R&D Theme

Development of Actuator Location Optimization Algorithm and Its Application to Modeling and Weather Problems

Progress until FY2022

1. Outline of the project

Since a weather field has a large number of degrees of freedom, weather simulations take quite a long time. Therefore, it is not practical to use an algorithm that performs a huge number of weather simulations for actuator selection. We will develop actuator-position-selection algorithms that can be applied to such large systems based on a mathematically formulated problem in this theme. To efficiently evaluate the performance of the algorithm, simulation models of relatively small systems are also developed in parallel with the development of the actuator-selection algorithm. For these test models, the developed algorithm shows that the actuation at the selected location can significantly modify the field with a probability of over 99% better than that at a randomly selected location (Figure 1). We finally show the effectiveness of the developed algorithm for a weather model.

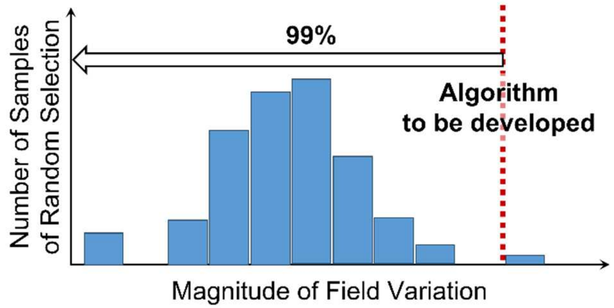


Figure 1: Objective of actuator-selection algorithm

2. Outcome so far

To take advantage of our prior knowledge, we organized and evaluated algorithms for sensor-position optimization problems, which are dual problems of the large-scale actuator-position optimization problems. First, we applied the currently available sensor selection algorithms to several sensor selection metrics for linear models and compared their performance. As a result, we found that the greedy method has high performance and low computational cost for sensor selection for systems with a large number of candidate sensor positions. We concluded that it is reasonable to proceed with algorithm development based on the greedy method. Hence, we proposed new greedy methods such as the random-selection elite group greedy method (Figure 2) to improve the performance of the greedy method. Furthermore, we theoretically guaranteed the performance of these new greedy methods. We found that the sensors selected by the greedy method for a performance metric based on a linear inverse problem can enhance other metrics for linear models. This suggests that sensor selection for the linear inverse problem, which is computationally inexpensive, may be able to replace sensor selection for other metrics.

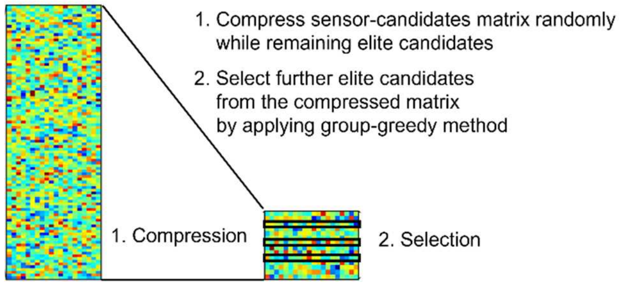


Figure 2: Random-selection elite group greedy method

To evaluate the performance of the actuator-selection algorithm, simulation models such as the linearized Ginsburg-Landau equation (Figure 3 (left)) and the Lorenz 96 model (Figure 3 (right)) were developed.

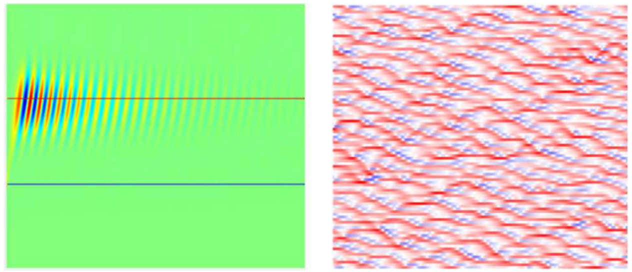


Figure 3: Simulation results of test models

3. Future plans

In collaboration with the themes "Mathematical problem formulation for actuator location optimization" and "Development of an evaluation method for optimized actuator location based on weather simulation" in this project, we will develop actuator-location optimization algorithms that can be applied to weather fields. First, based on the results in the previous works on sensor-position optimization algorithms, we will develop actuator-position optimization algorithms for linear models using the duality. Then, based on the knowledge gained from the development of the algorithms for linear models, we will develop actuator-position optimization algorithms that can be applied to nonlinear models, including weather models, and demonstrate the effectiveness of these algorithms.

R&D Theme

Mathematical Problem Formulation for Actuator Location Optimization

Progress until FY2022

1. Outline of the project

Actuator-position optimization problems are formulated to find actuator positions that efficiently change states such as the temperature and the velocity of the atmosphere. By clarifying the evaluation metrics, it becomes possible to quantitatively evaluate the effect of the actuator placement and to develop an algorithm to determine the actuator placement based on this evaluation index. If the formulated mathematical problem is too complex, it will be difficult to solve this problem for actuator placement in such a large degree-of-freedom field.

To formulate the actuator-placement problems, we first focus on sensor-placement problems for linear models, which have been studied in many previous works. We formulate the actuator-placement problem by deriving a duality of the existing sensor-placement problem for linear models (Figure 1). By using duality, the sensor placement algorithm can be converted to the actuator placement algorithm with only minor modifications, and thus, the development cost for it can be reduced. However, the actuator placement problem obtained by using duality must be interpreted, since the physical and engineering meanings of such problem is not clear. The knowledge gained from the formulation of the actuator-placement problems will be used to formulate the actuator-placement problems for nonlinear models, which will be important for application to weather fields.

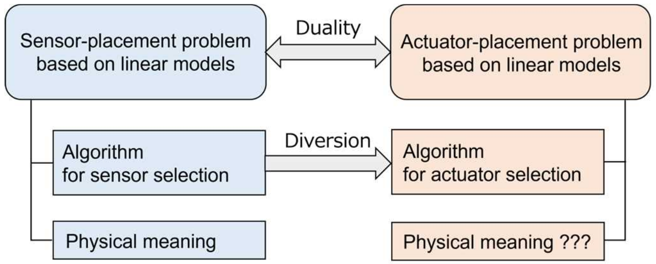


Figure 1: Formulation of actuator-placement problem using the duality

2. Outcome so far

Actuator-placement problems for linear models were formulated using the duality. By considering the duality of the sensor-placement problem for optimal state estimation for linear dynamic models we derived the actuator-placement problem for optimal control for linear dynamic models (Figure 2). The matrices Q and R that appear in both placement problems refer to the covariance matrices of the noises in the sensor-placement problem, whereas, in the dual actuator-placement problem, they refer to the weight matrices in a control evaluation metric, in other words the matrices associated with the states and inputs that we regard as important. Since actuators with the same properties will be assumed to be used in the control of the weather, it is natural to set the input weight matrix R to be a unitary matrix. The setting of the unitary matrix reduces the computation time required to normalize the matrix when actuator placement is implemented. This actuator-placement problem can be solved approximately by modifying the sensor-placement algorithm that has been developed in another theme.

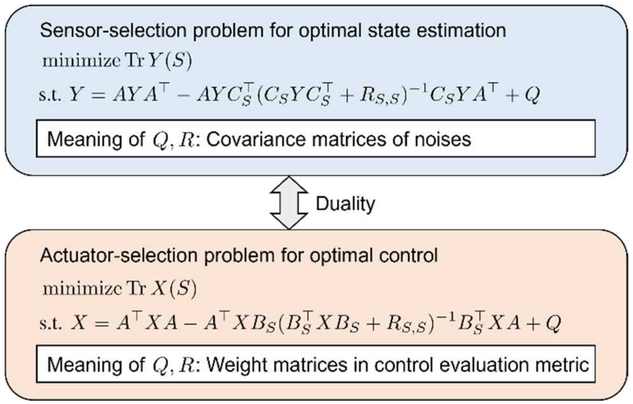


Figure 2: Dual placement problems for linear systems

3. Future plans

We begin to formulate actuator-placement problems for nonlinear systems. For this purpose, we focus on the singular vector method, which is often used in the field of meteorology. The singular vector methods deal with problems that aim to maximize the variation of the terminal state with respect to the variation of the initial state. By extending this method, we formulate a problem that aims to maximize the variation of the state trajectory with respect to the input to actuators (Figure 3). This allows more appropriate evaluation of actuator placement in the weather field.

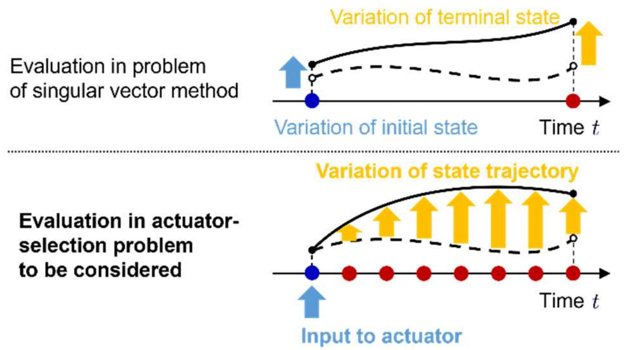


Figure 3: Actuator-placement problem to be considered

Goal8 Realization of a society safe from the threat of extreme winds and rains by controlling and modifying the weather by 2050.

Actuator Location Optimization for Large Degree-of-Freedom Fields

Here begins our new MIRAI
MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

R&D Theme

Construction of Evaluation Method for Optimized Actuator Placement on Weather Simulator

Progress until FY2022

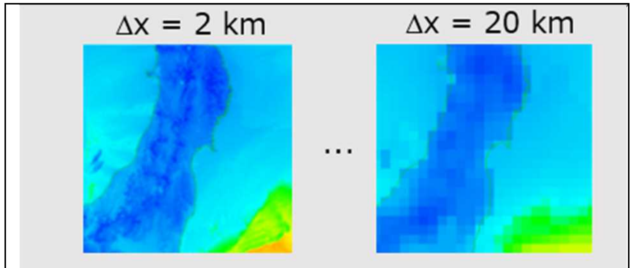
1. Outline of the project

We will construct a weather simulation technique to evaluate the effect of input by optimized actuators on a realistic flow in the atmosphere. The weather fields to be modified and controlled in this project is those of extreme weather such as local heavy precipitation. Reproduction of such kind of meteorological phenomena is not easy in simulations at current. Therefore, it is necessary to reliably reproduce extreme weather for evaluating the effects of inputs on extreme weather fields on a weather simulator at first. In addition, since there are various weather models and each of which has advantages and disadvantages, the selection of the weather model is also important. In this theme, we will clarify various parameters such as the weather model to be used, the boundary conditions, the size of the computational area, the resolution, etc., and establish techniques for appropriately evaluating the effect of the input by the actuator.

2. Outcome so far

So far, we have selected two weather models and conducted trial simulations. As weather models, we selected WRF developed mainly by NCAR (National Center for Atmospheric Research) in the United States and SCALE developed mainly by RIKEN in Japan. WRF model provides adjoint models that are required in typical methods used for the computation of sensitivities. On the other hand, SCALE is currently under active development in Japan, though it has not implemented adjoint models. It has the latest physical models and has the capability to run efficiently in various computer environments.

Optimization of actuator placement requires many iterations of simulations; therefore, it is important not only to reproduce extreme weather but also to achieve it at a low cost. Figure 1 shows the results of trial simulations using the WRF model. The color map shows the temperature field at 2 m above the ground. We investigated the influence of grid resolution on computational time and the quality of solutions. When the resolution is 20 km, the computational time is approximately 400 seconds, but the resolution is low, and it is difficult to reproduce extreme weather such as local heavy precipitation. On the other hand, when the resolution is 2 km, the detailed temperature distribution near land can be captured. However, it is difficult to perform a large number of simulations because high-resolution simulations require longer computational time. Therefore, we will clarify the conditions that can reproduce the target extreme weather phenomenon at the lowest possible cost.



✓ Conditions

Resolution (km)	2	4	5	10	20
Calculation time (s)	33,425	7,302	4,560	1,107	395

Figure 1: Trial simulation results (temperature at 2 m above ground)

Figure 2 shows a visualization of water substances and velocity vectors in a vertical section of a linear precipitation area reproduced by SCALE model. As shown in the figure, the local increase in humidity and the occurrence of updrafts are captured, and it suggests that the simulation was performed with sufficient accuracy to reproduce the linear rainfall area.

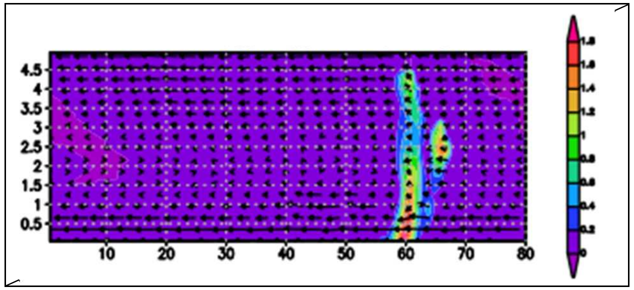


Figure 2: Visualization of water matter and velocity vectors in vertical section

3. Future plans

Each weather model has different characteristics. In addition, it is considered that there are various ways for optimizing actuator placement, and thus, we will effectively utilize both of the two selected weather models to construct an evaluation method for optimized actuator placement. In the next step, we will identify calculation conditions that can reproduce local heavy precipitation in multiple different scenarios and implement the function on the weather simulator to add the optimized input into the weather field. After that, we will perform computations to optimize the actuator placement for the extreme weather conditions reproduced on the simulator. Next, we perform calculations with the input of water vapor and heat at the optimized locations and confirm how the weather field changes. This will clarify how much the weather field can be modified by the input and whether the actuator placement can be effectively optimized. In addition, it is expected that we may be able to find more effective methods to modify the weather by analyzing how the input affects the weather fields.

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