Cooperative Mechanical Systems: Past, Present and Future

*Henk Nijmeijer and Carlos Murguia
Department of Mechanical Engineering, Eindhoven University of Technology
E-mail: h.nijmeijer@tue.nl, c.g.murguia@tue.nl

Abstract— In 1665 the Dutch scientist Christiaan Huygens discovered the in-phase and anti-phase synchronization of two pendulum clocks hanging on the wall. This 'sympathy' of clocks, as Huygens called such coordinated motion, has been observed in different areas like physics, nature, biology and engineering. The study of synchronization relies on a thorough understanding of the underlying dynamics of (time-delayed) coupled systems and extends also to larger groups of the one hand, to review a range of exiting and interesting examples of synchronized systems and in particular to focus on the means why pairs of coupled identical (oscillating) systems may exhibit identical oscillatory motion. On the other hand, we will give an approach that is suited to achieve coordination in mechanical systems, like robotics or automotive applications. Various (laboratory) applications are reviewed.

Key Words: Synchronization, coordination, time-delays, mechanical systems, robotics, nonlinear dynamics.

1 Introduction

In this paper a short review will be given on various examples of cooperative systems, or more generally systems that exhibit some kind of interaction, under which some joint motion is observed. In particular the focus of the paper is to highlight some of the ongoing work at the Eindhoven University of Technology (TU/e). No attempt is made to give a complete literature review. At this point we refrain from a formal definition, which in its full generality, may be extremely complex, see e.g. numerous publications in the physics literature\(^8\), \(^21\), \(^29\). Typical illustrations can be seen in a dancing coupling with music and lightshow, or a group of fireflies blinking at the same moment, but also more advanced examples may be thought of as the synchronized activity in brain cells or the rhythmic heartbeat. A cooperative system is in this paper a synonym for various other terms like synchronization, coordination, etc., where, depending on the particular application area, one of the terms is more popular than others. Synchronization is first encountered in scientific work of the Dutch scientist Christian Huygens\(^11\) who, according to one of his notebooks, discovered the in-phase and anti-phase synchronization of pendulum clocks hanging on the wall.

2 Cooperative Systems: Past

As stated in the introduction, the first written account on synchronization is due to the Dutch scientist Christian Huygens who in 1665 reported on in-phase and anti-phase synchronization of two pendulum clocks in his bedroom\(^11\), see Fig. 1. The description of the experiment, together with Huygens' explanation of the 'sympathy of the clocks' is remarkable, in particular when noting that at the day of writing differential calculus still was in its infancy -Newton at the end of the 17th century laid down the formal aspects of this theory. Huygens explained the anti-phase and possible in-phase synchronization of the two pendulum clocks, as can be seen in the original figure from his notebook, see Fig. 2, by the correct observation that the beam to which the clocks are attached serves as the medium for synchronization. Nowadays, a more accurate phrasing would be that the beam provides energy transfer from one clock to the other (and vice versa) through the beam. It is interesting to remark at this point that even today a complete mathematical theory describing the in-phase and anti-phase synchronization of the two pendulum clocks is still missing. One particular difficulty in this respect is the particular nature of the beam that should be modeled as being flexible, thus making the overall model as a combination of ordinary and partial differential equations\(^18\), \(^20\), \(^19\).

3 Cooperative Systems: Present

In recent years cooperative systems and/or formation control is receiving a rapidly growing interest. Applications are arising in a broader context of robotics, in particular for surveillance, cleaning, monitoring and cooperation. The key observation

![Fig. 1: Synchronization of two coupled van der Pol oscillators. Top panel in-phase synchronization, bottom panel anti-phase synchronization.](image1)

![Fig. 2: Huygens Pendulum Clocks\(^11\)](image2)
in all such applications is the fact that more and additional real-time sensors are becoming available, like in particular modern digital camera allow for almost-real time position information of the system. Of course, the development of newer sensors does not exclude the use of more traditional encoders, but they allow for additional and accurate state information in a dynamic environment. A very enlightening and interesting example is formed by robots participating in diverse soccer world championships. Perhaps the most advance league in this is the midsize league where the teams of mobile robots of the size a chair are playing against each other in a fully autonomous manner, see Fig. 3. Another appealing class is the humanoid league, where the aim is that the robots move and play soccer like humans!, see Fig. 4. Skills like walking, running and shooting a ball are most important to develop. Research in this direction will eventually provide knowledge to produce a team of android robots which will play soccer independently. In addition, nowadays the robots are forced under specific conditions to play the ball from one to each other, thereby coming closer to real soccer. One may notice that this type of cooperative motion is effective in a fairly elementary dynamic environment with a fixed ground area, clear goals and friendly and opponent robots. The camera vision, together with other sensory information is used in combination with nowadays mature localization techniques to determine the robot’s position and that of nearby other robots. The applications of cooperative robots, unmanned vehicles and underwater vehicles are mostly still of medium dynamic nature; although the environment is not fixed -like in an industrial pick and place situation- the changes are mostly at a relatively slow pace and such that the vehicles are able to react in time. Another closely related field in this context is that of teleoperation. In a teleoperated system one a master system ’guides’ a slave system along the desired paths, see Fig. 5. Teleoperation is of use in various settings and contexts, like for instance, long distance tasks (e.g. cleaning at unsafe or inaccessible places, exploration at Mars), where the time delay of communication seriously challenges simples control schemes. Recently, in collaboration with Dr.Oguchi at the Tokyo Metropolitan University, we have done some successful experiments of long distance cooperative control of mobile robots. In other teleoperated tasks the challenge is extended with typical aspects regarding the human (at the master robot) and the environment (at the slave robot). In the same vain one may consider the control of service robots where the operator or rather the supervisor makes the robot executes his task, that may be described in a supervisory manner. Although this application may still be in an embryonic stage, we have succeeded to launch a start-up company named ”Rose”, where a prototype robot, see Fig. 6, executes simple tasks in a service environment for elderly people. Note that in this type of cooperative systems the challenges are manifold, and besides the more control oriented tasks, another related but more software linked question deals with the architecture of the master slave control, and in particular requires to untangle a typical trajectory following task into more elementary tasks like ‘drive
forward’, ‘turn right’, etc... Cooperative control often is a mix between completely autonomous control and the more routine trajectory tracking control in robotics. In industrial applications like a distribution center or a luggage handling system at an airport, a (virtual) supervisor may assign tasks at a high level, and the ‘holons’, see Fig. 7, or robots in the distribution center have to arrange themselves such that the tasks are executed. Building such an environment, with sufficient room for optimal or sub-optimal performance, is an extremely interesting and challenging objective, see Fig. 8.

4 Cooperative Systems: Future

It is becoming transparent that more and more cooperative systems are emerging and challenges are great, and not only from a control perspective. Perhaps one of the most challenging objectives is to develop 100% safe cooperative autonomous vehicles, that operate almost exclusively on supervisory commands so that the vehicles may ride as a platoon (with coordinated acceleration and braking, and likewise coordinated autonomous steering), see Fig. 9. One should note that the here envisioned objective is different from the fully autonomous car as presently is gaining interest in various contexts. At the TU/e we have built up extensive experience on extending adaptive cruise controlled (ACC) vehicles towards cooperative adaptive cruise controlled (C-ACC) vehicles in a C-ACC following car uses as feed forward the instantaneous acceleration/deceleration of its predecessor, see Fig. 10. Indeed, by adding steering following capabilities, an autonomous following vehicle is obtained. Other applications are potentially foreseen in medical/brain contexts and more generally, the ‘system of systems’ context of which traffic and internet are a few examples. The goal in applications in such cases is often to achieve cooperative behavior with preferably a decentralized control structure where for instance only neighbors’ information is used in a feedback. Indeed, cooperative behavior of such a system of systems can be realized as a network synchronization problem. A key ingredient is that the systems in the network communicate information about their state to the systems they are connected to. This exchange of information ultimately results in synchronization of the systems in the network. The question is how the systems in the network should be connected and respond to the received information to achieve synchronization. In other words, which network structures and what kind of coupling functions lead to synchronization of the systems.

5 Conclusions and challenges

Cooperative control is becoming more and more a mature field and will combine advanced sensor and actuator technology together with more and more advanced control technology, enabling promising applications in diverse directions such as automation, automotive, security, and medical applications. A key element is the possibility of having advanced autonomous systems, that is, devices that can completely or almost completely act, on basis of self-acquired information. Since the system is often composed as a network of interacting systems, it is a key challenge to devise and synthesize the coupling structure and required controller to achieve coordination or synchronization. In this regard, a lot of work still has to be done.

References

2) S. Adinandra, J. Caarls, D. Kostić, and H. Nijmeijer. Towards a flexible transportation in distribution centers: A low-level motion control approach. In *proceed-
ings of the 7th International Conference on Informatics in Control, Automation and Robotics (ICINCO), pages 155–169.


