

# Development of Controlled Surface Acoustic Wave Planar Actuators

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## Abstract

This paper describes the development of Surface Acoustic Wave (SAW) actuators under closed loop control, which can be applied as ultra precision multi-axis manipulators. In papers presented so far on this topic, linear SAW actuators are driven in open loop. The slider is manipulated by inducing a repetitive small number of wave periods. Although very small steps have been reported for SAW actuators operating in open loop, the reproducibility of such open loop steering may be low in an environment with disturbances. Therefore, we focus on *closed loop control* of the SAW actuator. For this purpose, linear and planar demonstrators have been developed.

If very small steady state speed is required, the wave amplitude becomes smaller than the indentation of the slider and the surface roughness. As a result, a dead band appears in the response of the input signal to the speed of the motor, which makes control difficult. Using this knowledge, an alternative way of actuation has been found on which a patent has been filed: By simultaneously generating waves from opposite sides, the dead band can be eliminated, and the control of a SAW actuator resembles that of a voltage driven DC actuator.

In the absence of waves, the pretension between slider and stator leads to a high contact stiffness. Hence, after switching off power, no additional braking system is required. Once waves are present under the slider, the contact stiffness disappears macroscopically spoken. Instead of stiffness, damping is encountered. Experiments have shown that this applies for both traveling and standing waves. By generating a standing wave in a stator in a particular direction, the slider can be moved across that stator in any direction, without introducing a friction force. Only a damper force has to be overcome. This limits the number of actuators required for a planar actuator.

The planar motor concept proposed features a simple and compact construction with low moving mass, since the drive- and guiding-systems are combined, without the need for external bearings, transmissions or guiding systems. Compared to stacked linear systems, a high stiffness and good dynamic behavior can be achieved. Further experiments are planned to establish the potential benefits of a planar SAW motor in applications of precision engineering, nanotechnology and biotechnology.

## Introduction

Conventional multi-axis manipulators are often based on stacked constructions of linear systems comprising an electromechanical actuator, a transmission and a linear guiding system. Such concept results in a relatively large size and a reduced stiffness due to the series connection of components, and hence loss of accuracy and dynamic performance. For this reason, a parallel manipulator, consisting of fewer components would be favorable. In this paper, a direct driven planar (i.e. parallel) manipulator is presented, which is based on SAWs.

## SAW actuation principle

The actuation principle of a SAW actuator is based on moving a slider across an elastic solid medium, called stator, through the surface of which Rayleigh waves are propagating [1]. These traveling waves cause elliptical movement of particles at the surface, showing a fixed ratio between tangential and perpendicular motion. The waves are generated by applying an sinusoidal voltage to so-called Inter Digital Transducers (IDTs), finger shaped galvanic patterns applied at a locally polarized stator surface. To generate effective energy transfer, the impedance of the IDT is matched electronically. Our stator is made of PXE43, an isotropic piezo-electric poly-crystal. Considering the speed of Rayleigh waves in our stator and a frequency of 2.3 MHz, the wavelength becomes 0.95 mm. At practical voltages applied to the IDTs, amplitudes in the order of 20 to 40 nm occur, demanding a  $R_a$  surface roughness of about 20 nm. By ELID grinding a surface roughness of 10 nm has been attained. In order to generate sufficient traction force to move the slider and to prevent a squeeze air film between slider and stator, the contact surface of the slider (1 cm<sup>2</sup>) consists of many ball-segments, closely packed, made by lithographic etching of silicon [1]. To achieve high accelerations it is necessary to preload the slider. Depending on the application, several force generating principles can be used, e.g. a vacuum force, a magnetic force, etc.

## Linear demonstrator

In our first demonstrator the preload consisted of two sliders moving simultaneously at opposite sides of the stator and preloading each other by a spring, as shown in Figure 1. The required preload force between one of the sliders and the stator is identical to the force between the other slider and the stator. Consequently, the preload force does not load an external guiding system (required to avoid slider motion in  $y$ -direction), so the friction is limited. In addition, the preload force does not cause a bending load to the stator in this construction.

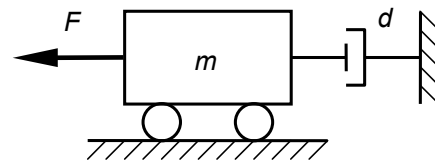
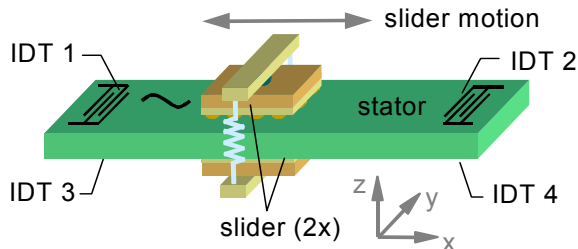


Figure 1: Linear SAW actuator with two sliders, preloading each other. Figure 2: Model of SAW actuator.

## Modeling for control

In papers presented so far, very small steps of 2 nm have been reported for SAW actuators operating in open loop [2]. In an industrial environment, disturbances will harm the reproducibility of this kind of steering. Therefore, we focused on closed loop control of the SAW actuator. Step response measurements showed a first order response from the amplitude of the 2.3 MHz sine to the speed of the slider. This first order behavior can be represented by the simple first order model, given in Figure 2. The damper  $d$  is part of the actuator model and the amplitude of the driving sine is proportional to the force  $F$  on the mass  $m$ .

This system resembles the behavior of a voltage driven DC actuator. For that actuator type (with internal resistance and negligible self-inductance), the damper in the model can be physically explained by a back EMF: for increasing speed, the induced voltage rises. For the SAW actuator, the physical explanation of the damper lies in the 'running-in and -out' of fresh material in the contact between stator and slider. In everyday life, this phenomenon is encountered when driving a car in the presence of cross wind. For a car that is standing still, a constant cross wind leads to a constant displacement of the car due to lateral elastic deformation of the tires (stiffness). But when the car is moving (material is running in and -out of the contact between tire and road), the cross wind leads to constant lateral speed. So although the contact stiffness is still providing the counter force, its macroscopic behavior is that of a damper.

## Dead band: cause and solution

The model proposed above suggests a linear system. However, measurements have shown that the linearity between sine amplitude and steady state speed does not exist for very low amplitudes, see Figure 3a. The problem is that if a very small steady state speed is required, the tangential motion must be so small that the perpendicular amplitude becomes smaller than the indentation of the preloaded slider against the stator and the surface roughness of the stator. For amplitudes below this threshold, no slider movement results so this dead band hampers good control.

This problem can be solved if one could use waves for which the relation between tangential and perpendicular motion is not fixed. In that case, the tangential motion can be chosen such that the low speed is achieved, but that the perpendicular motion is large enough. This decoupling between tangential and perpendicular motion can be achieved by using two Rayleigh waves from opposite sides: the longitudinal waves will interfere destructively (if they both have the same amplitude), while the transversal waves will interfere constructively. So the tangential motion is controlled by the difference in amplitude of the two Rayleigh waves, while the perpendicular motion is controlled by the sum of the amplitudes of the two Rayleigh waves. This idea was tested and proved to work, as is shown in Figure 3b. This technique was named 'Dual Side Actuation', or DSA. Since we believe that high performance in closed loop can only be achieved when this dead band is eliminated, a patent application has been filed. When DSA is used, the SAW actuator may now be considered as a linear system, so we can characterize it by a frequency response function (FRF).

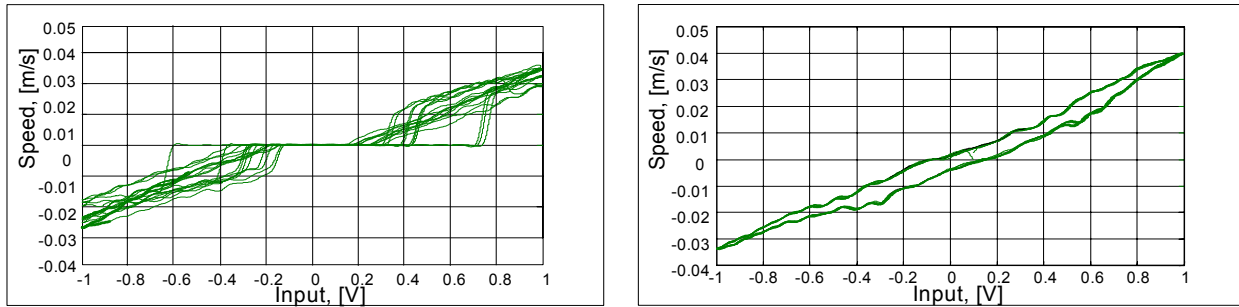


Figure 3: Open loop speed against input voltage, a) dead band present, b) dead band solved.

Note however, the large difference in behavior when the waves are present or when there are no waves. In the absence of waves, the pretension leads to a contact stiffness between slider and stator. Modeling the slider as a mass, this leads to a simple mass-spring system, with low damping. Once the waves are present, the contact stiffness disappears macroscopically spoken. Instead of stiffness, damping is encountered.

It can be concluded that, once the dead band between wave amplitude and response has been eliminated, closed loop control of the SAW actuator resembles controlling a voltage driven DC actuator, which implies applying straightforward control strategies. Because the low order of this mechanical system, a PID controller (maybe with some extra filtering), extended with acceleration and speed feed forward, is a good choice for a controller structure. Using this structure, early test showed a position error in the order of some encoder increments (i.h.c.  $0.15 \mu\text{m}$ ). Principally, the achievable bandwidth of the SAW actuator is limited only by the time it takes the wave to propagate to the slider.

### Planar SAW actuator

Using the knowledge obtained from the linear demonstrators, the actuator concept can be extended to a planar SAW actuator [3]. Using DSA and the way of modeling presented earlier, the main issue from a control point-of-view is the coupling between the different degrees of freedom. Our first planar SAW actuator demonstrator (Figure 4, size:  $250 \times 250 \times 60 \text{mm}$ ) had three stators in which Rayleigh waves can be generated in x- and y-direction. The moving part is a carrier with three sliders, which can be driven individually in x- and y-direction across their accompanying stators. Preload of each slider is performed by (adjustable) magnetic attraction between magnets connected to the carrier and a steel plate under the stators. Position measurement of the carrier is achieved using one planar encoder system, consisting of a grid plate connected to the carrier, and a read head, adjustable with respect to the base frame. Using this encoder reading, planar motion of a carrier is performed by controlling three DOFs: two translations (x and y) and one rotation  $R_z$ . In this way the system is over-actuated but not over-determined.

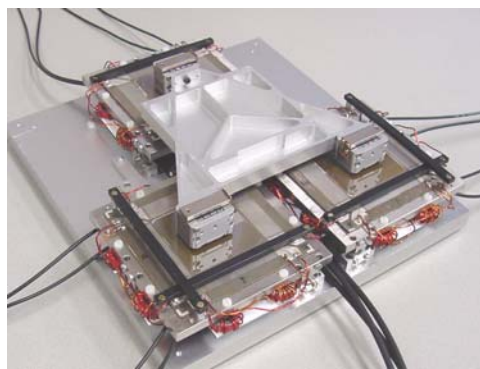


Figure 4: First Planar SAW actuator.

Decoupling is achieved using two transformations: one at the measurement side and one at the actuator side of the controllers. The transformation on the measurement side is such that the position (x, y and  $R_z$ ) of the centre of gravity of the slider is calculated. Note that this transformation needs absolute position information, so can only be correct after zeroing the incremental measurement system. The transformation on the actuator side (which is distributed over software and electronics in our set-up) is such that all IDTs (12 in total) cooperate to generate force at the centre of gravity in x or y direction and a pure torque. Using this strategy, three SISO (single input, single output) controllers can be used. The decoupling makes it almost like three separate control problems.

The first planar SAW actuator has demonstrated, amongst others, feasibility of generating a planar Rayleigh wave, composed out of two individual perpendicular waves (x- and y-direction) that interfere. This is basically possible since the stator substrate material PXE43 is isotropic. The direction of the composite wave is determined by the ratio of the individual waves, e.g. motion under a  $45^\circ$  angle occurs when both amplitudes for x- and y-direction are equal to each other. In this way, a slider can be driven across the surface in an arbitrary direction. Three of these sliders were used to generate planar motion of a carrier and to constrain in a stiff way the remaining degrees of freedom. In

this over-actuated set-up, *twelve* piezo actuators (IDTs) are required, each matched electronically and each connected to an individual amplifier. One may wonder whether it is possible to drive this carrier with a smaller number of actuators and amplifiers without affecting its behavior, thereby creating a simpler and more cost effective set-up?

### Reduction of number of actuators

Considering the set-up as shown in Figure 5, showing the carrier being supported by three sliders A, B and C. Each slider is now driven in one direction instead of two. When the carrier has to be moved e.g. in y-direction, both the sliders B and C are driven. Note that DSA is applied here, so IDTs at both sides of the accompanying stators are energized. In that particular case, moving the carrier implies that slider A has to slide across the stator, requiring a large (static) friction force. Practically, sliders B and C cannot overcome this force and no motion will occur. However, when applying DSA by energizing both IDTs that actuate slider A equally, a standing wave is created for slider A. Whereas no motion occurs in x-direction, the behavior of that slider has changed to that of the mass-damper model of Figure 2, implying that a damper is encountered instead of a friction force (in addition to the dampers felt at the locations of sliders B and C). Generally spoken, by generating a standing wave in a stator in a particular direction, the slider can be moved across that stator in any direction across the stator plane, without introducing a friction force. Only a damper force should be compensated for. Driving the carrier in x-direction is analogous in this set-up, when taking into account the distance from slider A to centre of gravity of the carrier, that has to be compensated by a torque supplied by the sliders B and C. Note that the orientation of the stators can be made such (3 times at 120°) that the driving behavior becomes equal for both x- and y-direction. Experiments have shown that this set-up (Figure 5) is feasible to drive the carrier in three degrees of freedom, requiring only half of the number of actuators and amplifiers compared to Figure 4, without affecting its driving behavior significantly.

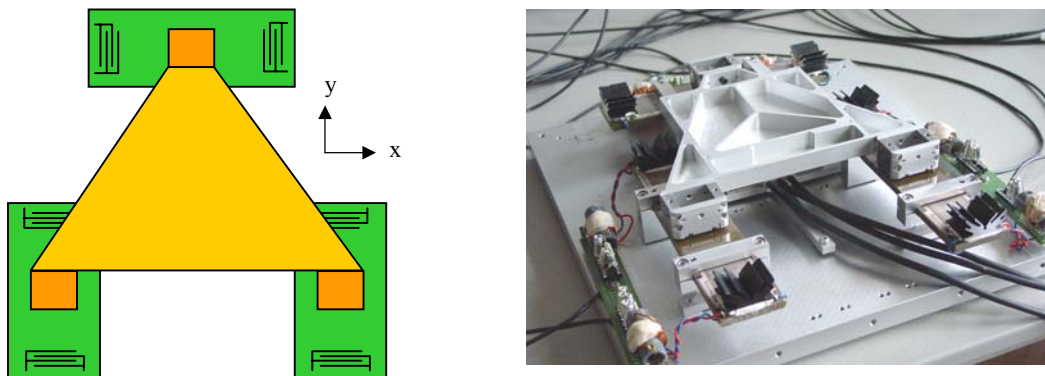


Figure 5: Planar SAW actuator with reduced number of actuators, constructed by three linear SAW actuators.

### Conclusions

In this paper the development of SAW planar actuators under closed loop control is described. To investigate the open loop and closed-loop behavior, linear and planar demonstrators have been developed. A different way of actuation has been found and patented, to overcome a dead band in the response of a conventionally driven controlled SAW actuator. In this way, the control of the SAW actuator resembles that of a voltage driven DC actuator. Modeling and experiments have shown that by generating a standing wave in a stator in a particular direction, a slider can be moved across that stator in any direction across the stator plane, without introducing a friction force. Only a damper force has to be overcome. This limits the number of actuators required for a planar actuator thereby creating a simpler and more cost effective set-up. The planar actuator concept proposed features a simple and compact construction with low moving mass, since the drive- and guiding-systems are combined, without the need for external bearings, transmissions or guiding systems. Compared to stacked linear systems, a high stiffness and good dynamic behavior can be achieved. Further experiments are planned to establish the potential benefits of a planar SAW actuator in applications of precision engineering, nanotechnology and biotechnology.

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