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STUDY ON AUTONOMOUS SURFACE ROBOT BASED ON MARINE ENERGY HARVESTING

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Abstract. *Recently, the global needs for the maritime domain awareness are gradually increasing. In order to satisfy these needs effectively, various marine robots are developed and applied globally. Among marine robots, the autonomous marine robot basically has the problem of the energy limitation due to its volume limitation. Therefore, the marine energy harvesting is necessary to operate it successfully. To study the autonomous surface robot (ASR) based on the marine energy harvesting, an ASR which has abilities of the stability-based locomotion using a catamaran, an anemometer and a magnetic compass, the wind energy-based propulsion using sails, a wire and a servomotor, the solar energy-based propulsion using solar cells and thrusters and the rapidity-based maneuvering using rudders is considered. Study results show the overview of the fundamentals of a sailing yacht, the development of the considered ASR and the need for additional studies.*
Keywords: Marine energy harvesting, Autonomous surface robot, Stability-based locomotion, Wind energy-based propulsion, Solar energy-based propulsion

1. **Introduction.** Recently, the global needs for the maritime domain awareness [1-3] such as a monitoring, an exploration and a reconnaissance are gradually increasing in civil and military application area. In order to satisfy these needs effectively, various marine robots are developed and applied globally.

Among marine robots, the remotely operated marine robot is affected by the cable dynamics while it has a high confidence level because it is operated by human operator on mother ship with the tether cable. The autonomous marine robot is not affected by the cable dynamics while it requires a high intelligence level because it is operated by itself without the help of human operator. In terms of the operational simplicity, the autonomous marine robot is more desirable for maritime domain awareness. However, the autonomous marine robot basically has the problem of the energy limitation due to its volume limitation. Therefore, the harvesting of marine energies such as wind, solar and wave is necessary to operate it successfully. For example, the wave glider [4] and sail drone [5] have optimal performances in terms of speed and duration. However, they still have the problems of speed and stability respectively.

To study the autonomous surface robot (ASR) based on the marine energy harvesting, an ASR which has abilities of the stability-based locomotion using a catamaran [6], an anemometer and a magnetic compass, the wind energy-based propulsion using sails [7,8], a wire and a servomotor, the solar energy-based propulsion using solar cells and thrusters and the rapidity-based maneuvering using rudders is considered.

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The overview of the fundamentals of a sailing yacht is described in Section 2 and the development of the considered ASR is described in Section 3. Finally, the conclusions are summarized in Section 4.

2. **Overview of Fundamentals of Sailing Yacht.** Related to the overview of the fundamentals of a sailing yacht, the representative sailing methods according to the wind direction are explained as follows.

According to the wind direction, the sailing methods for acquiring a propulsion force are different: if the sail is set at approximately 90 degrees from the longitudinal axis of the yacht when the wind is blowing from its back, it can go forward obviously. This is called a downwind sailing; if the sail is set at approximately 45 degrees from the longitudinal axis of it when the wind is blowing from its side, it can go forward because the resultant force is generated by wind and the lateral force is eliminated by its keel. This is called a crosswind sailing; if the sail is set at approximately 30 degrees from the longitudinal axis of it when the wind is blowing from its front except no-go zone, it can go forward by zigzagging because the resultant force is generated by Bernoulli theorem and the lateral force is also eliminated by its keel. This is called an upwind sailing. The sailing methods according to wind direction are shown in Figure 1. The left, middle and right sides respectively show the downwind sailing, the crosswind sailing and the upwind sailing.

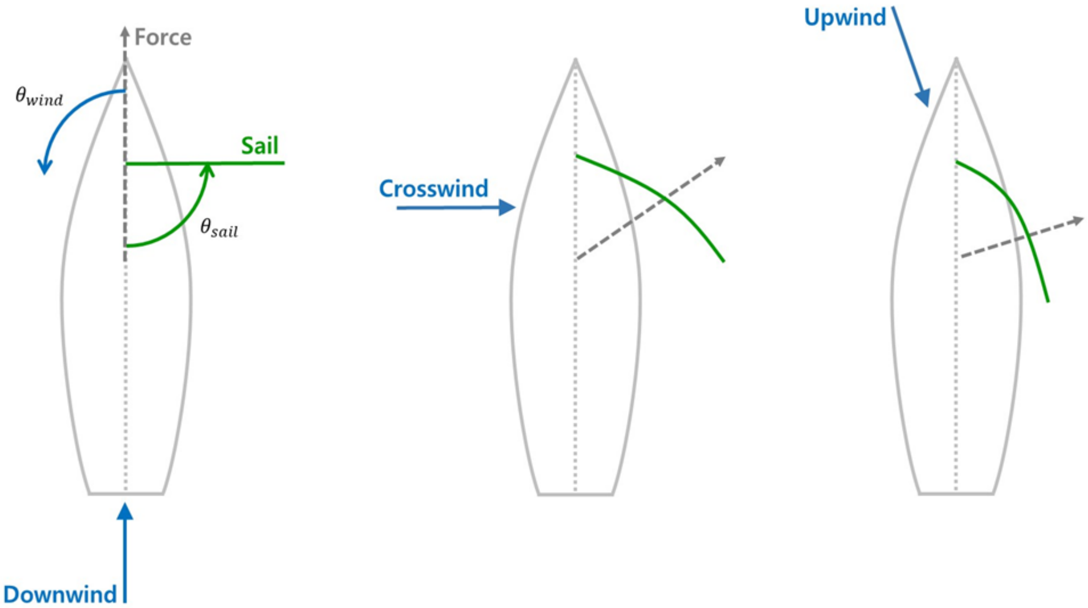

FIGURE 1. Sailing methods according to wind direction

3. **Development of Considered ASR.** Related to the development of the considered ASR, the system engineering process (SEP) [9,10] as a global standard of the R&D methodology is executed as follows.

Based on the established operation concept, the requirement analysis is executed and consequently the requirements of the mobility, the stability and the maintainability are derived.

Based on the requirement analysis, the functional analysis is executed and consequently the functions of the stabilizing-based locomotion function, the wind energy-based propulsion function, the solar energy-based propulsion function and the rapidity-based maneuvering function are derived.

Based on the functional analysis, the design is executed and consequently the hardware and software components are derived.

The body part and the sensor part are implemented by using one catamaran, one anemometer and one magnetic compass related to the stabilizing-based locomotion function. The primary propulsion part is implemented by using two sail, one wire and one servomotor related to the wind energy-based propulsion function. The secondary propulsion part is implemented by using two solar cells and two thrusters related to the solar energy-based propulsion. The steering part is implemented by using two rudders related to the rapidity-based turning. The 3D modeling of these parts is executed by using the computer aided three dimensional interactive application (CATIA) program. This 3D modeling enables to develop the ASR effectively in terms of time and feasibility. The modeling result of the ASR is shown in Figure 2.

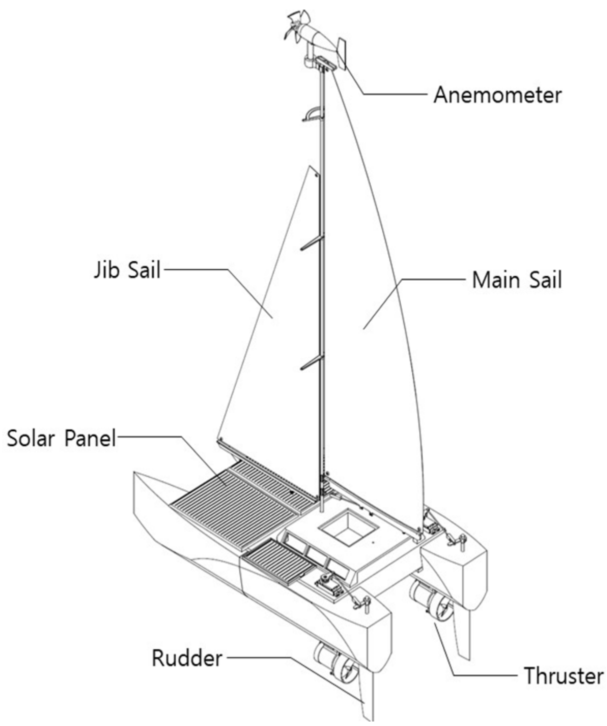

Figure 2. Modeling result of ASR

The speed generation rule according to the wind direction and the sail angle is implemented by analyzing the downwind sailing, the crosswind sailing and the upwind sailing. The rule is expressed by

$$R^i : \text{ if } \theta_{wind} \text{ is } A^i \text{ and } \theta_{sail} \text{ is } B^i \text{ then } v_{ASR} \text{ is } C^i \tag{1}$$

where R^i denotes the i-th rule, θ_{wind} is a wind direction, θ_{sail} is a sail angle, and v_{ASR} is an ASR speed. A^i, B^i and C^i are linguistic variables. In case of a downwind sailing, v_{ASR} is increased as θ_{sail} is increased. In case of a crosswind sailing, v_{ASR} is increased and then decreased as θ_{sail} is increased. In case of an upwind sailing, v_{ASR} is decreased as θ_{sail} is increased. The speed generation rule is shown in Table 1. This rule can be used in the speed control.

Table 1. Speed generation rule

θ_{wind} \ θ_{sail}	Small	Medium	Large
Large	Small	Medium	High
Medium	Small	Medium	Small
Small	Small	Very Small	Zero

Based on the design, the manufacturing is executed and consequently the hardware and software components are implemented.

The 3D printing of these parts is executed by using the rapid prototyping (RP) equipment. This 3D printing also enables to develop the ASR effectively in terms of time and feasibility. The prototype of the ASR is shown in Figure 3.

Figure 3. Prototype of ASR

Based on the analysis, the design and the manufacturing, the test and evaluation are executed and consequently the functions and then requirements are satisfied.

Firstly, the speed generation rule was verified by testing the downwind sailing of 170 degrees, the crosswind sailing of 90 degrees and the upwind sailing of 30 degrees. This verification of the speed generation rule is shown in Figure 4. In the upper case of the downwind sailing, the speed is increased as the sail angle is increased in the range 15 to 60 degrees. In the middle case of the crosswind sailing, the speed is increased and then decreased as the sail angle is increased in the range 15 to 45 degrees. In the lower case of the upwind sailing, the speed is decreased as the sail angle is increased in the range 10 to 20 degrees. According to the analysis of the results, the maximum speed is acquired at large, medium and small sail angles respectively. This means that optimal sail angle for maximum speed exists according to the wind direction as it is also deduced from the sailing methods in Figure 1.

Secondly, the straightness was verified by testing the downwind sailing of 170 degrees, the crosswind sailing of 90 degrees and the upwind sailing of 30 degrees in five times. This verification of the straightness is shown in Figure 5. In the upper case of the downwind sailing, the straightness is acquired in the error range of 10 degrees by changing the sail angle and the rudder angle. In the middle case of the crosswind sailing, the straightness is acquired in the error range of 20 degrees by changing the sail angle and the rudder angle. In the lower case of the upwind sailing, the straightness is acquired in the error range of 30 degrees by changing the sail angle and the rudder angle. According to the analysis of the results, the course control is executed with small, medium and large error angles respectively. This means that optimal sail and rudder angles for course control can exist according to the wind direction because the propulsion force and the lateral force are controlled by the sail angle and the lateral force is controlled by the rudder angle.

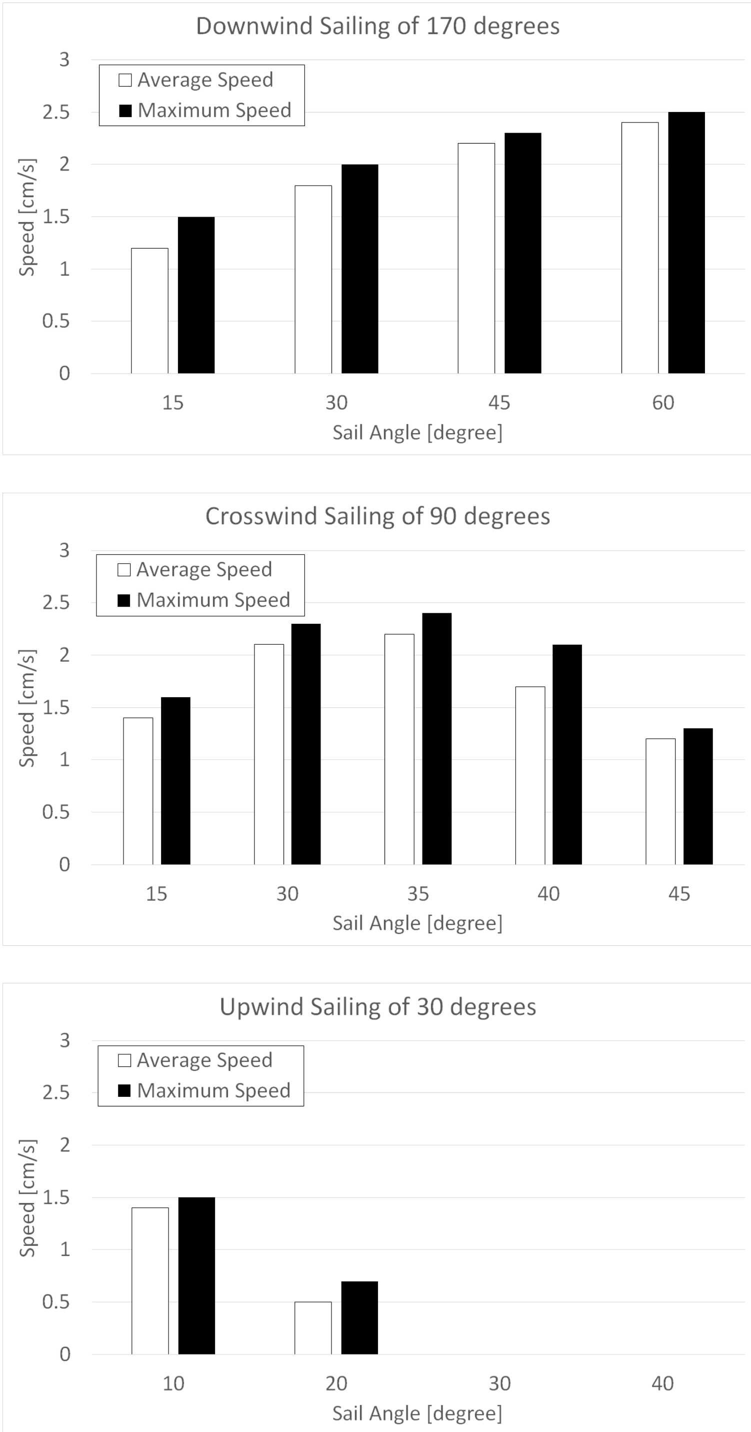

FIGURE 4. Verification of speed generation rule

From these results, the developed ASR [11] is proven to have meaningful components such as a catamaran, an anemometer, a magnetic compass, sails, a wire, a servomotor, solar cells, thrusters and rudders.

4. **Conclusions.** In this paper, an ASR which has abilities of the stability-based locomotion, the wind energy-based propulsion, the solar energy-based propulsion and the rapidity-based maneuvering has been well studied. The development of the considered ASR is summarized as follows: it requires the stabilizing-based locomotion using the catamaran, anemometer and magnetic compass to effectively implement the body and sensor parts of the ASR; it requires the wind energy-based propulsion using the sail, wire

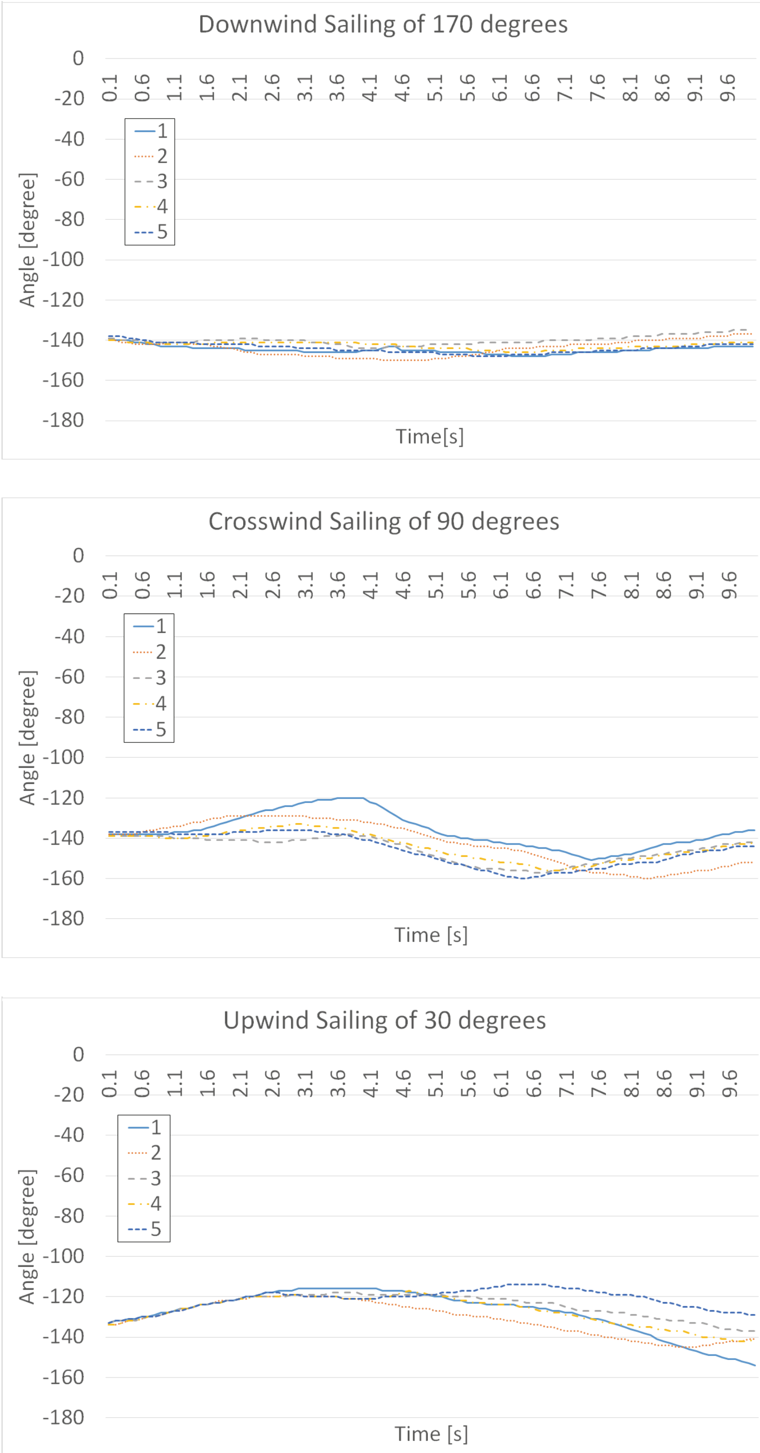

FIGURE 5. Verification of straightness

and servomotor to effectively implement the primary propulsion part of the ASR; it requires the solar energy-based propulsion using the solar cell and thruster to effectively implement the secondary propulsion part of the ASR; it requires the rapidity-based maneuvering using the rudder to effectively implement the steering part of the ASR. The study results showed the overview of the fundamentals of a sailing yacht, the development of the considered ASR and the need for additional studies. Through this, a basic development method of the ASR based on marine energy harvesting has been established. In the future, additional studies such as a path control for more concrete mission completion of the ASR will be conducted.

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