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Re: Review of the Dissertation Thesis of Ing. Ivo Herman
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Dissertation Title: *Scaling in Vehicle Platoons*
Author: *Ivo Herman*

As the title of this dissertation indicates, the main question being addressed is how the difficulty of the control problem for vehicular formations (traditionally called "platoons") *scales* with the size of the formation. Such scaling studies are motivated by trying to understand whether the performance of control algorithms for small formations (of say $N = 2, 3$) are fundamentally different from large-scale problems (involving, say $N \approx 100$). At the heart of it, this is a question of whether it is easy or difficult, or more precisely, what is the degree of difficulty, of controlling large-scale vehicular formations. In general, such questions are delicate to formulate, and it is usually difficult to give precise answers. This thesis makes important contributions in this regard.

To set the contributions of this thesis in a proper context, one must examine on the one hand the vehicular platoons problem as an instance of more general distributed/networked controls problems. On the other hand, one must find a way of answering the question of when is a control problem fundamentally difficult or easy, rather than the question of whether a particular controller design is satisfactory or not.

On the first issue, the automated vehicular platoons problem is an old one, dating back to the 60's. It is compelling in the sense that it offers the potential of alleviating congestion on crowded highways, and more recently, the potential of significant fuel savings when applied to platoons of heavy freight trucks (due to aerodynamic advantages of a formation). Since no really large ($N > 8$) such formations have been tested, one needs a preliminary theoretical understanding of how scalable such controlled formations would be under realistic constraints on sensing and actuation. This is the crux of distributed/networked control problems, it is the *architectural constraints* on the controller that make such problems difficult and different from traditional control problems.

In a realistic vehicular platoons problem, it is considerably more difficult for each vehicle to sense more than its immediate neighbors. This nearest neighbor sensing constraint dramatically changes the nature of how easy or difficult this control problem is. To get a full appreciation of this fact, observe that even in the linear quadratic setting, the optimal control problem for a vehicular platoon with constrained nearest neighbor sensing is non-convex (in contrast to the centralized controller design problem), and is yet unsolved. This thesis however provides bounds on performance (for large N) that are applicable to any controller design (including the optimal ones) that circumvent this non-convexity in the asymptotic limit of large N. This last point gets at the second issue of how does one quantify whether a control problem is hard or easy. For example, if a particular controller design performs badly, then is it because the designer failed at finding a good controller? or is it because the problem is fundamentally difficult, and no designer, no matter how skilled, can find a good controller? In standard control problems, this question is answered using optimal and robust control. If the best achievable performance over all controllers is not satisfactory, then it is a hard control problem, and not even the best designer can come up with a good controller. Such fundamental limitations on performance have been viewed intuitively and quantitatively using the plant's Right Half Plane (RHP) poles and zeros. In distributed/networked control problems with architectural constraints, such simple characterizations of limits of performance are still elusive in general. It is thought that not only are RHP poles and zeros relevant to this question, but also the topology of the sensing and actuation network as well.

To quantify the performance and robustness of a vehicular formation operating in uncertain environments, the present thesis studies the asymptotic (for large N) behavior of H^∞ norms of a controlled platoon from various disturbance inputs to various regulated quantities (e.g. position gap errors). The choice of the H^∞ norm is a useful one. Other studies of scaling in vehicular platoons focused on the H^2 system norm with its stochastic interpretation. It might be expected that different system norms will scale differently in N. Differences between system norms (e.g. H^2 vs. H^∞ vs. L^1) have not been found to be dramatic for low order control problems, but it has long been conjectured that as system orders increase (such as in large-scale platooning), there might be dramatic differences between optimal design problems in different norms. This issue is of fundamental importance. It implies that a system that appears to behave well in one norm ends up being arbitrarily fragile when robustness is measured using a different norm. For example, a formation might appear to behave well in the presence of stochastic disturbances such as wind gusts or road irregularities, but may actually be extremely fragile with respect to unmodeled dynamics (such as engine dynamics), or small delays in some sensor feedback loops. Investigating scalings in various system norms could uncover such hidden fragilities. In particular, the exponential scaling found in some settings in this thesis may indicate an extreme fragility which was not apparent in other H^2 or H^∞ norms scalings, which have all been polynomial in order.

The present thesis studies the scaling of Single Input Single Output (SISO) as well as Multi Input Multi Output (MIMO) H^∞ norms for formations with various node dynamics (i.e. number of integrators at each node) and both symmetric and asymmetric control feedbacks of either position or velocity errors. The results are asymptotic expressions that are valid for any Linear Time Invariant (LTI) controller design with a given number of integrators at each node. Thus the thesis provides answers to fundamental-limitations-of-performance questions that are independent of any one particular controller design. This is truly the central problem in distributed control design, namely quantifying how architectural constraints on the controller effect performance in large-scale control problems. The thesis has made an important contribution to this area.

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 the Degree of Ph.D.

Sincerely,

[redacted]

Bassam Bamieh
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