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APIS – A Miniaturized Robot for Precision Assembly with Low-Cost Piezoelectric Motors

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This paper deals with the requirements for and the realization of a miniaturized parallel kinematic robot named APIS, which is driven by low-cost piezoelectric motors and thus designed for low-cost applications. After the need and potentials of this concept have been clarified, a detailed description of the development process is given. In doing so, kinematic aspects as well as the driving concept and the robot control, including the development of a suitable motor control with power stage, are described. In addition to the first functional prototype some performance measurements are presented, which show that the robot is able to obtain a repeatability of less than 34 μm. To provide better results, possibilities for future developments are identified, including optimized sensor feedback and motion control.

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1. Introduction

Nowadays, the technological progress gives rise to a high miniaturization and an increase in function density. A research study published by iSuppli[1] predicts an annual growth of up to 12 % for the market of micro electro mechanical systems (MEMS) over the next three years. This trend demands innovative technologies as well as continuous improvements of modern manufacturing-plants and assembly processes so that precision and flexibility can be increased. Another challenge is to reduce production and machine costs. According to studies of Koelemeijer and Jacot,[2] up to 80 % of the total production costs of miniaturized systems or MEMS account for handling and the assembly process. To overcome the challenges stated above, a common research approach is the design of modular desktop factories. As for visionary desktop factories, it is necessary to develop highly modular systems by playing on the potentials of size adapted flexible handling systems which allow the following assumptions that make desktop factories very promising for micro production and especially for micro assembly:[3,4]

- saving energy and material resources
- high density of functionality
- operation in a local clean room cell
- easier control of waste and pollution
- increased accuracies
- improved dynamic, portability and agile reconfigurability
- lower maintenance, manufacturing and initial costs

Based on these assumptions some equipment has been developed in research and industry, whereas the field of desktop factories still is under development. The first impulse for desktop factories was given by MEL in Japan,[5] with the estimation that a 1/10 size-reduction of production machines could lead to a decrease of energy consumption of about 1/100 compared to a conventional factory. Nowadays, there are also a few examples in Europe of research and industry projects. In research, examples of modular production cells such as the system developed by Sitala et al.[6] can be found. Another concept of assembly modules mounted around a fixed platform is followed up in research projects by Gaugel et al.[7] and Rochdi et al.[8] and by the industrial manufacturer MiLaSys.[9] Further concepts from Uusitalo et al.[10] and Klocke Nanotechnik[11] follow up the idea of a fixed production cell equipped with a main handling device and several subsystems. In particular, these concepts point out that the size of the entire production system is limited by the size of the precision robot used so that highly miniaturized precision robots are obviously required. Examples are the miniaturized Pocket Delta,[12] the subsequently mentioned Parvus[13] or the size adapted robots of the MICABO-class.[14,15]

Motivated by this conclusion, this contribution addresses a new miniaturized robot system named APIS (Automatic PIezoelectric actuated Structure). APIS features a cost-saving and robust drive concept which is based on the use of piezoelectric motors that are capable of very small positioning movements in the range of a few micro degrees. Further specifications are high dynamics and an intrinsic friction clutch. This is a particular advantage offering great potentials in the matter of interactions between the robot and its environment. Owing to the friction clutch, the drives and thus the robot is much more robust against damaging than other robots such as Parvus. Examples of interactions are given by manual teach-in processes or by collisions.

The evolutionary designed structure allows APIS to be combined as a module within the base frame of Parvus so that certain components such as grippers or the *z*-axis can be flexibly interchanged. As a result, two generally different robot systems with two outstanding driving technologies can be used, which differ in costs, accuracy and robustness. Thus, a production system can be developed and optimally adapted to the desired task.

2. Realization of the mechanic

2.1 Kinematic structure

The kinematic structure of APIS features three degrees of freedom, allowing for positioning in the *xy*-plane. Relating to Fig. 1 and Table 1, it is a planar parallel structure with five revolute joints. Two active joints (A_1 and A_2 with q_1, and q_2) as well as three passive joints (B_1, B_2 and C) are shown. The serial end effector drive ψ is integrated into the passive joint C and completes the entire model. This design provides some key benefits. The passive joints allow for high miniaturization and weight reduction. The parallel structure also provides high sensitivity and dynamic performance over the corresponding workspace. This is comparatively better than a serial structure with comparable limb dimensions, since the parallel structure achieves a larger space of high repeatabilities.[6] The workspace of APIS is shown in Fig. 2 in comparison with the dimensions of a common credit-card.

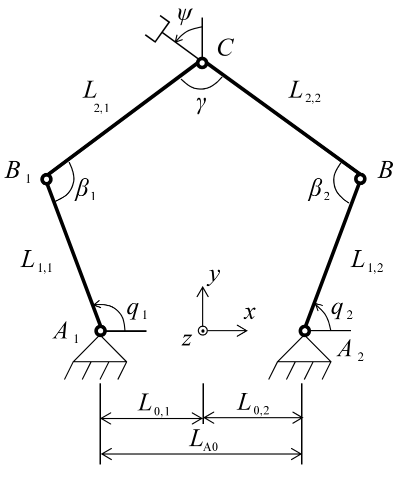


Fig. 1 Kinematic structure of APIS

Table 1 Nomenclature of the geometry

description	variable
distance to coordinate plane	$L_{0,1}$; $L_{0,2}$
center distance of the drive axis	L_{A0}
length of the limb	$L_{1,1}$; $L_{1,2}$; $L_{2,1}$; $L_{2,2}$
arm drive	q_1 ; q_2
active joint	A_1 ; A_2
end effector drive	ψ
passive joint	B_1 ; B_2 ; C
joint angle	β_1 ; β_1 ; γ

2.2 Drive and sensor concept

The active joints are composed of a rotary piezomotor and a matching rotary sensor. Before an adequate piezomotor can be selected it is necessary to identify the required drive torque, resolution and accuracy of the particular drive (q_1, q_2 and ψ).

Drive torque: The estimation of the drive torque includes a matlab simulation which takes into account the structure's mass moments of inertia, which results in a torque of 0.3e-3 Nm (Fig. 3). Also, the ball bearing's friction moment, which is in the range of 65e-6 Nm, was included in the calculation of the drive torque. Altogether a maximal drive torque of 2e-3 Nm (including a safety factor of 2) was assumed for the arm drives, as well as 0.13e-3 Nm for the end effector drive. The estimation is based on a maximal angular velocity of π rad/s and two ball bearings per joint.

Resolution: The angular resolution is an important criterion to achieve high sensitivity and position accuracy at the end effector. For this purpose the basic conditions of Parvus with 2.8e-3° (q_1 and q_2) and 22.5e-3° (ψ) are provisionally assumed as approximate values, but should not be regarded as a limitation.

Accuracy: The angular position is measured by a rotary sensor so that position errors of the drive are evened out by a PID controller. Hence, accuracy as well as repeatability play a secondary role.

There are currently few miniaturized rotary piezomotors commercially available. The following models are considered here:

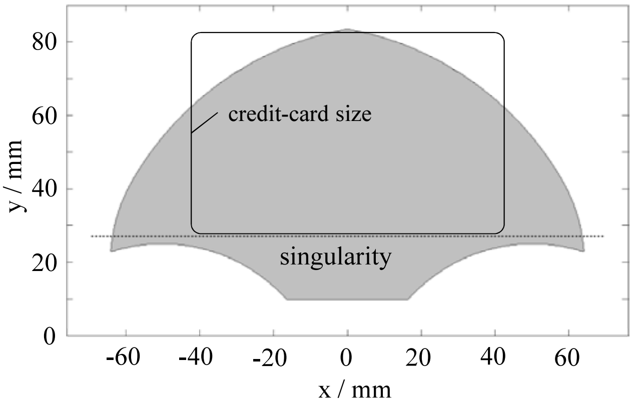


Fig. 2 Workspace of APIS in comparison with the dimensions of a common credit-card

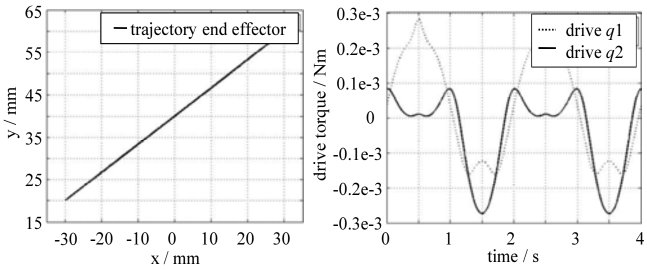


Fig. 3 Results of the drive torque analysis

- SR-1908 (SmarAct GmbH)
- R01S-10 (PiezoMotor Up. AB)
- PMLL-18R (DTI PiezoTech)
- X15G (Elliptec AG)[17]

The decision was borne by special key benefits of the X15G, such as the low price, low weight and design freedom of the motor's dimension, as shown in the following section. Further specifications are high dynamic motions, and a positioning resolution in the range of a few micro degrees as well as small dimensions and an intrinsic friction clutch. A primary deficit is the low shearing force (0.2 N), which results in a drive torque being low. The chosen X15G is an ultrasonic piezoelectric motor, which consists of two main elements, a stator and a rotor. These are shown in Fig. 4 as a part of the arm drive.

The stator includes an aluminum resonator with an integrated piezo element and a spring. The piezo element must be actuated by a PWM-signal (Pulse-Width Modulation). The excitation frequency must be chosen close to the mechanical resonance frequency of the resonator, which is typically between 77 kHz and 108 kHz (Fig. 5).[18] Consequently, the resonator produces an ultrasonic standing wave so that its tip performs an elliptic trajectory and induces motion in the rotor. Here the excitation frequency determines the rotational direction. As the rotor is one of the parts to be designed, it allows such things as the drive torque, velocity and resolution to be included as design variables. The drive torque is calculated by multiplying the shearing force and the radius of the rotor. The chosen rotor dimensions allow a compromise between estimated drive torques, step size resolution and available design space. A radius of 15 mm results in a torque of 3e-3 Nm at the arm drives and 10 mm results in 2e-3 Nm at the end effector drive.

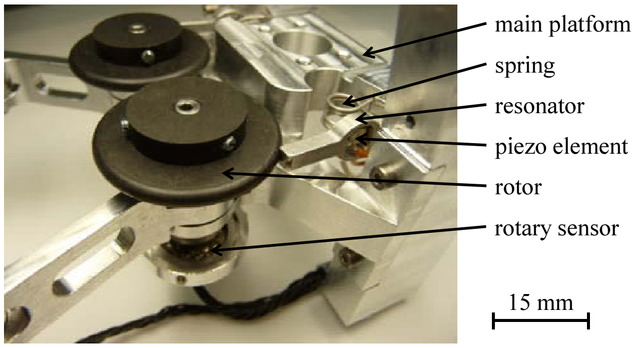


Fig. 4 Arm drive, bottom view

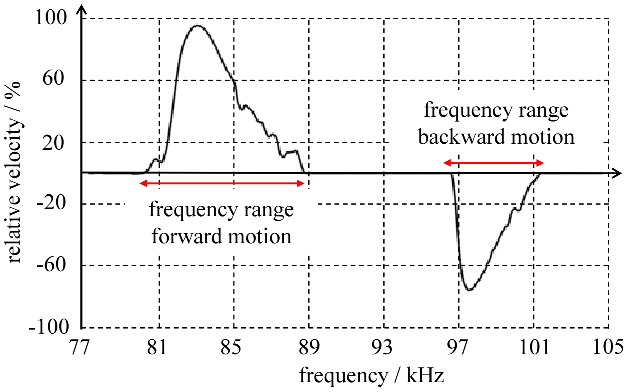


Fig. 5 Exemplary motion frequencies of X15G

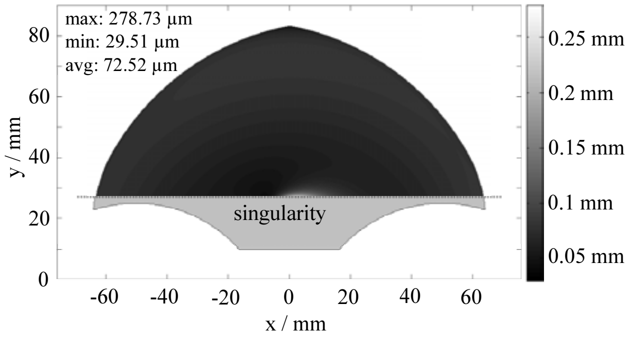


Fig. 6 Results of the sensitivity analysis

The dynamic PWM excitation method described here enables an averaged step size of circa 3 µm, which equals 11.5e-3° (q_1 and q_2) and 17.2e-3° (ψ). Better results can be achieved through the application of a direct voltage, called ultra fine positioning, which is comparable to a more static actuation. Consequently, the step size varies proportionally to the voltage with 1 µm/10 V, whereby angular step sizes of theoretically a few micro degrees are possible.

The angular positions of the piezomotors are measured by rotary angular sensors, thus their accuracy and resolution are important for the repeatability of the robot. Further boundary conditions such as low weight, size and friction torque are demanded with regard to the provided drive torque and the requirement of high dynamic motions. Based on these specifications, AS5045 from Austria Microsystems[19] was chosen. This magnetic rotary sensor includes a contactless measurement principle that uses the Hall Effect. Consequently, no friction torque is generated. Moreover an absolute measurement is done, which offers an operation mode of the robot without any indexing or homing at start-up. Finally, a very compact thin-shrink small outline package (TSSOP) is featured, enabling a space saving integration within the drive design. This is schematically shown in Fig. 4 and 8.

The resolution is 12 bit respectively 0.088°, which is comparatively larger than the resolution of the piezomotors. Therefore, the sensors are crucial elements to estimate the prospective repeatability. Fig. 6 shows a sensitivity plot in *xy*-direction, provided that the measurement error of one sensor resolution step which is dominant compared to the other errors, such as backlash of the ball bearings. Based on the averaged sensitivity of 72.52 µm conclusions on the prospective repeatability can be drawn. Usually, repeatabilities better than 72.52 µm can be estimated.

2.3 Resulting design

The design of the main platform, where the dimensions of the base frame are taken from the arm structure of Parvus, allows APIS to be combined in a module within the main frame of Parvus (see Fig. 7). This adds a serial degree of freedom in the vertical *z*-direction and permits a high interchangeability.

In Fig. 8 the hand axis is presented in more detail. The vacuum gripper is realized as a hollow shaft and enables the robot to handle micro parts. To reduce costs and to facilitate interchangeability, the mounting dimensions of the end effector are also identical to those of Parvus.

3. Realization of the motor control unit

The schematic of the entire robot control unit is pictured in Fig. 9. The central components are three controller modules, developed at the IWF. Each module controls one drive. In comparison to commercial controllers, which can be purchased from Elliptec AG, they are tailored to the particular needs of the motor control. They differ in equipment and offer extended functions, for example specified sensor feedback and dSPACE-interface. This allows these modules to be easily controlled by a higher level controller, which was realized with the DS1103 dSPACE system in this case.

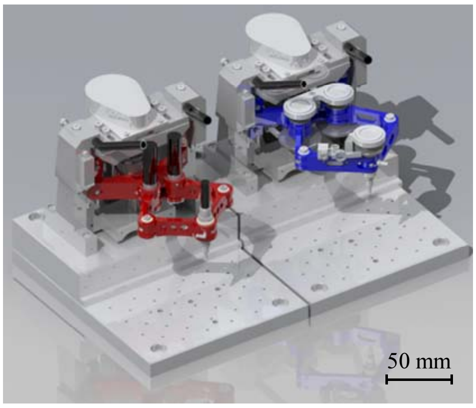


Fig. 7 Parvus (left), APIS (right) modular combined with the main frame of Parvus

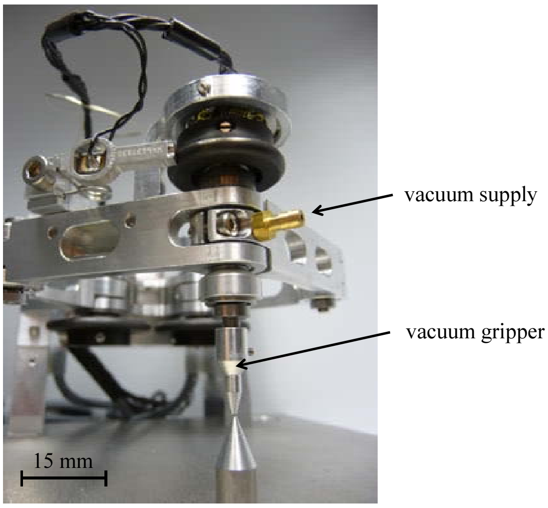


Fig. 8 Hand axis equipped with a vacuum gripper

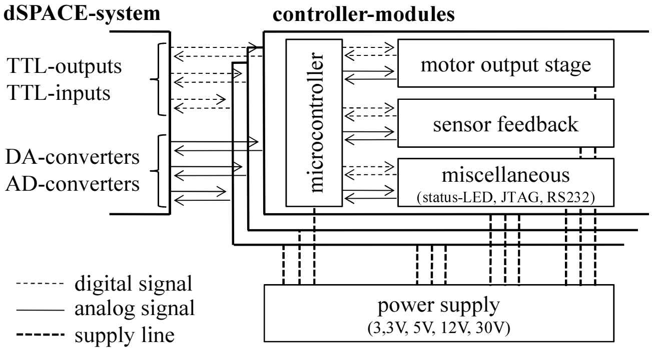


Fig. 9 Design concept of the robot control unit

To reduce costs and facilitate redesign, the motor control unit features a modular design. This will also shield the robot control unit from electric disturbances of the motor output stage. This is shown in Fig. 10. The different modules are connected via standard D-Sub9 connectors.

The basic module includes the 16 MHz 16 bit RISC microcontroller MSP430f2618 from Texas Instruments, which controls all peripheral modules and communicates with the higher level controller. An RS232 interface is also integrated, which allows the module to communicate over a serial interface, such as the hyper terminal of a common personal computer. Moreover, several program values such as the angular value or the actual frequency of the motor output stage can be readout online.

The communication between the main module and the higher level system is achieved via several digital and analog signals. Here, the motor speed is controlled by an analog voltage within the range of 0 V-10 V. The motor stops at 0 V and runs with full speed at 10 V. The rotational direction is digitized by a TTL-signal (transistor-transistor logic). Other TTL-signals are for deactivating the motor or enabling any additional functions for future developments.

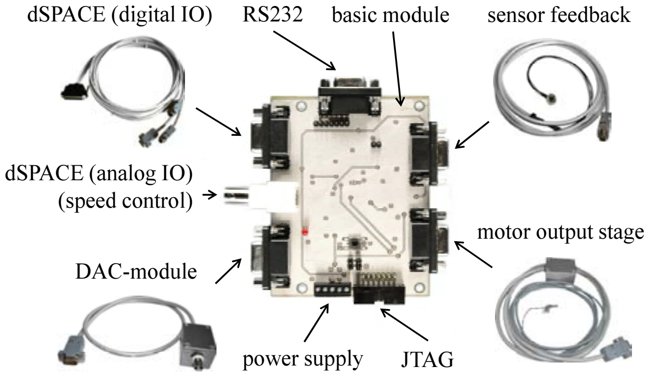


Fig. 10 Modular design of the controller module

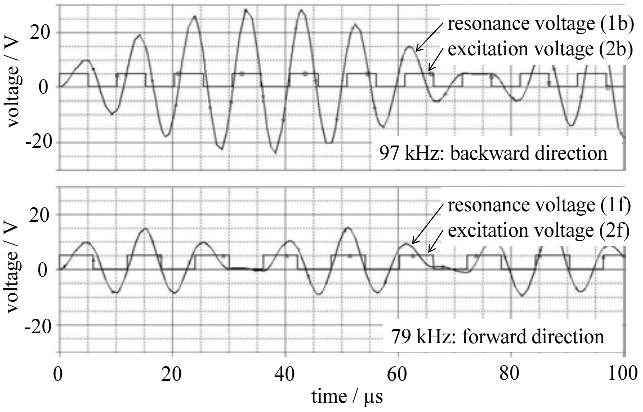


Fig. 11 Simulated resonator excitation, resonance of the LC-oscillator

The sensor feedback module includes the rotary sensor AS5045. The readout digital 12 bit angular code will be converted into an analog signal within the range of 0 V-10 V. To counteract noise, it has been shown that it is reasonable to project only a sector of 22.5° (360°/16) onto the analog 10 V range. Additional information about the coordination of the sector within the 360° is signalized by four binary coded TTL-signals which assign every sector to a defined position. This method optimizes the signal-to-noise ratio by a factor of 4^2=16 and makes a resolution of 12 bit possible.

The motor output stage supports both excitation methods described in section 2.2. Using the dynamic method, the low current PWM-signal of the microcontroller is amplified so that the required current of up to 1 A is available for the actuation of the piezo element. The amplitude of this excitation is also amplified from 3.3 V to 5 V. In addition, an LC-oscillator is generated with a coil, which is connected in series to the piezo element. This LC-oscillator will be excited in resonance to generate higher amplitudes and increase the motor power. In Fig. 11 the simulated resonances of both rotational directions are shown. The different amplitudes of the resonance voltages (1b, 1f) result from fixed part values but varying frequencies. This is disadvantageous because it becomes clear that the motor power also varies, depending on the rotational direction. Using ultra fine positioning, which is, however, not yet implemented in the software of the robot control unit, a variable DC voltage, which is generated by the DAC of the microcontroller, is amplified from 0 V-3 V to 0 V-30 V. This voltage span covers the range of an averaged step size of the dynamic excitation method.

4. Measurements

The repeatability of the first prototype was measured at the IWF using a method which is comparable to the ISO standard EN ISO 9283. Here, the positions at five defined points within the rectangular workspace were measured 30 times (Fig. 12). Table 2 summarizes the results with the best and worst case presented in Fig. 13. Altogether, the robot achieves a repeatability of less than 33.9 µm. Finally, the main specifications of the first functional prototype, which is shown in Fig. 14, are summarized in Table 3.

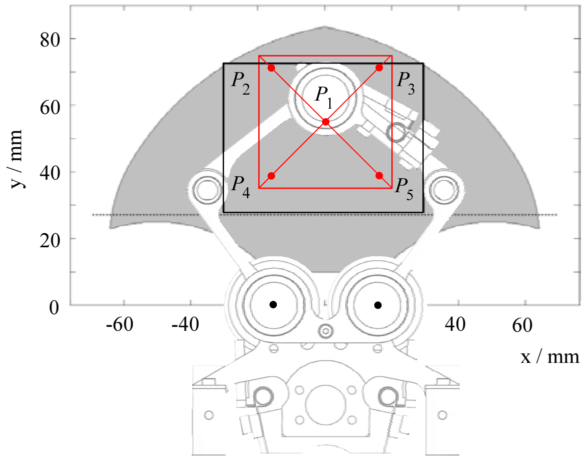
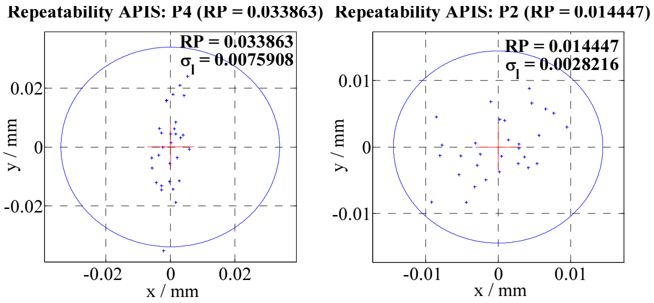


Fig. 12 Measured points within the workspace of APIS



(a) worst result (b) best result

Fig. 13 Repeatabilities of the first functional model

Table 2 Measurements of repeatability in *xy*-plane, measured points are referred to Fig. 12

measured point	x-direction	y-direction	number of measurements	repeatability RP	standard deviation σ_l
P1	0 mm	55 mm	30	21.3 µm	4.2 µm
P2	-16 mm	71 mm	30	14.5 µm	6.0 µm
P3	16 mm	71 mm	30	16.0 µm	6.0 µm
P4	-16 mm	39 mm	30	33.9 µm	7.6 µm
P5	16 mm	39 mm	30	14.6 µm	3.0 µm

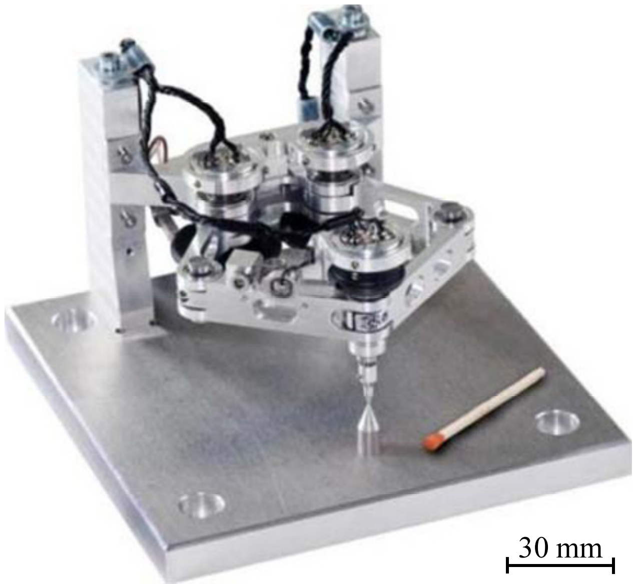


Fig. 14 First prototype of APIS

Table 3 Main specifications APIS

description	value	
workspace	60x45	mm²
footprint	100x25	mm²
repeatability (practical)	< 33.8	µm
max. angular velocity q_1 ; q_2	< 4.2	rad/s
max. angular velocity ψ	< 6.1	rad/s
angular resolution q_1 ; q_2 ; ψ	87.9e-3	°
costs per drive (resonator, rotor, sensor)	~ 50	€
total costs* (mechanical and electrical equipment)	~ 2900	€

**turned and milled parts constitute up to 75 % of total costs so that total costs strongly depends on quantity*

5. Conclusion and Future works

5.1 Conclusion

In order to provide a miniaturized and cost-saving assembly system, a parallel kinematic robot which is driven by gearless piezoelectric motors has been presented. After an introduction on the need and potentials of this concept, this contribution deals with the detailed steps of the development process. In doing so, kinematic aspects as well as the driving concept and the robot control, including the development of the entire motor control and power stage, are described. Finally, the first functional prototype is presented, along with results of repeatability measurements.

5.2 Future works

To enhance repeatability and drive torque, different concepts for future developments exist. The rotary sensor should be replaced by novel sensors to improve the angular resolution. It is recommendable that the sensor feedback system be adapted to the corresponding resolution. On this occasion it is reasonable to use a digital transmission format as opposed to the default mixed analog-digital transmission, which includes electric disturbances, limiting the resolution to 12 Bit. When using sensors with higher resolutions, it is also reasonable to implement the mentioned ultra fine positioning by direct voltage.

In addition, the motor output stage as well as the drive concept have to be optimized. The current drive torque is very low, which can be improved in several ways. One solution is to mount a second resonator onto the main platform so that the out of phase resonators will drive the rotor simultaneously. Another method is to redesign the LC-oscillator of the motor output stage by adding variable parallel capacities and inductances connected in series so that the resonance can be optimally adapted to the mechanical resonance of the particular resonator. In addition to this, the development of a separate LC-oscillator for every rotation direction will be considered. This will also reduce varying motor power between both rotational directions. Moreover, additional measurements and analyses are planned. Those are, for instance, absolute accuracy, transmission behavior or repeatabilities for various directions.

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