Proceedings IEEE Micro Electro Mechanical Systems
Amsterdam, The Netherlands, January 1995, pp. 66 - 71.

Devices for Particle Handling by an AC Electric Field

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Abstract – Devices for particle handling using an AC electric field are proposed and experimentally validated. With the application of balanced multi-phase high voltage in the $200V_{ptp}$ to $2kV_{ptp}$ range to a series of encased parallel electrodes with a center-to-center pitch length of 400µm, particles on a thin protecting and insulating film become charged and are conveyed by the created traveling field. Devices with various novel transportation and manipulation features, utilizing multi-phase AC electric fields that instantly generate particle driving forces, have been designed and produced. Their features include newly developed methods for particle conveyance smoothing, grouping, and sorting, as well as two-dimensional handling. Particle conveyance characteristics have been studied under the influence of three different voltage profiles and in diverse environments. Various particle materials with a 5µm to 400µm diameter range have been examined in experiments; *Fe*, *Al*, glass, and plastic spheres showed the best performances.

INTRODUCTION

There are several well-known methods for particle handling, such as regulated air or liquid flow, magnetic fields, surface vibration, and other mechanical means. However, through the appropriate use of electrostatic forces, very compact devices for particle conveyance and manipulation, possessing advantages over the above methods, can be created.

The method of using electrostatic forces for particle handling has already been outlined in various papers and proven in applications. DC electrostatic forces were engaged in surface cleaning and particulate dispenser processes as presented by */Novick 89/* and */Cooper 90/*. Transportation of fine particles by a three-phase traveling electric field was originally proposed by */Masuda 75/* in the early seventies. His discovery has been reported as an *electric curtain*, where fine particles are continuously levitated against gravity. Frequency and phase-lag effects on fine particle transportation for the electric curtain modes have been theoretically studied by */Gan-Mor 92/*, where they proposed large scale systems. Linear motion of microscopic objects was done by */Fuhr 91/*, and manipulation of cells by */Pethig 90/* and */Fuhr 91/*.

This paper focuses on micro-devices for particle handling, making use of AC electric fields. By this technique, a diverse range of particle substances showed an effective frequency dependent transportation performance. The proposed devices are connected to and activated by a multi-channel, PC-controlled, high voltage supply with a profile amplitude range of up to $2kV_{ptp}$. A major objective was to overcome fluctuating disturbances during the particle handling process, yielding a smooth and nearly tranquil manipulation over a panel's surface. Means for a improved conveyance are also presented in this paper. It is expected that the approaches described will lead to new applications in various fields, such as a parts feeder for micro electro mechanical systems (MEMS).

PRINCIPLE OF CONVEYANCE

Balanced, multi-phase high voltages are supplied to a series of encased, parallel electrodes which are covered and protected against electric sparkovers by a thin insulating film. Upon the activation, a traveling electric field is created around the electrodes. Particles on the film-surface become charged, and when the dynamic forces of the electric field overcome adhesion and gravitational forces, particles move with the traveling field in a direction in the plane perpendicular to the electrodes.

The electric field strength and its resulting force on the particle depends on the applied voltage. Consequently, regulation of the voltage amplitude offers a means to tune the force on the particles.

By this transportation process, particles proceed stepwise from electrode to electrode, producing an overall conveyance velocity in direct proportion to the electric field's low frequency and the electrode gap.

The conveyance principle is incorporated in the structure of the *electric panel*, as shown in Fig.1.

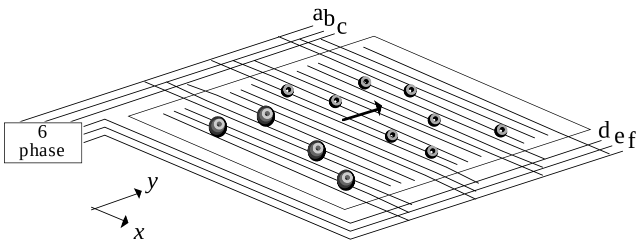

Fig.1: Simplified appearance of the *electric panel* device

A multi-channel, PC-controlled, high voltage supply is linked to the panel, where every sixth electrode belongs to the same phase state: a, b, c, d, e, or f.

Tab.1: Combinations to connect 6 electrode attachments a, b, c, d, e, and f to a multi-phase voltage source

source	*electrode attachment combinations*					
six-phase	a	b	c	d	e	f
three-phase #1	a, d		b, e		c, f	
three-phase #2	a, b		c, d		e, f	
three-phase #3	a		c		e	
two-phase #1	a, c, f			b, d, f		
two-phase #2	a, b, c			d, e, f		
two-phase #3	a, b			d, e		
two-phase #4	a			d		

The number of combinations for connecting the individual phases to the electrode attachments depends on the available number of electrode attachments. For example, six electrode attachments lead to a total of 8 combinations with a range of 1 to 6 phases. An overview of all the possible combinations for the six-phase case is given in Table 1. Particle motion is dependent on particle type and the effective gap between activated electrodes. With the variety of combinations, the connections most suited for specific particles can be made. A particle sorting function can be performed in this manner. Particle conveyance is generally done by the six-phase or three-phase #1 combinations.

Two types of balanced high voltage profiles are utilized: sine and square waves, each having a different effect on the particle conveyance dynamics.

Three structurally novel devices were developed: the ***electric panel***, the ***electric tube*** and the ***electric dots***. Each incorporates the same principle for particle handling, but serves a different purpose.

ELECTRIC PANEL DEVICES

Structures

As shown in Fig.2, the device is composed of parallel electrodes encased in epoxy resin, an insulating thin cover-film, a supporting panel, and electrode-attachments to the power supply.

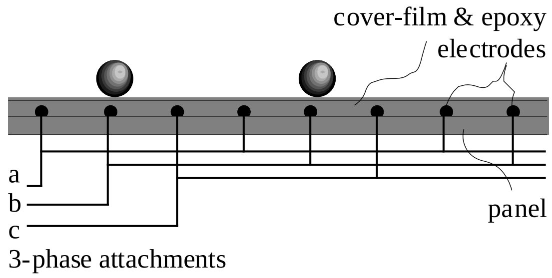

Fig.2: Basic structure of the *electric panel* with 3-phase electrode attachments

The parallel electrodes have a center-to-center pitch length of 400µm, a diameter of 50µm and are situated parallel to the surface at a distance of 25µm to 75µm. The *electric panel* represents the most compliant device. Due to the simple electrode design, the *panel* can be fabricated with various features as outlined in Fig.3 and Fig.4:

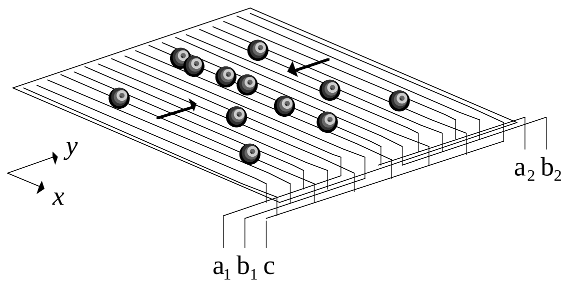

Fig.3: *Electric panel* for bi-directional particle transportation in *y*-direction and grouping along center line

Fig.3 shows the spatial appearance of a modified *electric panel*. The two electrode-attachments a and b, which correspond to their phases a and b, are inversed in one half-plane. By this *phase inversion technique*, particles can be gathered in the area of the central electrode or dispersed to the two peripheral electrodes when applying an inverse voltage profile sequence. By changing the attachments of electrodes a and b to a non-inversed configuration, the particles can be conveyed in one dimension across the entire surface.

An approach to achieving two-dimensional particle handling is shown in Fig.4. A second electrode layer perpendicular to the first can be added. Alternatively, a mesh interweaving the two layers can be employed. In order to endure the high voltage differences at the node-points, individual mesh-

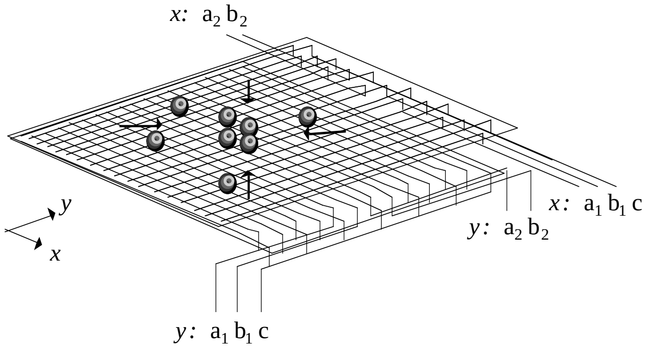

Fig.4: Electric panel for *x-y* particle handling and grouping in central and peripheral areas

electrodes must be covered with a sufficient insulation such as polyamide-imide. By applying the *phase inversion technique*, particles can be selectively accumulated into 9 different locations and along 6 different lines as well as conveyed two-dimensionally over the entire surface.

Particles

Particles involved in the experiments were in the 5μm to 400μm diameter range, held diverse moisture contents, and had different shapes and size distributions. Representative samples utilized in the experiments are shown in Fig.5.

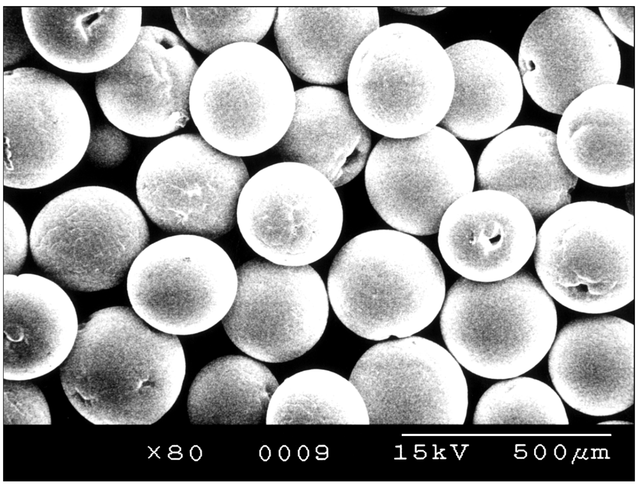

Fig.5: Al particles in the 200μm to 250μm diameter range (SEM micrograph)

Aluminum, other metals, glass, and plastic spherical particles were the most promising in a series of conveyance tests conducted on the *electric panel*. A selection of 70 different types of substances have been examined, and about half of the tested particle substances showed an acceptable frequency dependent transportation behavior. The applied sine profile based three-phase #1 voltage was approximately $1kV_{ptp}$ and the frequency varied from 1Hz to 50Hz. Raising the frequency higher than the 100 to 200Hz range caused the particle movement to cease with this configuration.

It has been observed that spherical particles smaller in diameter than the pitch-length were suitable for conveyance in most of the experiments. However, in cases where the particle shape has sharp edges, it is believed that the charge distribution is most concentrated at the edge, thus disturbing and distorting the conveyance process. A study of the charge distribution on the particle surface and its impact on particle conveyance dynamics remains for future research. For the following experiments, we focused on the usage of spherical and metallic particles.

Experimental Environment

The dynamic forces of the electric field acting on particles have been tested by the *electric panel* in various environments such as air, a vacuum, and in dielectric liquids. In atmospheric conditions, several problems must be solved due to the ever present humidity which leads to increased adhesive forces, causing particles stick to the surface. Furthermore, the generated electric forces decreased considerably in a vacuum environment, and the cause has to be investigated more closely. Good results could be obtained for particles being handled in dielectric liquids.

Conveyance Characteristic & Improvements

Some experimental results in particle handling reveal the improvements of conveyance smoothing on the *electric panel*. For normal particle transportation, a simple set of parallel electrodes is sufficient, but the produced conveyance shows a high sidewise fluctuating behavior. The cause of this disturbance is believed to lie in the unequal gaps between the electrodes and inaccuracies originating from the fabrication process which result in a non-uniform field. A further explanation can be found when considering a non-uniform charge distribution on the particle surface which imposes a torque on the particle itself. In the low frequency range, the voltage profile also has an impact on the transportation performance, as verified experimentally.

The goal to smoothen and improve particle conveyance dynamics on the *electric panel* can be solved by a simple method: A series of parallel electrodes are incorporated below and perpendicular to the already existing layer or simple a mesh with insulated wires is embodied into the device. The newly added layer is then supplied with a *constant* voltage.

The AC supplied layer works as the particle conveyor, whereas the DC supplied layer constrains the particles to track on the activated electrode. Therefore, this method is referred to as *tracked particle conveyance.*

Under the condition of three-phases #1 in Table 1, three different voltage wave profiles (Fig.6), with a voltage of $1kV_{ptp}$ and frequency of 2.5Hz, were applied to the *electric panel* to study its influence on particle conveyance. Particles were monitored by a high speed camera over a time span of 1.2s and a distance of 5mm. The resulting conveyor characteristics in the *y*-direction are shown in Fig.7 for tracked and in Fig.8 for normal, untracked particle conveyance. The high fluctuation of the normal conveyance is clearly visible in Fig.8. Among the tracked conveyance characteristics in Fig.7, the particles driven by a sine profile show a smooth and low-fluctuating behavior. For the square profiles, which result in high particle acceleration between the gaps, the tracking method maintains the sidewise fluctuation within a well defined range which is dictated by the electrode pitch. It should be noted that the profile of square #1 with an additional step produces a visibly smoother conveyance than that of square #2.

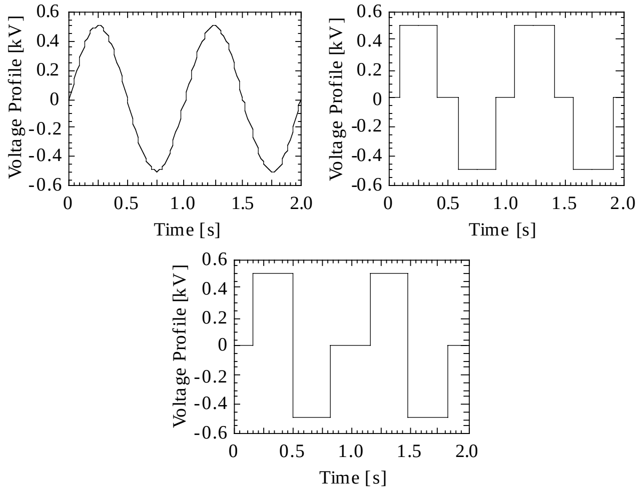

Fig.6: Tests of particle conveyance behavior employing 3 different voltage wave-profiles: sine, square #1 and square #2; here, one phase is shown

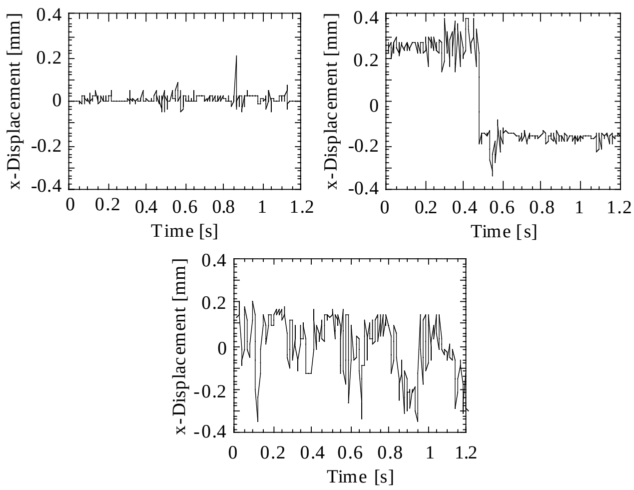

Fig.7: Tracked particle conveyance monitored in *x*-direction for each of the three voltage profiles with $1kV_{ptp}$ at 2.5Hz

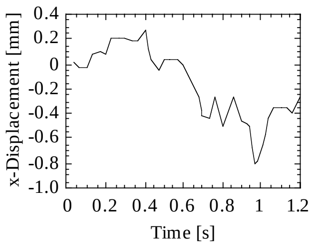

Fig.8: Untracked and high fluctuating particle conveyance monitored in *x*-direction for sine profile with $1kV_{ptp}$ at 2.5Hz

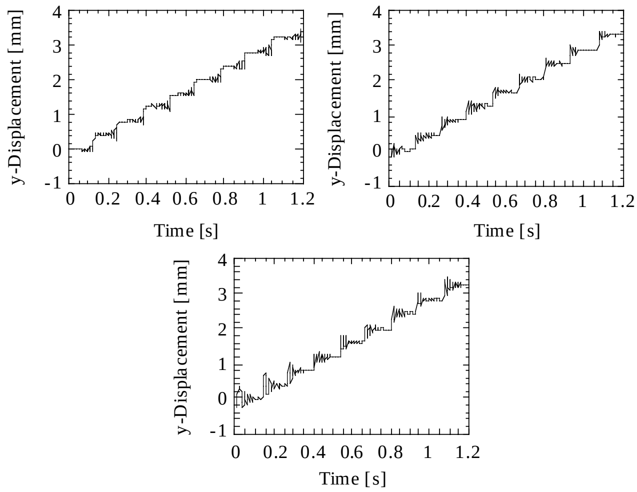

Fig.9: Tracked and stepwise particle conveyance monitored in *y*-direction for each of the three profiles with $1kV_{ptp}$ at 2.5Hz

The stepwise transportation from electrode to electrode is clearly shown in Fig.9 for the three voltage profiles. On comparing the monitored stepwise conveyance of the sine and the two square profiles, it is clear that the opposite oscillation response is the outcome of different accelerations. It will be interesting to employ custom wave-profiles incorporating only the favorable elements of the produced transportation characteristics for future experiments.

Particle Handling

Fig.10 shows the results of using the *electric panel* for particle accumulation. The *phase inversion technique* allows a group of particles to be gathered at the upper right corner, arranged in the center of the upper line and finally separated into the left and right corner. This technique also yields an assembly of particles along a desired line in central or peripheral areas.

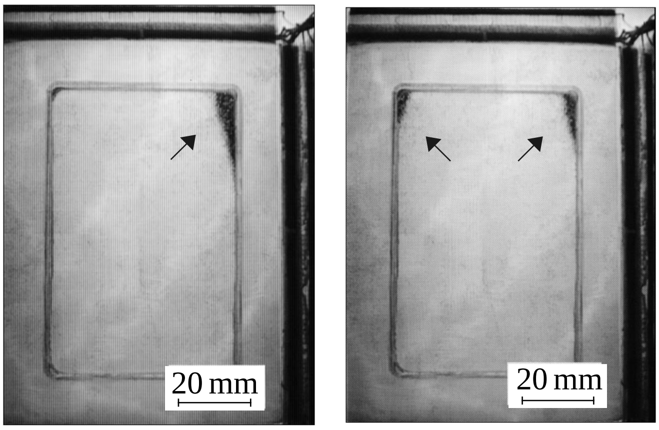

Fig.10: Electric panel allowing two-dimensional particle handling and accumulation

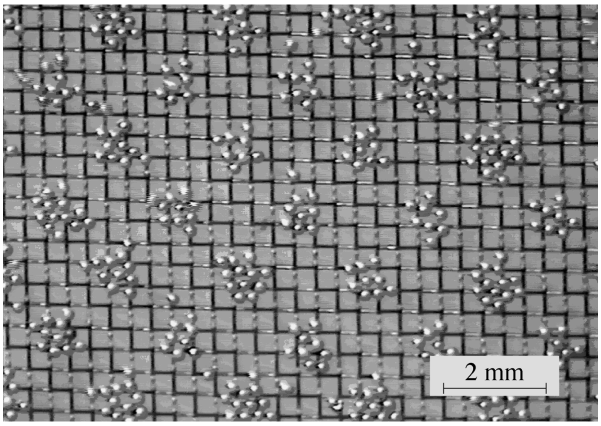

Fig.11: On supplying 6-phase voltage to the *electric panel*, *Fe* particles are conveyed in groups in *x*-*y* direction

Furthermore, it has been observed that a 3-phase voltage supplied to the electrodes shows less force generation on the particles than a 6-phase voltage. An increase in phases smoothens and also improves the particle conveyance characteristics necessary for fine manipulation. However, the additional phases make the whole device more complicated to fabricate.

The total area for the activated electrodes is larger for a 6-phase supply than a 3-phase supply. This phenomena can be observed directly in Fig.11. Groups of particles are concentrated in the active areas and conveyed in the *x*-*y*-direction forming a gap of the same width as the active area. The particles appear grouped in a checker board pattern.

One further advantage of the *electric panel* is that particles can be packed in a single layer and evenly arranged at any surface location. This interesting occurrence has previously only been examined and observed with larger sized particles in the diameter range of over 100µm. The actual limitations and its causes must be examined more closely.

ADDITIONAL DEVICES

Electric Tube Device

Fig.12 depicts a tube shaped device, which is named the *electric tube*.

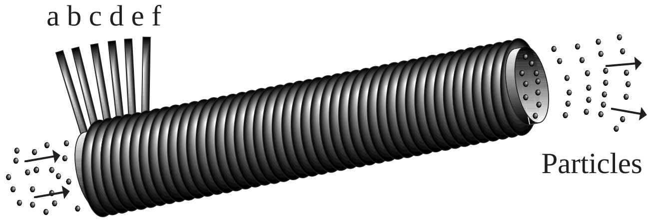

Fig.12: Appearance of the *electric tube* device

It embodies the same principle as the *electric panel*, but is made of a single layer of spooled electrodes with a defined and constant gap-width and an electrode center-to-center pitch length of 256µm.

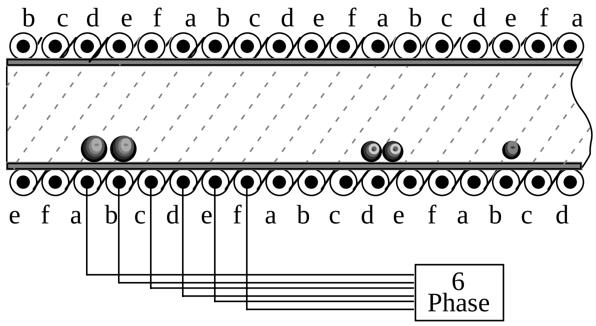

Fig.13: Cross-section of the *electric tube* illustrating its numerous attachments for a six-phase voltage supply

This *electric tube* is meant for particle mass transportation taking an inherent advantage of utilizing multiple electrode attachments, such as in Table 1. Particles can be transported due to their particular physical properties, whenever a multi-channel, PC-controlled, power-supply is used and a voltage phase sequence to activate desired electrode combination is sent to the device.

Preliminary results have been obtained for particle transportation under direct influence of gravitational forces in an *electric tube* which has been positioned vertically. The goal is to use a long *tube* in order to transport particles from one location to another.

Electric Dots Device

Fig.14 illustrates the concept of the *electric dots* device.

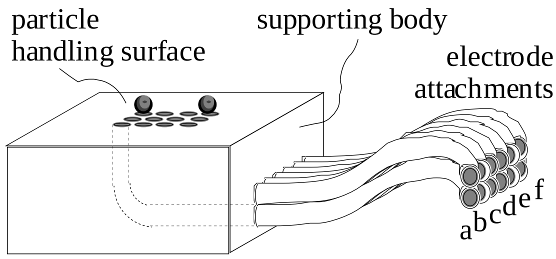

Fig.14: Appearance of the *electric dots* device

The manipulation electrodes appear as a matrix of dots in the handling surface. The device incorporates a bundle of insulated conductive wires, embedded in a supporting body. The surface has been ground in a plane normal to the wires to form the handling surface which is subsequently covered by a thin film. The particles are manipulated on the film-surface along the dot electrodes. The dots have a center-to-center pitch length of 400µm and a diameter of 50µm.

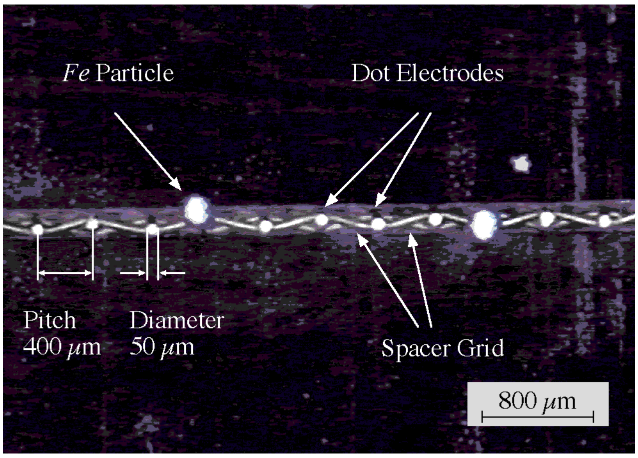

Fig.15: Electric field above *dot electrodes* conveying two *Fe* particles along dotted line

Particles are handled precisely from dot to dot, as shown in Fig.15 for a *Fe*-particle. By increasing the applied voltage amplitude, the conveyed particles form groups on the dots. The main drawback is the existence of electrostatics on the non-activated, surrounding surface which also attracts the particles.

CONCLUSION & FUTURE PROSPECTS

Three devices for particle handling by an AC electric field have been proposed and experimentally validated. The *electric panel* enables two-dimensional tracked manipulation which includes particle spot- and line accumulation, conveyance in particle groups and sorting. Experimental results show the difference between untracked and tracked transportation and also the influence of the applied sine and square voltage profiles. The advantages and drawbacks of applying three and six phase voltages have been discussed. The *electric tube* serves by its guiding shape as a particle sorting and mass transportation system. The *electric dots* device targets single particles to be conveyed along a defined dotted line.

Since no moving machine parts are involved, the forces of the electric field can reduce overall energy consumption.

The devices developed can also serve as a parts feeder and manipulator for MEMS. The compact size and simple design of the devices will allow further down-scaling.

Future experiments using more sophisticated devices will be based on the developed handling principle to perform improved particle sorting. Devices as the *electric panel* and *tube* will include linearly increased gap lengths to sort particles in groups of different sizes, size distributions, charges and moisture contents under additional influence of gravitational and centrifugal forces.

Future plans include refining the device structures, and making conveyance improvements by using uniquely designed voltage profiles.

ACKNOWLEDGMENT

We wish to acknowledge the appreciated and valuable collaboration of our colleagues Ju Jin, Shao-Jü Woo and Akiyoshi Fujita.

REFERENCES

- **Novick**, V.J., **Hummer**, C.R., and **Dunn**, P.F., "Minimum DC Electric Field Requirements for removing Powder Layers from a Conductive Surface," *J.Appl.Phys.*, vol.65(8) pp.3242-3247, Apr.1989
- **Cooper**, D.W., **Wolfe**, H.L., **Yeh**, J.T., and **Miller**, R.J., "Surface Cleaning by Electrostatic Removal of Particles," *Aerosol Science and Technology*, vol.13 pp.116-123, 1990
- **Masuda**, S., **Kamimura**, T., "Approximate Methods for Calculating a Non-Uniform Traveling Electric Field," *Journal of Electrostatics*., vol.1.pp.351-370, Nov.1975
- **Gan-Mor**, S., **Law**, S.E., "Frequency and Phase-Lag Effects on Transportation of Particulates by an AC Electric Field", *IEEE Transactions on Industrial Applications*, vol.28 no.2 pp317-323, Mar.1992
- **Fuhr**, G., **Hagedorn**, R., **Müller**, T., "Linear Motion of Dielectric Particles and Living Cells in Microfabricated Structures induced by Traveling Electric Fields," *Proc. IEEE Micro Electro Mechanical Systems Workshop*, Nara, Japan, pp.259-264, Jan./Feb.1991
- **Pethig**, R., "Applications of AC Electrical Fields to the Manipulation and Characterisation of Cells", *Conference Record 4th Toyota Conference*, Oct.1990