procedures are the effectiveness of the compensation model and the accuracy of the measuring equipment used for the calibration.

Another problem of a manually-driven coordinate measuring machine with rotational axes is represented through testing and verifying of the device accuracy characteristics. There are no international standards or guidelines for the measurement of such measuring devices with rotational axes. The problem appears also by choosing the right measuring method and the appropriate measuring equipment.

2 Methods for calibration and testing

As long as the measuring devices with exclusively rotational axes are mechanically configured as an industrial robot, we could still use the known related test methods and available equipment from the field of robot performance identification\(^10\). While such manually guided measuring devices have no own drive system, they have to be moved by an external carrier, which assures repeatable guiding. Therefore the optical measuring systems - such as camera, laser tracking or theodolite systems, known particularly from the robot performance identification - are not appropriate for these measurements.

The measuring devices with rotational axes might be considered as usual CMMs. For this purpose the experiences and methods of such techniques have been taken into consideration\(^11,12,13\). The assessment of measuring uncertainty of the whole anthropoidic measuring device with a probe can basically be the same as that performed by the CMM. However, the calibration of mechanisms with revolute axes and its verification requires a special approach, special measuring method and special equipment, such as we are know for the measurement of the CMMs. In practice, the measurements are carried out on reference bodies, such as line gauges or reference bodies. By these measurements all guiding and probe deviations go directly into the measuring result, and we cannot separate these different causes of
Existing measuring devices with revolute axes are calibrated and tested very differently. The method in Figure 1 uses special calibration and testing jig\(^1\). This jig consists of a bar with a set of predetermined precision balls, holes and a step gauge. It is mounted on an extensible vertical arm which can be adjustable in the space. By the initial calibration and testing the jig and the measuring device are placed on a large granite plate. The measuring device can measure the variety of positions for the testing jig in different areas of the volume. The data is then processed through a special programme designed to provide the relative misalignment and dimension of the whole arm system.

![Figure 1: Calibration and testing jig\(^1\)](image)

As a testing method for establishing the degree of volumetric accuracy, according to the ASME standard\(^2\) a ball bar approach can be used. Figure 2 shows a cone socket ball bar adapted for the measuring device with revolute axes\(^1\). With this apparatus a fixed length positioned in different positions and orientations of device working space is measured. On one side of the ball bar a probe is positioned in a cone socket and on the other side the ball is mounted in a magnetic socket of measuring device base. By the calibration measurements the measuring device is moved through multiple configurations in the device working space where the probe handle and all other joints must rotate. In such a way the calibration software calculates the vector length from the base to the centre of the ball at the probe which must remain constant.

![Figure 2: Cone socket ball bar adapted for measurements of devices with revolute axes\(^1\)](image)

The SCARA type measuring device can achieve the entire accuracy only with a calibration and compensation procedures. On the whole system these perform two main tasks: first, the calibration of kinematics on the circle gauge and then the calibration for the connection to the measuring system\(^3\).
For example, the repeatability measurements on the accurate CMM Zeiss UMC 850 - where the anthropoidic measuring device AMG-1 and the CMM, as the carrier and reference measuring system, were coupled together - did not prove to be useful. There appears a high dispersion of measuring results caused by CMM system deflection as a consequence of reaction forces when pushing such a measuring device with rotational axes.

From the above investigation and own experience on this area it was clear that only a robust mechanical equipment for measuring and guiding along any reference line adjustable in the space, can provide a promising high precision solution. It can be taken as an appropriate reference measuring system under stable environment conditions for the calibration and test measurements of manually moved flexible arm measuring devices. To confirm this supposition, the existing high precision length comparator in a stable environment of a climatic chamber in the laboratories of the Institute for Production Technology at TU Graz in Austria was used. It consists of a granite straight edge and an integrated drive sledge with air bearings as a reference straight line system. As a length reference system a laser interferometer system was used. On this high precision length comparator repeatability and accuracy measurements of the anthropoidic measuring device AMG-1 with exclusively rotational axes were carried out automatically.

Regarding the research and experimental work carried out in a close cooperation between the Faculty of Mechanical Engineering, University of Maribor, Slovenia and the Institute for Production Engineering, Technical University Graz, Austria, a new adjustable high precision reference length comparator has been developed.

3 New high precision measuring equipment

The main design requirements were to design a light, rigid, portable system, adjustable in the space which would be able to perform calibration and test measurements of devices with rotational axes automatically and with highest precision. As a result of the research work, a new high precision measuring equipment "MOLLI" was developed. The whole system consists of a reference line gauge, a bearing system, drive system, measuring system, control system and support arrangement (Figure 3).

![Figure 3: Main components of the measuring equipment MOLLI](image)

The idea of the proposed measuring equipment is to collect the calibration
data along a straight reference line adjustable in various space directions. While the distance measuring system is located separately from the reference line gauge beam, the main task of the reference line gauge beam system remains only to guide the sledge exactly within the demanded limitations, with respect to the orientation deviations, along the reference straight line. In this way we get the position deviations along the straight line at a constant orientation. The arrangement of this new measuring equipment is presented in Figure 4.

Figure 4: New reference measuring equipment in various space directions

At the initial stage of the design of a new measuring equipment we set a limitation for positioning accuracy which the measuring equipment should achieve. This limitation was established through repeatability measurements, made on the anthropoidic measuring device AMG-1. The experiment which was made on a high precision length comparator in a stable environment of a climatic chamber shows that the repeatability in the most advantageous workspace of AMG-1 is ±1.5 μm for the statistical probability of 95%\(^\text{16}\). However, there is no need for the measuring equipment to be better than this limitation. Therefore, the accuracy level of the measuring equipment MOLLI was set to ±2 μm for the statistical probability of 95%. To achieve this requirement many comparative studies and design simulations were done\(^\text{17}\).

The main components for the determination of the measuring equipment accuracy are the beam, the bearing and measuring system. For a reference straight line gauge a hollow ceramic beam with dimensions 100 x 160 x 2000 mm was chosen. The longitudinal straightness of the two perpendicular ceramic beam surfaces is manufactured with the tolerance of 1 μm/m. The calculations show that the bending deviation in the horizontal direction Z under the external force of max. 50 N does not exceed a deviation value of 1 μm or an angle of 0.5 \(\text{arc second}\)\(^\text{18}\).

Because of the anthropoidic kinematic configuration of the device to be measured, the end-effector moving forces change permanently. The results of experiments show that the moving force in the favourable part of the measuring space in different measuring positions from different directions does not exceed the
force of 5 N. While movements in the area, which is close to the singularity, cause higher moving forces, we make calculations with a value for the external force in X and Y direction of 50 N.

The reference measuring system is designed for measurements in various space directions. Since it is also possible to measure in vertical direction, a counterweight is needed. It is located and guided on separate shafts inside the ceramic beam and connected through a drive system with the sledge. These separate shafts allow for a completely separated guide of the counterweight from the ceramic beam and do not perform any deflection on the ceramic beam.

For the sledge bearing system we decided to take a L-type sledge with a preloaded vacuum-air bearing. It is very light, small and convenient for the connection with anthropoidic mechanism devices. Due to its L-type construction it is possible to support the line gauge beam in the Bessel-points and in spite of the supports, the preloaded sledge can make free movement along the whole beam length.

The measuring system consists of a laser interferometer to measure a longitudinal distance (X direction) and a control system to measure displacements perpendicular to the reference beam. Laser interferometer and the device to be measured, have to be linked with the computer for simultaneous triggering of the measuring event programmed with a drive control system.

We have provided a theoretically calculated measuring uncertainty for a simplified but corresponded model of the measuring equipment under constant environmental conditions. We divided the measuring uncertainty into the position and orientation part. The position part is measured with a separate laser device and with a displacement control system. The laser interferometer does not represent any accuracy problem. In X direction the mechanical part of the measuring equipment is the most rigid. We calculated the system deflection of about X=0.0005 mm under the external force F%=50 N. In this case the laser interferometer system could be replaced with the precision linear encoder, mounted directly to the ceramic beam surface.

The Y and Z directions denote the measuring equipment which is due to its length and slimness not so rigid. In the Z direction the maximum deflection - the weight of the beam m=40 kg, sledge as a movable load F=40 N and the sum of all external forces F=50 N - is about Z=0.0019 mm. If the force appears in the opposite direction, the relation is better. The most unfavourable results of the calculation are obtained in Y direction. In case the measuring equipment is extremely inclined the support number 2 must be about 1800 mm high. The problem can be also the connection between the support number 2 and the ceramic beam. Since the external force appears always in plus or in minus direction, the calculated deviation in Y direction, provided that the support and the connection are not rigid enough, can be about Y=0.024 mm in an extreme case at the top of the measuring area. In such a case a separated measuring system to measure this deviation would be indispensable.

Orientation deviations can only be due to the mechanical construction of the comparator and sledge. In the central part of the measuring device the orientation angle is in the worst case about 0.2 arc seconds around Y axes and about 0.6 arc seconds around Z axes, and always smaller than 2 arc seconds at the end of the measuring area. We only have to take care in case when the measuring equipment is extremely inclined and the support number 2 is about 1800 mm high. While here the calculated deviation in Y direction can be extremely high, the orientation deviation is not negligible. It can be about 4 arc seconds around Z axes.
The calculations show that the purposed reference length comparator can perform calibration and test space measurements of manual anthropoidic mechanism devices in micro millimetre area. In favourable case under the constant environment conditions the calculated accuracy level amounts to $\pm 2.5$ $\mu$m. To confirm this theoretical supposition we carried out experiments with the measuring equipment which we had developed.

For the measuring equipment we carried out the straightness measurements of the preloaded vacuum-air bearing system along the ceramic beam without and with a drive system as well as the measurements of the preloaded vacuum-air bearing system under the desired load. For this purpose we put the measuring equipment without supports to the granite plate. Measurements were carried out with an autocollimator and with electronic inclinometers in differential switching. On some characteristic positions the displacements were controlled with precision electronic probes. The measuring setup is presented in Figure 5.

Figure 5: Layout of the measuring setup for the new measuring equipment

Figure 6: Results of straightness measurements in Z direction
During the measurement we move the vacuum-air bearing sledge along the reference beam. The test positions were chosen every 100 mm. The first position was placed 100 mm from the beginning of the beam. After more than five repetitions of the same measuring procedure along the whole beam length, the straightness deviations were calculated from the autocollimator or inclinometer angle measurements. The results of the straightness deviation in Z direction are presented in Figure 6.

At this occasion we made measurements with autocollimator (AK) and an inclinometer simultaneously. From these two different methods of measurement we could recognize perfect correlation of the measuring results. Results presented in Figure 6 which are marked with AK Man. 1 and AK Man. 2 mean that the movements were done manually, without drive and counterweight influence first in a rigid connection of all support parts and second in loosened connection of all support key parts. With this experiment we check the influence of the construction elements to the beam accuracy deviation. From Figure 6 no obvious differences were noticed. Only the dispersion of measuring results by the loosened connection was a little bit larger. Further results are marked with Teor. OW, Teor. EL and Teor. OW+EL. These are theoretical results calculated with special simulation software which can take account of the beam own weight (Teor. OW), external loads (Teor. EL) or both (Teor. OW+EL) for the desired support location, material characteristics and the shape form. Finally the measurements were carried out also with a drive and counterweight system in both directions. The results are marked with AK Drive + for positive and AK drive - for negative X direction. Also, no hysteresis or obvious differences to prior measuring results were noticed. The dispersion of all measuring results in this direction was not larger than $2\sigma=0.9$ µm.

The results of straightness measurements in Y direction are presented in Figure 7. The notation marked in Figure 7 has the same meaning as the notation marked in Figure 6. Also, no hysteresis or obvious differences within different conditions of measurement were recognized. The dispersion of measuring results in Y direction was not anywhere larger than $2\sigma=1.1$ µm.

Figure 7: Results of straightness measurements in Y direction
The vacuum-air bearing can be adjusted according to the momentary changes in the perpendicularity of beam surfaces. Therefore, the side beam surface is fully responsible for the orientation deviations about the X axes. These angle deviations were measured with electronic inclinometers along X axes every 100 mm. The dispersion of this measuring result presented in Figure 8 was not larger than $2\sigma=1.5$ arc seconds.

![Figure 8: Results of angle deviation measurements about the X axes](image)

Already from previous Figures 6 and 7, some noticeable changes of orientation between 200 and 600 mm were observed. This is a systematical error caused by an imperfect beam manufacturing. These imperfections in angle deviations of 2 arc seconds are still in the demanded limits of measuring equipment. Because of the systematical character they can be compensated by means of software compensation, should this be necessary.

### 4 Conclusion

The experiments show that the proposed new measuring equipment can perform measurements in micro millimetre area. The theoretical calculations provided on a simplified but corresponded model promised the accuracy level of about $\pm 2.5$ $\mu$m. The experiments on the developed measuring equipment show that this level was successfully achieved. In this way the flexible arm measuring devices intended for geometrical measurements can be precisely calibrated and then tested if the calibration procedure had been performed successfully. On the other hand, there are no limitations to using the proposed measuring equipment as a reference gauge system for straightness measurements as well. And finally, the measuring equipment weighs (without supports) only about 60 kg which can solve the problem of transportation.
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