Water Flow Control Methodology to Inhibit Seaweed Twist Based on Physics Simulation

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Chapter 1

Introduction

1.1 Background

Seaweed is a valuable aquatic resources used to produce biomass oil [AA10, DD11, VVA08]. It was not focused as an alternative resource of fossil fuels until the 1980s, however, it was revealed that the marine biomass is possible to acquire dozens of times of yield amount of some terrestrial biomass shown in table 1.1 [Chi07]. The seaweed absorbs carbon dioxide and other greenhouse gases from heat power plant, and produces a lot of oxygen. Studies on the seaweed as an energy source has been ongoing since the 1980s [Jac80, BB87], making the control of seaweed cultivation a major issue in the field of seaweed research [Cor12, UAU08]. The seaweed cultivation is expected to help resolve global warming, waste in natural resources, and

Table 1.1: Comparison of some sources of biodiesel (Chisti 2007)

Crop	Oil yield (L/ha)	Land area needed (M ha)
Corn	172	1540
Soybean	446	594
Canola	1190	223
Jatropha	1892	140
Coconut	2689	99
Oil palm	5950	45
Microalgae[1]	136,900	2
Microalgae[2]	58,700	4.5

[1] 70% oil (by wt) in biomass

[2] 30% oil (by wt) in biomass

many other problems, but current technology cannot extract sufficient seaweed oil to offset the cost of seaweed cultivation. Water contamination caused by microorganism propagation is another problem in seaweed cultivation [SGB91]. The cost of cultivating seaweed as an energy source still exceeds the distillation cost of petroleum. Thus, the aim of the recent seaweed studies is to establish cultivation system for efficiently converting seaweed into energy.

1.2 Conventional Approaches for Seaweed Cultivation

In this section, we refer to related studies that show our study place. Xiu-geng et al. introduced the problem of traditional seaweed cultivation and proposed improvement way for solving the problem [XgYS99, Xiu04]. They classify the seaweed cultivation process into "Seed stock cultivation", "Adult plant cultivation", "Harvest", and "Processing". Interacting these processes composes the seaweed cultivation process. Then, they described that seaweed cultivation techniques are two type ways. One is a way to cultivate the seaweed in the stage of microalgae. Another is a way to cultivate the unit of large seaweed. As one of the studies about cultivation of large seaweed, Klaus et al. verified the growth rate of seaweed in the cultivation environment which is generated a circulation water flow by the bubbling equipment [LP03]. The experimental result shows that the floating cultivation of large seaweed dramatically increases the amount of once harvest by expanding the cultivation area. Recently, Heraoka et al. proposed an effective method for the floating cultivation of green laver. The method creates the unit of seaweed shown in fig 1.1, and realizes the high density culti-

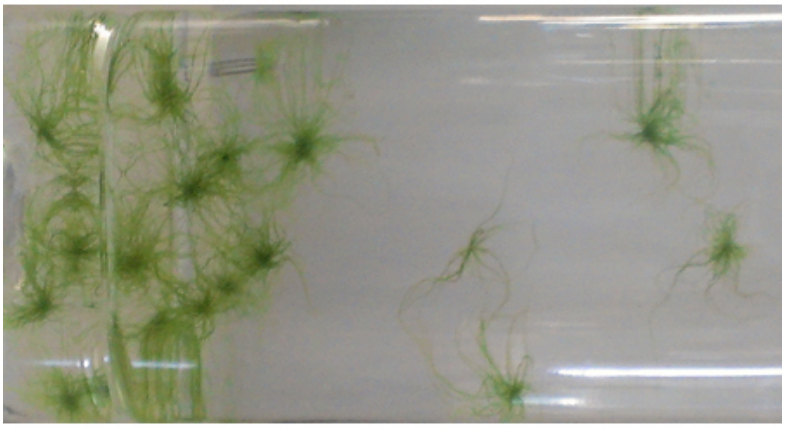


Figure 1.1: Seaweed (Green Laver) sprouted by Hiraoka et al. method

vation than the traditional cultivation. Watanabe et al. investigated the oil productivity and purity of large seaweed [Wat10]. They showed the industrial value of the oil by using an automobile fuel, and demonstrated that using the seaweed oil can drive the automobile. Senaha et al. show the analogy between mechanism of propagating heat transfer and growth substances such as carbon dioxide and other nutrients. They revealed to improve the growth speed by efficiently propagating these growth substances into seaweed at a viewpoint of thermofluid dynamics. In addition, they developed the water environment containing high concentrations of carbon dioxide for cultivating the green laver (fig 1.2).

Figure 1.2: The aquarium for cultivating seaweed (authority: Agribusiness Creation Fair 2013)

This paper classifies these approaches in the field of large seaweed cultivation into the ecological studies and engineering ones. The ecological studies focus on seaweed themselves. The objective of these approaches is to understand the photosynthesis feature of seaweed growth [Luc77, VVA08, Wat10]. These studies investigate the photosynthesis yield of seaweed by changing the biological condition of the photosynthetic organ of absorbing light power, concentration of carbon dioxide and others. The merits of these studies are to be possible to expect the optimal photosynthesis reaction of a seaweed species and understand the process of photosynthetic growth in an experimental condition.

However, it is hard to prepare the cultivation environment that realizes the optimal photosynthesis reaction. The analysis of general property consumes a lot of time for the experiment with the observation of the growth process of actual seaweed including individual difference.

The engineering approaches focuses on the effectiveness of cultivation process. The large objective of these studies is to improve the growth speed and the amount of harvest at once cultivation [YJI07, Cor12]. These studies are possible to propose the way to cultivate seaweeds in available tolerance as an actual cultivation. However, there are additional problems for applying the cultivation way in a lot of situations. The experimental cost is so expensive in order to introduce the cultivation equipment. In addition, the effectiveness should be verified after a long term of seaweed cultivation. These approaches take a process of trial and error. Therefore, the cost reduction for seaweed cultivation research is a significant challenge.

1.3 Research Objective

This study aims to solve the challenges of seaweed cultivation from a viewpoint of information science research. In particu-

lar, the computer simulation is an effective way as one of information processing techniques for achieving low cultivation cost. It simulates various situations in the seaweed cultivation. The simulation research is able to consider the situation that cannot verify In the actual cultivation by applying adaptive model and computation in the computer simulation.

In those backgrounds, this thesis proposes a novel way to control of seaweed twist in the green laver cultivation. The seaweed twist is known to reduce the growth speed of seaweed population and photosynthesis. The twist of green laver is one of physical phenomenon that is hard to control since the physical interaction between thin objects is complex. The knowledge about controlling the seaweed twist is valuable for streamlining interior cultivation.

As a first step of our study from the point of view of information engineering, this thesis aims to construct the platform of physical simulation for analyzing the twist formations among green lavers and to resolve the quantification problem of the twist formations. The twist formations are ambiguous and qualitative phenomena, which are interpreted differently by the human recognition. There is as yet no mathematical definition of the twist formations. Criteria of quantifying the formations is

able to numerically analyze the formations based on the physical simulation. As the second step of our study, this thesis aims to acquire the knowledge for controlling the twist formations by using the quantification factors of the twist formations in the first step. First approach of this step analyzes a way to reduce risk of happening the twist formations. As a result of a physical interaction with contact between seaweeds, there are twist-formed seaweed individual and non twist-formed seaweed individual. To control the twist formations is necessary to clarify the feature of the physical interaction that contributes to the formations. Then this thesis defines the dynamic feature of physical interaction as the interaction network. The network is able to analyze the feature of the interaction and the process of the twist formations from the point of view of information diffusion. In order to acquire the findings of reducing the twist formations, we proposes a way to analyze the process of the twist formations based on the interaction network and to verify the feature of the interaction that contributes to the happening of the twist formations. Second approach of this step verifies the adequacy of our simulation results and shows the application of the simulation. The adequacy should be proved a similarity between the twist formations of real world in a viewpoint of

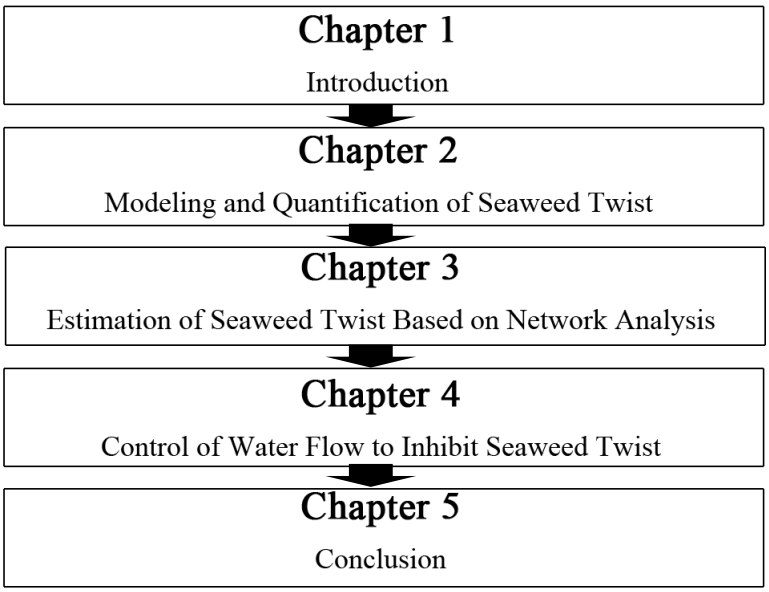


Figure 1.3: Outline of this thesis

analysis of the twist formations.

In particular, the objectives of our study are 1) to model the motion of seaweed twist in physical simulation, 2) analyze the physical interaction of seaweed twist formations and 3) control water flow to inhibit the twist formations. Figure 1.3 shows the outline of this thesis. This thesis is organized into five chapters. In chapter 1, we describe the background of seaweed cultivation studies. Then this chapter introduces the objective of our study that is focused on controlling of the seaweed twist from physical simulation.

In chapter 2, our objective is to construct the foundation of physical simulation for analyzing seaweed twist of floating

seaweed population. This chapter describes the modeling of seaweed twist by combining physics engine and fluid dynamics. The physics engine is one of software libraries for calculating physical motion. Then, this chapter proposes the quantification criteria for representing the twist of moving in aquatic tank.

In chapter 3, we propose methods for analyzing on the feature of physical interaction of the twist formations and estimating the risk of the twist formations based on network theory. Each proposed method is able to consider diffent occurrence processes of the twist formations. Then, the comparison experiment is carried out to analyze the occurrence process of twist formations in the motion of seaweeds. From the result of experiments, we analyze the occurrence process of the twist formations and shows the effectiveness of estimation method in regard of the reduction of the risk of occurence of the twist formations.

In chapter 4, we compare our simulation model with real motion of seaweed population. The objectives of this chapter are to verify the adequacy of simulation and to analyze features of water flow in order to inhibit the seaweed twist The experimental environment is hand-made with a small beaker and green laver population. A single rotator placed at the bottom of the beaker gives the water flow. Then, this chapter applies our es-

tablished method to a real world environment and to show the effectiveness of our method. As the result of experiments, this chapter proves that our simulation model is useful to simulate the behaviors of the seaweeds in a water flow and the twist formation as the macroscopic phenomena is properly modelled in our simulation.

Finally, we conclude this thesis and discuss future researches in chapter 5.

1.4 Conclusion

In this chapter, we introduced our research background and objective. Additionally, we explained about significances of controlling of seaweed twist for large seaweed cultivation. In the following chapters, we describe the detail of our modeling, estimation and control method for the seaweed twist formations.

Chapter 2

Physical Modeling and Quantification for Seaweed Twist

2.1 Introduction

This chapter describes the platform of physical simulation for representing the motion of "Green laver". The green laver is a string-shaped seaweed which has multiple leaves. The objective of this chapter is to simulate the seaweed twist formation of the green laver. Our study focuses on the seaweed twist of seaweed population of high density. Depending on the number of individuals increases the calculation cost of population motion. Therefore, the realization of motion simulation of seaweed

population takes ingenuity.

Our modeling is based on the following points:

- Construction of virtual fluid environment for reducing computational cost
- Modeling of seaweed population of high density
- Representation of natural twist formation

In order to solve these problems, we compound the fluid environment based on physics engine and the placement algorithm using the stochastic growth model.

Physical simulation is suitable for analyzing physical motion of various shapes of object. The seaweed twist is a complex and physical phenomenon that is caused by physical interference between individuals in water environment. The physical simulation should calculate the physical interaction between individuals for representing a behavior of seaweed population with water flow. Our simulation is executed in NVIDIA PhysX [Phy, MSJT08], part of physics computational software libraries. To combine rigid body and fluid dynamics is able to calculate the motion of the seaweed population in water. However, the calculation of fluid forces is not supported in the PhysX. In order to represent the motion in water, the simulation model should

be implemented drag force and buoyancy.

There is a technical problem if simulation uses physics engine. This problem is dynamic modeling with individual's size variation and initial placement problem of models. In order to test the different motion of seaweed population, the experiment requires the dynamic modelling that creates different patterns of seaweed population including individuals of multiple sizes. In the physical model with the mass, the simulation computes the collision process. If there is the overlap between the rigid bodies in an initial placement, the collision process performs erroneous collision calculation. When the volume of seaweed population is so high, it becomes hard to avoid the overlap. Therefore, there is the difficulty that must be placed so as not to overlap the initial placement of multiple individual models in the dynamic modelling process for avoiding the erroneous calculation on the program.

The seaweeds motion in the water environment characterizes the twist formations. The physical simulation is possible to analyze the motion quantitatively. Currently, there is no computational model to simulate the twist formations of seaweeds in the field of computational science. Therefore, it is impossible to measure the twist formation quantitatively by using conven-

tional researches in terms of twist representation. One of the twist representation researches is the knot theory [Oga13]. This theory discusses the twist shape of three dimensional objects. The objective of this theory aims to produce a mathematical description of geometric configuration such as the knotted string. These studies focus on an equivalent couple of knots. It is a given fact that the curve equations define these knots. The twist formations of seaweeds are complex structure. The formations cannot be represented by a mathematical expression. Thus, this theory cannot be applied to evaluating the complicated twist of seaweeds quantitatively in our physical simulation.

The objective of this chapter is to develop a novel way to detect and quantify the twist formations in the simulated floating seaweed population for solve the quantification problem of the twist formations. This thesis proposes the three representation factors of the twist formations. Human recognizes the twist state without a clear criterion. The reason is that the feature of twist is understood mechanically. It is assumed that a measurable physical quantity represents the feature. Therefore, three factors (, which are physical, geometric, and time) characterize the twist. These factors are able to quantify the twist formations. The feature vector of these physical quantities defines the state

between seaweed individuals. User classifies the "twist state" or "non twist state" from a pair of individual models. These "twist state" vectors indicate user's recognition of twists. In pattern recognition, support vector machine (SVM) are known familiarly as supervised learning models. SVM learns a set of given data patterns.

In the chapter 2, the SVM identifies the twist state from the feature vectors. First, the motion simulation shows the relationship between twist state and each physical quantity. Second, this chapter describes the classification way of the twist state based on these feature quantities. Then, the classification experiment verifies the classification accuracy of twist and non-twist of unknown feature vectors.

The rest of this chapter is composed as follows. Section 2.2 describes the modeling process. Section 2.3 proposes the characteristics of seaweed twist from three factors. Section 2.4 describe the detail of twist-state classifier of two seaweeds and discusses the accuracy of this classifier as quantification scale of seaweed twist. Section 2.5 concludes this chapter with some remarks. This chapter is based on the paper [OSYF13a, OYF13, OSYF13b, OIYF14b]

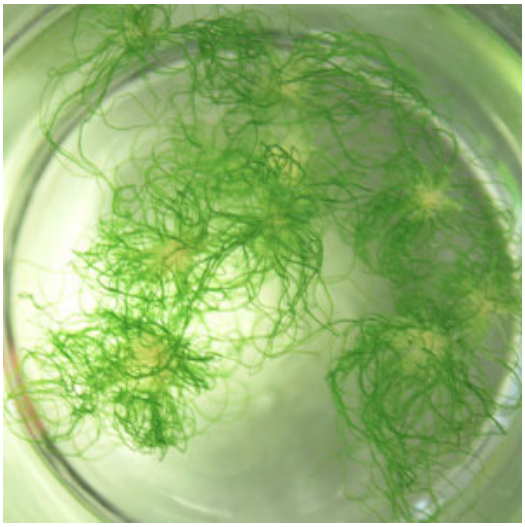
Table 2.1: Physical parameters of seaweed model

Physical parameters	Value
Density [g/cm^3]	1.2
Coefficient of restitution	0.05
Coefficient of static friction	0.5
Coefficient of dynamic friction	0.5
Length of rigid body [cm]	1.0

2.2 Physics Modeling of Seaweeds

The morphology of a physical model should be imitated a morphology of a target seaweed. Therefore, we narrows down the components of representing the morphology of the green lavers and incorporate these components into the modeling process. In addition, a movement of object in a fluid demands a calculation of fluid dynamics that is computationally expensive. In order to acquire a lot of seaweeds motion, we should be considered an approximation method of dynamics calculation in the computational cost as low as possible for each individual. This chapter explains a modeling method of botanical morphology formation and dynamics in terms of seaweed individual model with these matters in mind.

(a) Example of physical model of individual



(b) Example of actual seaweeds

Figure 2.1: The physics model of Ulva meridionalis (Green lavers)

2.2.1 Morphology

There are techniques of image based modeling and L-system [Lin91] as the typical method of morphology formation of seaweed. The L-system is an algorithm that represents a struc-

ture of natural objects and seaweeds by recursively applying replacement rules of into string of structure information. Physics Enhanced L-system [NRS11] and Genetic L-system Programming [Jac94] has been proposed as an improved method considering physical effects or natural selection by genetic operation. However, in case of using these recursive methods, it is difficult to preserve the structural information before the update using these recursive methods. There is also a drawback that the obtained morphology becomes regular. Image-based modeling is to create a realistic model to calculate the feature vectors from the image data. It is hard to set physical properties into the created model in this method. There is a stochastic model [Kan08] as a method of not using these techniques to represent the growth process of seaweeds. This model stochastically determines bending-extension of the foliage and branches for representing the growth process. Structure update is conducted by adding previous structure information. Therefore, the stochastic model performs the morphology formation, which is easy for humans to understand intuitively. The physical model consists of primitive of rigid body based on the structure obtained by using a probability model. Fig. 2.1 and table 2.1 show an example of physical model and the "Green lavar". In this cahpter,

we introduce the modeling process based on the following four stochastic components:

- Degree of freedom: angle constraint of branch
- Posture: direction and position of branch
- Number of Branches: maximum number of branches
- Growth Level: concept of time

The primitive of rigid and each component and body are described as below.

Sphere-swept volume (SSV) is adopted as a primitive of rigid body of virtual seaweed. SSV is rigid body with a bounding volume like the capsule of a drug. In other words, SSV is a form of moving sphere along a straight line. Collision detection between the SSV can be calculated at high performance by figuring out the shortest distance between two line segments. Thus, SSV is appropriate to represent a part of branches of seaweed.

A joint between rigid bodies is set into three degrees of freedom. Setting the degree of freedom in the direction of the swing direction and twist represents flexibility of seaweeds. The flexibility is different for each species of seaweed. The difference can be adjusted by parameters of degree of freedom of joint.

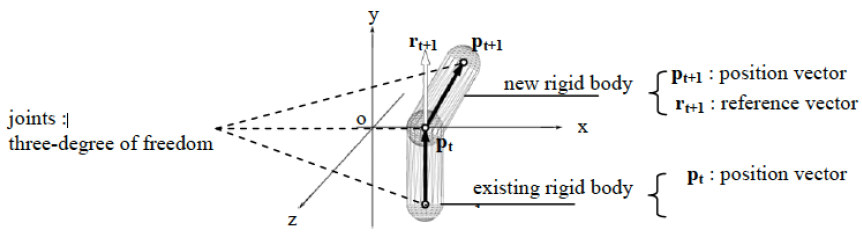


Figure 2.2: A image of constructing plant branch by jointing rigid bodies

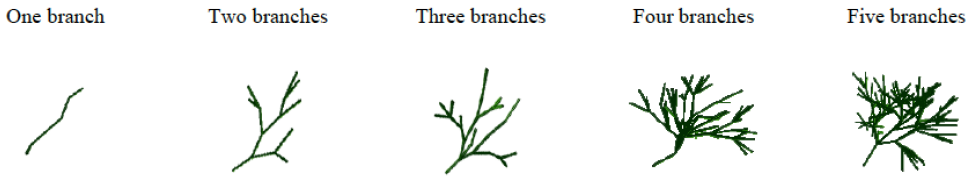


Figure 2.3: Result of applying 5 branching rules into a plant model

Each branch (rigid body) of the posture is represented by a position vector and rotation angle. The position vector is Cartesian coordinate system; it is the center of mass of rigid body. Rotation angle denotes the direction in which extends branch, the angle is Euler angles (roll angle, pitch angle, yaw angle). Rigid body (each branch) has a reference posture; the reference posture is the direction of a rigid body that is connected. Also, each branch can be bended posture freely under the constraints of the degrees of freedom from the reference posture. These concepts of component (primitive of rigid body, degree of freedom, posture) are shown in fig. 2.2.

Providing the maximum number of branching occurs any branching. The maximum number of branching MAX is given by integer. The number of branching for each branch is determined in the range of [0:MAX] with uniform random numbers. Fig. 2.3 shows the morphologies of virtual seaweed of setting an arbitrary number of branches. Branching does not occur in the case of MAX = 1, branches of seaweeds grow in a curve is obtained. The value of the MAX increases, the complexity of the form of branches also increases.

Growth level is an integer value that indicates the growth. The initial value is 0, there is no form of seaweed, in this state, and only the initial placement positions have been established. This position is defined as the position of seed of virtual seaweed. Each time that a growth level is increased by one, a new rigid body is added into the tip of rigid body that is already placed at the previous. Rigid body information to be added is stochastically determined as meet all of conditions of "degree of freedom" and "posture" and "branches".

Further, the new rigid body is created with the posture that is adjusted by the collision detection so as not to overlap with the other rigid. Patterns of the virtual seaweed, which are modeled by increasing the growth level, are shown in fig. 2.4. From

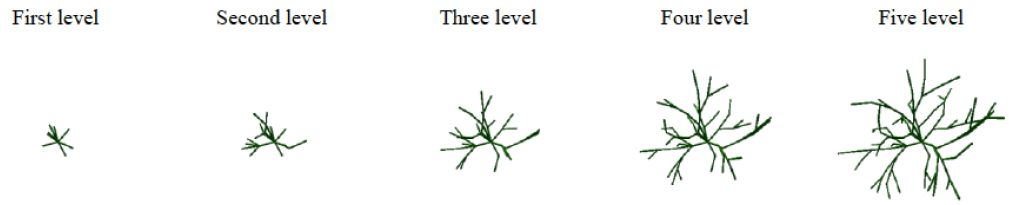


Figure 2.4: The shape formation by jointing rigid bodies

the results, this modeling method can automatically model dynamically growing seaweeds.

2.2.2 Population Model

Seaweed population model is placed within a tank model. When the number of individuals to simulate is large, the volume fraction of seaweed population model becomes high. Actual seaweed, which is cultivated at high volume fraction within a tank, grows up while finding out a vacant apace. In the case of physics modeling, it is hard to artificially explore a vacant space since morphology of each seaweed model is complex. If the physical model is allowed to overlap between the models, a fatal error occurs during the simulation run. Thus, in order to avoid the computational instability by false collision detection at the initial state, the placement problems of individual model must be solved. The placement problem of seaweed population depends on the shape of tank model and the effect between individuals.

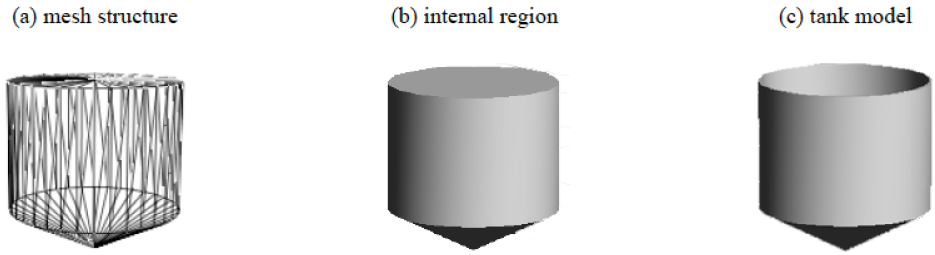


Figure 2.5: A example of tank model that has a triangle mesh structure and solid model of tank and its space

There are devised to model a state of placing all individual of seaweed population within a given tank model. Furthermore, a three-dimensional flow field within a tank model is required for moving seaweed population model.

Since a shape of tank can be designed in detail, it is desirable that model data is three-dimensional structure of the triangle mesh shown in fig. 2.5(a). Accurate modeling and simulation is executed as the model data is finely divided in the mesh. Two types of data are need as tank model. One is a stored data of inner region of tank, which is allowed seaweed population to exist (Fig. 2.5(b)). The other is the data of tank structure (Fig. 2.5(c)). The data of inner region of tank is used to detect internal or external region in modeling process of seaweed population. On the other hand, the data of tank structure is used to define the physical boundary for simulation process.

In the modeling process, the placement problem is classified

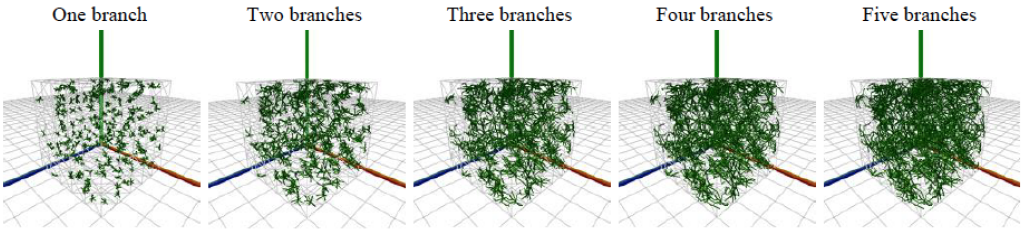


Figure 2.6: Result of applying dynamic modeling process into plant population

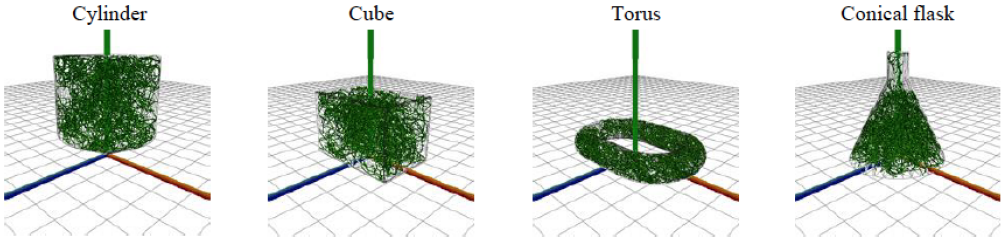


Figure 2.7: Examples of a plant population model which is modeled inside the tank of any shape

to initial position determination of individual and addition position determination of new rigid body. First, we refer the method of determining the initial position of individual model. The first step is to calculate the normal vector of all surfaces of the tank from the mesh data. Then 3-dimensional coordinates P(x_p, y_p, z_p) is determined by a random number, and a vertex Q(x_q, y_q, z_q) which is the shortest distance with P searched from the vertex set of mesh. The next step is to determine the inner product between the vector PQ and the normal vector of all surfaces including Q. If the product of inner products is positive, P is the initial position of model.

Then, the addition position determination of new rigid body considers collision with other rigid bodies. After random vector determined by the rotation angle and position of a rigid body to be added, the tip of the rigid body position is detected whether a tank. Collision avoidance with other individuals is used for the shortest distance between the line segments. Since the rigid body is SSV, it can be calculated the segment of the central axis of the rigid body. The rigid body collides If the shortest distance between the line segments is less than the diameter of a sphere. Therefore, the random number determines the rotation angle of the position vector again. A position cannot be determined in any number of times, and then stop the addition of the rigid body. Fig. 2.6 shows dynamic modeling of the seaweed population box-shaped tank. Then, the results of modeling the seaweed population at the high volume fraction within culture tank model shape that are used in reality is shown in fig. 2.7.

2.2.3 Dynamics Computation

In this study, physics engine is employed for simulating seaweed and fluid motions. The net force of gravity, friction, buoyancy, and drag determines the motion of seaweeds. The translational and rotational motions in the position of the center of mass

describe the motion of rigid bodies. Each equation 2.1 and 2.2 show the equation of motion

$$F = m\frac{dv(t)}{dt} \tag{2.1}$$

$$T = \frac{dL(t)}{dt} \tag{2.2}$$

where, F is the force vector, m is the mass of rigid body, v is the linear velocity of rigid body, t is the time, T is the torque, L is the angular velocity of rigid body.

The physics engine cannot computes fluid forces. The implementation of computation expressions supports these forces. Buoyancy and drag force represent the resistance in fluid. These strengths of forces are defined in the equation 2.3 and 2.4

$$F_B = \rho V g \tag{2.3}$$

$$F_D = \frac{1}{2}\rho A C_D u^2 \tag{2.4}$$

where, ρ is the fluid density, V is the volume of right body, g is the gravitational acceleration. A is the projected area of object, C_D is the coefficient of drag force, u is the relational velocity between object of fluid.

In order to examine a pattern of water flow that makes avoiding seaweed twining, we require a realistic water flow model.

Then, the computation of drag force needs the fluid velocity around the object. Therefore, fluid analysis method constructs the flow field. There are finite element method (FEM) and some particle methods (MPS [Kos96, KTO95], SPH [Mon92]) as these methods. These methods solve the Navier-Stokes equation, which consumes large computational efforts. For the prolonged simulation, these methods are not suitable. In this study, it is modeled by the lattice Boltzmann method [CD98]. The lattice Boltzmann method (LBM) is one of fluid analysis methods without the Navier-Stokes equation [MZ88]. The LBM uniformly discretizes a simulating a water volume into lattices and make it possible to simulate fluid movement as a continuum by use of particles distributed in the lattices. A particle distribution function is obtained by calculating ensemble average of a number of particles in each lattice. A fluid density and velocity are easily computed in this way. The number of particles is provided by the real number. Therefore, the LBM realizes the high-speed simulation than methods previously described.

The virtual particles have some velocities in LBM. In a discretizing time, they leave in the lattice or move to other lattice once at each time step Δt. Some particles change the direction of velocity by collision. All particles are located in lattices at each

time step. Particle collision appears in all lattices at the same moment. We employ D3Q15 model as a particle distribution model in LBM. The model only considers the mass conservation and momentum one.

To calculate a time evolution of particle distribution, we use the lattice Boltzmann equation defined by eq.(2.5).

$$f_i\left(x+e_i\Delta t, t+\Delta t\right) = \left(\frac{\lambda-1}{\lambda}\right) f_i\left(x,t\right) + \frac{1}{\lambda} {f_i}^{eq}\left(x,t\right) \quad (2.5)$$

This equation is an evolution equation for the virtual particles. $f_i(x,t)$ is a distribution of particle i in a lattice. i is a particle velocity direction. λ is a relaxation frequency. Particles move by iterating collision and they transit from a movement state to a equilibrium state at a constant rate. ${f_i}^{eq}$ is a local equilibrium distribution. This particle equilibrium distribution function is given by eq.(2.6),

$${f_i}^{eq}\left(x,t\right) = \omega_i \rho \left(1 - \frac{3}{2}\vec{u}^2 + 3\left(\vec{e_i}\cdot\vec{u}\right) + \frac{9}{2}\left(\vec{e_i}\cdot\vec{u}\right)^2\right) \quad (2.6)$$

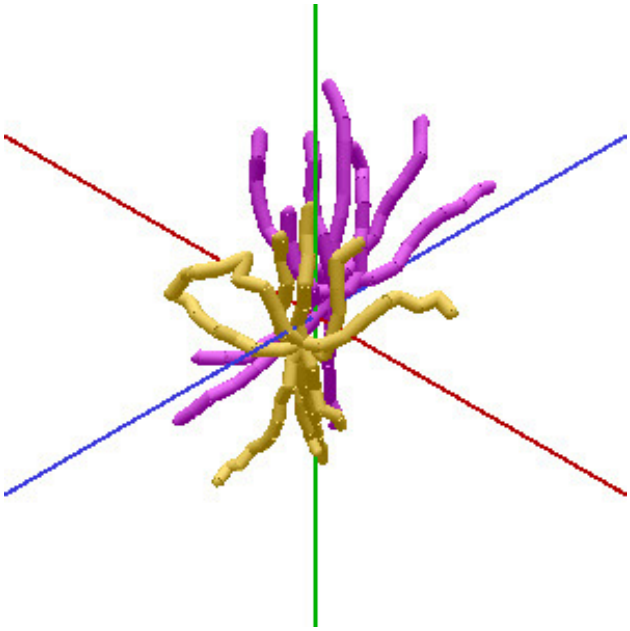
$$\text{where,} \quad \omega_i = \begin{cases} \frac{2}{9} & : \ i = 0, \\ \frac{1}{9} & : \ i = 1..6, \\ \frac{1}{72} & : \ i = 7..14. \end{cases}$$

and ρ is a density of fluid, $\vec{u}$ is a velocity of fluid, $\vec{e_i}$ is a velocity of particle. By adding ${f_i}^{eq}$ to the particle distribution function, eq. 2.6 guarantees a situation that the fluid transits to the equilibrium state. In lattices making a border as an obstacle, the particle distribution function cannot give particles' direction to the fluid as the obstacle. Therefore, we apply *bounce-back* to such lattices as a boundary condition. This condition rebounds particles into the opposite of direction with 180 degree from an obstacle.

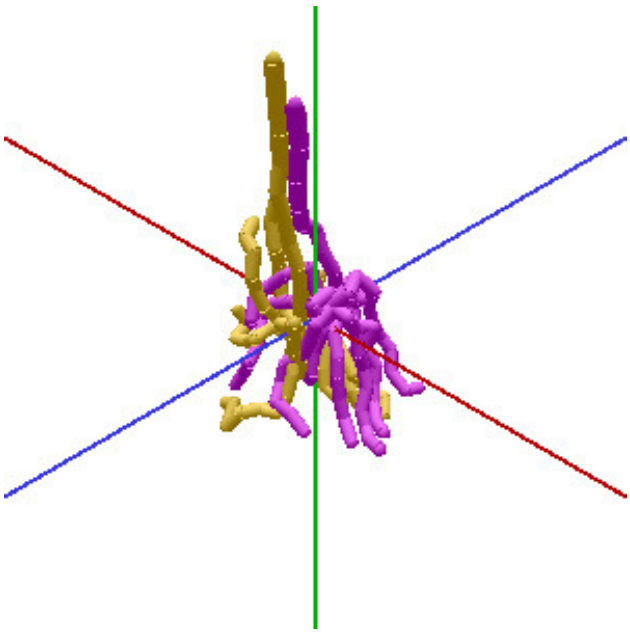
2.3 Representation of Seaweed Twist Characteristics

In this section, three physical quantities characterize the twist in order to take advantage of computer processing. The first one as a physical factor is the average number of contacts between two individuals. The second one is a geometric factor which uses the average distance between centroids. The last one is the duration time for two seaweeds kept connected, which considers a time factor.

In order to verify the relationship between these quantities and the motion of a pair of seaweed models, this section focuses



(a) Non-twist state



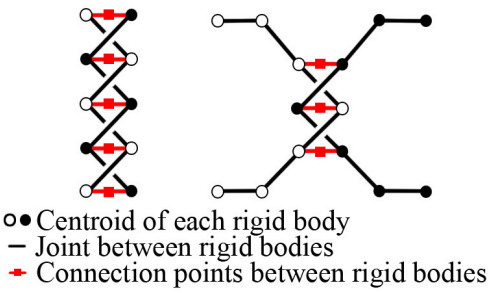
(b) Twist state

Figure 2.8: The circulation motion of a pair of individuals for 90.0 seconds simulation. The pair transits from non-twist state to the twist one

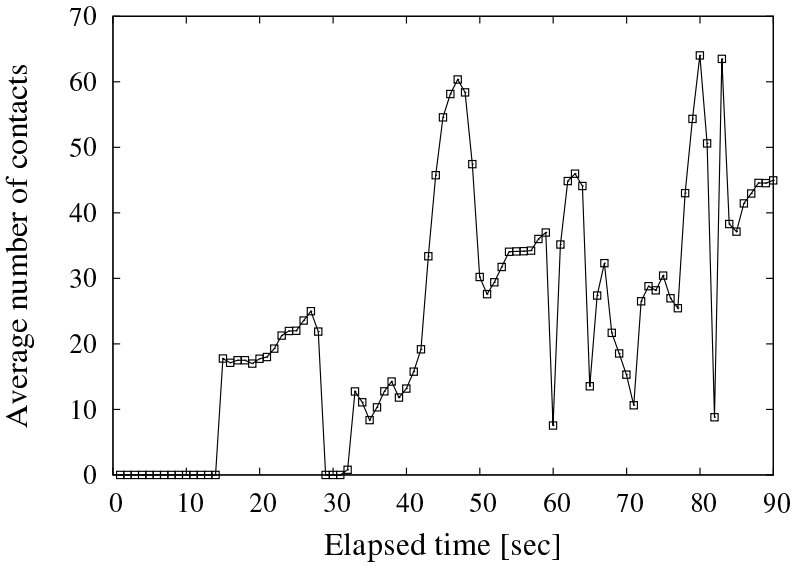
on a motion of one pair of seaweed models in the circulation simulation of seaweed population model. The pair of seaweed models becomes non-twist such as fig. 2.8(a) until the elapsed time 30.0 seconds in the simulation. On the other hand, the pair forms twist such as fig. 2.8(b) after the elapsed time 30.0 seconds in the simulation.

2.3.1 Physical Factor

The twist restricts the motion of each other ̓s individuals through physical contacts among leaves. The number of contacts between two individuals quantitates the degree of connection state. The twist state increases the number of contacts shown in figs. 2.9(a) and 2.9(b). In a lot of cases, the connection of physical model declines drastically at a certain moment. The sudden decline is caused by the discrete time steps dt, in physics computation. Because of this, the number of contacts cannot be a measure for the twists. Hence, an arbitrary time window averages the number of contacts in order to overcome the problem. The average number of contacts during the recent DT time steps, is used as the physical parameter between individuals at



(a) Comparison between states



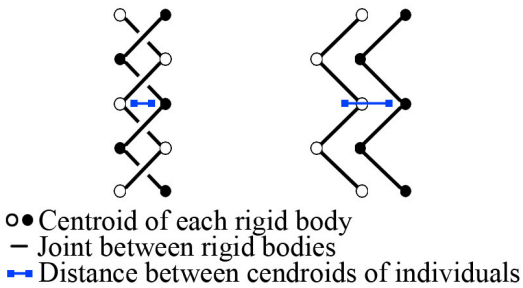
(b) The time variation of connections of the pair in fig 2.8

Figure 2.9: The average number of connections between individuals

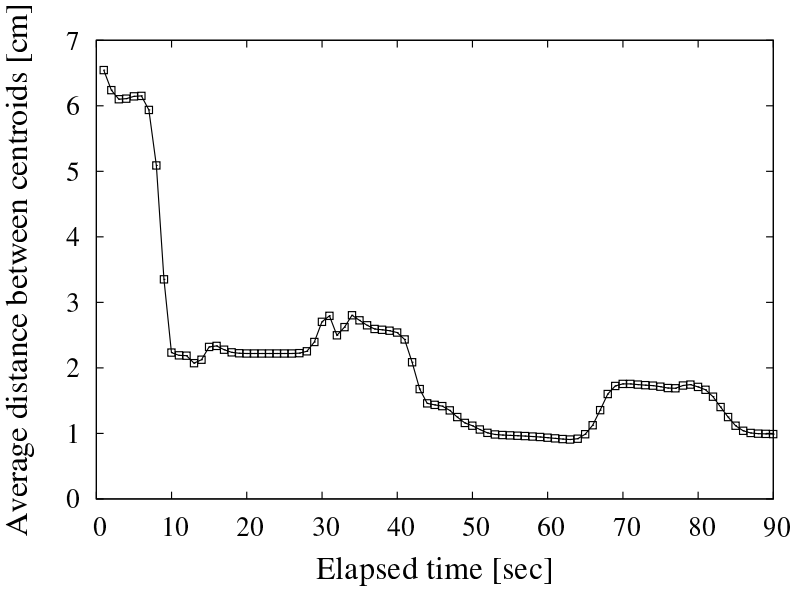
the time t. The physical parameter $\overline{C}(t)$ is express as follows.

$$\overline{C}(t) = \frac{1}{DT} \sum_{s=t-DT}^{t} C(s) \tag{2.7}$$

Where, $C(s)$ is the number of contacts at the time s, and DT fixed to 5.0 seconds in this paper. When the value of DT is short, the parameter emphasizes the local change of states in



(a) Comparison between states



(b) The time variation of geometric distance between the pair in fig 2.8

Figure 2.10: The average distance between individual's centroids

the simulation.

2.3.2 Geometric Factor

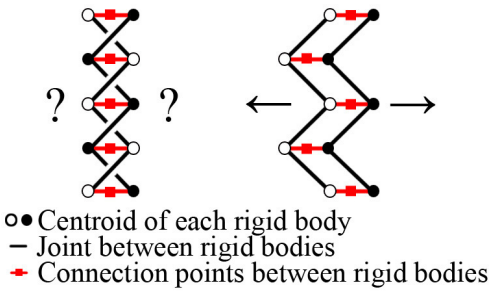
The distance between centroids of seaweed models represents the geometric distance between two models. The focused pair of seaweed models is keeping non-twist such as fig. 2.8(a) until

the elapsed time 30 in the simulation. Also, The focused pair of seaweed models is keeping twist such as fig. 2.8(b) after the elapsed time 30 in the simulation. In the fig. 2.10(a), the number of connections between models is same, however, the left pair 's distance between centroids is shorter than the right one from the result of fig. 2.10(b). The focused pair of seaweed models until the elapsed time 30 in the fig.2.10(b). The form of twists has a tendency to make the distance shorter. The centroid of the individual seaweed $G(t)$ at the time t is expressed in equation 2.8.

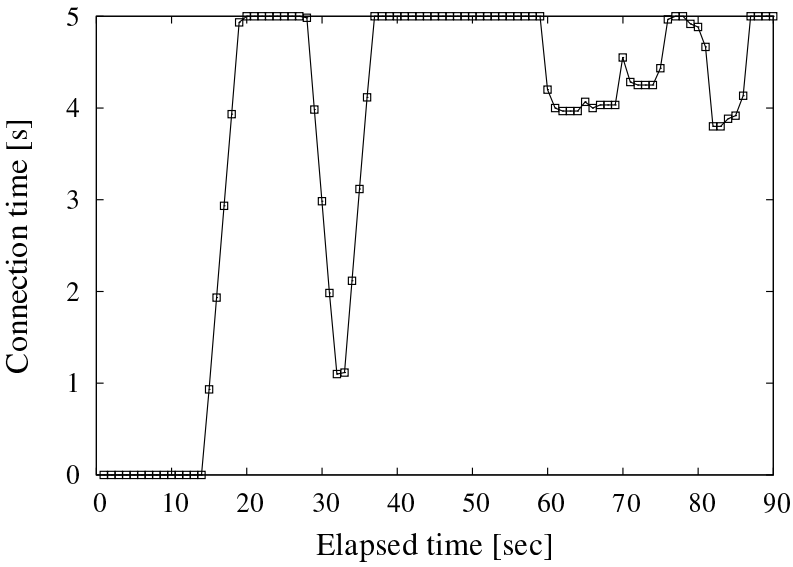
$$G(t) = \frac{\sum_{i=1}^{N} m_i x_i}{\sum_{i=1}^{N} m_i} \tag{2.8}$$

where, N is the total number of rigid bodies composed of individual model, m_i is the mass of i th rigid body, x_i is the centroid position of i th rigid body. Here, x_i is three diminutional vector. Therefore, the fig. 2.9 shows the average distance between centroids $\mathrm{D}_{IJ}(t)$ at the time t can be expressed as follows.

$$\overline{D}_{IJ}(t) = \frac{1}{DT} \sum_{s=t-DT}^{t} \{G_J(s) - G_I(s)\} \tag{2.9}$$



(a) Comparison between states



(b) The time variation of connection time between the pair in fig 2.8

Figure 2.11: The time for keeping the connections

2.3.3 Time Factor

2.3.4 Geometric Factor

The appropriate force field is needed for unraveling the twist of seaweeds. Once the seaweeds form the twist, the formation is kept for a while. In the twist formation, the required force field

is complicated than non-twist states for separating two individuals. The duration time for keeping connections can measure the complexity of connections (hereinafter referred to as the connection time). Question marks and arrowed lines in the fig. 2.11(a) shows the needed force directions for unraveling these states such as fig. 2.8(a) and 2.8(b). The connection time indicates the degree of how much they stick together as the time factor of twist. The following equation 2.10 define the connection time $E(t)$ between a pair of seaweeds at the time t.

$$E(t) = \sum_{s=t-DT}^{t} \{e(s)\} \tag{2.10}$$

$$e(t) = \begin{cases} dt & (C(t) > 0) \\ 0 & (otherwise) \end{cases} \tag{2.11}$$

2.4 Twist-state Classifier between Pieces of Seaweed

2.4.1 Classification Procedure

The first step of the twist classification procedure is to vectorize these feature quantities, which are the average number of connections, the average distance between centroids, and the connection time. This vector characterizes a state between in-

dividuals from three viewpoints.

To train SVM to detect twists autonomously, the second procedure is a creation of teaching signals for the twists. The user answers twist state or non-twist state after watching motions of a pair of seaweeds which are picked up from the simulations. This question is repeated many times and the answers are used as the teaching signals for twist and non-twist. SVM is trained with the dataset $X(X_1, X_2,..., X_n)$ for the pattern learning. After learning, the SVM is evaluated with the unknown dataset $Y(Y_1, Y_2,..., Y_n)$ whether twist state or non-twist one.

2.4.2 Classification Experiment

Objective

The objective is to detect the dynamic twist state of pairs in the floating seaweed population. Here, the classification experiment verifies the accuracy of dynamic twist-state classifier. Additionally, this experiment ascertains that the proposed feature vectors are possible to represent the twist of seaweeds.

Conditions

The twist-state classifier performs a random sampling from multiple feature vectors in the floating seaweed population. The

Table 2.2: The classification result of unknown data

State	Error ratio[1]	Precision ratio	Recall ratio	Error ratio[2]
Twist state	0.0	0.91(50/55)	1.00(50/50)	0.0
Non-twist state	0.06	1.00(45/45)	0.90(45/50)	0.1

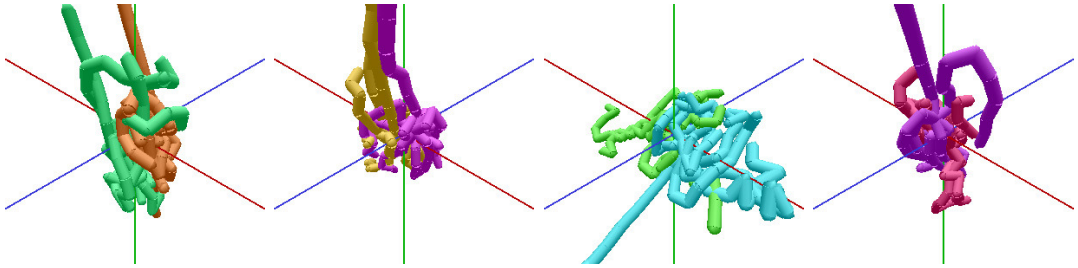
[1] Error ratio of the training data (100 vectors)

[2] Error ratio of unknown data (100 vectors)

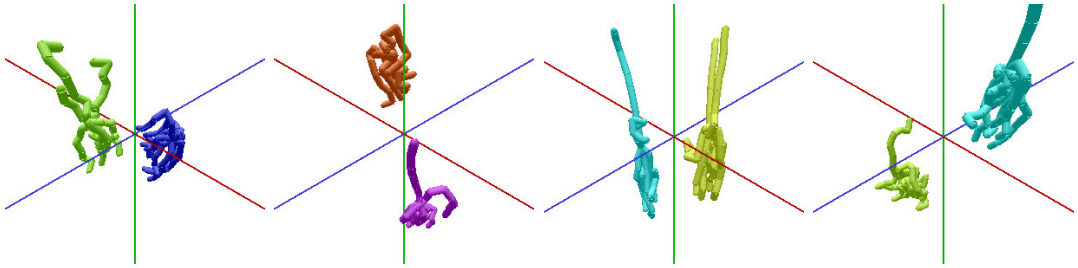
number of samples is 100 pairs. Fifty percent of samples are twist states, and others are non-twist states. The twist-state classifier learns the pattern of these feature vectors of pairs. Then, 100 unknown vectors are created in the same way. This experiment classifies these vectors into twist or non-twist.

Classification Results

The classification result is shown in table 2.2. The precision ratio is the accuracy of classification. The recall ratio is the completeness of classification results. The method can classify the 95 % of the total pairs into the twist and non-twist in user's recognition. The precision ratio of non-twist and the recall ratio of twist show 1.0 of the maximum value. Fig. 2.12 illustrates four samples of a pair of seaweed models from these classified results. This twist-state classifier specifically distinguishes between the twist state and the separation state. The error of classification is observed in case of discerning the non-twist states. It appears



The classification result of twist pairs



The classification result of non-twist pairs

Figure 2.12: Comparison between the classified twist and non-twist

that these pair models form the twist state from a single perspective. These pairs are easy to mistake for twist formation in a visual way.

Discussion

These results show that the proposed vector captures the essence of twists. It indicates that the vector makes it possible to detect twist states autonomously. The error of classification arises from the distribution or the number of created training data.

The big difference between twist and non-twist was correctly detected but the subtle difference cannot. The sample was picked up randomly from the simulation but the number of samples was not enough or there is not enough samples to detect the subtle difference. Therefore, the revision of training data would improve the accuracy of twist-state classifier. The accumulation of training data increases the pattern of recognizable twist. A single simulation result provides lots of twist information with user. The classification measure of twist can be created only a few cycles of simulation. This measure realizes both quantitative evaluation and fast analysis of twist.

2.5 Conclusion

In this Chapter 2, we have established a method of dynamic modeling and simulation of seaweed population for high volume fraction in any spatial data. To analyze the changes in the physical state of seaweed population unique to the motion by the numerical analysis by simulation, show that our method is useful in engineering. In addition to the numerical data covered in this paper, the data obtained from this simulation are many. We will be able to discover the factor has not been known until now by

appropriate analysis of these data collected. Additionally, we proposed the feature quantities of the twist for quantifying the twist of seaweeds. These quantities realized the classification of twist and non-twist in the floating seaweed population using the SVM. The conclusions are as follows:

- Three factors, which the average number of connection, distance between centroids, and connection time, characterizes the twist state
- The twist classification based on these feature vectors shows the high classification accuracy for unknown states of pairs

This chapter solved the problems for evaluating the seaweed twist formations quantitatively.

Chapter 3

Estimation of Seaweed Twist Based on Network Analysis

3.1 Introduction

This chapter establishes the application of an simulation analysis toward the seaweed cultivation techniques [OIYF14a] using our simulation that models the natural motion of seaweed twist in the chapter 2. This physical model has various physical properties of seaweed, such as orientation, velocity, geometric shape, contact status and so on. In order to understand the detail of processes of the seaweed twist formations, we defined these representation factors of the physical interaction at the formations in the chapter 2. Each factor characterizes the twist formations as a macroscopic phenomenon from the spatiotemporal dynam-

ics of seaweeds.

This chapter focuses on risk calculation of occurring the twist formations among seaweed population. The big goal in this study is to control the twist formations based on computer simulation. We consider that the analysis of the risk of occurring the twist is important for accomplishing the goal. The main topic in this cahpter is to propose the estimation method of the twist risk between seaweed. To calculate the risk means to verify dynamic process of the twist formations with seaweed motion. Therefore, the risk calculation leads to acquire the significant findings that identify a major point of controlling the seaweed motion at various cultivation situations. The risk calculation requires an effective way to understand dynamic process of twist formations in seaweed motion. Interaction network is suitable to look down at the interaction between individuals from a viewpoint of seaweed population. We visualize the relation of the twist formations by creating an undirected weighted interaction network, called a twist network in this chapter 3, based on values of twist formations obtained through calculation. In this chapter 3, this thesis proposes a nonlinear evaluation function based on quantification factors in the chapter 2 in order to calculate the occurrence risk of twist formations, which in turn

depends on interaction in seaweed motion. The calculation of link weight of interaction network defines this function. The analysis of risk of twist formations means to estimate the occurrence of twist formations. Kernel diffusion [ISKM05, KLB08, KL09, KLA10, LTD+06, NGO+10, SK03, TN04, YVK04] is one of the link analysis methods based on information diffusion for achieving this objective. This method is applied to estimate the network structure with link change. The diffusion kernel propagates the similarity between nodes into other nodes according to the link relation of the network. In this chapter, we introduce analysis methods using von Neumann and Laplacian diffusion kernels into the link analysis of the twist network. In addition, we describe the findings about the reduction of occurrence risk of twist formations for controlling the formations through comparison experiment of evaluating multiple analysis methods.

This chapter is organized as follows. In Section 2, we provide the details of our physical simulation that models seaweed motion. We define a twist evaluation function and introduce the way to construct the interaction network of twist formations. in Section 4 we proposes the analysis method of using the two diffusion kernels mentioned above. Section 5 contains an account of the experimental results of our numerical analysis and a dis-

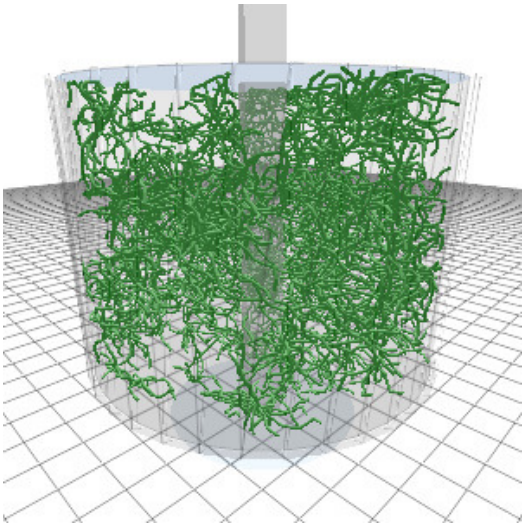


Figure 3.1: Physical model of a single piece of seaweed and of seaweed population

cussion of the reduction of occurrence risk of twist formations from these results. We present our conclusions in Section 6.

3.2 Physical Simulation

In this chapter, the seaweed model is constructed as a multiple rigid bodies based on actual shape. Fig. 2.1 shows a seaweed modeled using our simulation. The model's form variation is determined by adding new rigid bodies while avoiding having them collide. Joint constraints are restrictions in motion between connected rigid bodies. Unconstrained rotation represents the flexibility of seaweed. Each rigid body has four physical properties – density, restitution coefficient, dynamic friction coefficient, and static friction coefficient. Plant elasticity is typically determined

by measuring the value of Young's modulus, the rigidity modulus, and the volume elasticity modulus. Since values of these for an actual plant depend on moisture percentage, density, and other factors, the standard value of plant elasticity is difficult to define, so a small value of the restitution coefficient represents the elasticity of seaweed adequately.

To consider the heterogeneity of plant growth in modeling the population, the number of rigid bodies that constitute the individual seaweed model changes according to interaction with other individuals. In terms of the form variation, a rigid body is added with probability p by taking into account collision avoidance. Each piece of seaweed is placed somewhere in arbitrary space. Thus, this modeling method creates various patterns for a seaweed population. The seaweed population thus simulated in a tank is shown in fig.3.1.

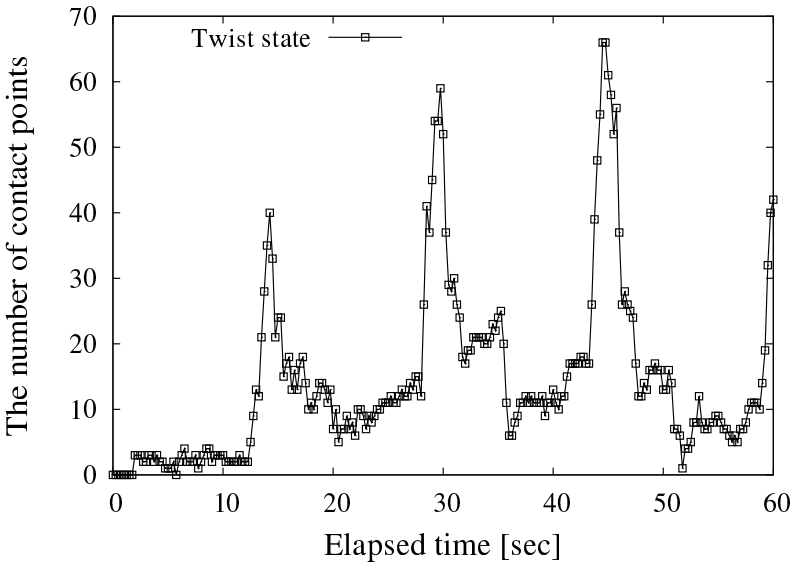
Seaweed dynamics are realized by numerically integrating the external forces, including gravity, friction, restitution, buoyancy, and drag force. Drag force computation requires the determination of water flow velocity. In order to develop realistic water flow, we use the Lattice Boltzmann Method (LBM), a technique for the computational analysis of fluid dynamics [CD98]. The LBM numerically simulates fluid motion by calculating the time

evolution of the particle velocity distribution based on the idea of cellular automata. This method can represent water flow to a high precision without noise. For details of the dynamics, please refer to the chapter 2.

3.2.1 Simulation Results

The seaweed twist formation occurs due to geometric change from contact. It is important to ascertain the extent of change from the viewpoint of the physical model. One objective of our simulation is to analyze the geometric formation of seaweed from simulation results. In the simulation environment, water flow is defined as an axial circulation flow along the central upright pole of the tank model shown in fig.3.1. Two patterns are observed from the simulation results in terms of the geometric twist formation between individual piece of seaweed. One is where seaweed causes twisting and persists in the twist state. The twist of this pattern is a general twist state shown in fig.3.2(a). The other pattern is where seaweeds separate shortly after they come into contact with each other. This pattern shows that seaweeds do not develop a twist or are easily separable if they do develop one. The deference in these patterns is detectable from the number of contact points between pieces of seaweed. Fig.3.2(b)

(a) Twist state of two seaweeds



(b) Time evolution of the number of contact points between two seaweeds

Figure 3.2: Twist formation in a pair of pieces of seaweed and typical pattern of the time evolution with the number of contact points between two pieces of seaweed

shows typical instances of the time evolution with the number of contact points in the twisted state. From these results, we assumed that the twist between two pieces of seaweed occurs when the number of contact points increases rapidly. Furthermore, the geometric form becomes twisted as shown in fig.3.2(a) while the number of contact points is nonzero. The number of contact points varies greatly and periodically, however, with circulation flow because it depends on the contact strength of each point. It is thus difficult to detect twisting between pieces of seaweed merely from the number of contact points between them at any given time.

3.3 Dynamic Twist Network

A measure criteria is required to understand the occurrence process of twist formations. Three physical variables, which are the number of contacts, the contact time and the centroid distance between two seaweeds, quantify these features of twist formations. In particular, the number of contacts and the contact time is able to strongly characterize the twist formations comparing with the centroid distance. The number of contacts and the contact time increase only when two seaweeds is twisting. In

terms of the centroid distance becomes short In case of occurring the twist formations, however, the distance becomes also short when two seaweeds does not twist or contact. Therefore, the measure criteria of twist formations defines a real-valued function of two variables based on two variables which are the number of contacts and the contact time in this chapter. This is capable of calculating the transitional state of twist formations as real value. Furthermore, networking the physical interaction between seaweeds is an effective approach to estimate the risk of twist from seaweed motion. A dynamic state variation should be considered to visualize the interaction, since twisting depends strongly on seaweed motion. In this section, we describe the quantitative evaluation function of the transitional state of twisting, and propose calculation for detecting expected the occurrence risk of twist formations based on the interaction network between pieces of seaweed.

3.3.1 Twist Evaluation

The method we propose here for quantitatively evaluating of transitional state of twisting is new. However, we need to create evaluation criteria in order to understand the occurrence process of twist formations, which is qualitative. The criteria should

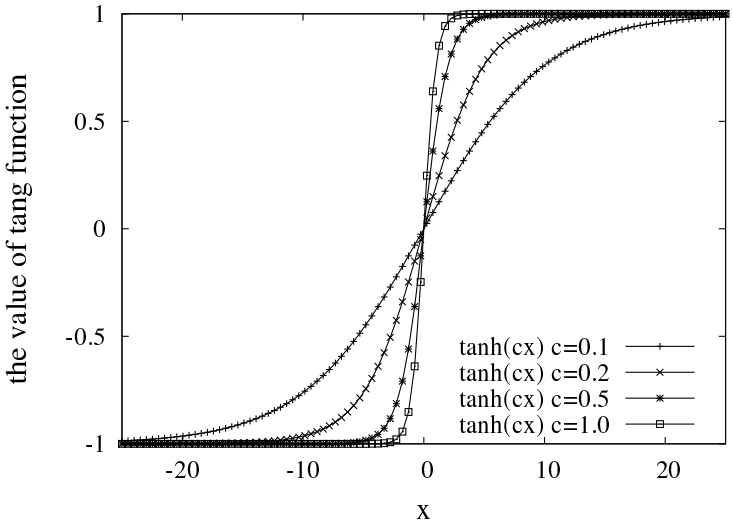


Figure 3.3: Time evolution of the twist evaluation function based on the activated function

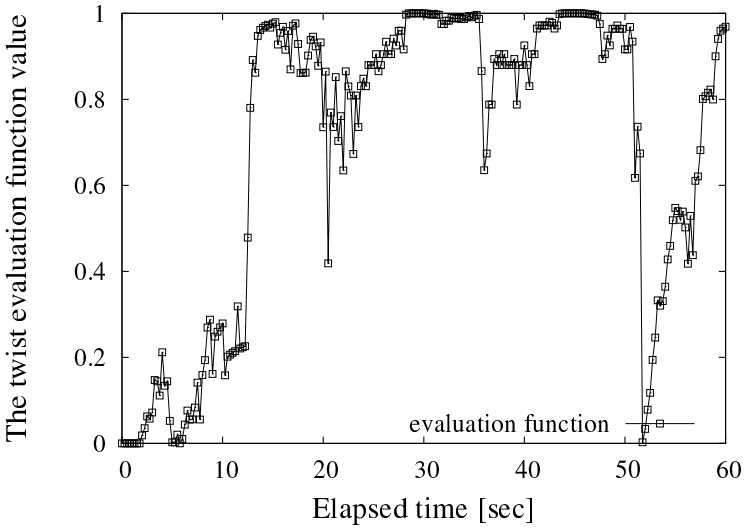


Figure 3.4: Time evolution of the twist evaluation function based on the activated function

represent the physical properties of twisting in seaweed strongly. We take into account the following two physical properties:

- The number of contacts between individual pieces of seaweed
- Contact time between individual pieces of seaweed

Twisting restricts the motion of seaweeds due to the adhesion of their leaves. The number of contact points quantifies this motion constraint in twisting. The risk of the occurrence of twisting rises with the increase in the number of contact points, as shown in fig.3.2(b). Once begun, twisting persists for a long time until twisted seaweed is separated again. Contact time between pieces of seaweed shows this feature. Therefore, the criteria for evaluating the transitional state of twisting should be designed by combining the number of contact points and the contact time of pieces of seaweed.

A hyperbolic tangent (tanh) function expresses the activation response, and represents a rapid monotonic increase when the value of the variable exceeds 0, as shown in fig.3.3. Both the number of contact points and the contact time are non-negative. If these parameters are introduced into the argument for the tanh function, the function computes twisting as an activating response through the contact state. We propose the evaluation

function $\omega_{ij}(t)$ for the twisting shown in Eq.(3.1),

$$\begin{aligned}\omega_{ij}(t) &= \tanh(\frac{\beta h_{ij}(t)}{2}) \cdot \tanh(\frac{\gamma n_{ij}(t)}{2}) \\ &= \frac{1-e^{-\beta h_{ij}(t)}}{1+e^{-\beta h_{ij}(t)}} \cdot \frac{1-e^{-\gamma n_{ij}(t)}}{1+e^{-\gamma n_{ij}(t)}}\end{aligned} \tag{3.1}$$

$$h_{ij}(t) = \begin{cases} t - t_s & (n_{ij}(t) > 0) \\ 0 & (n_{ij}(t) = 0) \end{cases} \tag{3.2}$$

where i and j are individual numbers, t is the current time, t_s is the start time of the first contact between pieces of seaweed, $h_{ij}(t)$ is the contact time between individual pieces of seaweed i and j at time t, $n_{ij}(t)$ is the number of contact points between pieces of seaweed at time t, and β and γ are adjustment coefficients. Fig.3.4 shows the time evolution of twist evaluation value for the two patterns in fig.3.2(b).

The state of separation between pieces of seaweed is classified as an inactive and twisting is classified as activated. This function is a real-valued, and whose values are in interval [0.0:1.0]. The activated state shows a value close to 1. Eq.(1) then denotes the product of the tanh function concerning $n_{ij}(t)$ and the tanh function concerning $h_{ij}(t)$. This function prevents false detection of twisting when one variable, – either $n_{ij}(t)$ or $h_{ij}(t)$, – assumes a high value and the other assumes a low value. In

such cases, the function distinguishes twisting from accidental contact between pieces of seaweed.

3.3.2 Network Structure

Networking is an effective method for the numerical visualization of interactions during the motion of a population, swarms, etc. Using the networking method, it is possible to analyze the seaweed population from the individual to the collective level. In this section, we describe the creation of the twist network. A node here represents an individual piece of seaweed, and the link shows contact between individual pieces of seaweed. The connection weight between individuals i and j is defined by the twist evaluation function $\omega_{ij}(t)$. Since $\omega_{ij}(t)$ depends on time t, the structure of the twist network changes dynamically.

In order to analyze network features, we need to understand the network structure. This also holds for the twist network. A graph Laplacian $L(t)$ of the network represents the structure of twist network. Graph Laplacian $L(t)$ is a square matrix, as shown in Eq.(3.3). This Laplacian matrix subtracts adjacency matrix $A(t)$ from degree matrix $D(t)$ of the node of the network.

$$L(t) = D(t) - A(t) \tag{3.3}$$

When the number of individuals in the seaweed population is N,

the adjacency matrix, the degree matrix and the graph Laplacian matrix is an N×N matrix. Adjacency matrix $A(t)$ is a matrix where each element $a_{ij}(t)$ is the value of the connection weight $w_{ij}(t)$, as shown in Eq.(3.4).

$$a_{ij}(t) \;=\; \omega_{ij}(t) \tag{3.4}$$

Degree matrix $D(t)$ is a matrix whose diagonal elements $d_{ii}(t)$ represent values of the degrees of node i, and all other of whose elements equal 0. The degree of node $d_{ii}(t)$ is shown in Eq.(3.5).

$$d_{ii}(t) \;=\; \sum_{j=1}^{N} w_{ij}(t) \tag{3.5}$$

Elements $l_{ij}(t)$ of the graph Laplacian $L(t)$, excluding the diagonal elements, show the connection weight between nodes i and j. The diagonal elements $l_{ii}(t)$ are the degrees of node i, excluding the self-loop. The graph Laplacian in the twist network is able to easily show the time transition of the interaction in the seaweed population.

3.4 Estimation for Seaweed Twist

3.4.1 Standard Approach

The standard approach to link estimation involves measuring the similarity between network structures. If the weights of the

link at times t and $t - dt$ are high similar, the change in the link weight becomes small in the next time step, $t + dt$. In contrast, the change in link weight becomes large in link weights of low similarity. The adjacency matrix is a basic matrix to understand the network structure. The use of a difference matrix of the adjacency matrix at time t and $t - dt$ is the most commonly used approach in link estimation.

The adjacency matrix of the twist network is hereafter expressed as $A_{tw}(t)$. In order to calculate the risk of occurrence of a twist at time $t + dt$ from the state of twisting at time t, we define three twist estimation models using two diffusion kernels and the difference between adjacency matrices. All models use the difference value of the adjacency matrix at times t - dt and t. This matrix is defined as $DM(t)$ by Eq.(3.6).

$$DM(t) = A_{tw}(t) - A_{tw}(t - dt) \tag{3.6}$$

We describe difference value model $E^{DM}(t)$ as follows:

$$E^{DM}(t) = A(t) + DM(t) \tag{3.7}$$

The model adds $DM(t)$ to the current adjacency matrix $A_{tw}(t)$. Difference value model $E^{DM}(t)$ is used to calculate twisting between individual pieces of seaweed with a direct change in value.

3.4.2 Twist Estimation Based on Diffusion Kernels

Von Neumann Diffusion Kernel Method

The diffusion kernel is a link analysis scale proposed by Kondor et al. [KL02]. It is a matrix representing the strength of the relationship between nodes based on the connection weights between them. The diffusion kernel matrix is classified into two types of kernel, based either on the graph Laplacian kernel or on the adjacency matrix. The von Neumann diffusion kernel is based on the adjacency matrix, and has been proposed by Kandola et al. [KSTC02] as a calculation method for the relative importance of nodes. Eq.(3.8) shows the formulation of the von Neumann kernel $vNK_\alpha(t)$.

$$\begin{aligned} vNK_\alpha(t) &= A(t)(I - \alpha A(t))^{-1} \\ &= A(t)\sum_{n=0}^{\infty} \alpha^n A^n(t) \\ &= A(t) + \alpha A^2(t) + \alpha^2 A^3(t) + \ldots \end{aligned} \tag{3.8}$$

The elements of the von Neumann diffusion kernel matrix are biased either to importance or to relevance by the value of diffusion coefficient $\alpha(0 \leq \alpha < \infty)$.

Laplacian Diffusion Kernel Method

Laplacian diffusion kernel $LK(t)$ is an N×N matrix, and the value of elements $lk_{ij}(t)$ is given by Eq.(3.9):

$$\begin{aligned} LK_{\alpha}(t) &= e^{-\alpha L(t)} \\ &= I + \alpha\frac{-L(t)}{1!} + \alpha^2\frac{(-L(t))^2}{2!} + \dots \end{aligned} \tag{3.9}$$

where α in Eq.(3.9) shows the degree of diffusion at the Laplacian kernel. The value of α has to satisfy ($0 \leq 1 - \alpha \cdot \max(l_{ii}(t)) \leq 1$). Maclaurin expansion of the Laplacian diffusion kernel represents the similarity computation between nodes in n paths. The Laplacian diffusion kernel $LK(t)$ is used for network link analysis, link prediction, classification, etc. The Laplacian kernel excludes the network hub, meaning that the hub is an individual piece of seaweed twisted in with many other such individuals. In the twist network, the Laplacian kernel focuses on twisting of individual pieces of seaweed that do not significantly affect many other individual pieces of seaweed.

If the elements of the adjacency matrix of the twist network are defined by Eq.(1), these diffusion kernels show the calculated value of the risk of twist between unlinked individual pieces of seaweed. We propose two link estimation methods using the diffusion kernel matrix to calculate expected twisting between

individual pieces of seaweed from the twist network structure at time t. First, $E^{vNK}(t)$ adds the von Neumann kernels of $DM(t)$ to $A_{tw}(t)$. However, $DM(t)$ is divided into a negative definite matrix $DM^{-}(t)$ and a positive definite matrix $DM^{+}(t)$ by the element value of DM(t). $DM^{-}(t)$ is converted to an absolute value for all elements. The next process applies the von Neumann diffusion kernel method to $DM^{-}(t)$ and $DM^{+}(t)$. $vKN_{\alpha}^{-}(t)$ is defined as the von Neumann diffusion kernel matrix of $DM^{-}(t)$, and $vKN_{\alpha}^{+}(t)$ is defined as the von Neumann diffusion kernel matrix of $DM^{+}(t)$.

$$E^{vNK}(t) = A_{tw}(t) + \{vKN_{\alpha}^{-}(t) + vKN_{\alpha}^{+}(t)\} \tag{3.10}$$

Furthermore, $E^{LK}(t)$ adds the Laplacian kernels of $DM(t)$ to $A_{tw}(t)$. $LK_{\alpha}^{-}(t)$ is defined as the Laplacian diffusion kernel matrix of $DM^{-}(t)$, and $LK_{\alpha}^{+}(t)$ is defined as the Laplacian diffusion kernel matrix of $DM^{+}(t)$.

$$E^{LK}(t) = A_{tw}(t) + \{LN_{\alpha}^{-}(t) + LK_{\alpha}^{+}(t)\} \tag{3.11}$$

The estimation value is, however, only the non-diagonal elements in all models.

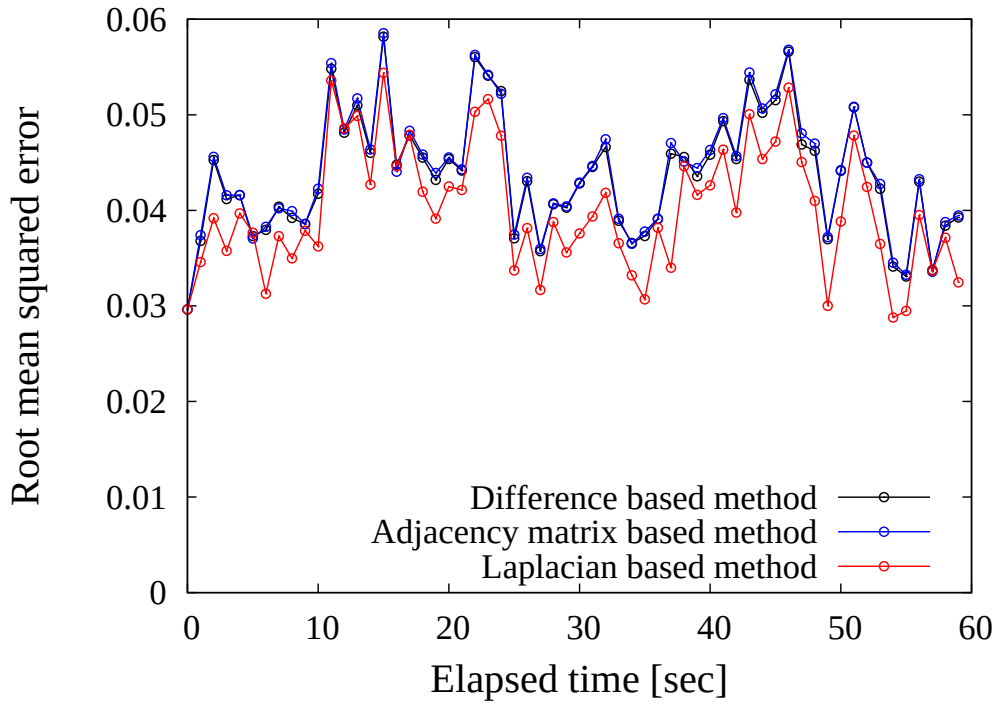


Figure 3.5: Comparison of time evolution of twist evaluation performance for each calculation interval $dt = 1.0$

3.5 Verification of Twist Estimation Accuracy

3.5.1 Experimental Conditions

We here verify the performance of our proposed estimation methods. The performance is evaluated given 60 seconds of results of physical simulation. This simulation is the same one acquired the results of fig. 3.2(b). For the evaluation scale of the calculation of twisting at time t, our experiment uses the root mean squared error ($RMSE(t)$) between the estimation matrix at time t and the adjacency matrix at time $t + dt$, as shown in

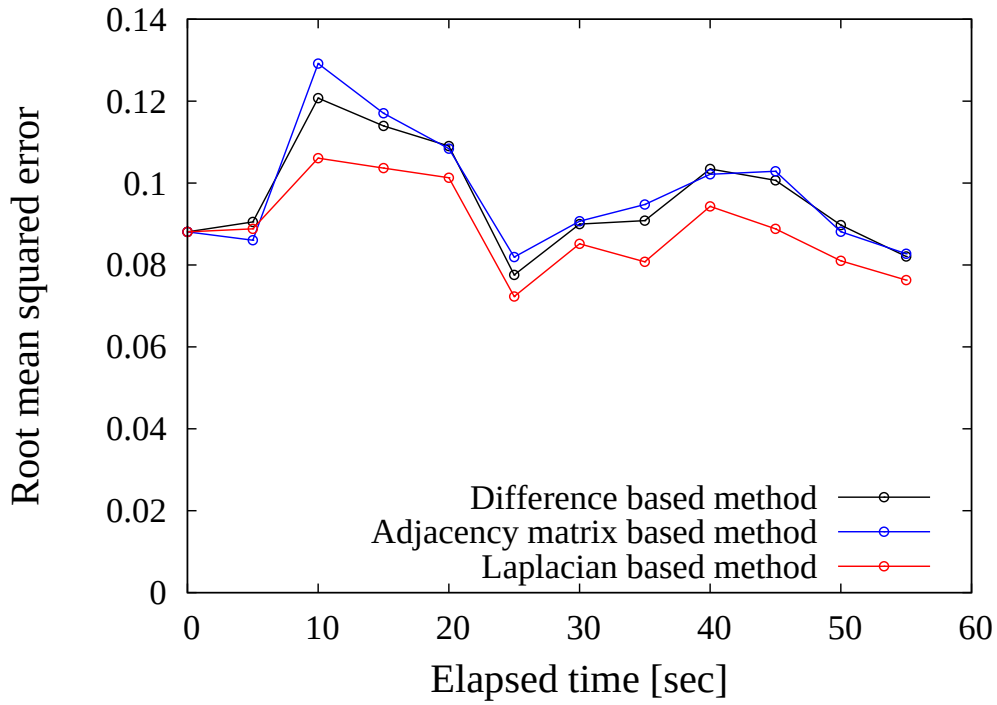


Figure 3.6: Comparison of time evolution of twist evaluation performance for each calculation interval $dt = 5.0$

Eq.(3.12).

$$RMSE(t) = \sqrt{\frac{\sum_{i=1}^{N}\sum_{j=1}^{N}(a_{ij}(t+dt) - e_{ij}(t))^2}{N^2}} \tag{3.12}$$

where $a_{ij}(t+dt)$ is the value of the relevant element of $A_{tw}(t+dt)$ and $e_{ij}(t)$ is value of the element of the estimation matrix $E^{DM}(t)$, or $E^{vNK}(t)$ or $E^{LK}(t)$. The parameters i and j represent the number of individual pieces of seaweed in the model. The number of individual pieces of seaweed is $N = 100$ in the simulation for a number of trials of 1. Water flow is converged to a steady state in the second half of the simulation time. The

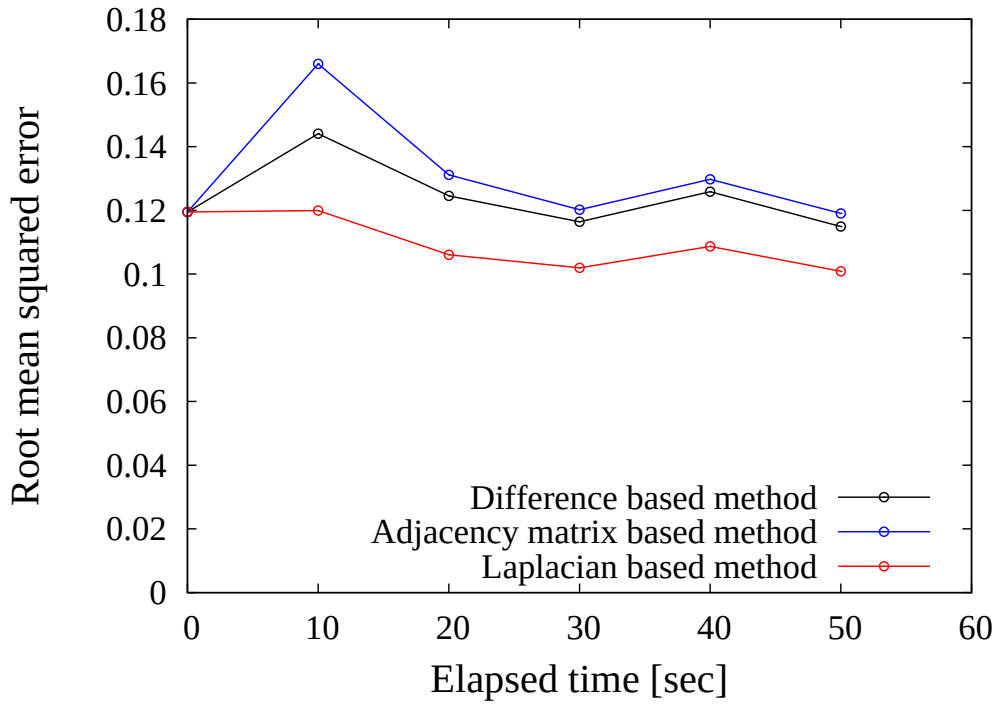


Figure 3.7: Comparison of time evolution of twist evaluation performance for each calculation interval $dt = 10.0$

estimation experiment is performed by setting the estimation interval dt to 1.0, 5.0, and 10.0 seconds.

3.5.2 Analysis Results

Analysis results are shown in fig.3.5-3.7. The difference value-based model $E^{DM}(t)$ does not calculate twisting of individual pieces of seaweed whose link weight does not change. In other words, $E^{DM}(t)$ is unable to predict twisting in future. However, the adjacency-based model $E^{vNK}(t)$ performs worse than or similar to the difference value-based model $E^{DM}(t)$ in our

experiment. This is because in $E^{vNK}(t)$, it is easy to diffuse the similarity of strong twisting into all potential links with or without the expected twisting. It becomes the reason for reducing the value of $RMSE(t)$.

The Laplacian kernel-based model $E^{LK}(t)$ exhibits the best performance because it is able to exclude the effect of strong twisting. This method $E^{LK}(t)$ realizes the high value of $RMSE(t)$ better than other methods by focusing on the similarity diffusion among indirect links. These comparison results indicate that twisting is considered to be one of the diffusion phenomena including strong locality. Thus, if two pieces of seaweed have a strong relation through individual pieces of seaweed in common, the risk of twisting increases. However, this feature does not relate to the degree of twisting among the individual seaweeds in common.

3.6 Conclusion

We have proposed a quantitative scale for calculating twist between individual pieces of seaweed by creating a twist network as a link weight. We then proposed a method for calculating the twist risk for a seaweed population using two diffusion ker-

nel matrices and one difference matrix of adjacency matrices. The analysis results have shown that the diffusion kernel based on network theory can be possible to estimate the occurrence of twist phenomenon. The evaluation using the Laplacian diffusion kernel was superior to that using other methods. This chapter established the analysis method of estimating the risk of expectable the twist formations in a viewpoint of simulation research.

Chapter 4

Control of Water Flow to Inhibit Seaweed Twist in Real Environment and Physical Simulation

4.1 Introduction

The aim of this chapter is to apply our established method to a real world environment and to show the effectiveness of our method.

The solution of increasing the seaweeds causes a different problem where the seaweeds tend to form the twists that disturb photosynthesis shown in Fig. 4.1. The inhibition of the formations of the seaweeds is a major challenge to improve the

seaweed energy productivity.

The water flows in an aquatic tank affect the formations. The relation between the formations and the flows should be clarified with some concrete data in order to inhibit the formations. Generally, the system for measuring flow velocity can analyze actual flow fields. The method is effective in cases where the size of seaweeds is large enough, however, the analysis is difficult since the string-shaped is not easy to detect the motion. This study proposes an innovative way to analyze the relations between the twist formation of small seaweeds and the flows using physical simulation. First, we established a real experimental environment to test how much the twists of seaweeds are formed when the various water flows to stir small seaweeds are given. The environment is hand-made with a small beaker and small seaweeds called " Green laver". The green laver is one of the string-shaped seaweed. Our simulation was developed to properly model the experimental environment and the twist formations. In the simulation, we found water flows that inhibited twist formations. Then, this paper describes the results when we applied our simulation results into the inhibition of twist formation in a real world, and discusses the feature of an effective flow for inhibiting the formations.

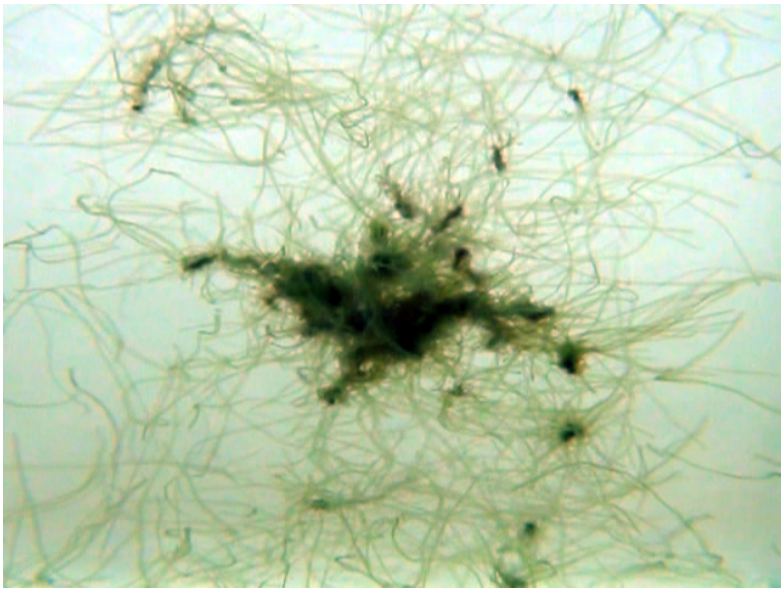


Figure 4.1: The actual twist formation among green lavers

The rest of this paper is composed as follows. Section 4.2 explains the experimental environment in our simulation and a real world and proves the adequacy evaluation for our simulation. Section 4.3 discusses the reason of occurring the twist formation from the results of our simulation and real world experiment and proposes the control way to inhibit the formations. Section 4.4 concludes this study with some remarks. This chapter is based on the paper [OSYF13a, OIYF15, OIYF14b]

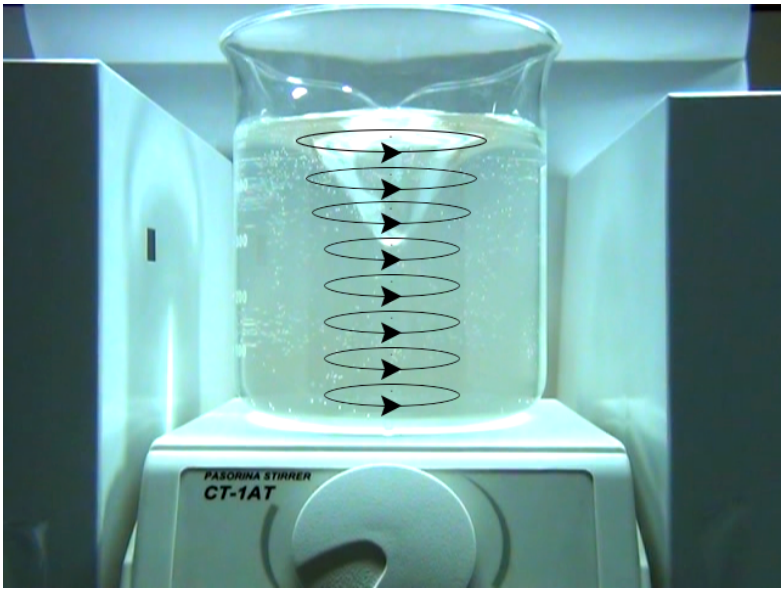


Figure 4.2: Experiment environment using a magnetic stirrer. These arrows show the water flow direction in the beaker

4.2 Experiment Environment in Our Simulation and a Real World

4.2.1 Experiment Environment in Real World

The experiment environment in a real world shows in fig. 4.2. A single discal rotator placed at the bottom of the beaker generates the water flow. The dimension of rotator (W/D/H) is 40.0 x 40.0 x 2.0 [mm]. The discal rotator has two cuboids, whose lengths are 10.0 x 40.0 x 2.0, in a cross shape on the top, and embeds two neodymium magnets. The diameter of a magnet is 6.0 mm, and the magnetic flux density is 2,800 Gs. A DC motor with brush whose output is controlled in a real-time by a

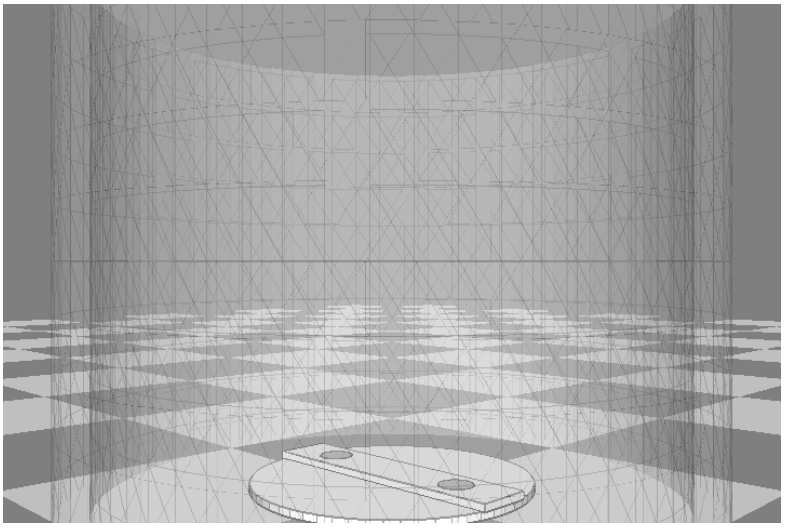


Figure 4.3: The physical model of the rotator and boundary with the same shape and size objects as the real objects.

microcomputer drives the rotation of the rotator. In the experiment environment, the DC motor is controlled in a same way as the simulations. The two kinds of water flows, i.e. steady and unsteady, are tested and the number of twisted are counted indirectly by the images captured by a camera.

4.2.2 Physical Environment in Our Simulation

The boundaries of the beaker and the discal rotator are modeled with the same shape and size objects as the real objects (Fig. 4.3). The rotating speeds of the rotator in the simulation are tuned to realize the same output in the real rotator drived by the microcomputer. Our simulation model computes buoyancy

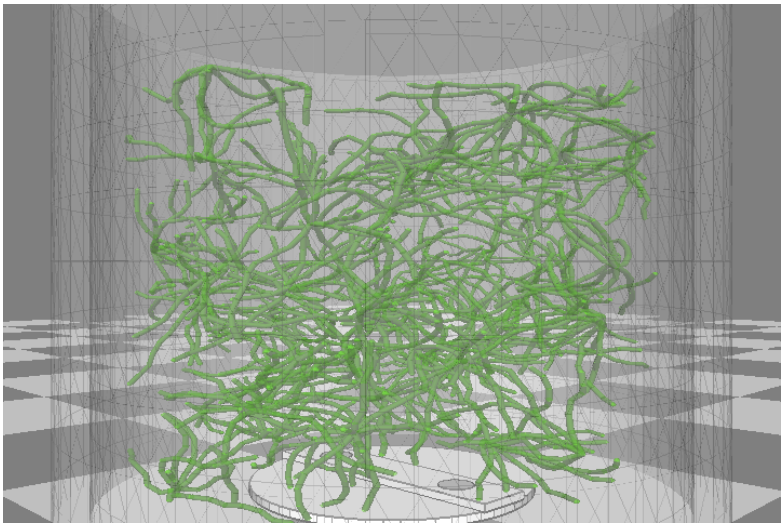


Figure 4.4: A example of the physical model of our simulation environment

F_b and drag force F_d for representing the resistance in fluid, and adopts lattice Boltzmann method, one of numerical fluid analysis for creating the flow field in fluid. The details of the dynamics in our simulation are described in chapter 2. Our simulation model is shown in fig. 4.4.

4.2.3 Evaluation of Twist Formations in a Simulation

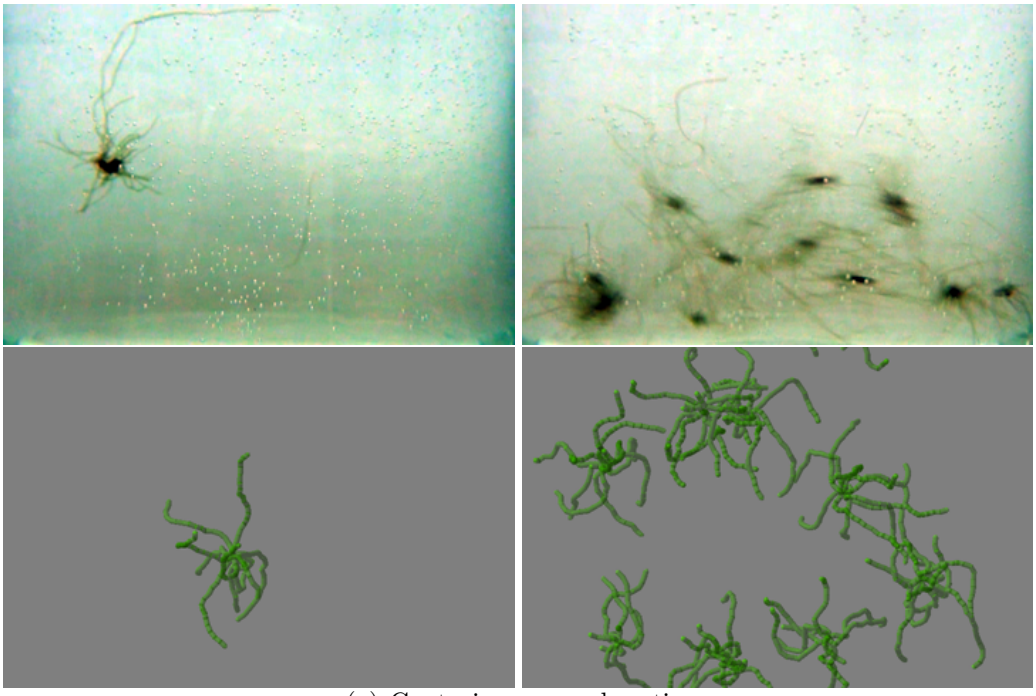
To capture the twist formations in the simulation model is not easy because the formation is not a micro but macroscopic phenomenon. In the developed simulation model we proposed a novel way to detect the seaweed twist formation using a nonlinear support vector machine (SVM). From advance verification, the average numbers of contact between rigid bodies, the average

distance of centroids, and the contact time for a time window DT characterized the twist between two seaweeds in the chapter 2.

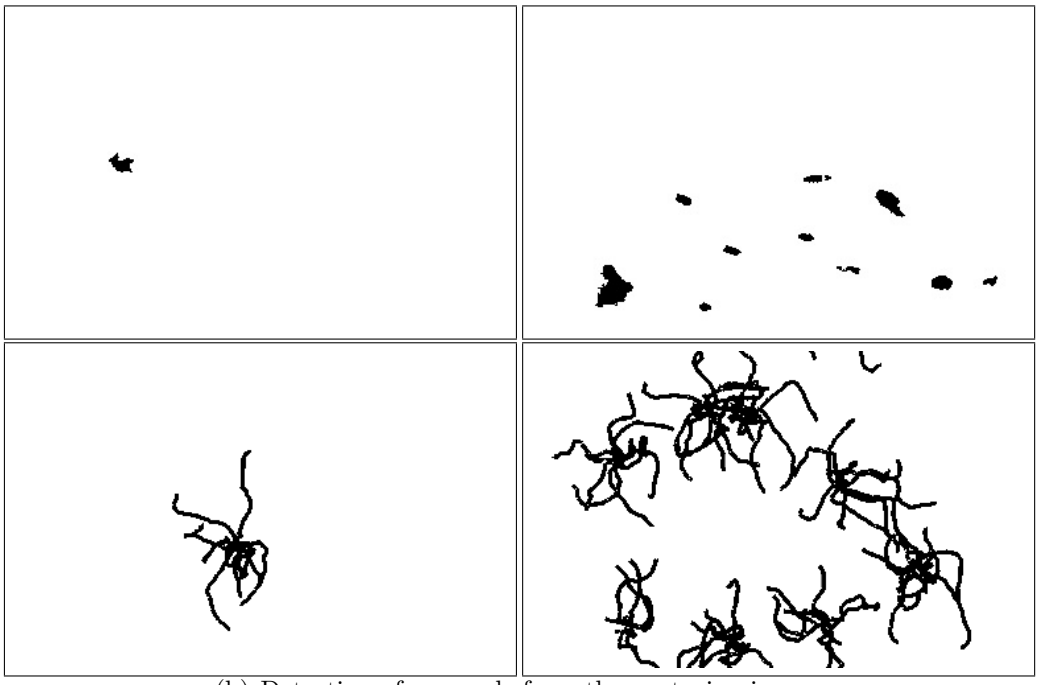
The learning of the SVM is performed using the three dimensional vector of these values and teaching signals which were created by the results of human recognitions. The SVM was able to classify simulated seaweed twists close to human's recognition. The number of twists formation can be counted autonomous in a real-time with SVM in the simulation.

4.2.4 Adequacy Evaluation for Our Simulation

The image processing is applied to compare the results of the real world environment and the simulation model. To be fair for the comparison, the image processing is also applied to the simulation results and our simulation model is evaluated in terms of the twist formations. Fig. 4.5 shows the process of comparing the real world experiment with the simulation experiment based on the detection of pixel area as the twist formations. The first step converts a movie of seaweed motion into a series of successive frame images in a real environment. In cases of the simulated environment, the images are also captured from the same camera view point. Fig. 4.5(a) shows the examples of captured



(a) Capturing seaweed motion



(b) Detection of seaweeds from the capturing images

Figure 4.5: The result of applying our image processing

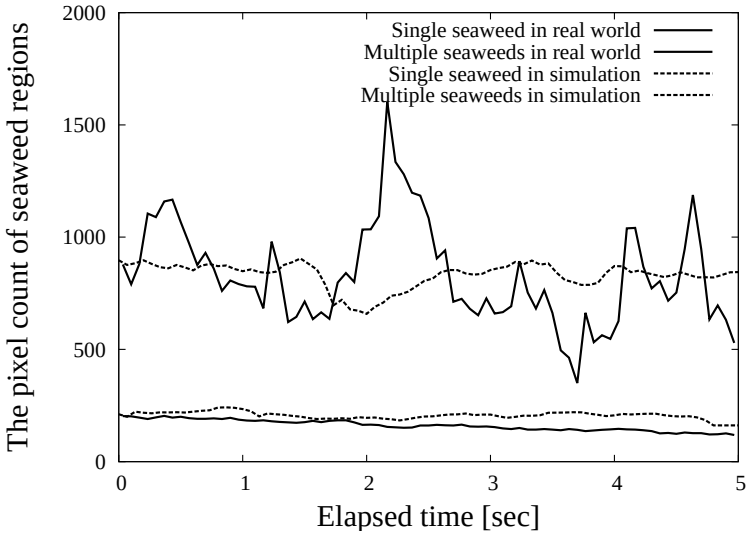


Figure 4.6: The change of the pixel count of seaweed in a simulation and a real world (The black pixels represent the seaweed area)

imageries. The second step calculates the difference of the images between the background image and the captured imageries. Both RGB color images are converted to the gray scale color. The binary images are created from the difference images based on an appropriate threshold to extract the pixel area of the seaweed. The difference image detects a region of twist of seaweed as a connected pixel area. However the image includes the noise from air bubble, vortex, light, and rotator. The trimming operation is executed to eliminate the effect of the vortex and rotator before this step. Additionally, the pixel area is excluded as the environmental noise, mainly caused by the bubbles, if the number of pixels of a single connected area is less than a threshold.

This operation is called “ Connected-component labeling ” in the research field of image processing [WKCS03, SHS03, Sha02, HCSW09, HW90, FPWW03, DST92]. Fig. 4.5(b) shows the result of this process.

In the real experimental environment, a single individual has a twist formed by several string-seaweeds at the center. The green color becomes dense at the center because the seaweeds congest at the twist. The above image processing captures only this parts. It means that the pixel count of the black regions represent the areas of the twist formations. On the hand, the image processing in the simulation captures the whole individual, which causes the increase of the detected areas of twist formations. To reduce the difference, the scale of the areas of the detected twist formations in the simulation is adjusted to the real world results.

Fig. 4.6 shows the comparison of the number of detected pixel counts of a single and ten seaweeds in a simulation and a real world. The scale is already adjusted. As the result, in a case of single, the counts vary in a similar manner in both environments, in a case of multiple, the change tends to be large the difference, however, the average change is similar in both environments. Therefore, the twist formations are properly modeled and scaled,

which can allow us to compare the results of our simulation and a real world.

4.3 Experiment

4.3.1 Summary and Objectives

The number of twists formation can be counted autonomously in a real-time with SVM in our simulation. With the simulation model and techniques, this study analyzes correlation between seaweed twist formations and water flow motions under controlled fluid velocities in order to verify effective water flow characteristics for preventing seaweed twist. The objective of our experiment is to identify the reason for the twist formations when the water flow is steady and to introduce the effective alterations for avoiding the formations into the water flow.

First, we demonstrate that the steady flow cannot detangle the formations and we discuss the reason in terms of the steady flow characteristics and the changes of the number of twist formations in a simulation and a real world. Then, this section describes unsteady flow characteristics to solve the problem and prove the adequacy of our simulation results by applying the characteristics into a real water flow.

4.3.2 Conditions

The steady flow is generated by the rotator rotating at the rate of 500 rpm (rotation per minute). If the rotating speed is too large, it is hard to process the captured images of the moving seaweeds since the deep vortex in the experiment environment emerges as a large noise. The total experiment and simulation time is 60.0 [s], and the rotators keep on driving during the experiment. The dimension of the beaker (W/D/H) is 51.0 x 120.1 x 51.0 [mm].

4.3.3 Twist Formations with a Steady Flow

Fig. 4.7 shows the change in the pixels count of seaweeds and the number of twist formations using the SVM with a steady flow. These results show that the seaweed twist becomes a convergent state under the condition of steady water flow velocity fields, and the steady water flow cannot inhibit the seaweed twists regardless of water flow velocity.

The flow generates a vortex motion in the center of the beaker. The vortex is the swirl flow whose velocity is depending on the distance from the center. The fluid velocity in the circumferential location of vortex shows the fastest velocity within a beaker. On the other hand, the velocity at the point of center of the vor-

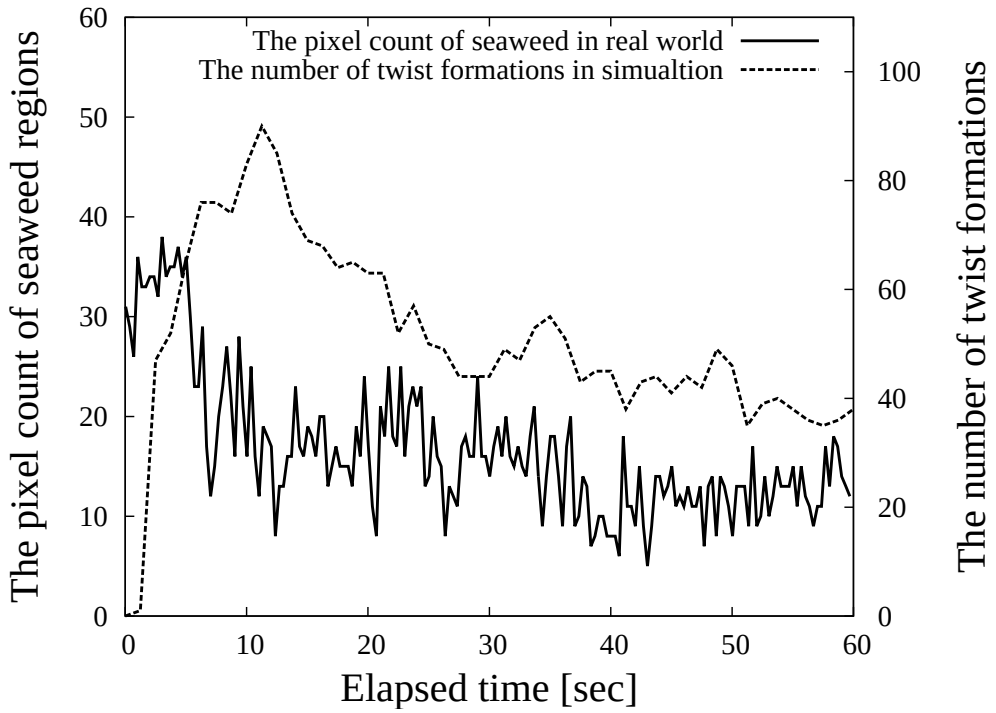


Figure 4.7: The change of the criterions about the twist formations when the state of water flow is steady

tex and the boundary surface is close to zero. Then the difference in pressure by the vortex occurs between inside and outside. The difference generates another circulation flow in vertical direction, however, the flow does not emerge within the vortex. Therefore, the vortex gathers seaweeds toward the center and bottom of a beaker while rotating fast. The twist formation is caused by the vortex flow. Controlling the occurrence of the vortex is an effective way for avoiding the formations. Thus, we verify the effectiveness of unsteady flow that reduces the effect of vortex for inhibiting the formations. In order to prevent the

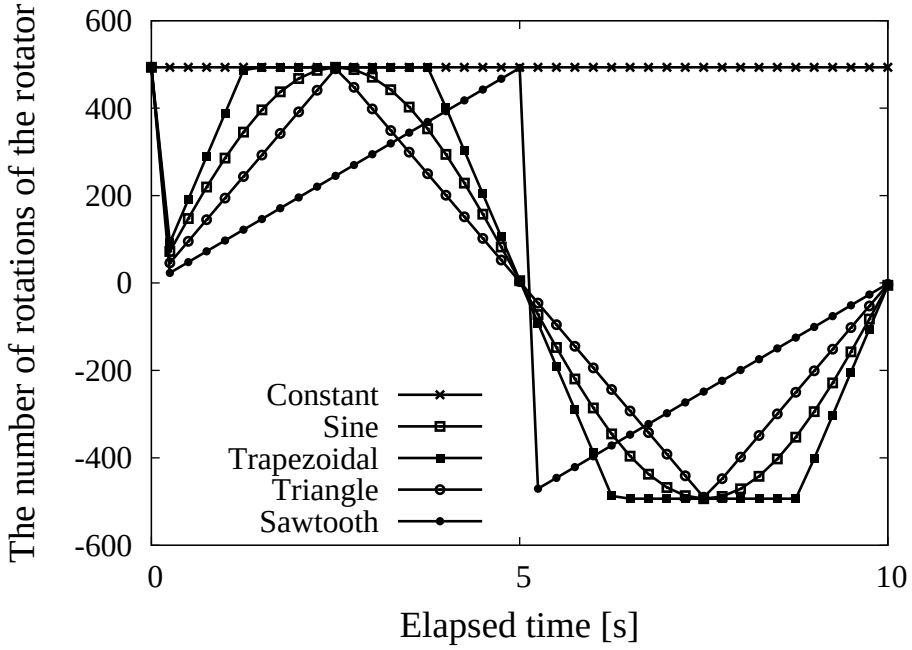


Figure 4.8: The periodic functions for altering water flow

vortex, it is required to decelerate or turn over a velocity of the rotator. When the water flow velocity is low, seaweed settles at the bottom of the beaker or reduces the physical activity.

4.3.4 Effectiveness of Controlling Water Flow

Our study proposes an adaptive way to control the water flow while increasing seaweed's physical activity using five periodic functions for altering the water flow. These functions are shown in Fig. 4.8 and applied to the output function of microcomputer. The controlled water flow repeats to flow back periodically according to the wave shape of sine, trapezoidal, triangle

and sawtooth. The period is set to 10.0 s in our experiment in order to verify the relation of the twist formations between the steady flow and unsteady flow.

Fig. 4.9 shows the comparison results in our simulation and a real experiment environment. From these results, all controlled unsteady water flows show the seaweed twist avoidance is observed more often than the steady water flow. In particular, the water flow of altering the trapezoidal function is the most effective for reducing the twist formations in a simulation. Then, the real world experiment also shows that the water flow of altering the trapezoidal function is also effective. Therefore, the drag force variations produced by the unsteady water flows is possible to alter the convergent state of the twist formation and inhibit the formations. Our experimental results show that our proposed method can inhibit the twist formations even in the real environment.

4.3.5 Frequency Effect of Controlling Water Flow

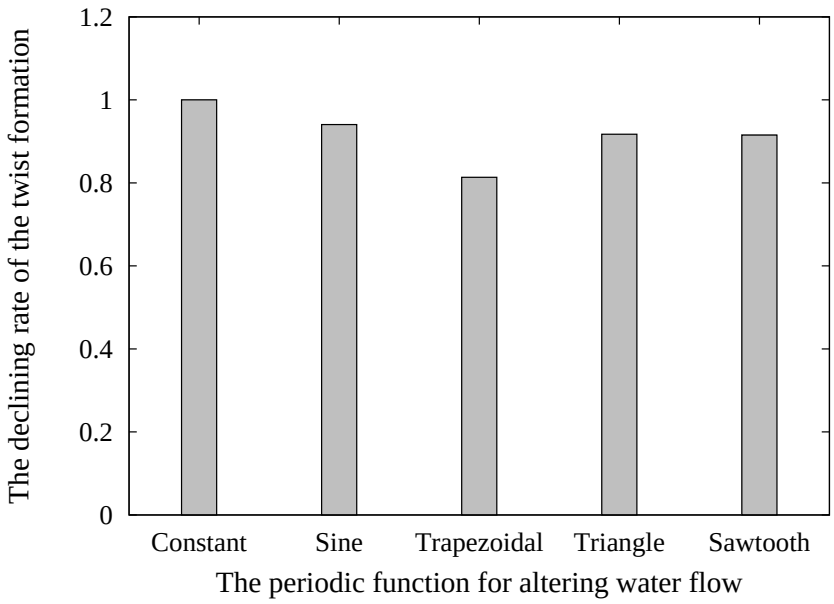
Using the unsteady flow of trapezoidal function that is the best flow in our simulation, we tested frequency effect of the flow period. The set of tested periods is 5.0, 10.0, 15.0, 20.0, 25.0, 30.0 s. The results are shown in Fig. 4.10.

We ascertain that the periodic flow with the short period is effective for inhibiting the twist formations than a steady flows and other unsteady flows. As the period becomes longer, the formation cannot be controlled well since the flow generates the motion of the effect similar to steady flow seaweed. Fig. 4.11-4.12 shows the comparison of transition of the seaweed motion between the optimal flow and the steady flow in this real experiment. From the result, our experimental results show that our proposed method can inhibit the twist formations even in the real environment by the seaweed motion reduces the risk of the twist formations from the vortex.

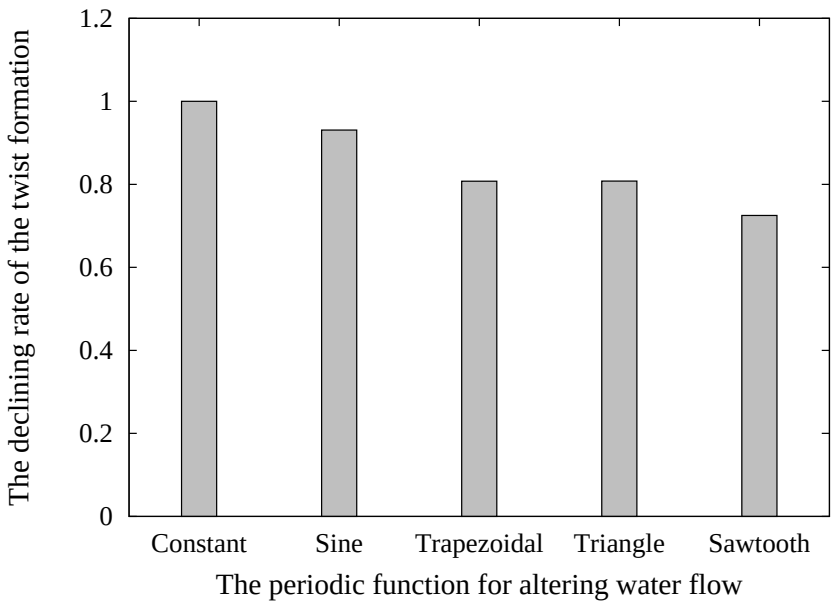
4.4 Conclusion

We established a way of controlling the twist formations applying the periodic function of short period. The experimental results also show that the twist formation as the macroscopic phenomena is properly modelled and captured by SVM in our simulation. Our simulation method must be useful to find a more effective control method to inhibit the twist formations. This chapter acquired the finding of the reason of forming the seaweed twist and established the controlling of water flow for

inhibiting the formations. Additionally, we proved the adequacy of our simulation in a viewpoint of the representation of the twist formations from the experimental results.

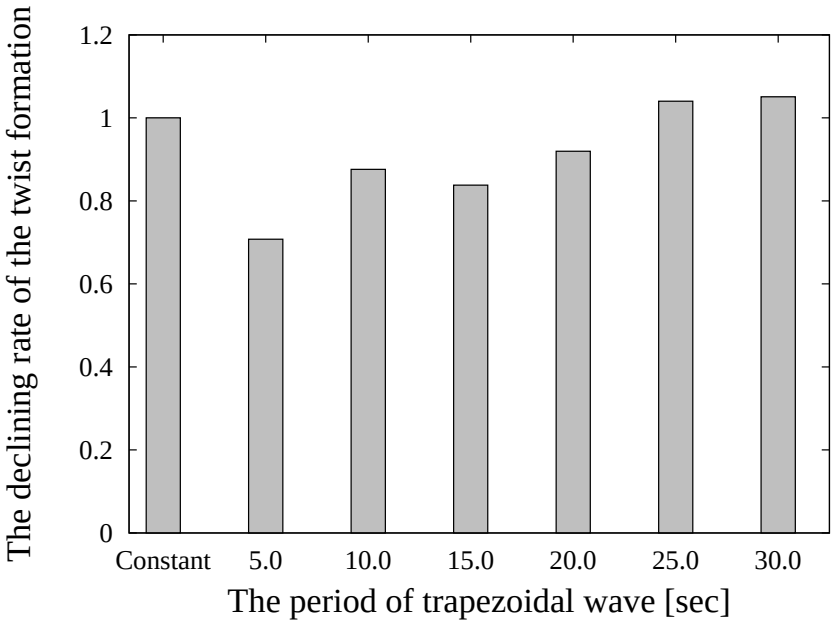


(a) The declining rate of the twist states in our simulation

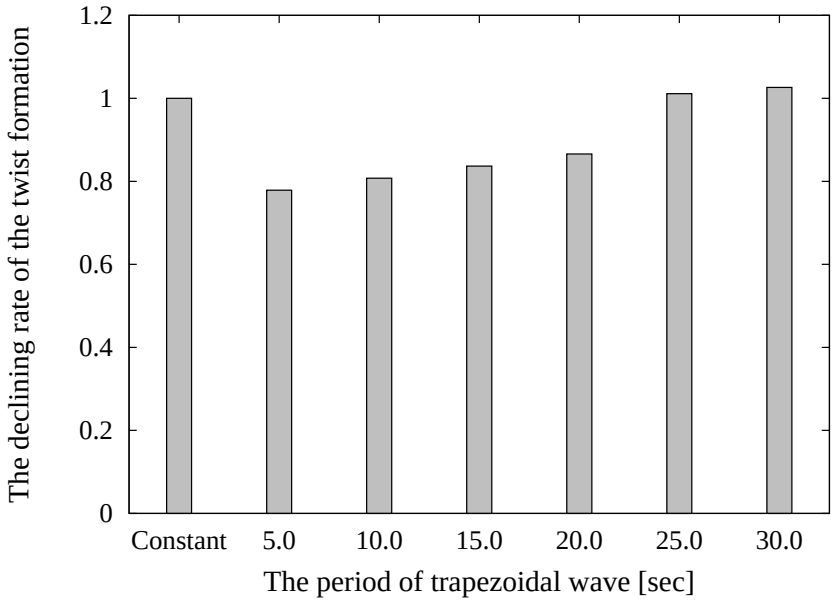


(b) The declining rate of the twist pixels in a real world

Figure 4.9: The comparison results of the declining rate of the twist states in our simulation and a real world: These results show inhibiting the twist formation among five wave-shaped water flows.

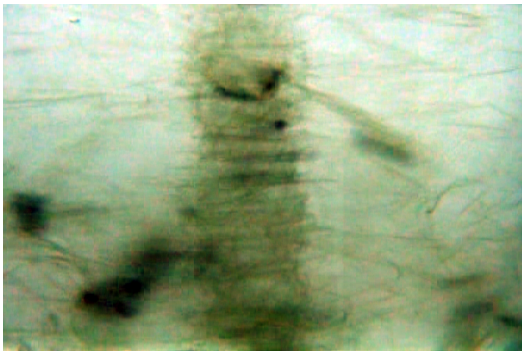


(a) The declining rate of the twist states in our simulation

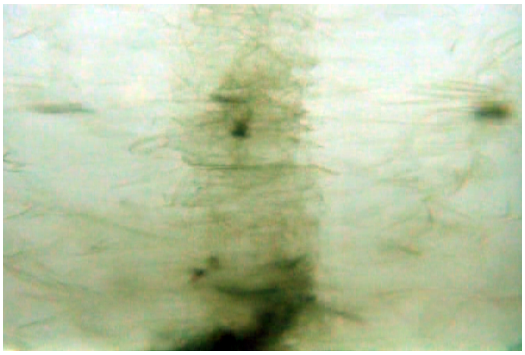


(b) The declining rate of the twist pixels in a real world

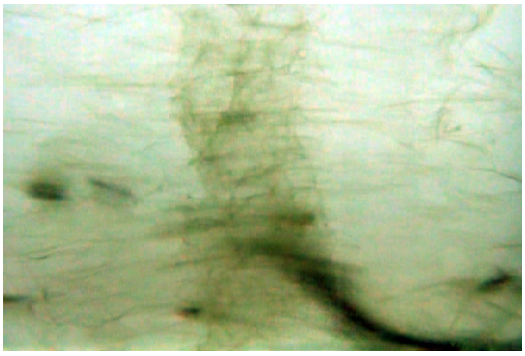
Figure 4.10: The comparison results of the declining rate of the twist states in our simulation and a real world: These results show inhibiting the twist formation among six period of the trapezoidal wave and constant.



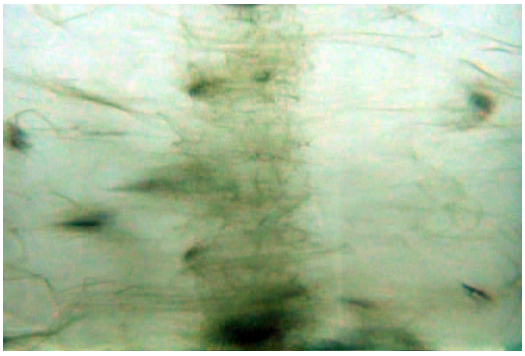
(a) t = 30.0



(b) t = 40.0

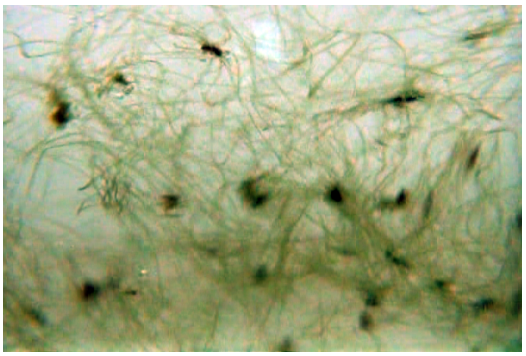


(c) t = 50.0

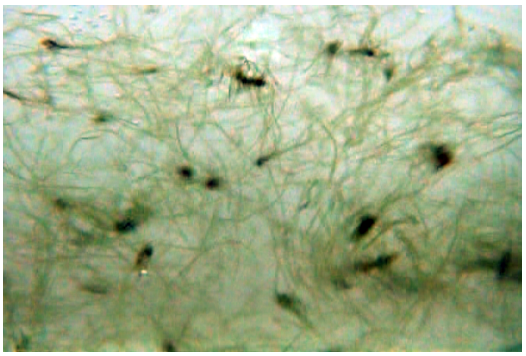


(d) t = 60.0

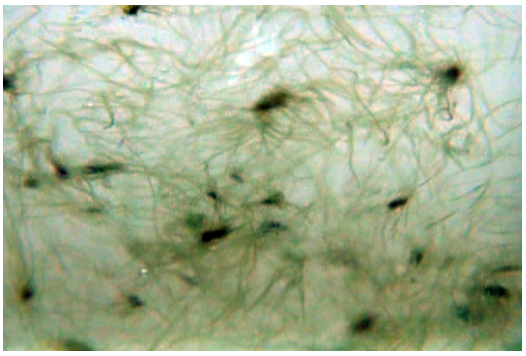
Figure 4.11: The motion of seaweeds with a steady water flow (t = 30.0, 40.0, 50.0, 60.0)



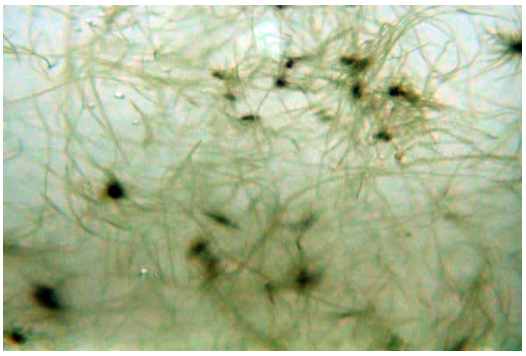
(a) t = 30.0



(b) t = 40.0



(c) t = 50.0



(d) t = 60.0

Figure 4.12: The motion of seaweeds with an unsteady water flow using the trapezoidal function (, whose period equals to 5.0 sec and t = 30.0, 40.0, 50.0, 60.0)

Chapter 5

Conclusion

In Chapter 1, we introduced our study background and the conventional researches in the field of seaweed cultivation. Additionally, we explained the place of our study and described our challenges and objectives.

In Chapter 2, we proposed the modeling of seaweed twist formations as the foundation of our study. This modeling is implemented by considering the seaweed shape, population, dynamics computation in fluid based on physics engine. From the simulation results, our simulation model creates the natural seaweed twist formations based on the physical interaction among seaweeds. Additionally, we proposed the innovative way to quantitative evaluate the formations using nonlinear support vector machine. This way showed the high accuracy of automatic classification of the formations as a human's recognition.

This chapter established a methodology to solve the challenges in the field of seaweed cultivation from a viewpoint of physical simulation.

In Chapter 3, we proposed an analysis method to estimate the happening of the seaweed twist formations with a time evolution. This method considers the seaweed twist formations as one of physical interactions through a contact between two seaweeds, and we represented the relation of the interactions using our quantitative criteria of the formations as the interaction networks. To analyze the dynamic link structure, we proposed two analysis methods based on the diffusion kernel matrices as the method to estimate the formations in future. Our method showed high performance than a conventional method and is able to estimate the happening of the seaweed twist. This chapter established an analysis method for connecting the information processing and controlling of the seaweed twist in the field of seaweed cultivation and others.

In Chapter 4, we introduced the application and adequacy of our simulation model. This chapter constructed an actual experiment environment for stirring the "Green laver", and modelled the physical model in a virtual space as a same object of the real world. In order to verify the adequacy of the experiments

in our simulation and a real world, this study captured images of motion of seaweeds by position fixed camera. From these images, we proposed the way to detect the seaweed twist region in an image and showed that the pixels of region vary in a similar manner in both environments. These results showed that the twist formations are properly modeled and scaled, which can allow us to compare the results of our simulation and a real world. Additionally, this study found that a vortex in a water environment is major caution of happening of the seaweed twist formations from the stirrer experiment with a steady water flow, and we explained that a steady flow cannot detangle the formations. Then this study proposes an adaptive way to control the water flow while increasing seaweed 's physical activity using periodic functions for altering the water flow. This way acquired the effective performance for inhibiting the twist formations. Finally, we tested frequency effect of the flow period using the unsteady flow of trapezoidal function that is the best flow from the verification. From the result, we demonstrated that our proposed method can inhibit the twist formations even in the real environment by the seaweed motion reduces the risk of the twist formations from the vortex. This chapter ascertained the caution of the twist formations and established the

controlling of water flow that is able to inhibit the formations.

Finally, we summarize this thesis with some remarks and gives some directions toward the future work. In this thesis, we propose a simulation foundation of seaweed motion analysis. Our simulation represents some natural twist formations and evaluate the formations. These results mean that the challenges of the twist formations in many research fields is analyzed by using a computer. Then the thesis established a water flow control methodology for inhibiting the twist formations. To overcome this issue, we have to discuss about general versatility from the point of view of other type of seaweed and the difference of growth process. The followings are the rest as some challenges in a future work.

1. Analyzing a twist formation mechanism mathematically for the other shaped seaweeds.

2. Applying the water flow control to seaweed motion in the different growth stage.

3. Analyzing an effect of growth of seaweeds when seaweed cultivation controls water flow for a long time.

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