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Review of "Distributed optimization for multi-object manipulation by shaping spatial force fields" submitted by Ing. Martin Gurtner in the field "Control Engineering and Robotics" at the Faculty of Electrical Engineering, Czech Technical University in Prague.

The work presented by Ing. Martin Gurtner is about the position control of micrometer size objects by force field shaping. Force field shaping based manipulation is an efficient approach for the manipulation of objects at small scales, in the millimeter-micrometer range especially. It has gain a lot of attention recently. In most of his work, Ing. Martin Gurtner uses dielectrophoretic effects (based on the application of nonlinear electric fields).

Dielectrophoresis is widely used to control the position of cells in lab on a chip devices. However, it is used in a passive way. Ing. Martin Gurtner proposes an **original approach**, where he controls in real-time the value of the electric field depending on some feedback. The problem thus becomes a **robotic control problem**, and he applies the methodology from control theory to the problem of multi-object manipulation by shaping spatial force fields. In this thesis, Ing. Martin Gurtner investigates all the aspects of the control loop, including control-oriented modeling, optimization to inverse the model and the proposition of a 3D position sensor for feedback. **This thesis is for me the perfect example of someone mastering control theory, applying it to a field that was not addressed before, with the constant concern of the practical constraints.** This work will undoubtedly serve as a reference for the future years.

The thesis is **well written**. It is composed of 5 chapters. The first one presents an introduction. It is followed by 4 chapters, each corresponding to a journal paper that has been published (Chapters 2, 3 and 4), or is about to be submitted (Chapter 5). Maybe my main regret from this thesis: the introduction is rather a (very good) explanation of the approach (that should be included in all textbooks related to the application of control theory), than a deep analysis of the state of the art. The manuscript also lacks a general conclusion and perspective section. These elements can be found in the different chapters, but mainly focus on the specific issues addressed in the chapters. I would have liked to get a broader image, as Ing. Martin Gurtner has undoubtedly a clear view that would have been worth sharing with the community. Apart from that small regret, I'm impressed by the **quantity and the quality of the work** that I will comment chapter by chapter.

Chapter 2 proposes a **3D position sensor** for measuring the position of micrometer size objects, to be used for position feedback in the control loop. Feedback is usually obtained from image processing, which is computationally demanding and limited to 2D position feedback. Here, a method based on twin-beam illumination is proposed. The accuracy is around a few micrometers, which is fine for objects of tens of micrometers. The refresh rate is around 10Hz, which is not so high, but again, it is 3D. This chapter is not the main scientific contribution of the thesis, but it demonstrates the **practical sense** of the Ing. Martin Gurtner, who provides a useful 3D position sensor and experimental measures of the height of a micrometer size object, which is **rarely seen in the literature**.

Chapter 3 proposes a **control-oriented model of the dielectrophoretic force**. This chapter together with the following one dealing with the inversion of the model is the core of the thesis. Accurate modeling of the dielectrophoretic force is well-known, but the methods (based on finite element model or method of moment), are not usable for real-time computation of the force. A few approaches, clearly referenced, had been proposed before, but none could be used for complex electrode patterns. Here, a numerical approximation of the mixed boundary value problem is performed once off-line. It is approximated by an analytical function that is used online. This model is original, and the approach is relevant and is an efficient solution to the problem addressed. It is validated by both numerical simulations and by experiments. It was at the date of the publication of the paper, to the best of my knowledge, **the unique control oriented model of the dielectrophoretic force able to address complex systems**.

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Chapter 4 addresses the issue of the **inversion of the direct model** to compute the control signals. Force fields are shaped by actuators distributed in space, and the thesis here addresses the problem of controlling independently several objects. This necessitates to solve a huge optimization problem, that would require important computation time. This thesis proposes to simplify the optimization problem into several subproblems. An adaptation of the ADMM method is developed in this chapter, where each smaller optimization problems are solved collaboratively to avoid conflicts in the solutions. As all the rest of the thesis, the approach is clearly motivated and well explained. Ing. Martin Gurtner proves the genericity of the approach, and it's interest for the microrobotic community by performing simulations and experiments using three different actuation principles (electric fields, magnetic fields and acoustic fields), which is **truly remarkable**. He also demonstrates a **deep intellectual integrity** in the discussion of the performances of the results, where he clearly states the advantages but also the limitations of his work. The methodological framework developed in this chapter will undoubtedly be a **reference for the future controlled manipulation using distributed force shaping actuation**.

Chapter 5 addresses the usability of the currently developed non contact manipulation platforms, which are most of the time complex and bulky. The motivation here is to propose a **compact and inexpensive platform** to facilitate the deployment of such systems. As an example, the dielectrophoretic actuation has been selected. However, a standard computer is still needed for the control. It would have been even more convincing if Ing. Martin Gurtner would have proposed a fully portable version, with embedded control as well. However, to me the main contribution of the chapter is the demonstration of really nice and **convincing experiments**, performed on objects of a few tens of micrometers, which demonstrate **the ability of the candidate to conduct practical work** at a scale where any manipulation becomes a challenge.

In summary, the thesis proposes a general framework for feedback distributed manipulation by force shaping that was clearly missing. It does not only provides the **theoretical tools**, but also demonstrates successful **experiments**. This has to be underlined as making prototypes and experiments on micrometer scale objects is highly demanding and necessitates addressing both **scientific and technological issues**. The objective of the thesis, being the closed loop control manipulation of objects based on distributed for field shaping, has been reached. **The work is novel, rigorous and inventive**. For all these reasons, **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.**

Yours sincerely,

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