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Artificial Flying Creature by Flapping

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***Abstract*—This paper proposes an artificial flying creature by flapping in a virtual air environment obeying physics law. For this purpose, a concise air drag computation method is introduced. The air drag plays the role of the environment force against the creature. The motion of the creature is automatically computed by use of the physics modeling software system and visualized as an animation movie. Results show that the creature with several pair of wings can fly by flapping as "a life as it could be".**

***Keywords*—artificial life, air drag, physics modeling, flying**

I. INTRODUCTION

Studies on virtual creatures and their behaviors' acquisition have been attracted since the beginning of 1980.

Terzopoulo and et al. [1] made the short movie film of the artificial fish, which seemed to be a real fish. Their fish is modeled by springs and sensors, and its motion is determined by a few rules and by solving the second order differential equation. Their work was so impressive at that time. However, it was not taken account of the fish environment, namely the effect of water drag. K. Sims et al. [2] exampled swimming of various artificial lives. They propose a mainframe work for the artificial life to acquire its proper behavior. They adopted an artificial neural network (ANN) to control the fish behavior, and an evolutionary computation method that the ANN can output proper behavior signals. Swimming is simulated based on physics modeling and its result is instantly animated as a movie. Although the swimming behavior they showed seems to be real, it is not clear if they considered the water environment. Their work for which they adopted physics modeling is worthy of remark. K. Sims work has been still followed up [3].

C. Reynolds [4] proposed a model of "flock of flying birds". His birds' model is named "Boids". Boids assumed three forces for the crowd, such as separation, alignment, and cohesion. Separation is the steer force to avoid crowding local flockmates, alignment is the steer force towards the average heading of local flockmates, and cohesion is the steering force to move toward the average position of local flockmates. He successfully made the short movie film of flock of flying birds. However, his birds did not use the air drag and buoyancy, and lifting force. Defined three forces were only used for flocking.

This study proposes a modeling and simulation method for an artificial flying creature (AFC) as A-life. AFC is put in the fluid environment, especially in the air environment. Therefore, the environment must be a field obeying the physics law and has an effect on AFC. Motion of AFC is computed by use of physics modeling in consideration of the air environment under the physics constraint and it is simulated by animation at the same time. Therefore, flying locomotion must be computed as fast as possible.

Several methods have been developed to figure out the fluid effect in the field of mechanical engineering. These methods essentially solve the Navier-Stokes differential equation. In most of cases, the finite element method (FEM) and the finite difference method (FDM)[5] are employed to accurately solve it with voxels. Because the number of voxels is huge, they consume a lot of computing resources. It is said that it takes four to seven minutes per frame [6] for visualization. Also, the moving particle system method (MPS) [7] has been recently used for the fluid simulation in a field of computer graphics. As well as FEM and FDM, MPS is a time-consuming method because it needs a lot of particle elements to solve the fluid effect. These time-consuming methods are not suitable for doing research for A-life and simplifications are needed to be able to do simulation in any reasonable amount of time, since we need on-line simulation. We prefer solving the fluid effect qualitatively to solving it accurately if the obtained results are practical enough.

The rest of this paper is constructed as follows. Section Two describes three forces, the gravity, the buoyancy and air drag to make the air environment in physics modeling. Section Three explains how to model flying with gliding and flapping locomotion for an artificial creature in the constructed air environment by using Newtonian equation. In Section Four, numerical experiments for flying are shown. Then, we describe composite flying consisting of gliding and flapping in Section Five. Finally, our work is summarized in Section Six as conclusion.

II. MODELING AIR ENVIRONMENT

In the air environment, an object is affected by the gravity, buoyancy, air drag, and lifting force. The lifting force causes when the object is flying in the air with high-speed like an airplane. As a creature cannot have power to fly with such high-speed, we do not deal with flying with high speed. Also, it is reported the fluid vortex has the effect on insect flying [8]. This effect causes when an insect flaps it wings with high-speed. Our creature is not assumed to flap with such high-speed as well. Thus, the air environment concerns on the gravity, buoyancy, and air drag in our model.

A. Physics modeling

Physics modeling is adopted to achieve flying simulation of an artificial creature. PhysX offered by NVIDIA [8] is used to solve the differential equation for flying locomotion. PhysX can deal with the gravity, friction, collision, and solving the rigid body motion. So, we add the buoyancy and air drag, which are given in the air environment.

B. Buoyancy and air drag

The buoyancy is added to physics modeling. It is defined as a force directed to the mass center of a rigid body by (1),

$$F_b = -\rho_a V g \,. \qquad (1)$$

F_b, ρ_a, V, and g are the buoyancy, the density of rigid body, the volume of rigid body, and the gravity, respectively. Because AFC density is much heavier than the air density, it is possible to neglect the buoyancy in the air.

An empirical equation has been used for the air drag to design a wing in the fluid engineering and is expressed by (2),

$$F_d = \frac{1}{2}\rho_a C_d S U^2 \qquad (2)$$

F_d, S, U, and Cd are the air drag, the representing surface area of the wing, the relative velocity of the wing, and the drag coefficient, respectively. The air drag works at the center of gravity. In applying (2) to the rigid object, the air drag is calculated for only the surface facing to the direction of the velocity, where this surface becomes the representing surface. We divide the representing surface into n-pieces of surface (sub-surfaces) to calculate the air drag more practically. Then, equation (3) is used to calculate the air drag for the i-th sub-sub-surface.

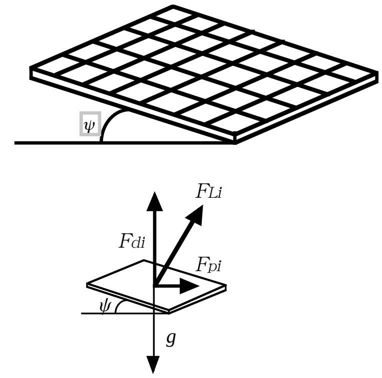


Figure 1. The air drag for gliding

$$F_{d\,i} = \frac{1}{2}\rho_a C_d s_i u_i^2 \;(i = 1,2,...n)\,. \qquad (3)$$

s_i and u_i are the i-th sub-surface area and relative velocity, respectively.

III. FLIGHT BY GLIDING AND FLAPPING

Based on (3), Newtonian physics models for flying by gliding and flapping are formalized.

A. Gliding

Gliding is that an object is falling from some height position to the ground. However, when the object is initially set without tilting, gliding will not cause. Let us consider a thin plate put with some tilted angle in the air as shown in Fig. 1. The lower surface of the plate becomes the representing surface. Then, this surface is divided into n sub-surfaces. When the plate is dropped, the relative velocity u_i in dt seconds at the center of the i-th sub-surface becomes (4),

$$u_i = g dt \,. \qquad (4)$$

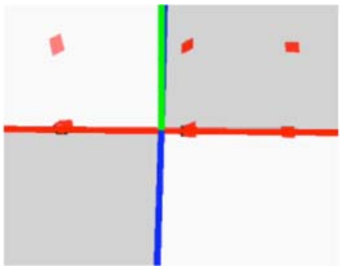
g is the gravity. By substituting (4) into (3), the air drag F_{di} is obtained as

$$F_{d\,i} = \frac{1}{2}\rho_a C_d s_i (gdt)^2 \;(i = 1,2,...n)\,. \qquad (5)$$

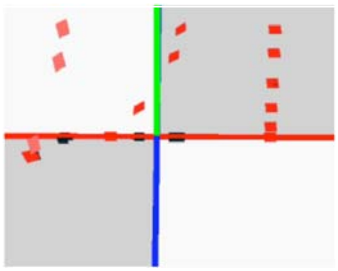
Then, we have the lifting force F_{li} as

$$F_{l\,i} = \frac{1}{2}\rho_a C_d s_i (gdt)^2 \cos\varphi \;(i = 1,2,...n)\,, \qquad (6)$$

φ is the angle of the plate tilted downward. This lifting force makes the moving force, F_{pi}, horizontally expressed by (7),



(a) Falling plates when the air drag is not given. Plates falls down vertically to the same place



(b) Falling plates affected by the air drag

Figure 2. Falling plates from views of different angls

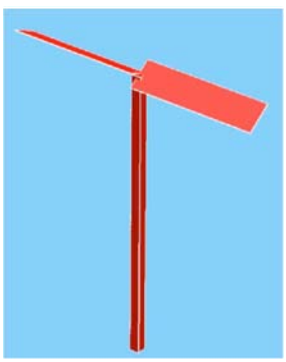


Figure 3. A bamboo-copter model

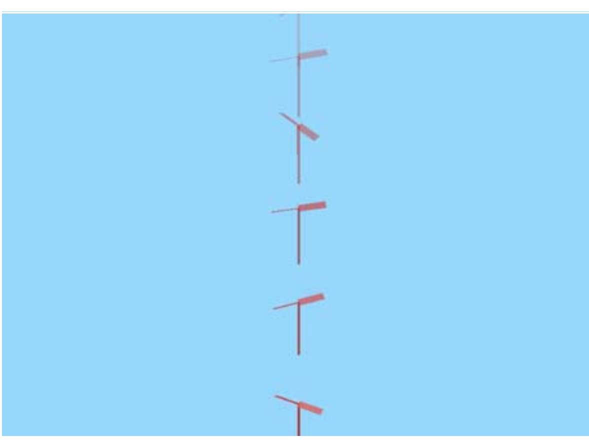


Figure 4. Bamboo-copter flight simulation

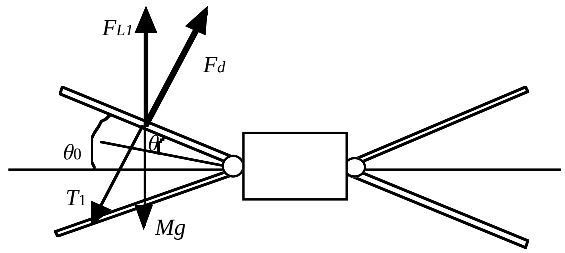


Figure 5. A flapping unit model

$$F_{pi} = \frac{1}{2}\rho_a C_d s_i (gdt)^2 \cos\varphi sin\varphi \ \ (i = 1,2,...n). \qquad (7)$$

If the plate has some initial velocity in the horizontal direction when it drops, the moving force, F_{pi}, horizontally becomes slightly different. However, it is possible to calculate it in the same principle. The gliding distance can be controlled by the angle φ and the initial velocity.

Fig. 2 shows physics simulation. In Fig. 2 (a), the plates are put in the air without the tilted angle. In Fig. 2 (b), the plates are put with some tilted angle. The gliding (falling) phenomenon is observed.

We apply our air drag computation method to the bamboo-copter (the famous Japanese children toy). A model of the bamboo-copter is shown in Fig. 3. Two wings are set in the opposite direction each other at the top of a pole. They are tilted slightly in the opposite direction each other as well. When the pole of the bamboo-copter is rotated, the reference velocity is given to the wing and the air drag to the wing shown in (5) arises. Then, the air drag makes the lifting force shown in (6). In this way, the bamboo-copter is forced to move upward. However, the rotation speed becomes gradually slow and the rotation stops soon. As soon as the bamboo-copter stops rotating, it begins to rotate in the opposite direction. This is because the air drag arises in the same principle expressed by (4) and (5). The bamboo-copter flight can be easily simulated by the proposed method. Fig. 4 shows a snapshot of the flight simulation.

B. Flapping

We deal with a simple unit for the flight of flapping as shown in Fig. 5. This unit consists of a body and two flat plates (wings). The wing is swung downward and upward alternatively between $2\theta_0$. The representing surface of the wing (the plate) is divided into n sub-surfaces as well. Two wings are joined with the body by joints with one freedom. Let us consider that the wing is swung downward from the most upper position to θ with the angular velocity ω_1. Then, the torque at the center of gravity of the sub-surface works, written by

$$\begin{aligned} T_{1i} &= m_i r_i^2 \dot{\omega}_1 \\ &= F_{1i} r_i \ \ (F_{1_i} = m_i r_i \dot{\omega}_1). \end{aligned} \qquad (8)$$

where m_i, r_i, and F_{1i} are the mass of the sub-surface, the distance from the joint to the center of gravity of the sub-surface.

Let I, M, T_1, and r be the inertia of the wing, the mass of the wing, the given torque of the wing, and the distance between the center of gravity of the wing and the joint. Then, the moment at the center of gravity of the wing around the joint is written by

$$\begin{aligned} I\frac{d^2\theta}{dt^2} &= \sum_{i=1}^{n} m_i r_i^2 \dot{\omega}_1 + \sum_{i=1}^{n} mgr_i \cos(\theta_0-\theta) \\ &= T_1 + Mgr\cos(\theta_0-\theta) \\ &= Mr^2\dot{\omega}_1 + Mgr\cos(\theta_0-\theta). \end{aligned} \tag{9}$$

By integrating (9) on θ, we have

$$\frac{1}{2}I\omega_d^2 = \frac{1}{2}Mr^2\omega_1^2 - Mgrsin(\theta_0-\theta) \tag{10}$$

where

$$\omega_d = \frac{d\theta}{dt}. \tag{11}$$

The air drag F_d against the wing is expressed by

$$\begin{aligned} F_d &= \frac{1}{2}\rho_a C_d S U_1^2 \\ &= KU_1^2 \end{aligned} \tag{12}$$

where U_1 is the velocity of the wing and expressed by

$$U_1 = r\frac{d\theta}{dt} = r\omega_d. \tag{13}$$

By substituting ω_d^2 into (13), we have

$$F_d = 2Kr^2\left[\frac{1}{2}Mr^2\omega_1^2 - Mgrsin(\theta_0-\theta)\right]/I^2 \tag{14}$$

The upward lifting force F_{L1} is obtained as

$$\begin{aligned} F_{L1} &= F_d\cos(\theta_0-\theta) \\ &= 2Kr^2\left[\frac{1}{2}Mr^2\omega_1^2 - Mgrsin(\theta_0-\theta)\right]\cos(\theta_0-\theta)/I^2. \end{aligned} \tag{15}$$

In the same way, we have the downward lifting force F_{L2} as (16) when the wing is swung up.

$$F_{L2} = 2Kr^2\left[\frac{1}{2}Mr^2\omega_2^2 + Mgrsin(\theta_0-\theta)\right]\cos(\theta_0-\theta)/I^2. \tag{16}$$

where ω_2 is the angular velocity of the wing swung upward from the most lower position to θ .

Since the workload done by swinging the wing downward and upward the wing is equal to the potential energy that the unit is lifted up by the height, h, from the initial position, we have

$$\int_0^{2\theta_0} 2(F_{L1} - F_{L2})d\theta = (M_0 + 2M)gh. \tag{17}$$

in swinging two wings, where M_0 and h are the mass of body and the height that the unit obtains. By solving (17), the following relation

$$4KMr^4(\omega_1^2 - \omega_2^2)sin\theta_0 / I = (M_0 + 2M)gh \tag{18}$$

is obtained. Therefore, the obtained height becomes

$$h = \frac{4KMr^4(\omega_1^2 - \omega_2^2)sin\theta_0}{I^2(M_0 + 2M)g}. \tag{19}$$

If our unit flies up, the height h must be positive. Thus, we have the relation (20) for flying.

$$\omega_1 - \omega_2 > 0. \tag{20}$$

For the flight by flapping, inequality equation (20) means that the wing is swung down fast and up slightly slowly The obtained result is so simple and so important.

IV. Flight Simulation by Flapping Based on Physcs Modeling

Physics modeling is used to solve the motion equation. For the flight of flapping, we only construct the air environment, which generates the buoyancy and air drag. However, it becomes necessary to keep the creature body parallel with the horizontal line. Even though the angular velocity of the left wing is equal to one of the right wing, the body loses a balance. This happens because small errors are accumulated in solving the motion equation. This section describes how to control the body balance, and then some results of the flight simulation by flapping are shown.

A. *Controlling the Body*

An artificial neural network (ANN) and a genetic algorithm (GA) are applied to control the body balance.

Two ANNs are used for the unit model shown in Fig. 6 and each is set to a joint between the body and a wing. The ANN consists of three layers, namely, two neurons in the input layer, two neurons in the hidden layer, and two neurons in the output layer. Two signals are given to the first layer. One signal is the inner product of the vertical vector and the forward locomotion vector. Another one is the inner product of the vertical vector and the wing direction vector. Two signals are output from the third layer. One is the angular velocity to control the right wing for swinging downward. Another is one to control the left wing for swinging down, too.

Figure 6. A unit model of AFC

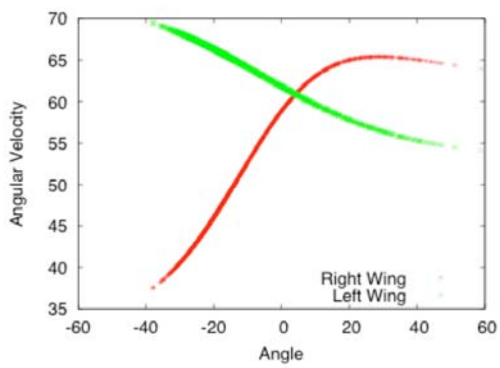


Figure 7. The right and left angular velocities obtained by the best individual

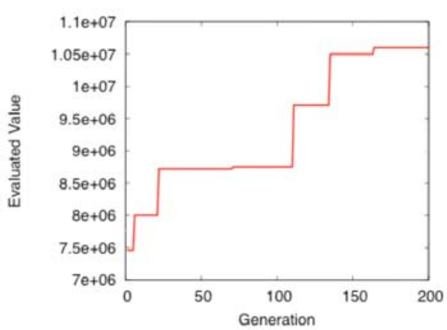


Figure 8. The transition curve of the fitness function along generation

The real number coded GA (RCGA) is used to determine adequate synapses in the ANNs. A fitness function adopts the accumulated height. The number of individual is ten. The elite preserving strategy and the rank selection are used for reproduction. The mutation rate and crossover rate are 0.05 and 0.1, respectively. The procedure is terminated when the number of generation reaches two hundred. Fig. 7 shows the angular velocities of the right and left wings on the best individual. When the angular velocity of the right wing is large, the angular velocity of the left wing is small. The opposite is approved as well. Fig 8 shows transition of the fitness function.

B. Flight Simulation of Artificial Flying Creature with Plural Wings

By jointing units shown in Fig. 6, the flight of AFCs with one, four, six, and twelve pairs of wings are simulated by use of ANN controllers obtained in the previous section. Joints used for AFC models have one-degree freedom. Figs. 9, 10, 11, and 12 are snapshots that AFCs with one pair, four pairs, six pairs, and twelve pairs of wings respectively are flying. Fig. 13 shows a snapshot that AFCs with two wings are flying in flocking.

V. DISCUSSION

The average pressure obtained by the proposed drag computation method is examined. We compare it with one obtained by FEM. Fig. 14 shows the velocity distribution computed by FEM when a rectangular shape object is set in stationary flow.

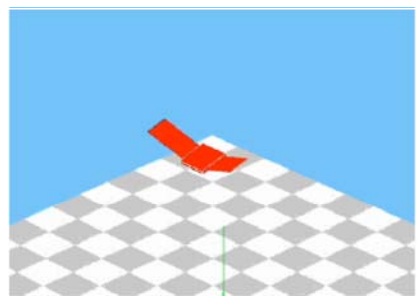


Figure 9. Two wings AFC

Figure 10. Eight wings AFC

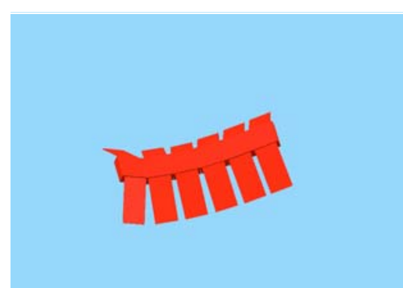


Figure 11. Twelve wings AFC

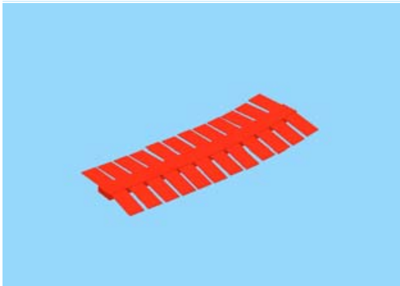


Figure 12. Twenty four wings AFC

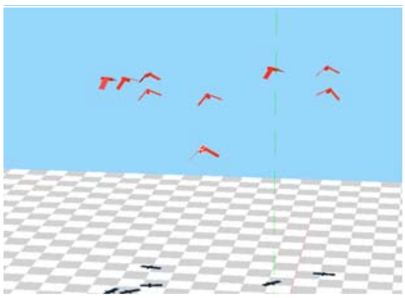


Figure 13. A flock of two wings AFC

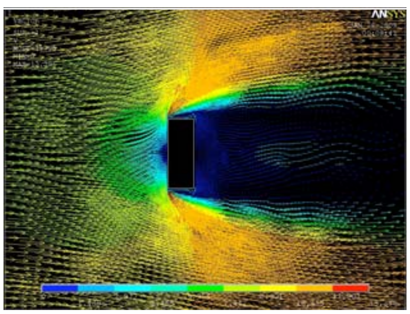


Figure 14. Velocity distribution by FEM

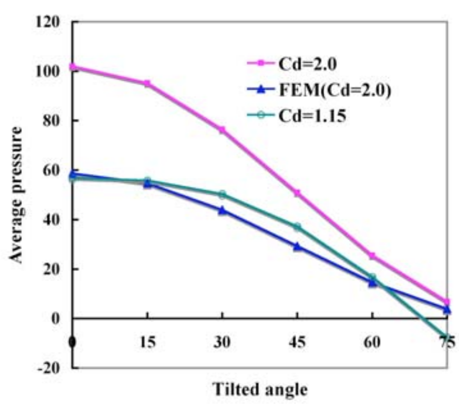


Figure 15. Pressure comparison between FEM (Cd=2.0) and the proposed method (Cd=2.0 and 1.15)

Fig. 15 shows a comparison of the averaged pressure against the stationary flow in inclining the object to every 15-degree in CCW. In experiments, $Cd = 2.0$ is set for FEM. $Cd = 2.0$ and 1.15 are set for the proposed method. The results show that the average pressure of the proposed method set by $Cd = 1.15$ fits one of FEM set by $Cd = 2.0$. This means that it is necessary for the proposed method to adopt Cd smaller than one given by a fluid mechanics textbook.

VI. Conclusion

In order to do research an artificial flying creature, a concise air drag computation method is proposed. The proposed method is based on the empirical method, which is used in mechanical engineering. It is prepared for the air environment. Two flying methods, gliding and flapping, are easily formalized. However, it is not necessary to calculate formalized equation directly. We only produce the air drags against sub-surfaces, into which the representing surface is divided, using the relative velocity. Physics Modeling can yield the relative velocity and solve motion equations. It is possible to apply the proposed method to the flight of feathering.

Advantage of the proposed method is that the computation method is concise and computation time for the flight simulation is so fast. To design controllers, evolutionary computation strategy, for instance the real-coded genetic algorithm, is employed. This is the time-consuming strategy. If we use other methods and solve the Navier-Stokes differential equation, one frame for a short movie may takes some minutes. Other methods are not suitable to do research for the artificial creature.

We have already attempted to apply the proposed method to other models. Such models are controlling wings separately, and flying the artificial creature by composing of gliding, flapping, and feathering. The same principle can be applied to make a water environment as well.

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