Redesign of Cartesian Diver for Underwater Expression Combining Dynamic Fabrication with Non-Contact Manipulation

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Abstract. In this study, we aim to combine dynamic fabrication with non-contact manipulation system applying the mechanism of Cartesian Diver. To achieve this, we propose the design method for underwater objects and non-contact manipulation technique using water pressure with PID control. We successfully designed and manipulate the object by our method. We discussed the principles and methods to create a digitally designed and fabricated the diver and to stabilize it in the middle of water.

Keywords: Dynamic Fabrication; PIDcontrol; Cartesian Diver; Underwater

1 Introduction

Cartesian Diver is known as a toy which swims up and down underwater. The diver is often used as demonstration of Pascal's law and Archimedes's principle. It uses the change of water pressure and specific structure to swim objects underwater situation. In this paper, we computationally design the diver in the context of dynamic fabrication and non-contact manipulation. Thus, this work expands the expressions of underwater entertainment situation such as aquarium or theme park.

Dynamic fabrication is one of the widely spreading research topic in Human Computer Interaction (HCI) communities. Some dynamic fabrication studies, for example, balanced models [8], spinnable objects [1] and floating objects [13], are proposed. More recently, Prévost et al. presented a bistable balanced object using movable embedded masses [7]. This study is one of example which enhance the degree of freedom in dynamic fabrication. Moreover, there are some methods adding controllability to fabricated objects using non-contact manipulation systems; controlling magnetic field [5], acoustic field [6] or air jets [4].

In this work, we aim to combine dynamic fabrication with non-contact manipulation system applying the mechanism of the diver. Our contributions are

- to propose the design method for underwater objects,
- to propose the non-contact underwater object manipulation method and implementation and
- to conduct quantitative evaluation about relationship between parameter of fabrication and stability of manipulation.

2 Related Work

2.1 Fabrication

In HCI communities, optimization algorithms and digital fabrication techniques are frequently used for adding controllable physical properties to the real-world objects. These methods are applied to various targets, such as musical instruments [12][11], mechanical toys [2][14][15], and toys-redesigning [9][10].

Prévost et al., Bächer et al., and Wang et al. applied voxel carving for controling the center of mass to balancing objects [8], spinnable objects [1] and floating objects [13]. Moreover, Prévost et al. presents a bistable balanced objects using embedded movable masses [7]. In this study, we combined underwater non-contact manipulation system with dynamic fabrication for adding spatial controllability to underwater objects.

2.2 Manipulation

The methods to control the real-world objects are categorized into two types. Putting actuators inside the objects or actuating their surroundings such as air or water. The latter method is also divided to two ways; contact or non-contact.

Follmer et al. proposed contact manipulation system using shape-changing display [3]. Examples of non-contact manipulation include magnetic field [5], acoustic field [6], and air jets [4].

In this study, we introduce underwater non-contact manipulation technique using water pressure with PID control.

3 Design Method

To design a 3D model to function as the diver, we define four fundamental requirements. To swim up and down underwater situation, the diver

1. has to float when you put it into a water tank and
2. is necessary to have a hole which water enters into it when water pressure is applied to the water tank.

To make the diver swim with the correct orientation which defined by the designer,

3. the hole is located on the same vertical line with center of gravity and
4. rotation moments should not be occurred.

We formulated these requirements for applying them to digital fabrication system. Requirements 1. and 2. are formulated as:

$$\boldsymbol{F_G} + \rho_w V_{max} \boldsymbol{g} > \boldsymbol{F_B} > \boldsymbol{F_G} \quad (1)$$

where $\boldsymbol{F_G}$ is the gravitational force on the object and $\boldsymbol{F_B}$ is the upward buoyancy force. V_{max} is maximum volume of water that our setup can apply to the diver, ρ_w is water density and g is gravitational acceleration. Also, requirements 3. and 4. are formulated as:

$$\boldsymbol{C_B} \times \boldsymbol{F_B} = \boldsymbol{C_G} \times \boldsymbol{F_G} \quad (2)$$

where $\boldsymbol{C_G}$ is the center of gravity and $\boldsymbol{C_B}$ is the center of buoyancy. Figure 1 shows our design method overview.

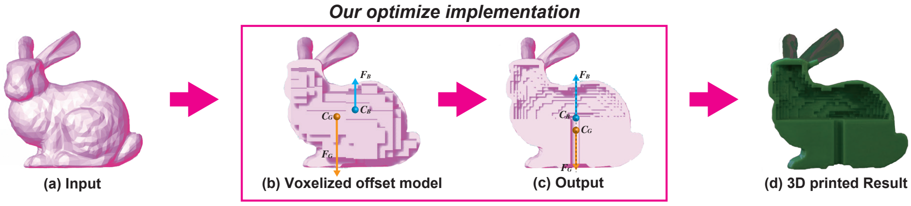

Fig. 1. Overview of our design method to create the Cartesian Diver. (a) First, we prepare a solid model as input. (b) Second, offset the model and voxelize it. (c) Then, apply voxel carving algorithm and (d) the model is 3D printed as the diver.

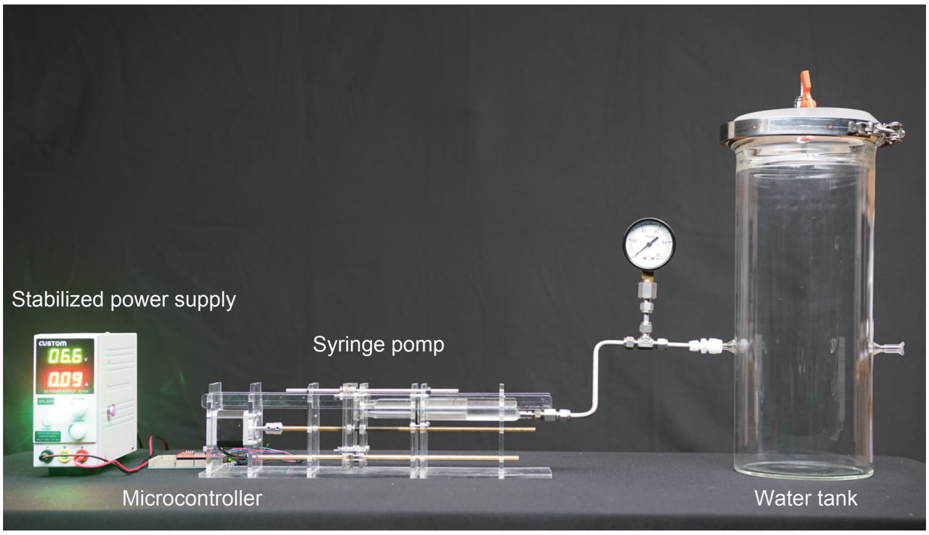

Fig. 2. System setup.

4 Manipulation method and system setup

To manipulate the position of the diver, we adopt PID control and implement the system setup (Figure 2).

Our system consists of a water tank which is connected to a syringe pomp by a tube. The syringe pomp moves forward or backward by a stepping motor. The motor is controlled by a microcontroller. When it works, water pressure inside the tank is changed and it comes to decrease or increase the buoyant force applied to the diver. We installed a camera to track the position of the diver and send the value to the microcontroller.

Besides changing the water pressure, there are several ways to manipulate the diver; changing the temperature of the liquid or using two kinds of liquid each density is different. However, these methods have disadvantages of responsiveness and interactivity.

In this study, therefore, we adopt PID control to manipulate the diver. PID control can be expressed mathematically as:

$$N(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (3)$$

where $N(t)$ is rotational speed of the stepping motor, K_p is a factor of proportionality, K_i is integration constant and K_d is differential constant. Also, $e(t)$ indicates difference between a target position and the present position of the diver. Figure 3 shows pipeline of PID control.

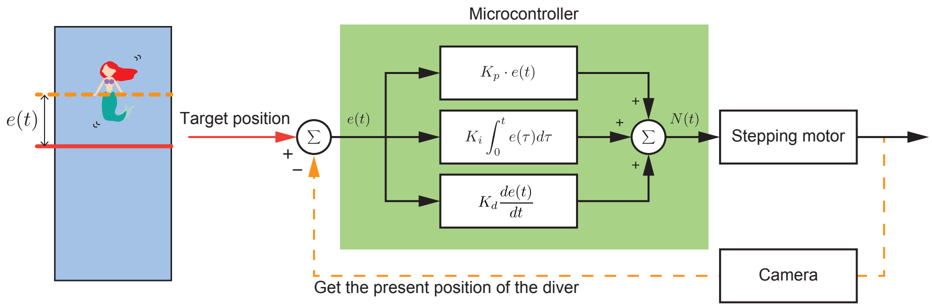

Fig. 3. Block diagram of PID control.

5 Result

5.1 Fabrication

We fabricated a variety of the divers and attained a result that they swim up and down in the correct orientation. However, it has limitation about material properties; water solubility and density.

Due to manipulate the diver underwater, we cannot use water soluble materials as 3D printing material. In this study, we do not consider a material which density lighter than water because it is rarely used in 3D printing.

5.2 Manipulation

We observed the position deviation of the diver under applying PID control. Gravity, buoyancy, and fluid resistance are applied to the diver while the diver is moving. Fluid resistance F_D is defined by the properties of the fluid, the shape, and the speed of the object:

$$F_D = \frac{1}{2} \rho v^2 C_D S \quad (4)$$

where ρ is the density of the fluid, v is the speed of the object relative to the fluid, C_D is the drag coefficient and S is the cross sectional area. The cross sectional area is defined as orthographic projection toward direction of movement of the object. Therefore we examined effectiveness of the cross sectional area of the diver to stability under the control (Figure 4).

Under the control, the object oscillate near the target position. It is caused by two system setup factors; frictional force applied to the syringe pomp and image processing delay. We need to improve the system setup to decrease these factors in the future work.

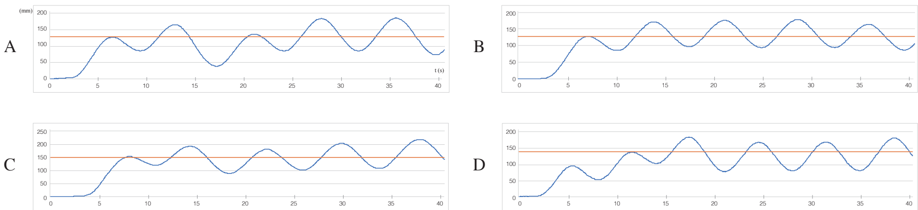

Fig. 4. These graphs show behavior of four Cartesian Divers under PID control. Those cross sectional area are different; A is 425π, B is 400π, C is 350π and D is 300π. Those volume ($62800mm^3$) and and the material (3D printed PLA) are same. Red line is the target position.

6 Conclusion

In this study, we aim to combine dynamic fabrication with non-contact manipulation system. To achieve this, we proposed the design methods applying the mechanism of Cartesian Diver.

We successfully design and manipulate the diver and discussed limitations.We observed the motion of the diver under applying PID control. Then we discussed about limitation about material properties and system setup. We believe this study extends the possibilities of new underwater expressions.

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