Consensus-based Control of Multi-Agent Systems: Distributed Target Tracking and Analysis of Time Delays

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This thesis deals with the distributed control of multi-agent systems, with a particular focus on consensus theory. Consensus is a graph-based method aiming at an asymptotic agreement upon the value of a state variable of interest among the members of a network. In this work, consensus is analyzed from two points of view.

First, a distributed target tracking application is explored in a multi-UAV scenario. Specifically, the drones are asked to generate a formation while collaboratively estimating the states of a target. For this purpose, a well-known flocking protocol is selected as the formation strategy and simulated in the ROS/Gazebo environment. As the obtained behavior differs from the expected one, several adjustments are required to achieve satisfactory performance. The improved protocol is then validated through a real swarm of two quad-copters, providing coherent results with the simulation expectations. Then, consensus is employed to distribute a target estimation algorithm in a sensor network. Specifically, a distributed version of the Kalman Filter is implemented in a real swarm of two quad-copters equipped with visual cameras. The experimental results showcase successful information fusion between the two platforms. Next, a Multiple Models Kalman Filter is designed to enhance the accuracy of the estimation procedure. In particular, three filters found in the literature are tailored to reduce their computational and communication load and compared through a Monte Carlo simulation campaign. Finally, the algorithm yielding the lowest estimation error is coupled with the improved flocking protocol in the ROS/Gazebo environment, generating a cascade application. The main contributions of this first part of the thesis are the improvement of the state-of-the-art flocking protocol, the experimental validation of the formation and estimation procedures, and the design of a distributed scheme for a Multiple Models Kalman Filter.

The second part of the thesis focuses on the analysis of time delays in a network of homogeneous linear systems. The first objective is to find a scalable consensus condition holding for any arbitrarily large number N of agents. The study is performed in the frequency domain and starts with a modal decomposition of the system. This generates $N-1$ disagreement modes associated with the non-zero eigenvalues of the Laplacian interaction matrix. Then, a sufficient condition for consensus is provided through the depiction of a stability boundary in the complex plane of the Laplacian eigenvalues. This result can be applied to any arbitrarily large N, simplifying the state-of-the-art analysis of delayed consensus. The second objective is to determine the crossing direction of the characteristic equation's imaginary roots caused by a delay increase. A posi-

tive (negative) direction indicates that a higher delay makes the corresponding characteristic root cross the imaginary axis towards the right- (left-)half complex plane. In the literature, this quantity is computed for every crossing frequency displayed by the system's disagreement modes. In this work, a direct link is found with the system's frequency response function, avoiding the root sensitivity explicit computation. The main contributions of this second part of the thesis are the scalability of the delayed consensus condition and the depiction of a graph that contains the crossing direction information. Several consensus protocols found in the literature are analyzed throughout the chapters to show the effectiveness of the results.