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主　論　文　の　要　旨

論文題目　Forecast and control of dynamical systems with data assimilation: Applications to COVID-19 epidemic and to Lorenz models（データ同化を用いた力学系の予測と制御：COVID-19 流行モデルと Lorenz モデルへの応用）

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論　文　内　容　の　要　旨

Data assimilation is a widely used technique in numerical weather prediction and in other fields, as for example in earth science, in economics, and more recently in epidemiology. It is a mathematical tool that optimally combines theories and observations to find the precise signal and unknown parameters of a physical system, and to forecast its evolution. Ultimately, the question arises whether this technique can be used for controlling the evolution of the system in a prescribed direction?

In this thesis, we firstly apply data assimilation techniques to an infectious disease model to study the effectiveness of parameter estimations and system predictions. Secondly, we design the control simulation experiments (CSEs) of two chaotic dynamical systems and investigate the most effective perturbation signals. In addition to these studies, we also provide the work that drove us to the data assimilation framework, namely the bibliometric analysis of mathematical publications using tree-based methods.

The thesis is arranged as follows: In Chapter 1, the general framework of data assimilation is introduced. The theoretical developments of Kalman filter and ensemble Kalman filter (EnKF) are reviewed. Some special versions of EnKF are also discussed, as for example the ensemble transform Kalman filter (ETKF) and the ETKF with localization.

In Chapter 2, we introduce an extended SEIR infectious disease model together with a data assimilation scheme for the study of the spread of COVID-19. In this framework, undetected asymptomatic and pre-symptomatic cases are considered, and the impact of their uncertain proportion is fully investigated. The standard SEIR model does not consider these populations, while their role in the propagation of the disease is acknowledged. An ensemble Kalman filter is implemented to assimilate reliable observations of three compartments in the model. The system tracks the evolution of the effective reproduction number and estimates the unobservable subpopulations. The analysis is carried out for three main prefectures of Japan and for the entire population of Japan. We also perform sensitivity tests for different values of some uncertain medical parameters, like the relative infectivity of symptomatic / asymptomatic cases. The regional analysis results suggest the decreasing efficiency of the states of emergency.

In Chapter 3, we study the control of chaotic dynamical systems with data assimilation techniques. In numerical weather prediction (NWP), sensitivity to initial conditions often leads to an intrinsic limit to predictability, but it also implies an effective control in which a small control signal grows rapidly to make a substantial difference. In this chapter, we extend the well-known Observing Systems Simulation Experiment (OSSE) and design the CSE, in which the application of a small signal drags the systems in a prescribed direction. An idealized experiment with the Lorenz-63 three-variable system shows that we can control the system to stay in a chosen wing of the Lorenz's butterfly attractor. Using longer lead time forecasts, we achieve more effective controls with a perturbation size of about 3% of the observation error. The idealized CSE is a starting point for CSEs applied to more realistic dynamical systems. A long-term aim would be for example to reduce weather disaster risks by adding small perturbations to the weather system.

The CSEs are further developed and applied to a more complicated scenario in Chapter 4. This CSE is aimed for reducing the number of extreme events in the Lorenz-96 model. The 40 variables of this model represent idealized meteorological quantities evenly distributed on a latitude circle. The reduction of occurrence of extreme events over 100 years run of the model is discussed as a function of the parameters of the CSE: the ensemble forecast length for detecting extreme events in advance, the magnitude and localization of the perturbations, the quality and the coverage of the observations.

The framework for the bibliometric investigations (sketched during the master program) is presented in Chapter 5 since the large-scale research has been performed at the beginning of the PhD program. This chapter contains also the result of these investigations. The factors that affect the citations of mathematical articles are carefully studied by using a tree-based classifier.

Let us finally mention that Chapter 3 and 5 correspond to published papers, Chapter 2 has been submitted for publication already a couple of months ago, while Chapter 4 is going to be submitted for publication by the end June 2022.