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Stereo-vision-based AUV docking system for resetting the Inertial Navigation System errors

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Abstract: Autonomous Underwater Vehicles (AUVs) are used for underwater exploration of the sea floor. AUVs use an Inertial Navigation System (INS) and sonar sensors to recognize their positions in the underwater, but recognition errors are possible. Global Positioning System (GPS) that have been useful for all bind of vehicles moving on the ground or in the air could not be utilized in water because radio signals could not penetrate into the water. As the task progresses, the INS accumulates recognition errors. As the accumulated error is increased, the success rate of the task is decreased. In this study, we propose a stereo-vision-based docking system using AUV for resetting the integrated INS errors. The experiment simulates the AUV returning to the docking station by using the INS navigation system. The experimental results show that our proposed method enables to dock the AUV and reset the INS errors.

Keywords: Visual servoing, Real-time multi-step GA, AUV, Docking, Dual-eye, INS

1 INTRODUCTION

Underwater vehicles are used to trace submarine cables, for submarine surveys and inspection of underwater structures [1, 2, 3]. All of these tasks require considerable underwater working time. Two main types of underwater vehicles are used in underwater tasks: Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV). In terms of operating time, two types of underwater vehicles rely on different types of power sources. ROV uses cables to obtain power from the ground or from the mother ship. AUV uses a battery mounted on itself to obtain power. But, each has its own specific problems. For an ROV, the cable can be damaged by friction with rocks on the sea floor and the tension of the several thousand meters of cable affects the deep-sea operations. For an AUV, the capacity of the battery is the main problem. In addition, the manual operation of ROV can be a heavy burden to the operator during long-term underwater tasks. For the reasons, the underwater vehicle predominantly used for long-term tasks is AUV.

The operation for the long-term task of an AUV involves three stages: (1) the mother ship conveys the AUV to the vicinity of the destination, (2) the AUV disengages from the mother ship, enters the water, and performs the task and (3) the AUV returns to the mother ship before the battery power is consumed. AUV operations are limited to activities that can be completed within the duration that is supported by the capacity of the batteries. Modern power devices allow long operational periods but an AUV must return to the mother ship for recharging. For solving this problem, underwater battery recharging with a docking function is one of the solutions to extend the operation time of AUV.

There are three stages in a recharging operation: (1) long-distance navigation, (2) approach and (3) short-distance docking. When the AUV must return to the docking station for battery recharging, AUV uses the navigation system such as the Inertial Navigation System (INS) and sonar sensors. However, no matter INS or sonar sensor, the positioning precision is not high[4, 5, 6]. Therefore, the navigation system used in the long-distance navigation stage cannot be used directly in the stage of the short-distance docking. Among these three stages, the accuracy required for the stage of the short-distance docking is the greatest. Therefore, homing accuracy and robustness against disturbance due to currents are critical requirements for the short-distance docking operation.

There are many studies about the homing accuracy of the underwater recharging system[7, 8]. A number of studies by the authors use a stereo-vision-based docking system[9, 10, 11], whereby the relative pose between the underwater vehicle and a known 3D marker is estimated by using a Real-time Multi-step Genetic Algorithm (RM-GA), which allows real-time 3D pose estimation. These studies have verified the stability of the proposed system in a simulated pool and have performed short-distance docking operations in the real sea environment. However, these studies are short-distance docking operations by using the ROV. The ROV is different from AUV in that ROV has a tension problem with the cable that affects the accuracy of the experiment. Moreover, short-distance docking is just one of the complete recharging stages. In this study, the experiment carried out includes all the stages of the recharging operation. In addition, the underwater vehicle used in the experiments is AUV, which does not have the tension of the cable to affect the accuracy of the experiment.

Because the underwater vehicle used in this study is different from previous studies, the stability of the proposed system used on the AUV must be verified prior to the formal experiment. A preliminary experiment was carried out. The preliminary experiment is an iterative docking experiment. After the preliminary experiment verify the stability of the proposed docking system for the AUV, the formal experiment simulates the process of an AUV performing a task. The AUV uses an INS to approach the docking station and then the AUV uses a stereo-vision-based docking system to complete the docking operation. The experimental results show that the proposed docking system for the AUV allows underwater movement and docking. The INS errors are reset after the AUV completes the docking operation.

2 HARDWARE FOR THE AUV EXPERIMENTS

The hardware used in this study is divided into three parts: AUV, docking station, and recognition unit. The experiment simulates a realistic recharging operation by docking the docking pole on the AUV to the docking hole on the docking station. The hardware for the docking experiment is discussed in this section.

2.1 Recognition Unit

In our proposed recognition system, the function of recognizing an object is achieved using only stereo-vision. The recognition program is installed on a computer named GA-PC, as shown in Fig. 1(b). GA-PC was installed in a container that processes camera signals and sends operational instructions to the AUV. Two interfacing boards, PCI-5523, are used in the GA-PC to receive images from the dual-eye camera on the AUV. Figure 1(a) shows the overall block diagram for the proposed docking system. Real-time pose estimation uses the 3D model-based matching method and the RM-GA is implemented as software in GA-PC(software will be described in the next section). Using the real-time estimated relative pose between the AUV and the target, GA-PC sends movement command signals to the AUV by TCP/IP. Recorded logs in files were stored in GA-PC during operation and downloaded when the AUV returned to the surface.

2.2 Autonomous Underwater Vehicle

The AUV for this study is called Hobarinn and was manufactured by the National Maritime Research Institute in Japan. Figure 2 shows the coordinate systems for the AUV. Σ_H is the coordinate system for the AUV and the origin is the center point of the two cameras. The specification of the AUV is shown in Table 1. For the experiments, dual-eye camera and three docking poles are attached to the AUV. And, GA-PC installed in a container is fixed to the rear of the AUV.

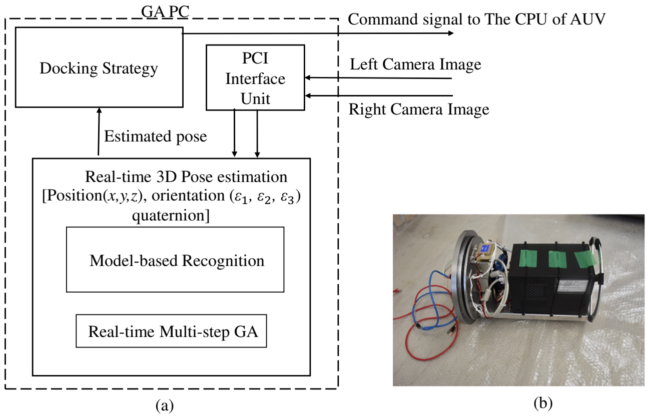

Fig. 1. (a) Block diagram of the proposed system and (b) Photo of the GA-PC

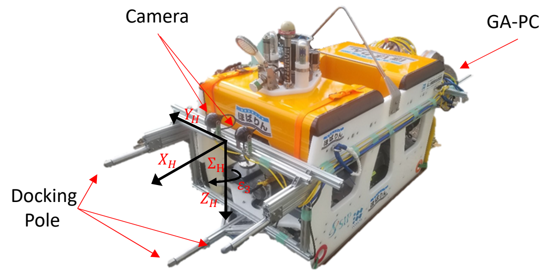

Fig. 2. Autonomous Underwater Vehicle

2.3 Docking Station

A unidirectional docking station was designed to demonstrate underwater battery recharging as shown in Fig. 3. The docking station is 0.60 [m] long $\times$ 0.45 [m] wide $\times$ 3 [m] high. The docking station is fixed in the simulation pool. The docking station has a 3D marker and three docking holes. The power supply device and the AUV are mechanically coupled to each other so automatic recharging occurs when the AUV fits its docking pole into the docking hole.

3 SOFTWARE FOR THE AUV EXPERIMENTS

Real-time pose (position and orientation) estimation using RM-GA has been developed for the docking operation by our research group. The real-time pose estimation method is calculated using a dual-eye camera and 3D markers. In this section, the method is briefly discussed for the reader's convenience. Details of the use of the RM-GA for real-time 3D pose estimation are described in a previous study [12].

3.1 3D Model-Based Matching Method

Feature-based recognition uses 2D-to-3D reconstruction calculations, for which information about the target object is determined from a set of points in different images. If a point in one image is incorrectly mapped to a point in another image, the pose of the reconstructed object does not represent that of the real 3D object. A pose estimation method using 3D-to-2D model projection is used for in this study because

Table 1. Specification of the AUV

Max. depth [m]	2000
Dimensions [mm]	1200 × 700 × 760
Weight [kg]	270
Duration [h]	8
Number of Thrusters	Horizontal thruster x 4 Vertical thruster x 2
Navigation sensor	INS, DVL, Sheet Laser Pressure Gauge, GPS antenna(AIR) Surveillance Camera(forward)
Observation sensor	Turbidimeter, CT Sensor, PH Sensor Profiling Sonar, Observation Camera Underwater Acoustic Measurement Device
Other Equipment	Iridium Beacons, LED Flashers Acoustic Positioning Transponders, Blast Releasers

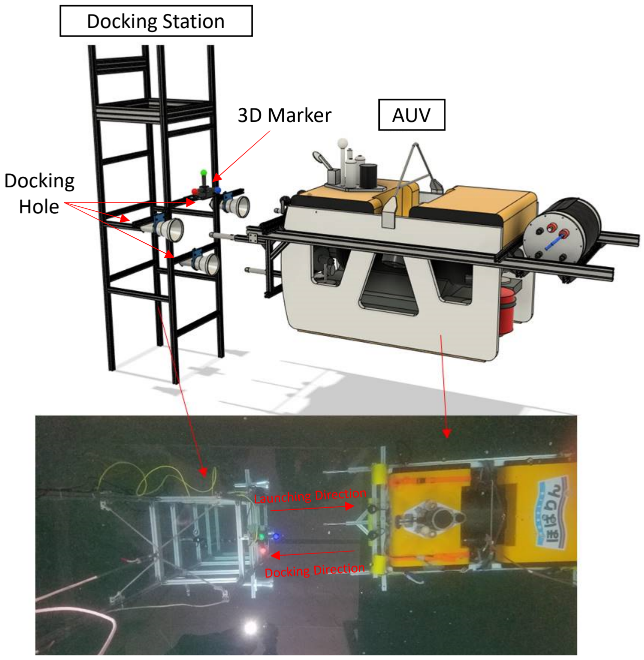

Fig. 3. The docking station for the experiments

forward projection from 3D-to-2D generates unique points in 2D images without any errors [13].

Using the 3D-to-2D approach, a model-based matching method is used to recognize the 3D marker and to estimate its pose in real-time. A model-based matching method uses the known shape, color and size of the 3D marker and models with assumed poses are predefined and distributed in the 3D search space in front of the dual-eye camera. Each model is then projected onto the two camera images, as shown in Fig. 4, where Σ_M is the 3D marker coordinate system for the proposed system, Σ_{M_i} is the i-th model coordinate system, Σ_{CL} and Σ_{CR} are the left and right camera coordinate systems, Σ_{IL} and Σ_{IR} are the left and right image coordinate systems, and the origins of Σ_M and Σ_{M_i} are the intersections between the three lines perpendicular to the faces to which the spheres of 3D marker face are attached. The j-th point on the i-th model in 3D space is projected onto the left and right camera images and these positions are calculated using camera projection geometry. Finally, the best model (most overlapping to the 3D marker) for the target object that represents the true pose has the highest fitness value.

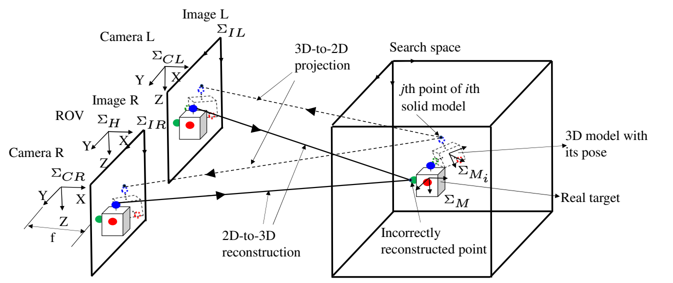

Fig. 4. 3D model based matching system with a dual-eye camera, using 3D-to-2D projection and 2D-to-3D reconstruction

3.2 Real-Time Multi-Step Genetic Algorithm

The problem of finding/recognizing the 3D marker and detecting its pose is converted into an optimization problem with a multi-peak distribution. The fitness function is used to calculate the correlation between the model and the real target. Refer to [14, 15] for detailed descriptions of the derivation of a fitness function from a correlation function. When the model and the real target coincide, the fitness value is a maximum. The highest peak in the fitness distribution represents the true pose of the target object. The fitness function must have its highest peak at the true pose of the 3D marker so the pose estimation problem is an optimization problem and the RM-GA solves this in real-time.

A genetic algorithm, the RM-GA, is used to estimate the relative pose between the ROV and the 3D marker. The right of Fig. 5 shows the flowchart for the RM-GA. A random population of models with different poses is generated in the 3D search space. A new pair of left and right images that are captured by ROV's cameras is input every 33 [ms]. The GA procedure is performed continuously every 33 [ms] with 43 evolutions for every image. The fittest new generation is then forwarded to the next step as the initial models for the next new generation, which is closer to the real target 3D marker that is projected naturally to the camera images. The RM-GA performs this procedure repeatedly to search for the best solution that represents the correct pose of the target object. The convergence behavior for the GA procedure is shown in the left of Fig. 5, from the first generation to the final generation.

3.3 Docking Control

A proportional controller is used to control the AUV. The six thrusters that are mounted on the AUV are controlled by sending a command voltage based on the feedback relative

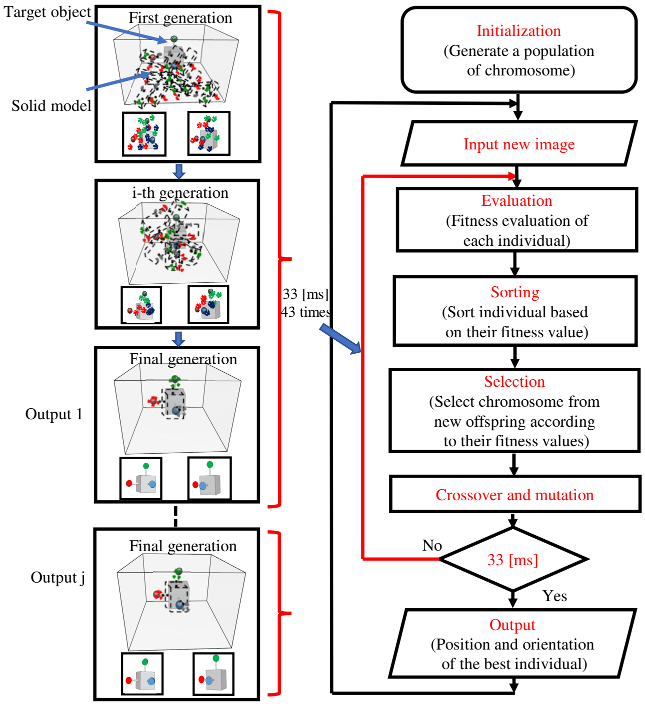

Fig. 5. Flowchart for the RM-GA: the terminal condition is defined as 33 [ms] because the video frame rate is 30 frames per second for the proposed system

pose between the AUV and the target object. The control voltage for the six thrusters is controlled using the following equations:

$$\textit{Vertical axis rotation}: V_1 = J^{-1}k_{p1}(\varepsilon_{3d} - \hat{\varepsilon_3}) \quad (1)$$

$$\textit{The depth direction}: V_2 = J^{-1}k_{p2}(x_d - \hat{x}) \quad (2)$$

$$\textit{Horizontal direction}: V_3 = J^{-1}k_{p3}(y_d - \hat{y}) \quad (3)$$

$$\textit{Vertical direction}: V_4 = J^{-1}k_{p4}(z_d - \hat{z}) \quad (4)$$

The equations use a Jacobian matrix J to define the relationship between the observed velocity of the AUV and the input voltage. A more detailed explanation of why a Jacobian matrix J is used and how it works is given in a previous study[16]. $(\varepsilon_{3d}, x_d, y_d, z_d)$ is the relative desired pose between the AUV and the 3D marker, $(\hat{\varepsilon_3}, \hat{x}, \hat{y}, \hat{z})$ is the relative estimated pose between the AUV and the 3D marker and $K_p = diag(k_{p1}, k_{p2}, k_{p3}, k_{p4})$ is defined as the gain for each deviation. In the experiments, the value of K_p is $(k_{p1}, k_{p2}, k_{p3}, k_{p4}) = (0.4, 0.5, 0.4, 1.0)$.

4 EXPERIMENTS USING THE AUV

Two experiments are conducted: an iterative docking experiment and INS navigation system and the stereo-vision-based docking system. The experiments were conducted at the simulation pool of the National Maritime Research Institute in Tokyo. The environment for the experiments is shown in Fig. 6.

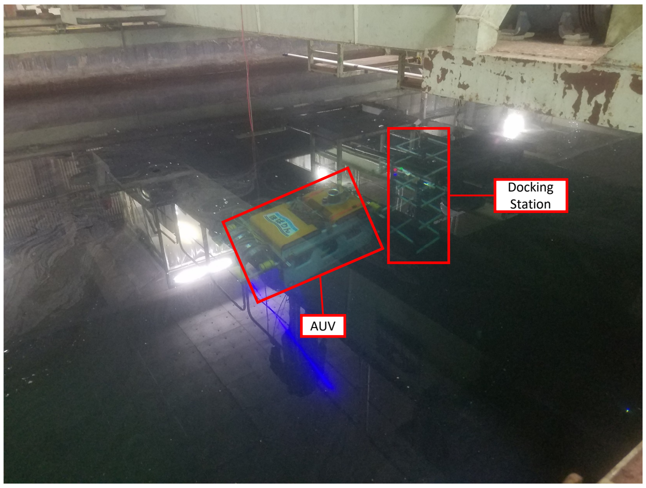

Fig. 6. The experimental environment for the AUV in the simulation pool

4.1 Preliminary Experiment: Iterative Docking Experiment

The preliminary experiment is an iterative docking experiment to confirm that the proposed system for the AUV can complete the docking operation. The robustness of the system is verified in the preliminary experiments.

The AUV was initially manually guided to the front of the docking station until the 3D marker was in the field of view (at a distance of approximately 950 [mm] from the target). Visual servoing then proceeded until the AUV achieved a stable position within the docking conditions for 165 [ms]. When the AUV fulfilled the docking conditions, it began to insert the docking pole by gradually decreasing the x-axis distance between the AUV and 3D marker until it reached 220 [mm]. When the docking operation was complete, the AUV returned to a distance of 600 [mm] from the 3D marker in the x-axis direction for the next docking iterations. As shown in Fig. 7, continuous iterative docking was conducted successfully for 10 iterations. Figure 7(a) shows the fitness value for 10 continuous docking experiments. Figure 7(b) - (e) show the desired pose and the estimated pose in each axis of the AUV, as recognized by the RM-GA. The iterative docking experiment shows that the AUV can perform the docking operation using just stereo-vision.

4.2 Formal Experiment : INS Navigation System and the Stereo-Vision-Based Docking System

The formal experiment simulates the AUV returning to the docking station for recharging. In this experiment, the INS is combined with the proposed docking system. The operations for this experiment are shown in Figure 8. There are six stages, all of which are performed three times. About the

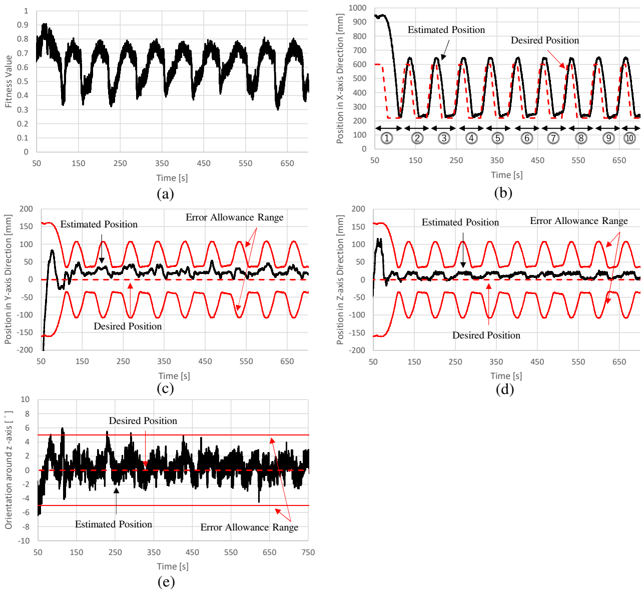

Fig. 7. Iterative docking experiment: (a) fitness value, (b) position in x-axis direction, (c) position in y-axis direction, (d) position in x-axis direction and (e) orientation around z-axis

mode of the control system, the navigation system using the INS is set to Mode 30 and the docking system is set to Mode 32. Figure 8 shows that in phase 1, the AUV uses the navigation system to move near the docking station and detect the presence of the 3D marker in the captured image. When the AUV detects the 3D marker (fitness value $\geq$ 0.5), the operating mode of the system changes from the navigation system (Mode 30) to the docking system (Mode 32). When the AUV's control system uses the docking system, the calculation for the navigation system is not stopped. In the docking mode, the AUV controls its own pose to achieve docking. In phase 4, the docking operation is completed and the AUV moves away from the docking station and then prepares for the next task.

The experimental results of the INS data for the navigation system are shown in Fig. 9. The navigation system for this experiment uses GPS to locate the position before into the water and then uses its own navigation system. For ease of understanding, the data from the GPS address are converted to the relative position of the central point of the docking station. The distance between the starting point and the docking station is set as 1[m], 2[m] and 4[m]. However, from the experimental results, all the starting points are wrong. In particular, there is a difference of 1 meter in the starting point of the first recharging operation. The black circles show that the INS errors are reset in the docking mode (Mode 32). In the docking mode, the AUV controls its pose using the stereo-vision-based docking system to achieve docking. When the docking operation is completed, the current pose of the AUV is accurately determined ($[x, y, z, \epsilon_1, \epsilon_2, \epsilon_3] = [0, 0, 0, 0, 0, 0]$ in the navigation system and $[x, y, z, \epsilon_1, \epsilon_2, \epsilon_3] = [180, 0, 0, 0, 0, 0]$ in the docking system). This information is used to reset the INS errors. About the peaks generated in the navigation mode after the docking operation, especially in the y-axis, this is because the navigation system of the AUV is not installed in the center of the AUV. When the AUV rotates during phases 2 and 4, the position of the navigation system changes accordingly.

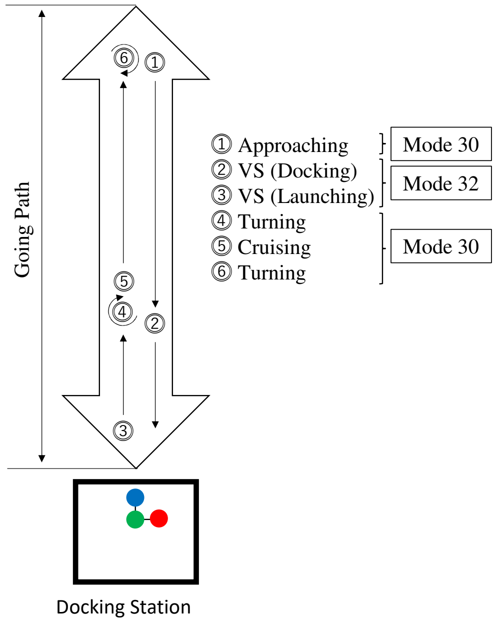

Fig. 8. The operations for the final experiment

5 CONCLUSION

This study conducts a docking experiment for battery recharging on the sea floor in a simulation pool using an AUV. The AUV approaches the docking station using INS and automatically performs the docking operation using only visual information from a dual-eye camera. The experimental results show that the errors that are generated by the AUV when the INS is used for navigation are reset after the AUV completes the docking operation. Future study will develop the proposed system for a real sea environment and perform sea trails to dock an AUV and allow underwater battery recharging using the proposed docking system.

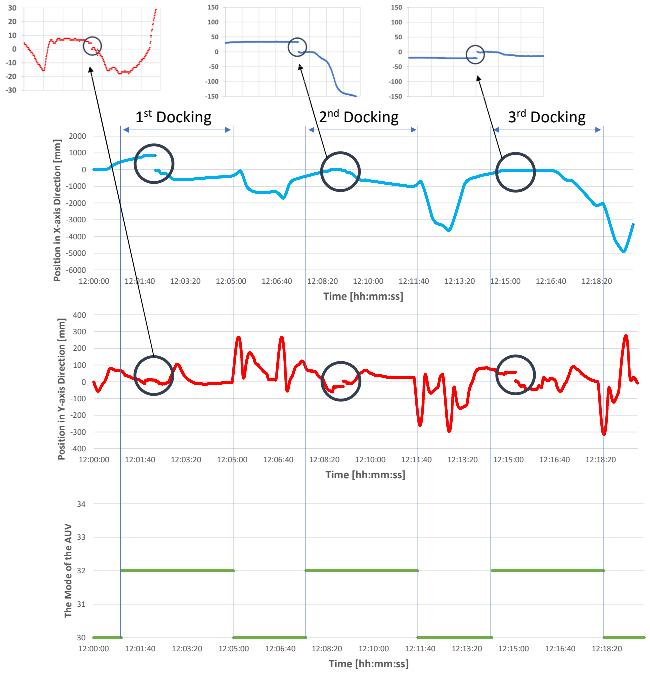

Fig. 9. Experimental result for the INS data

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