euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

Novel design of a kinematic coupling precision fixture for repeatable multiple-inclined repositioning

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Abstract
In precision manufacturing, the demand for positioning solutions that enable accurate and precise positioning and repositioning of one object relative to another is critical. Current state-of-the-art solutions employ expensive motorized chucks or stages that provide near-continuous variation in position or rotation with a final resolution and precision that largely depends on the accuracy of the control of said motorized units. Other less versatile, but simpler solutions make use of basic kinematic coupling principles taking advantage of the deterministic nature of the positioning they provide. The work presented here combines the rotational flexibility of a motorized chuck while maintaining the high precision of a deterministically defined positioning concept obtained through kinematic coupling principles. By using multiple sets of radially distributed three vee-grooves paired with three spheres on two different wedge-shaped bodies, it is possible to change the inclination of the top plane of the upper wedge with regards to the bottom plane of the lower wedge solely by rotation of the two wedge-shaped bodies relative to one another. The developed apparatus has been manufactured in stainless steel 316L and evaluated using a tactile coordinate measurement machine showing *xyz* single-digit micrometer range repositioning repeatability, as well as an inclination angle with average of the variances of 10 µrad for 10 repeated measurements of seven different angles respectively. Lastly, the apparatus has been tested in a measurement setup for a laser scanning confocal microscope showing little need for training of the user, while providing a degree of flexibility and repeatability usually only achievable with complex goniometer systems.

Kinematic Coupling, Positioning, Goniometer, Fixturing

1. Introduction

When measuring high quality surfaces with complex geometries it is higly desireable to be able to accurately and repeatably locate and measure specific features that may be in the dimensional order of a few microns. Therefore the use of accurate and precise fixtures for positioning is part of the fundamental need to ensure high quality measurements with reduced uncertainty.

There are several ways in which this particular need may be satisfied such as through the use of expensive motorised chucks or stages providing near-continuous variation in positional or rotary translation. However the accuracy and repeatability of these motorized chucks are highly dependent on the accuracy of the employed control unit, thereby increasing the demand and thus the cost for such units.

Another way to ensure a high degree of accuracy and repeatability is through the use of kinematic coupling principles that exploit the discrete individual constraining of each of the six degrees of freedom (DOF): *xyz*-translation and *xyz*-rotation. One of the main abilities of kinematic couplings is the deterministically defined positioning behaviour which leads to an inherent high accuracy and repeatability. Such kinematic principles have been known for centuries, and prominent historical persons such as W. Thomson, 1st Lord of Kelvin (1824-1907) and J. C. Maxwell (1831-1879) are the originators to the most well-know coupling principles: the Kelvin Clamp and the Maxwell Clamp that can be seen in Figure 1 [1].

The work presented in this study exploits the potential application of kinematic couplings principles in the construction of a fixturing unit through the combination of the rotational flexibility of motorized chucks with the deterministic behaviours of the kinematic coupling capabilities by the Maxwell Clamp design.

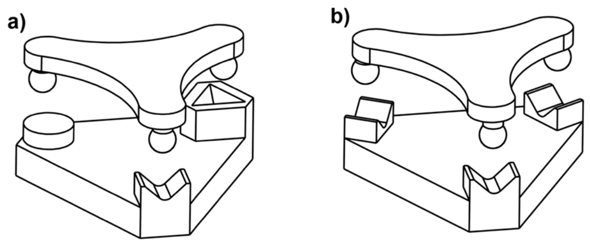

Figure 1. a) Kelvin Clamp constraining all six DGF through a triangular hole, a channel and a flat face; b) Maxwell Clamp constraining all six DOF through three identical wedge-shaped channels. Adapted from [2].

2. Precision Fixture Design

Published work on design and testing of kinematic coupling principles, as well as general experience with kinematic coouplings presented by Slocum et. al. (1988-1992), was consulted throughout development and testing of the precision fixturing device presented in this study [3-5]. Furthermore, work by Hale et. al. (2000) has been consulted in the design of vee angle for improved repeatability [2].

The developed fixture consists of, but is not limited to, four-part components that are stacked on top of each other. The interfaces between the components contain kinematic coupling elements referring to the concept of the Maxwell Clamp, shown in Figure 1. A schematic drawing of the designed fixture can be seen in Figure 2.

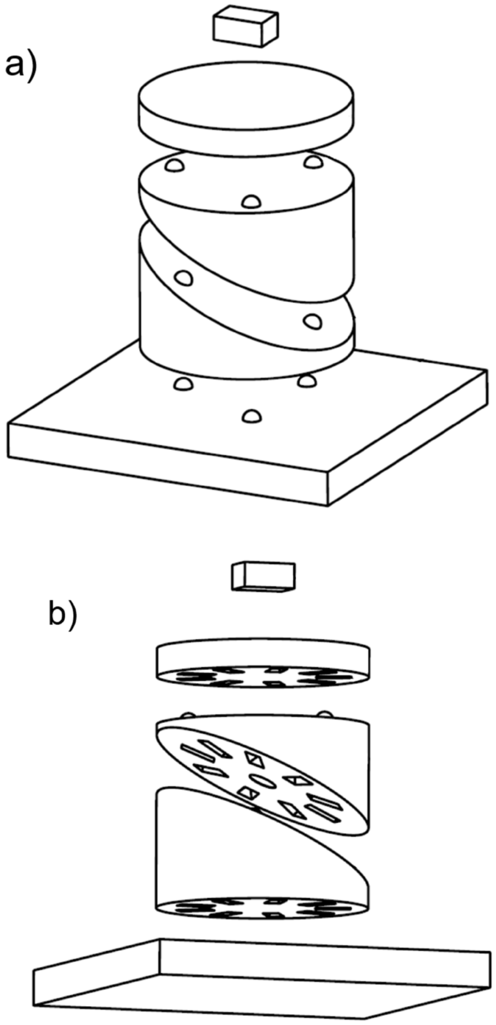

Figure 2. Schematic line drawing of the fixture as seen from two different viewing angles: a) Top isometric view; b) Bottom isometric view

As it can be seen in Figure 2, the top face of the three lower components contain kinematic elements in the shape of spheres, while the bottom face of the three upper parts contains kinematic elements in the shape of vee-grooves. By incorporating multiple sets of three vee-grooves, radially distributed over the bottom faces of the three upper parts, it is possible to allow for a relative rotary motion between the part components.

2.1. Multiple-Inclined Repositioning

When applying a relative rotary motion between the two central wedge-shaped part components of the fixture, the resulting top plane is tilted relatively to the bottom plane. This inclinational motion is illustrated in Figure 3. Due to the multiple sets of radially distributed three vee-grooves it is possible to achieve a certain amount of discrete steps in the inclination range. The design is presented in Figure 2 and 3. It allows for five discrete inclinations of the top plane within the inclination range of 0 degrees to 25 degress.

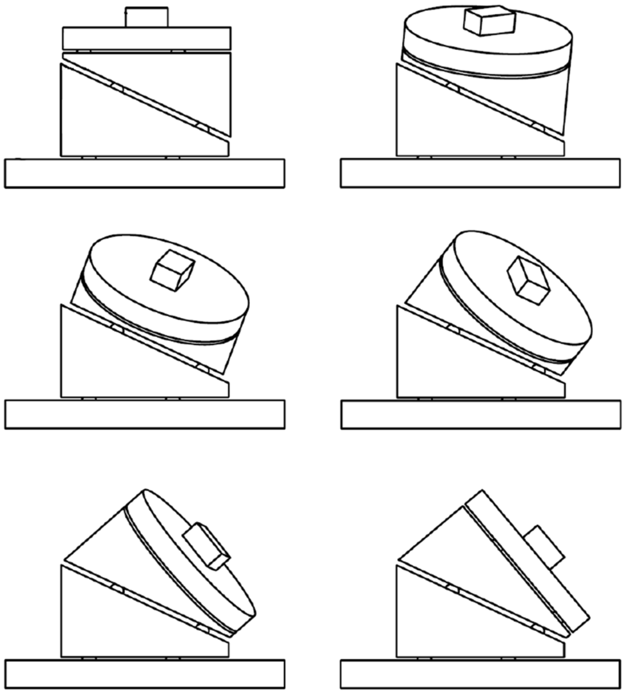

Figure 3. The designed fixture axially rotated to reveal six of seven different inclination steps that can be achieve with the current amount of radially distributed sets of three vee-grove kinematic elements.

3. Inclined Kinematic Goniometer Experimental Validation

In order to experimentally validate the developed inclined kinematic goniometer, a physical model has been manufactured in AISI 316L Stainless Steel using CNC milling. The manufactured model is shown in Figure 4 in its 0 degree and 25 degree inclination configurations.

The fixture restacking repeatability has been determined using a Zeiss OMC850 coordinate measurement machine (CMM) equipped with contact probe having a synthetic ruby sphere with nominal diameter of 3 mm. By fixating the lower component and repeatably restacking the full fixture, the movement of the center point of the top component has been evaluated by three different operators each performing 10 repeated measurements. The associated expanded uncertainty with the *xyz*-measurement of the top plane center point has been evaluated according to the ISO 15530-3:2011 [6]. The inclined repositioning has been evaluated following the same procedure of restacking all fixture components apart from the lower fixated component, and evaluating the top plane inclination relative to the bottom plane by performing 10 repeated measurement at each individual inclination.

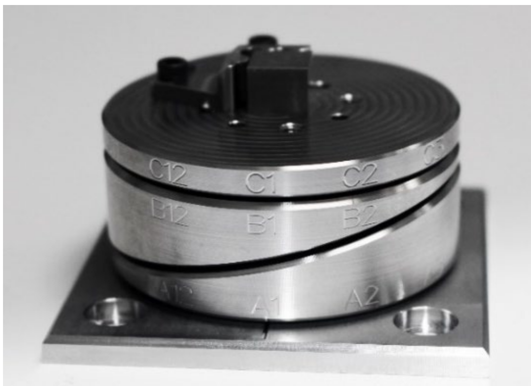

Figure 4. The manufactured precision fixture prototype shown in horizontal as well as maximum inclination configuration.

4. Results and Discussion

From Table 1 it can be seen that an expanded uncertainty of 3 µm was achieved for the *x* and *z* position while the *y*-position showed an expanded uncertainty of 8 µm. Due to the setup of the measurement strategy such expanded uncertainty includes the reproducibility of that specific fixture through different operators.

Table 1. Measured reference position of fixture top center point in horizontal position stated with its associated expanded uncertainty.

Measurement ID	Avg. /mm	U /mm
x-position	35.206	0.003
y-position	34.989	0.008
z-position	31.976	0.003

It can be seen from Table 2 that the standard deviation (STD) of the inclination angle of the top plane relative to the bottom plane of the precision fixture ranges from 3 µrad, as the lowest value achieved for the horizontal postion, to 14 µrad as the highest for an inclination of about 22°. The average variance for any angle is evaluated to be 93 µrad^2 (standard deviation of 9.6 µrad). The difference in STD for the different angles is deemed due to the shift in the position of the center of mass of the fixture during the rotary motion. This can also be seen from Figure 3 where the center of mass of the two top compontents is placed along the central axis in the horizontal position while it is shifted towards one side in the position at the maximum inclination. Additional investigation of the influence on the stability of the fixture due to the translation of the center of mass may provide an explanation towards the difference in STD.

Table 2. Repeated measurements of the seven different angles achieved with the manufactured prototype fixture. STD_{rel} evaluated based on STD/(180-AngleAvg).

≈ Angle /°	Avg. /rad	STD /µrad	STD_{rel} / × 10^{-4} %
0	≈ 0	3	1.4
6	0.112	7	2.2
12	0.218	7	2.4
18	0.311	11	3.9
22	0.382	14	5.1
24	0.424	13	4.7
25	0.436	8	2.9
Avg	-	9.6	-

After the preliminary geometrical investigation of the repeatability of the fixture, a lab scale test session was conducted. The fixture was tested in a measurement setup with a laser scanning confocal microscope. It is shown in Figure 5. For this test an experienced operator and an inexperienced operator were subjected towards the use of the fixture. It was found that the inexperienced operator was equally capable of using the fixture as the experienced operator after performing few measurements. This suggests that a simple and intuitive design of the fixture components was achieved. For this test an alignment component was mounted on the top face of the fixture allowing for the placement of measurement samples having an overall *xy* size of 10 mm by 10 mm.

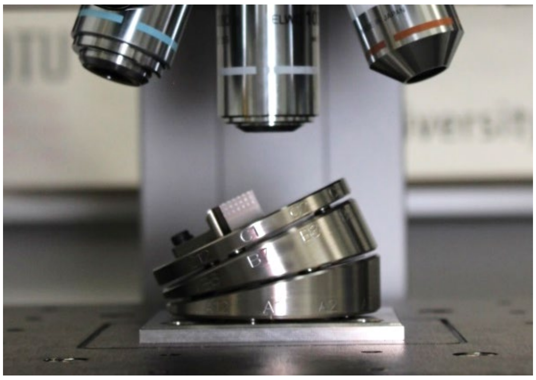

Figure 5. The manufactured precision fixture in a measurement situation with a confocal laser scanning microscope where the surface roughness of a sidewall geometry of a protruding feature is being evaluated.

The manufactured fixture gives an indication of the capabilities of the presented design, even though additional improvements may be able to reveal even more possibilities. One well known limitation for kinematic couplings with small spherical elements is the large impact from the Hertzian contact stresses giving rise to potential indentation and brinelling of the adjacent contact element. An example of this phenomena was actually found and is shown in Figure 6. This example of brinelling in the case of the fixture originates from the combination of 5 mm diameter spheres as the circular contact element and the application of AISI 316L Stainless Steel with a low yield strength of 250–350 MPa. However, there are means for solving this issue such as changing the shape of the contact element as well as altering the material either by changing the base material to a material with a higher yield strength or by subjecting the material towards hardening or surface treatment procedures.

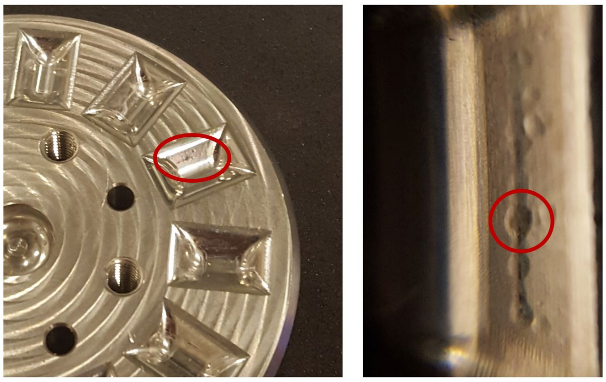

Figure 6. Indentation/Brinelling happening in the fixture vee-groove due to the combination of a small sphere diameter and a soft material.

The current design of the fixture exploits an incremental range with seven steps between 0° and 25°. However with a modified design it would be possible to change this range as well as to vary the amount of incremental steps. Furthermore a different area of application may be achieved by exchanging the current kinematic contact elements with other type of contact elements with different properties.

5. Conclusion

In this study a novel design of an accurate kinematic coupling fixture for repeatable multiple-inclined repositioning has been presented and validated. The developed fixture exploits the concept of multiple stacked Maxwell Clamps thereby combining some of the flexibility from conventional motorized chucks with the high precision of a deterministically defined position concept found in the field of kinematic couplings. The experimental validation of the fixture design showed repeatability in the single-digit micrometer range and an average STD of the inclination angle repeatability of about 10 µrad. These results were achieved despite the effect of brinelling that was experienced. By implementing the suggested changes a much improved repeatability could be achieved. The current design of the fixture exploits a selected range of inclination angles and inclination steps, however with potential design alterations the fixture concept may be manufactured to suit a much broader range of applications.

Acknowledgements

This study was funded by the Department of Mechanical Engineering at Technical University of Denmark.

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[6] ISO 15530-3:2011 Geometrical product specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement – Part 3: Use of calibrated workpieces or measurement standards, International Organization for Standardization (ISO), Geneva, Switzerland