DESIGN OF A PARALLEL HYBRID MICRO-SCARA ROBOT FOR HIGH PRECISION ASSEMBLY

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Abstract: **The trend to miniaturization in the field of consumer and investment goods is leading to increasing interest in the field of precision assembly of small components.**

Until now most machines for precision assembly have been many orders of magnitude larger than the workpieces to be handled or the necessary workspace. The Institute of Machine Tools and Production Technology of the Technical University of Braunschweig and Micromotion GmbH, a manufacturer of miniaturized zero-backlash gears and actuators are now working together to develop a small-scale SCARA robot featuring a parallel hybrid kinematic structure. This new robot, with a base area of less than 150 x 150 mm² will position small workpieces with a mass of up to 50 g with a repeatability of better than 1 µm.

This paper describes the basic design process and design decisions made in the development of this parallel hybrid micro SCARA robot, which will be exhibited at the HANNOVER FAIR 2005 as a technology demonstrator.

I. THE IMPORTANCE OF MICROASSEMBLY

In a wide range of consumer goods and investment goods there is a clear trend to miniaturization. This trend is leading to a yearly growth of the world market for products based on micro system technology of 20%, and therefore, increased interest in micro-production technologies [1],[6].

The findings of the “Mikropro” study into the international state of the art in the field of micro-production technology can be summarized as follows for the area of automated microassembly [2]:

- The trend to multifunctional, hybrid sub-assemblies in the field of microsystem technology is leading to increasing demand for devices that can precisely position and assemble micro-components with an accuracy of less than 1 µm
- Up to 80% of production costs are incurred in assembly, which is increasing the need for high speed and high process stability during the assembly process
- Most existing precision assembly machines and robots are very expensive, so there is a clear need for simple, cost-effective assembly automation
- There is a trend to place the complete assembly system inside a clean room environment, leading to a requirement for very compact, modular assembly automation

Until now there have been a variety of different technical solutions for dealing with the above mentioned trends.

II. PREVIOUS APPROACHES

The state of the art for precision robots can be summarized as shown in Fig. 1. The simplest classification is into serial, parallel and hybrid structures, which in turn can be sub-divided into further categories.

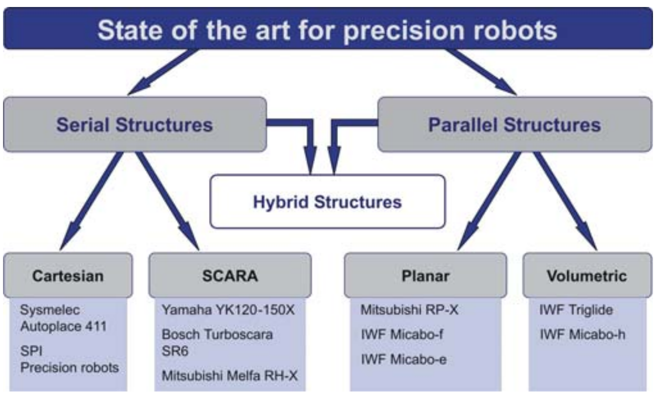

Fig. 1 State of the art for precision assembly robots

The first category covers cartesian robots. These are typically very large in comparison to the components to be handled and are often as a result, very expensive. However, they do provide a repeatability between 1 and 3 µm, as demonstrated by, for example, the “Sysmelec Autoplace 411”. The second category covers SCARA robots, which have a large workspace in relation to their physical size, but only achieve a repeatability of +/- 5µm, even in the case of the most accurate designs. In the field of parallel robots, there are few examples in industrial use. The Mitsubishi RP-X is an exception, achieving a repeatability of +/- 5µm. Most other developments in this area are limited to university research projects, in particular at the Technical University of Braunschweig in Germany, where extensive experience with parallel structures has been gathered, for example with the Triglide robot, which has achieved a repeatability of better than 1 µm [5],[6],[7].

As the “MikroPro” study has shown, these existing solutions have the common feature of being very expensive and very large and there is now growing market demand for smaller, cheaper robotic devices for positioning and assembly. The development of such robots is now being made possible by new enabling technologies, in particular zero-backlash micro-gears and highly dynamic micro-motors with integrated incremental encoders, which are allowing proven robot arm structures to be miniaturised. Furthermore they allow the use of proven control technology and avoid the complexity of “alternative” actuator technologies such as Piezo actuators [5],[7].

III. BASIC DESIGN REQUIREMENTS

Based on the findings of the “MikroPro” study and also direct contact to a number of potential users the following basic specifications could be established. Furthermore quantitative specifications were also fixed, as shown in table 1.

- Positioning repeatability better than 1µm
- Simple and modular structure
- Small envelope, to allow easy integration into a “table factory” system
- Lower production costs than existing systems
- Easy access to the working area of the robot to allow automatic feeding of components to be assembled

IV. ROBOT ARM DESIGN APPROACH

Before commencing with the detailed design of a robot in device to fulfill the above mentioned requirements, a number of basic design decisions needed to be made.

- Required number of degrees of freedom?
- Parallel, serial or hybrid structure?
- Appropriate degree of miniaturisation? (At which point does further miniaturisation have a negative effect on accuracy?)
- Use of conventional joints or compliant mechanisms?

From the practical requirements of potential users it became quickly clear that 4 degrees of freedom are necessary. 3 translational axes are required to allow the workpiece to be positioned in three orthogonal linear coordinates. In most practical micro assembly applications the workpiece must also be orientated, so a fourth rotational axes is also required.

Table 1: Basic requirements

Criterion	Value	Unit
Workspace	54 x 85 x 20	mm^3
Footprint (area of robot base)	< 150 x 150	mm^2
Repeatability	< 1	µm
Linear speed (X,Y,Z directions)	> 100	mm/s
Rotational speed (θ axis)	> 160	$^0/s$
Angular resolution (θ axis)	< 0.005	^{0}
Payload	50	g

Before deciding on the appropriate parallel or serial basic structure more detailed analysis was required. Conceptual designs for both, serial (Fig.2) and parallel (Fig.3) SCARA- structures were designed and then the achievable positioning resolution at all points in the chosen workspace analyzed.

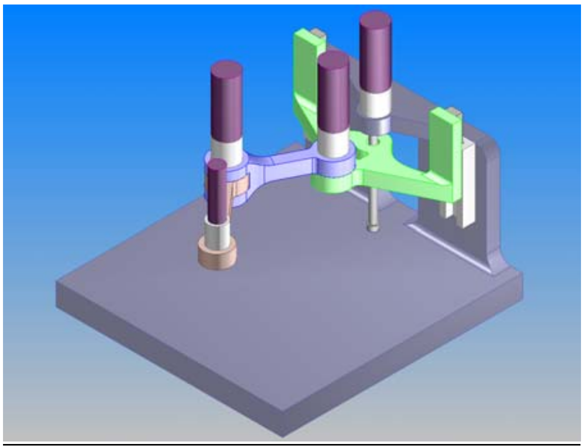

Fig 2:Concept for serial SCARA structure

Fig. 2 shows a miniaturised serial robot arm. Micro gear-motors are placed at the primary axis (shoulder and elbow joints). Fig. 3 shows a parallel structure where two serial arms are connected at the hand axis. Here, too, micro gear-motors drive the shoulder joints.

The elbow joints are passive and here pre-loaded ball bearings are used to provide backlash-free joints. For both concepts a gear-motor is mounted at the hand-axis to provide an additional rotational axis in order to orientate the workpiece.

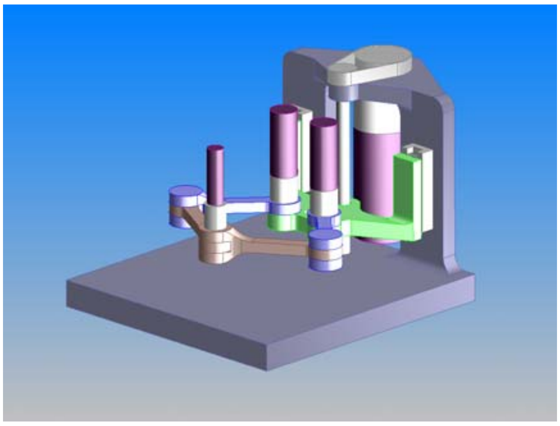

Fig 3: Concept for parallel SCARA structure

Figures 4 and 5 show the results of this analysis for the serial and parallel basic structures respectively. The serial structure has a resolution map which only achieves sub-µm accuracy in very limited areas of the available workspace. The parallel structure in comparison achieves sub-µm accuracy over almost the complete workspace and also has a symmetrical resolution map. Furthermore the parallel structure should offer a significantly better dynamic performance, because only the gear motor for the fourth (rotational) axes is carried by the moving arm. Furthermore the passive joints of the parallel structure are easier to miniaturize than active joints. For these reasons the parallel SCARA structure was chosen as the basic structure for further development.

An argument against the parallel structure is the more complex control due to the closed kinematic structure. Nevertheless, the steady decrease in the cost of computing power means that in this case the mechanical advantages of the parallel structures are more important.

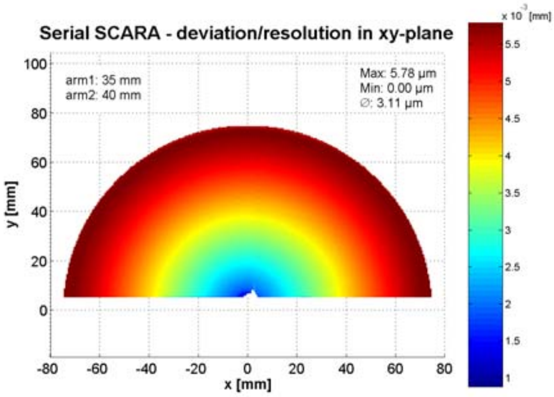

Fig 4: Resolution for serial SCARA (x-direction)

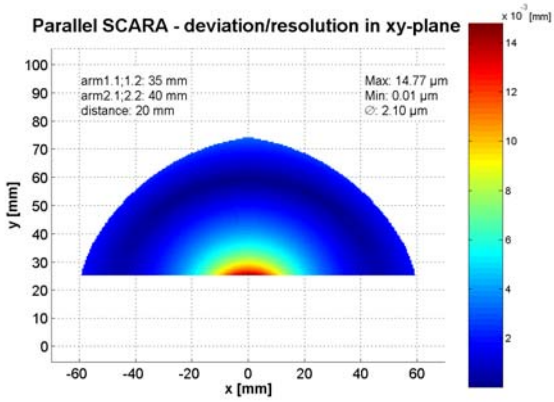

Fig 5: Resolution for parallel SCARA (x-direction)

As indicated above a key enabling technology is zero-backlash gears. In 2001 Micromotion GmbH introduced the Micro Harmonic Drive® gear into the market and this technology is now established in a range of industrial applications [3], [4].

The Micro Harmonic Drive® is the only micro-gear currently available that offers the same positioning accuracy as the large-scale Harmonic Drive gears used in industrial robots.

Fig. 6: Micro Harmonic Drive®

Fig. 7 shows the basic components of this gear, which uses only 6 components to achieve reduction ratios between 160:1 and 1000:1. These ratios are necessary to create adequate torque from currently available micro-motors, which are capable of rotational speed up to 100 000 rpm, but only offer torques of a few µNm.

Fig. 7 shows the gear mounted to a pancake-type micro-motor.

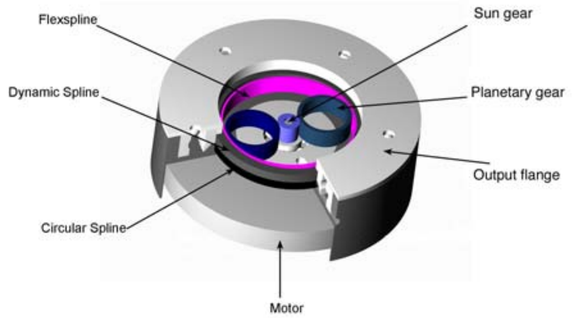

Fig. 7: Micro Harmonic Drive® gear components

As can be seen from Fig. 8 the principle of operation is the same as "macro-technological" Harmonic Drive gears as used in large scale industrial robots.

The basic elements of the Micro Harmonic Drive® gear system are the Wave Generator consisting of two planetary wheels and a sun gear wheel and the three gear wheels

- Flexspline,
- Circular Spline and
- Dynamic Spline.

The Wave Generator deflects the elastically deformable Flexspline elliptically across the major axis. Due to that the teeth of the Flexspline engage simultaneously with the two ring gears - Circular Spline and Dynamic Spline - in two zones at either end of the major elliptical axis. Across the minor axis of the elliptically deflected Flexspline there is no tooth engagement. When the sun wheel of the Wave Generator rotates, the zones of tooth engagement of the Flexspline travel with the angular position of the planet wheels of the Wave Generator. A small difference in the number of teeth between the Flexspline and the Circular Spline (the latter has two teeth more) results in a relative movement between these gear wheels. After a complete rotation of the planet wheels of the Wave Generator the Flexspline moves relative to the Circular Spline by an angle equivalent to two teeth. The Dynamic Spline is used in the flat type gear system as the output element and has the same number of teeth as the Flexspline and therefore the same rotational speed and direction of rotation. With respect to the planned miniaturization of the Micro Harmonic Drive® the planetary gear configuration for the Wave Generator possesses the following advantages:

- All gear components can be manufactured using the high precision LIGA-technique
- The assembly effort can be minimized, because the Wave Generator consists of only three components
- The total reduction ratio of the gear increases due to the planetary gear. This design can therefore flexibly adapt the very high rotational speed of micro motors in only one stage to the specific requirements of a given application
- This variant of the Wave Generator possesses only a low moment of inertia and therefore enables a highly dynamic positioning performance

By using a planetary gear for the Wave Generator it is possible to vary the total ratio of the Micro Harmonic Drive® over a large range. For the shown gear size, reduction ratios from 160 up to 1000 can be realized in a single stage.

Excluding the input and output bearing arrangements the outer dimensions of the Micro Harmonic Drive® are 1 mm axial length and 8 mm in diameter.A gear module of 34 µm must be used to realize the necessary high reduction ratio and the small dimensions simultaneously. The single gear wheels of the Micro Harmonic Drive® are manufactured by electroplating and consist of a nickel-iron-alloy. Due to the high yield point of 1.500 ^{N}/mm², the low elastic modulus of 165.000 ^{N}/mm² and its good fatigue endurance this electroplated alloy possesses the necessary properties for perfect functioning of the flexible gear wheels of this micro gear system.

By providing an angular repeatability of 10 arc seconds, The Micro Harmonic Drive® gear is the only micro gear currently available that provides sufficient accuracy for a micro robot of this kind. As can be seen in Fig. 3 both upper arms of the parallel structure are driven by Micro Harmonic Drive® gears combined with micro-motors with integrated encoder.

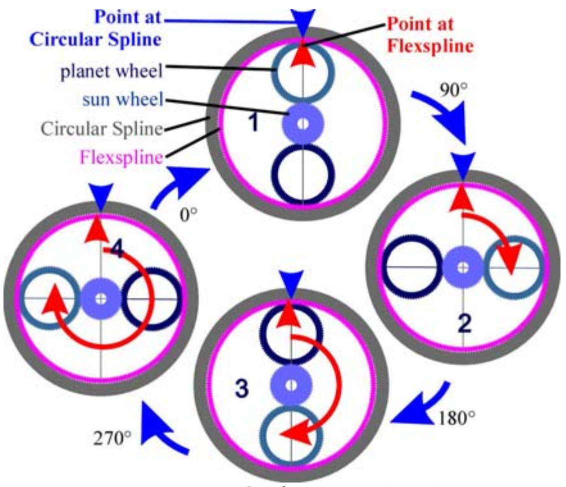

Fig. 8: Principle of Operation (MST)

V. DETAIL ARM DESIGN

Having made the basic design decisions described above, the detail design of the arm has concentrated on providing a lightweight yet highly stiff arm construction. Figure 9 shows the results of a typical FEM analysis of the upper and lower arm segments. The sectional profiles of the arms have been optimized in order to minimize weight without sacrificing stiffness.

Figures 10 and 11 show design alternatives for the vertical Z-axis. The Z-axis could conceivably be mounted at, or near the hand axis, but this would greatly increase the complexity of the design. The decision was therefore taken to move the complete arm structure vertically. This solution is made possible by the passive, lightweight structure and the small, lightweight gear-motors. This also has the advantage of allowing higher assembly forces to be exerted. Toothed belt, steel belt and ball screw drives have been compared and the ball screw solution has been chosen for providing the best combination of speed, accuracy and stiffness.

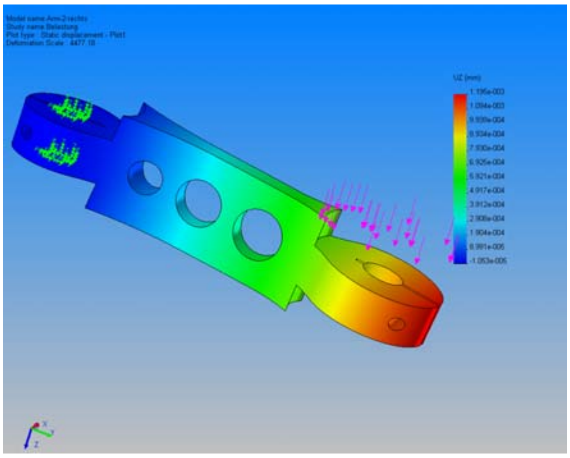

Fig. 9: FEM Lower arm displacement for load of 0.5N

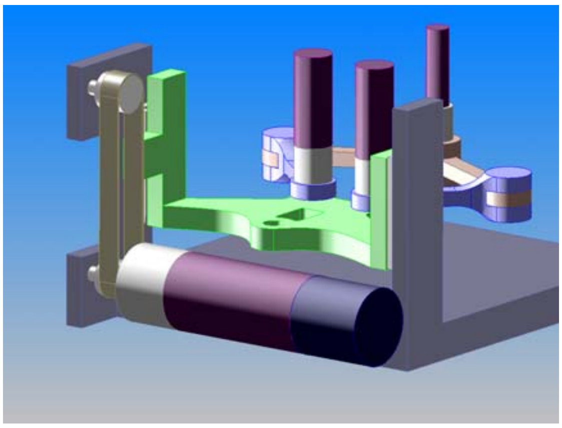

Fig. 10: Design alternative – Belt drive for Z-axis

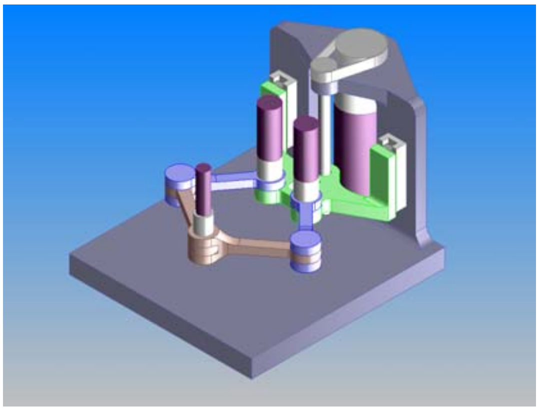

Fig. 11: Design alternative – ballscrew drive for Z-axis

On the basis of these decisions an optimized design has now been realized as shown in figure 12.

The hand axis is executed as a hollow rotational axis, so allowing media to be passed along the central rotational axis. For the demonstrator robot it is planned to use a conventional vacuum gripper. In the future it is also planned to mount sensors or mechanical and electrostatic micro-grippers developed at the IWF, Braunschweig in cooperation with the Institute for Microtechnology (IMT), Braunschweig [6].

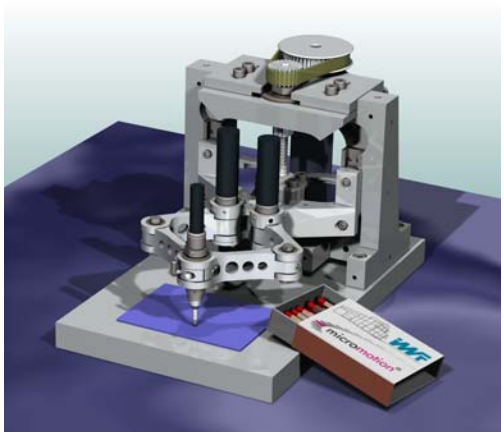

Fig 12: Optimized design

This picture shows the adopted parallel hybrid structure as well as the optimised design of the arm sequence. Simulation of the structure indicated that the robot can fulfil the quantitative requirements shown in table 1 above.

VI. OUTLOOK

The prototype robot is now under construction and validation tests will soon commence. If the tests are successful then this innovative micro-robot will be demonstrated to the public for the first time at the HANNOVER FAIR in April 2005.

VI. REFERENCES

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