Review of the Dissertation Thesis:
"Distributed manipulation by controlling force fields through arrays of actuators"
submitted by Ing. Jiří Zemánek in the field of Control Engineering and Robotics, at the Faculty of Electrical Engineering, Czech Technical University, Prague.

It is my privilege to provide a review and recommendation for this thesis, which has been submitted for the award of the Ph.D degree. This review is structured so as to address, in order, the six categories required to conform to the requirements for awarding a Ph.D. degree in the Czech Republic.

1. The extent to which the subject of the thesis is relevant to the current needs of the scientific community.

The thesis describes the theory and development of an automated control system for the dielectrophoretic and magnetophoretic manipulation of small objects. Dielectrophoresis (DEP), which is defined as the induced motion of a particle when it is electrically polarised in a non-uniform electric field, has over the past 30 years received increasing attention by engineers and researchers in the physical and biomedical sciences. A special feature of DEP is that the induced motion of the particle depends solely on its intrinsic physical and dielectric properties. Thus, apart from representing a non-contact method for manipulating particles, the selective manipulation of a particular particle type does not require the chemical labelling or fluorescent tagging, for example, of the particles. It therefore offers the huge potential as a tool for a wide range of applications that include: drug discovery; isolation of cancer cells from biological fluids; manipulation and monitoring of stem cells; the controlled assembly of nanoparticles. The magnetic 'sister' of DEP, namely magnetophoresis, has received far less attention. As such, this thesis represents an exploration into new territory with potential outcomes yet to be appreciated.

I have no hesitation in stating that the subject of this thesis addresses current and unmet needs of the scientific community.

2. The extent to which the main objectives of the work have been fulfilled.

The original stated objectives were accomplished and include:
i) A closed-loop feedback control system that offers a virtually unlimited range of electrokinetic particle motion, as well as the simultaneous manipulation of several objects at once.
ii) The development of a prototype system for magnetophoretic manipulation of particles.
iii) A mathematical model that is suitable for use in the control of both DEP and magnetophoretic manipulation of particles.

3. The extent to which the methods used in the thesis are appropriate.

All of the applications of DEP and magnetophoresis require the development of dedicated control algorithms; electrical actuators and sensors; and appropriate microfabrication protocols. In my opinion the methods described are novel, timely and provide important guidelines for future advances. This is accompanied by a comprehensive review and analysis of pertinent research published by others.

4. The main results and contributions of the work.

The key and novel approach described in the thesis (chapter 5.5), for non-contact micromanipulation of particles by controlled DEP, was to investigate the advantages to be gained by controlling the phase angles of the voltages applied to the electrodes. This approach has been adopted by others for long-range transport of particles by so-called travelling wave DEP, but is not appropriate

for microscopic manipulation. The current approaches described in the literature employ DEP 'field cages' and modulation of the voltage amplitudes. The control of voltage phase simplifies the hardware implementation and extends the manipulation parameters to include electrorotational as well as translational forces. Innovative geometries for the micro-electrode arrays are also described, that avoid the expensive multilayer fabrication required for travelling wave devices, for example.

A closed-loop (rather than the commonly employed open-loop) feedback control strategy (chapter 5) based on real-time numerical optimization was developed and tested. Numerical simulations and convincing laboratory experiments (chapters 3.2 and 3.3) are described for specified location positioning, steering, and subsequent disassembling of several microscopic objects.

Mathematical modelling of DEP is an important aspect of the design, development, testing and analysis of the performance of any DEP system. Chapter 4 of the thesis describe excellent tests of the accuracy of existing models in both simulations and laboratory experiments. . The standard model for the DEP of microparticles, known as the point-dipole approximation, is shown to provide good approximations even for relatively large particles located near an electrode edge. Refinements of the model offered by multipole approximations (quadrupole, and octupole) were found to offer less than a 10% improvement in accuracy. These were important facts to confirm in the development of the control system, and were achieved using simulations that compared the dipole approximation against the 'gold-standard' Maxwell stress tensor method that has the disadvantage of requiring massive computational power.

5. The extent to which the work is important for the further development of science.

As mentioned in part 1 of this report, the electrokinetic techniques developed in this work offer important new tools for applications that include: drug discovery; medical diagnostics and treatment; the controlled assembly of nanoparticles.

6. Does the thesis satisfy the conditions of a creative scientific work?

A standard way to address this question is to ask whether a thesis submitted for the award of the Ph.D degree contains work that is worthy of publication in an international, peer reviewed, scientific journal of high repute. The author of this thesis, Jiří Zemánek, makes this assessment an easy task for us. Some of the contents of his thesis have already been published as:

i) Tomáš Michálek and Jiří Zemánek, *Dipole and multipole models of dielectrophoresis for a non-negligible particle size: Simulations and experiments*, Electrophoresis **38**: 1419-1426 (2017)

ii) Jiří Zemánek, Tomáš Michálek and Zdeněk Hurák, *Phase-shift feedback control for dielectrophoretic Micromanipulation*, Lab Chip **18**: 1793-1801 (2018)

These two excellent publications, as well as two others cited in the thesis, certainly represent creative scientific works of high order. The work described in the thesis has also been presented at several international conferences.

Based on all these considerations, I am therefore pleased to state that the author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving a Ph.D. degree.

Ronald Pethig
1st August 2018