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ORIGINAL ARTICLE

A ship-to-ship automatic docking system for ocean cargo transfer

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Abstract The world's first ship-to-ship automatic docking system has been developed to provide a safe and reliable solution for docking between two ships exchanging containers in ocean. The system consists of vacuum pads, robot arms, cables, automatic winches and fenders. Basically, the docking status is maintained by contact force of fenders and cable tension controlled by automatic winches. All the developmental procedures from the conceptual design to the final prototype-system demonstration are presented focusing on the details of the two most important features: the passive- and emergency-mode controls. The passive-mode control makes the docking system freely follow the relative motion between the two ships without resistance. In case of emergency, the emergency-mode control is activated and the docking connection can be instantly released. A prototype was built to demonstrate the technical and operational feasibility in the actual ocean environment.

Keywords Automatic docking · Ship-to-ship mooring · Side-by-side mooring · Container loading · Mobile Harbor

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1 Introduction

In accordance with rapidly increasing cargo transfer volumes worldwide, the trend is toward reliance on ultra-large container ships. Since small-scale and shallow-water ports cannot accommodate such ultra-large container ships (ULCS), the potential of very large floating ports [1–3] and Mobile Harbor (MH) [4] has been studied. The MH is a ship equipped with docking and crane systems to transport containers between ships on the open-water environment in ocean (Fig. 1). Once a large container ship is single-point moored in an open-water area with considerable depth, a MH can directly approach the container ship, establish ship-to-ship mooring, perform loading and unloading operations, and transport the cargo to nearby inner harbors.

Furthermore, the need for ship-to-ship mooring between two ships in the middle of ocean has also been increased by a combination of environmental, economic, and military factors [5]. Because of environmental concerns and regulations, single-hull oil tankers cannot approach to certain coastal area and cannot enter the destination harbor for oil transfer. Then, the oil should be transferred to a double-hull oil tanker while at sea, which requires ship-to-ship docking as a precursor. As for military purposes, there has been increased demand to establish bases at sea instead of on land when a large military deployment to a distant area should be carried out. This will require frequent transportation of goods between ships in ways that demand safe and reliable ship-to-ship mooring.

Because cargo handling at sea is currently performed with manual operations, considerable human power and operational time are required, the operational conditions for cargo handling are not satisfactory, and, above all, there is a danger of human casualties and dangerous collisions between the two ships. Thus, the ship-to-ship mooring is

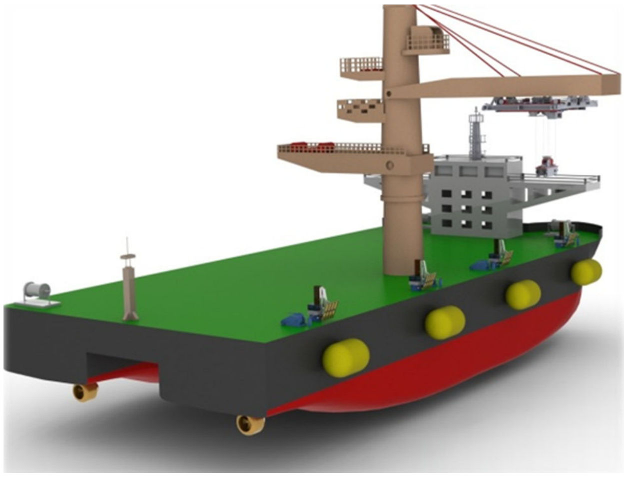


Fig. 1 Mobile Harbor A1-250

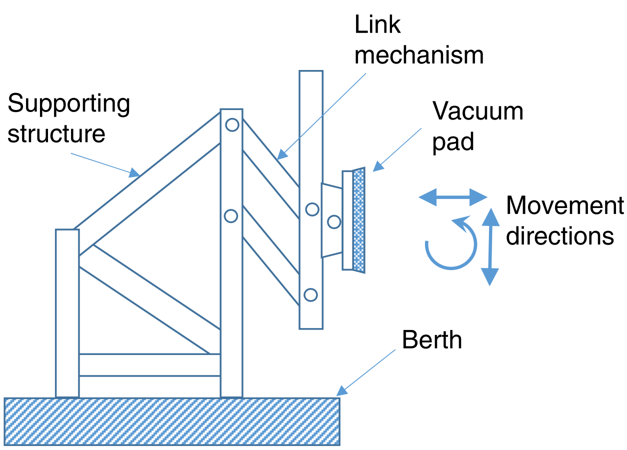


Fig. 2 An automatic ship-to-berth mooring system for quay side application (Cavotec [6])

only possible when a highly experienced special pilot is present aboard the ship. Even so, the danger of ship-to-ship mooring is always present. Consequently, it is necessary and valuable to develop a ship-to-ship automatic ocean docking system (S2S-ADS) to enable fast and safe ship-to-ship docking, and to increase the efficiency of cargo handling between ships in ocean.

As for similar existing technologies for automatic docking systems, a ship-to-berth system that enables automatic mooring of ships at berth has been developed [6] as shown in Fig. 2. However, due to the limitations of its operational and load bearing mechanisms, it can be used only in calm sea areas such as berth area, and is not applicable to open-water areas, where the effect of waves and wind is considerable. In addition, since its link mechanism and supporting structures are used to sustain the berthing force, the mechanism itself and the supporting structure must be complex, large and heavy to be equipped

Table 1 Comparison of the proposed docking system and other relevant systems

Items	S2S-ADS (present)	Ship-to-berth mooring system (Cavotec)	Lo/Lo of the US Navy
Operation principle	Automatic	Automatic	Manual
Operation in open sea	Possible	Impossible	Possible
Docking establishment time	25 s	15 s	30–60 min
Release time	7 s	3 s	30 min
Main components	Robot arms, vacuum pads, cables, winches, fenders	Vacuum pads, hydraulic system, heavy supporting structure	–
Docking force carrying components	Winches, cables, fenders	Hydraulically actuated links	–

onboard. The United States Navy has been trying to develop a ship-to-ship automatic docking system (S2S-ADS) for Sea Base operations under similar requirements [7] but has not yet obtained a proper solution.

To resolve such problems and issues, the present study focusses on the development of a S2S-ADS that can automatically perform mooring and de-mooring operation between the two ships safely and promptly up to Sea State 3, which indicates slightly rough state of the sea when the significant wave height is between 0.5 and 1.25 m, and still maintain docking state adequate for efficient cargo handling between the two ships. Equipped with robot arms that move vacuum pads to the hull surface, and automatic winches that maintain actual docking force by controlling tensions in the cables connected to the vacuum pads, the developed system can realize diverse levels of docking force even with a lighter and smaller sized system. In addition, fenders were installed on the hull surface of the barge to absorb any contact energy between the two ships and to maintain the minimum distance. A comparison of the characteristics of the existing ship-to-berth mooring systems and the new S2S-ADS is provided in Table 1.

In this paper, the details of the design process from concept to requirement analysis and determination of specifications for the S2S-ADS are described in Sect. 2. The construction of the prototype and controller, focusing on the description of the passive- and emergency-mode control systems are presented in Sect. 3. An actual ocean demonstration using the prototype is described in Sect. 4 and, finally, the overall conclusions are presented in Sect. 5.

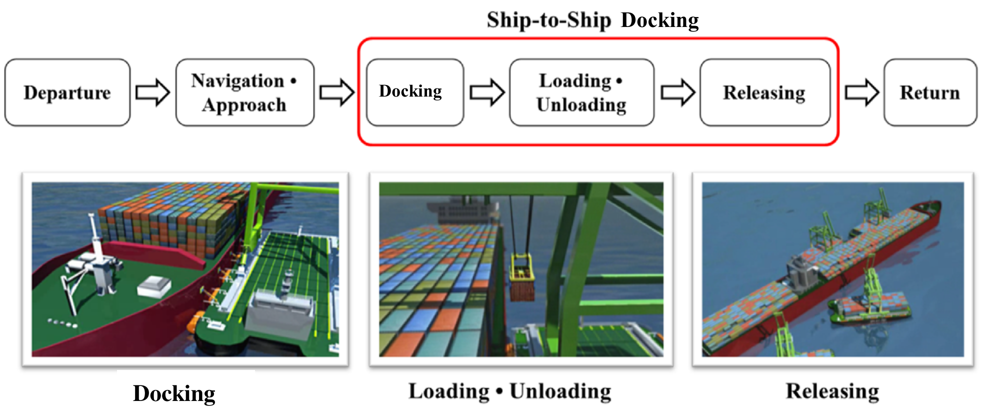


Fig. 3 Scenario of Mobile Harbor operation

2 System design of the automatic docking system

In this section, the overall system design of the S2S-ADS for MHs as well as the prototype system for the ocean demonstration is described.

The scenario of the MH operations is shown in Fig. 3. When a MH is navigated and approaches the target ship, ship-to-ship docking is established and the loading and unloading operations are performed. After this is done, ship-to-ship docking is released and the MH transports the containers to their harbors of final destination. To perform such operations, having a safe, reliable and quick docking operation is crucial for the success of the entire MH operation.

2.1 Functional requirements and design concept

The target ship to which the current development of S2S-ADS was to be applied as an exemplary and standard operation was a 5,000 TEU container ship (STX Offshore & Shipbuilding Co., Ltd.) with an overall length (LOA) of 294 m. The catamaran-type 250 TEU MH (MH-A1-250) depicted in Fig. 1 was equipped with the S2S-ADS. The specifications of the target container ship and the MH are listed in Table 2. As for the working conditions in open-water areas, the MH was to be moored side-by-side with the target ship, which is in a single-point mooring (SPM) state, using the S2S-ADS on the MH.

The functional requirements of the whole MH and the docking system were previously studied [8–10] using the axiomatic design principle proposed by Suh [11]. According to Kim et al. [10], the fifth functional requirements of the MH system that are related to the present development of the S2S-ADS can be denominated as follows.

FR5: Dock to the target ship

– FR51: Approach the MH to the docking location.

Table 2 Specifications of the target container ship and the Mobile Harbor A1-250

Items	Target container ship (5,000 TEU, STX)	Mobile Harbor (Catamaran)
Displacement (ton)	75,797	7,469.3
LOA (m)	294.1	76.75
LBP (m)	283.0	70.0
Breadth (m)	32.2	33.0
Depth (m)	22.1	11.0
Draft (m)	12	5.3
KG (m)	14.151	14.471
LCB (m)	−4.294	0.402

– FR52: Make the ship not to move away from an intended location.
– FR53: Maintain relative distance between the MH and the target ship.
– FR54: Prevent damage from a collision or contact between the MH and the target ship.
– FR55: Keep surrounding environment in check.

Among the functional requirements of FR5, the development of the automatic docking system was directly related to FR53 and FR54. The functional requirement FR53 can be denominated as follows [10]:

FR53: Maintain relative distance between the MH and the target ship.

– FR531: Automatically deploy and lock the locking structure of the docking system to the hull surface of the target ship.
– FR532: Lock the docking system to the target ship within certain distance.
– FR533: Lock the docking system for various surface conditions (ship hull curvature, welding bead, moisture, and others)
– FR534: Automatically release and retract

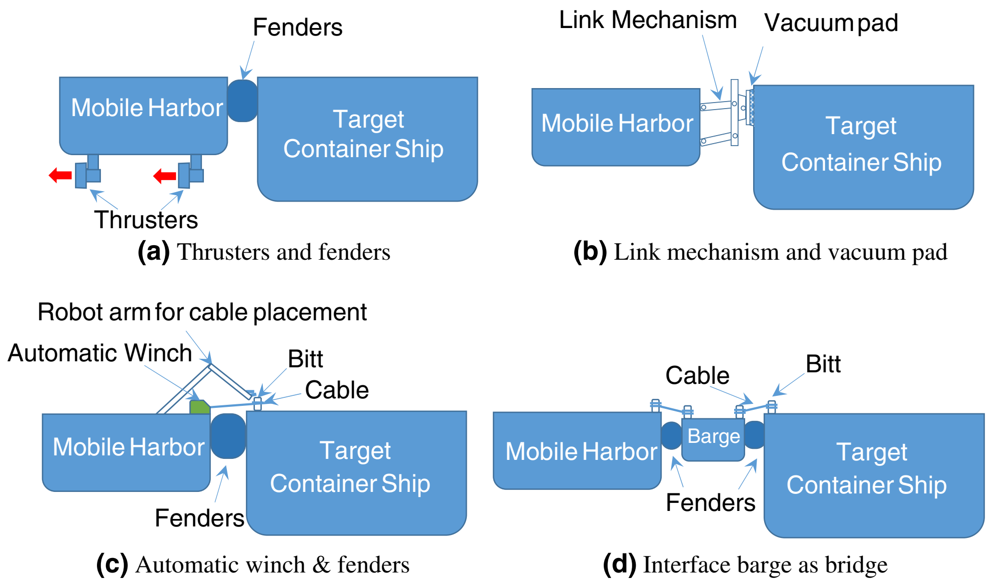


Fig. 4 Initial design ideas for ship-to-ship docking

– FR535: Limit relative movements and relative distances during docking.

Based on the functional requirements listed above, a number of initial conceptual designs were derived from brainstorming and survey of related technologies. Several concepts studied are shown in Fig. 4.

- The concept shown in Fig. 4a uses side thrusters to push MH against the target ship with fenders between the two ships. This concept fulfills most of the FRs listed above except FR535 but would bare concerns for FR52 and FR54, since pushing the ship against the other ship would place too much load to the single-point mooring system of the container ship and would bare potential danger.
- The concept shown in Fig. 4b uses a link mechanism to attach vacuum pads to the hull surface of the other ship and maintain relative distance between the two ships. This concept can fulfill most FRs but cannot guarantee the fulfillment of FR54 since the link mechanism only cannot avoid the danger of collision between the two ships. Moreover, the link mechanism could be excessively heavy and require tremendous power to avoid any contact between the ships in Sea State 3.
- The concept shown in Fig. 4c uses an automatic winch to control a cable tied to a bitt in the other ship. This concept is able to fulfill most FRs but is difficult to fully fulfill FR531, FR533, and FR534, since the cables should be tied to the bitts in fixed locations, and it would be difficult to automatically tie and untie cables from the bitt.
- The concept shown in Fig. 4d employs a floating barge between the two ships. This concept can fulfill most FRs but it cannot fulfill FR531, FR533, and FR534. The concept requires manual operation and the barge should be separately towed or carried by a ship.

The various initial conceptual designs described above were comprehensively evaluated for economical effectiveness, safety, and operational feasibility. As a result, a novel system as shown in Fig. 5 was devised by taking and combining partial merits from the three concepts in Fig. 4a, b, c. The merits of employing vacuum pads and a robot arm instead of a rigid link mechanism to establish a secure point for docking at any part of the hull surface of the target ship were utilized. As for the S2S-ADS, instead of manually transporting cable to a bitt, the robot arms are used to transport vacuum pads to any part of the hull surface for attachment. Also, automatic winches were employed to control the tension in the docking cable and to maintain the docking status. The new concept is shown in Fig. 5, which is using a robot arm to attach vacuum pads to the target ship, and is utilizing an automatic winch that controls the cable attached to the vacuum pads, to control tension and maintain the docking state. This new concept can fulfill all the FRs. It can fulfill FR531 and FR533 by employing the robot arm and vacuum pads to establish a secure point for docking at any part of the hull surface of the target ship. FR54 is fulfilled by adding fenders to the system. FR532 and FR535 are fulfilled by the automatic winches and cables. Finally, FR534 is fulfilled by the robot arms that can move the vacuum pads.

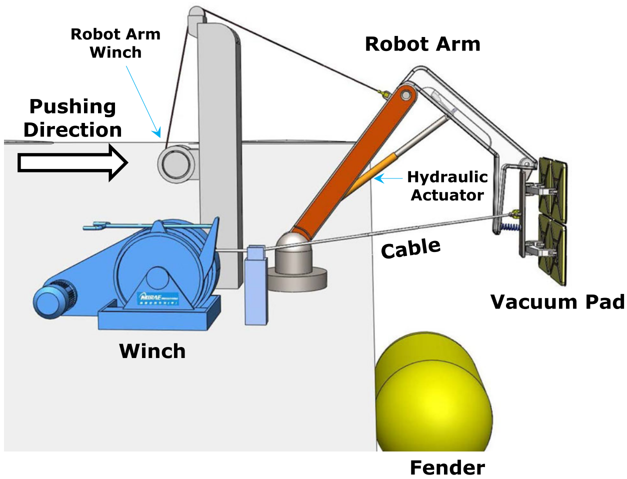


Fig. 5 Proposed novel design for the ship-to-ship automatic docking system

The proposed one unit of the ship-to-ship docking system (S2S-ADS) consists of a robot arm, vacuum pads, an automatic winch, cables, and fenders as shown in Fig. 5. The robot arm has the robot-arm winch to move the whole robot arm and the hydraulic actuator to move the end part of the robot to impose more precise control. The arrangement of the whole system for the MH A1-250 that consists of four units of the S2S-ADS is shown in Fig. 6 as a top view. The operational procedure of the S2S-ADS is shown in Fig. 7 as a flow chart. To be able to control the system more effectively, these procedures were further denominated into ten control states that are explained in Sect. 3.1.

For the final design of the automatic docking system, the sizes of the equipment, the capacity of the actuators, and the number of necessary units had to be calculated. One of the most important elements for this was calculating the mooring force required to stably maintain a proper distance between the two ships. The mooring force calculation followed OCIMF [12] and PIANC [13], and the results are provided in Table 3. Since the calculations are based on steady state and the pre-compression force of the fenders is not included in the docking forces, the docking systems were designed with enough safety margin (safety factor of 4) to consider dynamic effect of the ships.

2.2 The prototype design for the ocean demonstration

To test the technical and operational feasibility at minimal cost without constructing the whole MH, a low-cost barge (LOA 46 m, Breadth 15 m, Draft 1,800 ton) instead of an actual MH was selected. Instead of a 5,000 TEU container ship, a 3,000 ton ocean training ship was used for the actual demonstration at sea. Two versions of S2S-ADS were designed. One was for the MH A1-250 and the other was for the ocean demonstration. The final specifications of the automatic docking system for MH A1-250, and the ocean demonstration, based on the results of the docking force calculations, are given in Table 4. The S2S-ADS unit that was designed and used in the ocean demonstration was about 80 % scaled down model. The S2S-ADS design for the ocean demonstration had similar but smaller individual capacity compared to that for the MH and the number of the S2S-ADS for the ocean demonstration was two, which was the minimum number to test the feasibility, instead of four as shown in Table 4.

3 Hardware arrangements and controller

The hardware arrangements and components for the ocean demonstration, finally designed in detail, are illustrated in Fig. 8. The main parts consist of robot arms, which moves the vacuum pads (which are attached to the hull surface with vacuum suction pressure and play a role identical to that of the bitts of quay walls) to the hull surface of the

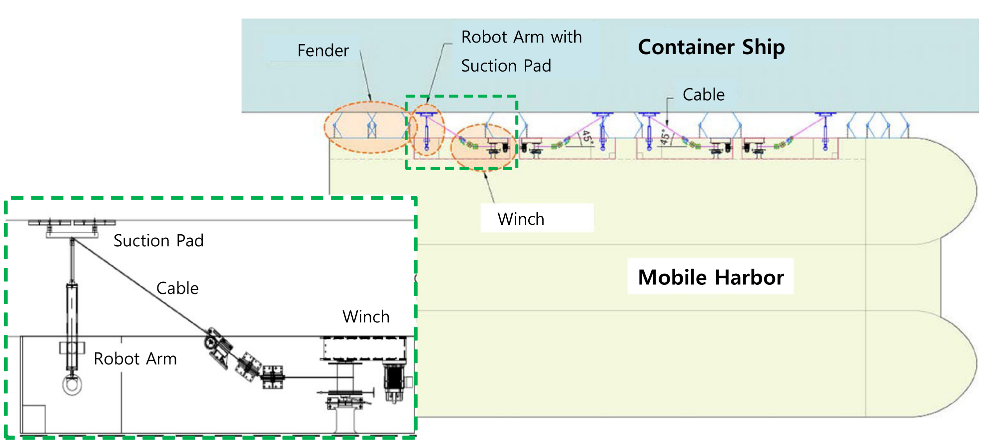


Fig. 6 Arrangement of the Mobile Harbor docking system (*Left* magnified view, *Right* overhead view)

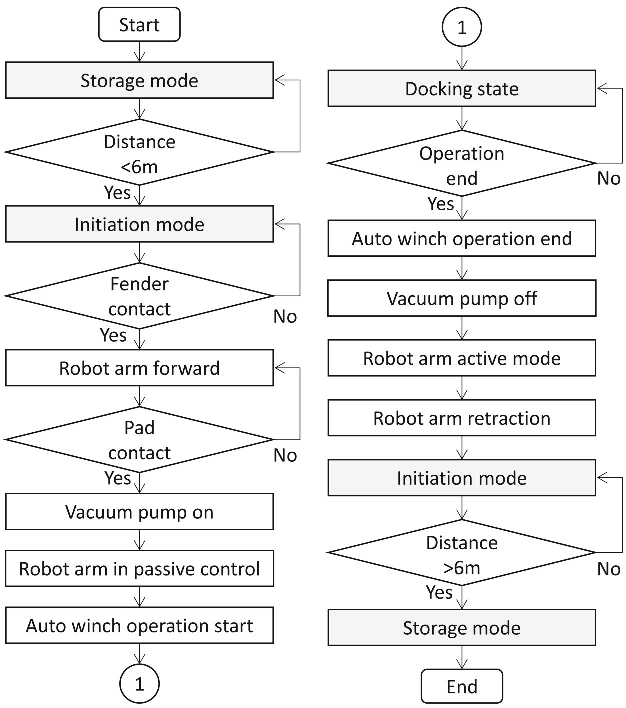


Fig. 7 Operational flowchart of the ship-to-ship automatic docking system

Table 3 Docking force required for Mobile Harbor A1-250 docking operation

Items	Designed (MH A1-250 to a CC)	Demonstration (barge to a training ship)
Wind force (ton)	4.9	0.7
Current force (ton)	3.2	2.1
Wave drift force (ton)	2.5	1.5
Total combined force required (ton)	10.6	4.37

Table 4 Specifications of one mobile harbor docking system

Items	Designed (MH A1-250 to a CC)	Demonstration (barge to a training ship)
Sea state	3	3
Size of vacuum pads (m × m)	2.2 × 2.2	1.76 × 1.76
Capacity of vacuum pads (ton)	15	6
Maintained cable tension (ton)	7.5	3.0
Number of units	4	2

target ship; and automatic winches, which control the necessary docking force by pulling the cables connected to the vacuum pads.

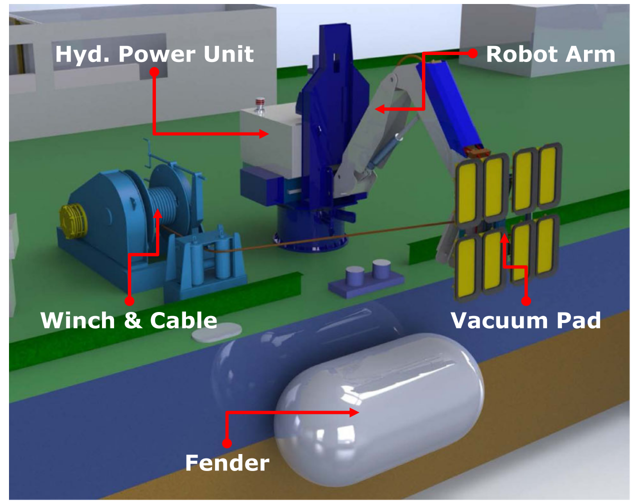


Fig. 8 Hardware and its arrangement for the demonstration system

The vacuum status in the pads was created by the vacuum pump with the capacity of 42 l/s and 7.5 HP with 60 l vacuum tank. These capacities instantly created and maintained less than −740 mmHg of near vacuum status in the vacuum suction pads with the total inner volume of 31 l and the area of 1.54 m^2. As a result, the vacuum pads could safely withstand the cable tension of up to 6 ton. In addition, the material used in the pads was neoprene that enabled proper sealing of vacuum even on the rough surface.

In addition to the power units needed to operate the automatic winches, separate hydraulic power units were necessary to operate the robot arms and were combined with the body of the robot arm unit, thus improving the appearance of the system and the use of space. For the ocean demonstration, the total of the two units were installed on the bow and the stern of the barge. The arrangement is similar to the one shown in Fig. 6 except that only two units in the middle were installed in the demonstration system (21.5 m between the robot arms).

An operational diagram of the controller for the S2S-ADS is provided in Fig. 9. The basic operation of the system was realized through sequence controller using Programmable Logic Controller (PLC). The hydraulic control for passive-mode operation of the robot arms was interlocked with the PLC system by embodying a separate control system using proportional control valves. The motor controller for operating the automatic winches was separately constructed and interlocked with the PLC as well.

The key technologies of the new control system are the passive-mode control technology for the robot arms and the emergency-mode control technology for the docking control system. The control states along with passive- and emergency-mode controls of the docking system are described in the following section.

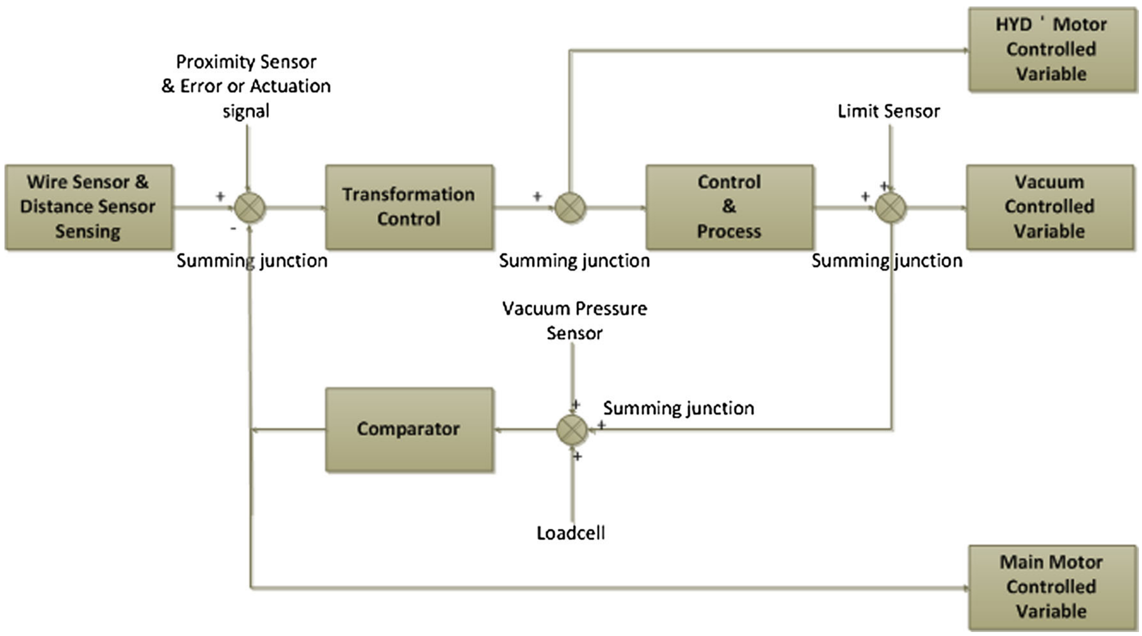


Fig. 9 Composition of the controller for the automatic docking system

Table 5 Definitions of control states

States	Definition of state
S1	The robot arm is retracted for storage mode (Robot Arm Retracted)
S2	The system checks the status of all the sensors (Docking System Check)
S3	The system goes into initialization mode extending the pad right inside fender and keeps the idle mode waiting for an order (Docking Initialization)
S4	The system waits for the fender to make contact (Fender Contact Check)
S5	The robot arm attaches vacuum pads (Vacuum Pad Attachment Check)
S6	The winch starts operation while robot arm goes into passive mode (Automatic Winch Operation Start)
S7	The system maintains docking status monitoring any emergency signal or procedural order (Maintain Docking and Monitor Emergency)
S8	The winch releases cable tension for vacuum pad detachment (Automatic Winch Release)
S9	Vacuum pad is detached by releasing vacuum pressure (Vacuum Pad Detachment Check)
S10	Robot arm goes back to idle mode retracting back the vacuum pad to the system idle location (Vacuum Pad Retraction)

3.1 Control states

The whole control procedure for the automatic docking system was subdivided into ten control states named as S1 through S10 as shown in Table 5 and Fig. 10. The S1, S3, and S6 are the states that communicate with the integrated control system and wait for the operation order. The S4–S7 are the states to establish docking state. The S8–S10 are the states in the process to release docking state. Detailed descriptions follow.

The S1 state describes the system-ready state when the MH is in a proximity to the other ship; when the distance between the two ships becomes less than 6 m. In this state, all the components of the system are switched on for imminent establishment of docking.

The system state is switched to S2 when the distance becomes less than 5 m. The S2 state is for the final check of all the components before actuating the components for docking.

When all the check results turn out to be normal, the state is changed to S3, in which state the robot arm is switched from retracted storage mode to the initiation posture. In the initiation posture, the vacuum pads are extended about 1 m from the storage-mode position at the edge of the deck and right inside of the fender width.

When the docking system reaches the initiation-mode position, the state is changed to S4 as shown in Fig. 11a. The S4 state is maintained until the fender makes contact with the hull surface of the target ship.

The system state is changed to the S5 state once the contact of the fender is confirmed as shown in Fig. 11b. In the ocean demonstration, the confirmation was given by a crew who monitored the process in proximity to the docking system unit. The S5 state lasts until the robot arms attach the vacuum pads to the hull surface of the target ship

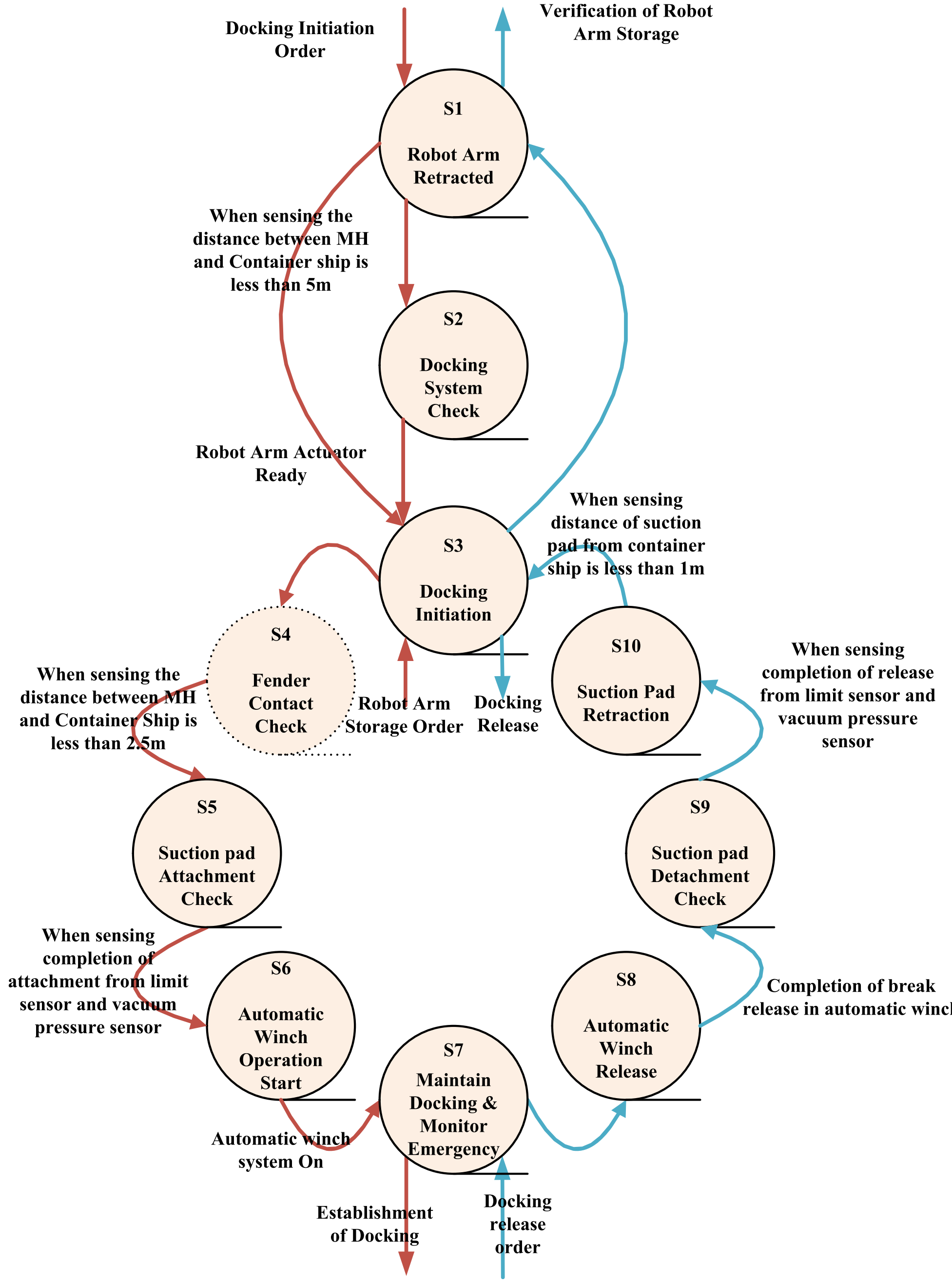


Fig. 10 Sequential schematics of control states and procedures (*Red color* docking establishment, *blue color* docking release)

and the attachment of the pads is confirmed. In the first part of the S5 state, both the hydraulic cylinder and robot-arm winch move the pads within 30 cm from the hull surface. When the distance becomes less than 30 cm, based on the ultrasound distance sensor measurement, only the hydraulic cylinder moves the pad against the hull surface of the target ship. Then, the vacuum pad is attached by decelerating the pad right before the contact. The contact sensors and pressure sensors on the pads are used to confirm secure attachments. The S5 state is changed to the next state once the vacuum state is properly maintained in the pads for more than 3 s.

In the S6 state, the robot arms go into passive mode switching the robot-arm hydraulic cylinder and robot-arm winch to passive mode. Then, the automatic winch starts operation for automatic tension control. More details about the passive mode will be given in the separate paragraphs in Sect. 3.2. Once the attachment of the pads, and the start of automatic winch operation, is confirmed, this information is sent to the central control systems so that the thruster

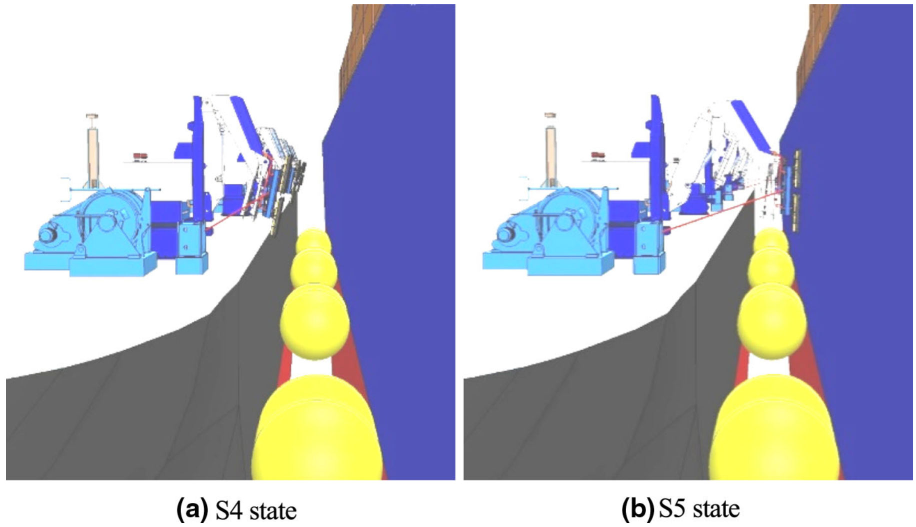


Fig. 11 S4 and S5 states for establishment of automatic docking

operation toward the other ship can stop. The automatic winch uses hydraulic actuators and a brake system to maintain the intended tension in the cable, by monitoring the load cell values that correspond to the cable tension force. Utilizing a load cell on the winch structure was more practical solution for the present application compared to the method that requires separate measurements from the fenders [14]. The state is changed to the next state when the central system confirms that the thruster is switched off.

In the S7 state, the system enters into the constant docking state maintaining the attachment of the pads and constant cable tension. The system also enters into standby mode for any kind of emergency. In this standby mode, the docking control system monitors outputs from three types of sensors, ultrasound distance sensors, vacuum pressure sensors, and limit sensors, of the docking system and the signal outside of the docking system for occurrence of any type of environmental or operational emergency.

When the docking control system receives the docking release order from the central control system, the state is changed to the S8 state, the initialization state for docking release operation, and the tension and the cable are released from the winch.

In the S9 state, the robot arms detach the vacuum pads from the hull surface of the target ship after vacuum pressure is released. When the detachment of the vacuum pad is confirmed, the side thruster is turned on to make a distance between the two ships. Then, when the distance between the two ships becomes more than 40 cm, the state is changed to the S10 state.

In the S10 state, the robot arms start to return back to the initiation-mode position and goes back to the S3 state. When the distance between the two ships becomes further than 5 m, the robot arms are further retracted going back to the storage-mode position.

3.2 Passive-mode control

One of the key control technologies of the docking system is the passive-mode control in the S6 and S7 states. The main role of the robot arm is attaching the vacuum pad to the hull surface of the target ship (and detaching it later). Since the docking force is maintained by the automatic winch that controls the tension of the cable attached to the vacuum pads, and because the robot arms do not have any active role while the pads are attached, it is essential that the robot arms should not interfere with the relative movement of the two ships or operation of the automatic winch.

For these reasons, the passive mode for the robot arm was designed. Engagement of the passive-mode operation is achieved by maintaining constant pressure in the hydraulic actuator of the robot arms. By maintaining constant pressure in the hydraulic system, the torque exerted to the robot arm joint would be constant. Then, this constant torque only cancels out the constant gravity force exerted by the robot arm's own weight. This will make the robot arm to passively move against the added or subtracted force introduced to the robot arm joint that results from the relative movement between the two ships and in addition will make the posture of the robot to be maintained even in an accidental or emergency situations such as detachment of vacuum pads, which can protect the docking system and the ships.

3.3 Emergency-mode control procedure

Another key control technology of the docking system is the emergency-mode control. The main benefit of a system having vacuum pads and a robot arm is that they enable the docking system to be instantly disengaged from the target ship if an emergency situation ever occurs. Such

Table 6 Definitions of emergency situations for different emergency procedures

Emergency procedures	Definition of emergency situations
E1	When an abnormal signal is observed when each subcomponent of the docking system is checked
E2	When the fender is not able to make contact to the hull surface of the target ship when enough time and movement of the ship are given
E3	When the vacuum pad attachment cannot be confirmed by vacuum pressure sensor and contact sensor
E4	When there is an emergency signal from crane system during crane operation while maintaining docking
E5	When there occurs emergency situation outside of Mobile Harbor due to severe weather condition or other emergency
E6	When sensor malfunction is observed
E7	When communication malfunction is observed

emergency actions can be activated from the emergency-mode control system, which can take the required sequential actions based on assessment of conditions being monitored in the surrounding ocean environment, regarding the movement of the two docked ships, and from the docking system itself. Table 6 shows seven emergency response procedures defined in the emergency-mode control system to identify and respond to various emergency situations.

The E1 procedure is taken when an emergency situation occurs during the docking system check procedure in the control state S2. When any abnormal or false signal is observed during the status check on the robot-arm hydraulic cylinders or robot-arm winches, the system sends an emergency signal to the central control system and switches the state from S2 to S1.

The E2 procedure is taken when an emergency situation occurs during the contact of the fenders to the hull surface of the target ship while the docking system is in the S4 state. In the E2 procedure, the docking system sends an emergency signal to the central control system and changes the state from S4 to S7 to check all the signals from the sensors and the outside. When the S7 state is reached, the system is changed back to S3.

The E3 procedure (shown in Fig. 12) refers to the emergency situation that can occur during the vacuum pad attachment operation in the S5 control state. During this operation, readings from the four contact sensors mounted on the circumference of its pad array and a vacuum pressure sensor inside are checked and an emergency signal is sent when the attachment of the pad cannot be confirmed from the sensor readings. In the E3 procedure, the control state is first changed from S5 to S7 to gather all the signal inputs. Then, the system is changed back to S3 after going through the S9 and S10 states for proper retraction of pad.

The E4 procedure refers to the emergency situation that can occur once the docking is established, and the docking status is maintained in the S7 control state. When there is an emergency signal from the crane system while maintaining docking, the system sends an emergency signal to the central control system, and the system is changed back to S3 after going through S7, S8, S9, and S10.

The E5 procedure (Fig. 13) refers to the emergency situation that can occur from the outside of the MH due to severe weather condition or other emergency. When this emergency signal is received from the central control system, the docking system goes back to either S1 or S3 from S7 state, depending on the severity of the emergency. The environmental emergency signal can be generated by occurrence of severe weather, abnormal impact from unusually strong waves, and severe relative motions between the two ships. Since the emergency signal from the outside can occur at any control state, the E5 procedures are defined from various states as shown in Fig. 13.

The E6 procedure refers to the emergency situation that can occur from any malfunction of the sensors when the S7 state is maintained. The docking system detects any sensor abnormalities by comparing the output value of each sensor to the error limit range of each sensor. In the E7 state, the system sends out its emergency state signal and maintains the S7 state in the passive control mode so that the problematic sensor can be replaced.

The E7 procedure refers to any malfunction in the communication between the central control system and other docking systems. In the E7 procedure, the system sends out emergency signals to the operator and maintains the S7 state.

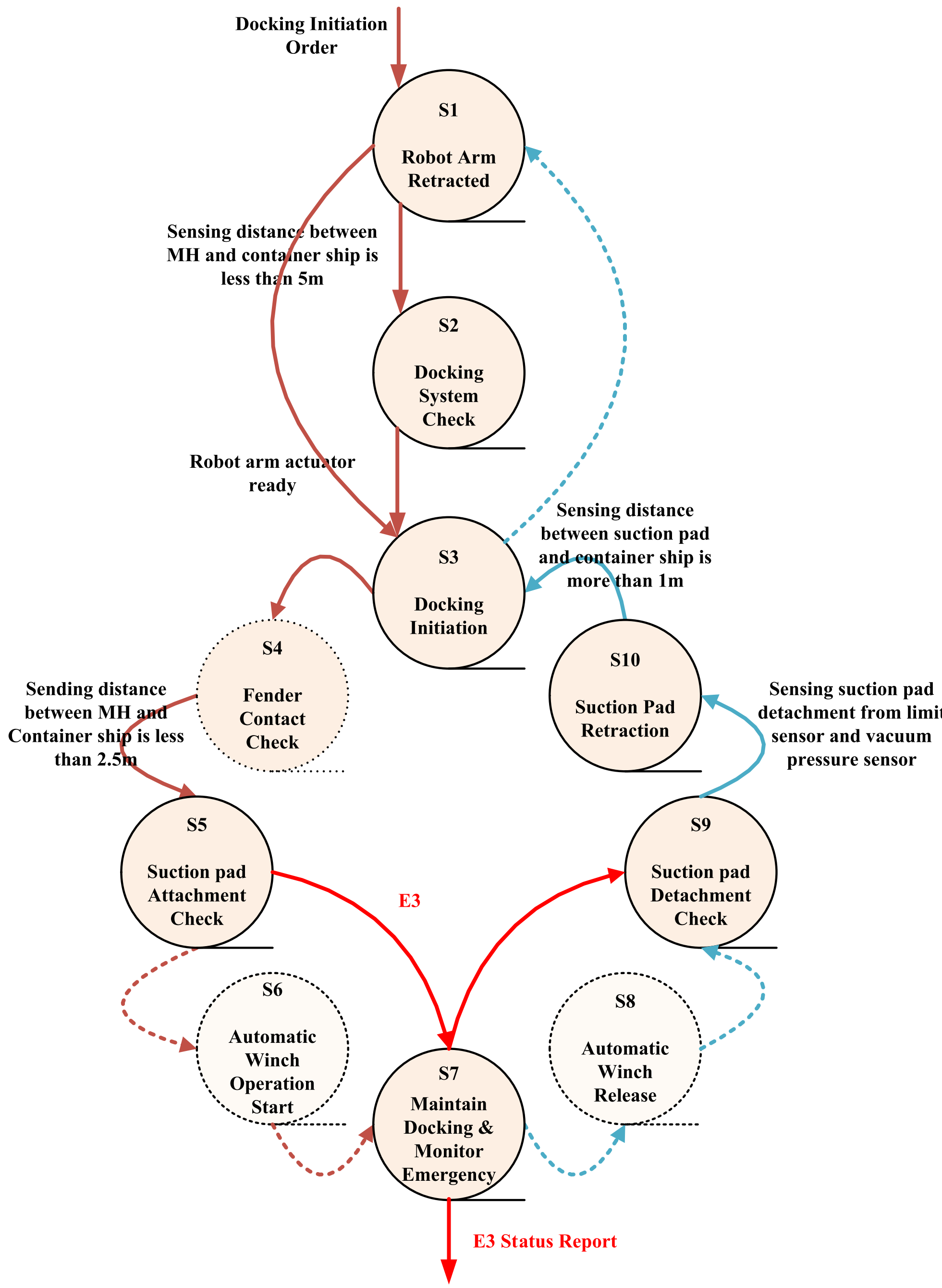
4 Ocean demonstration

Two *S2S-ADS* are installed on a barge ship to demonstrate and verify its full functional capability.

4.1 Venue of the ocean demonstration

The venue of the ocean demonstrations was in open-water area at approximately 400 m from the quay walls of the Korea Maritime University at the water depth of 30 m. The *Hanwoori*, the target ship, was anchored using single-point mooring. As for the sea weather, information provided by the Korea Meteorological Administration (KMA) obtained through Gwang-An light beacons, which are located approximately 10 km from the venue of the demonstration, was used as reference data for reading the sea state during the ocean demonstration.

Fig. 12 The E3 emergency procedure shown as *red arrows*



4.2 Performance of the ocean demonstration

While MHs can approach the target ships using their own propulsion system, a tug boat was used to move the barge for the docking operation demonstration against the *Hanwoori*, the target ship that simulated the role of the container ship. Right after the fenders made contact with the *Hanwoori*, the automatic docking system went into operation. Once the attachment of the vacuum pads was complete and the automatic control of the cable tension was initiated, the pushing action of the tug boat stopped, and the two ships' docked state were maintained wholly by the operation of the automatic winches, vacuum pads, cables, and fenders. The actual demonstrations of the ocean demonstration processes are shown in Fig. 14.

4.3 Test results and discussion on the ocean demonstration

The docking demonstration was successfully accomplished in the Sea States of 1 through 3. The several results on the absolute roll motions measured by a gyro sensor (Fig. 15a,

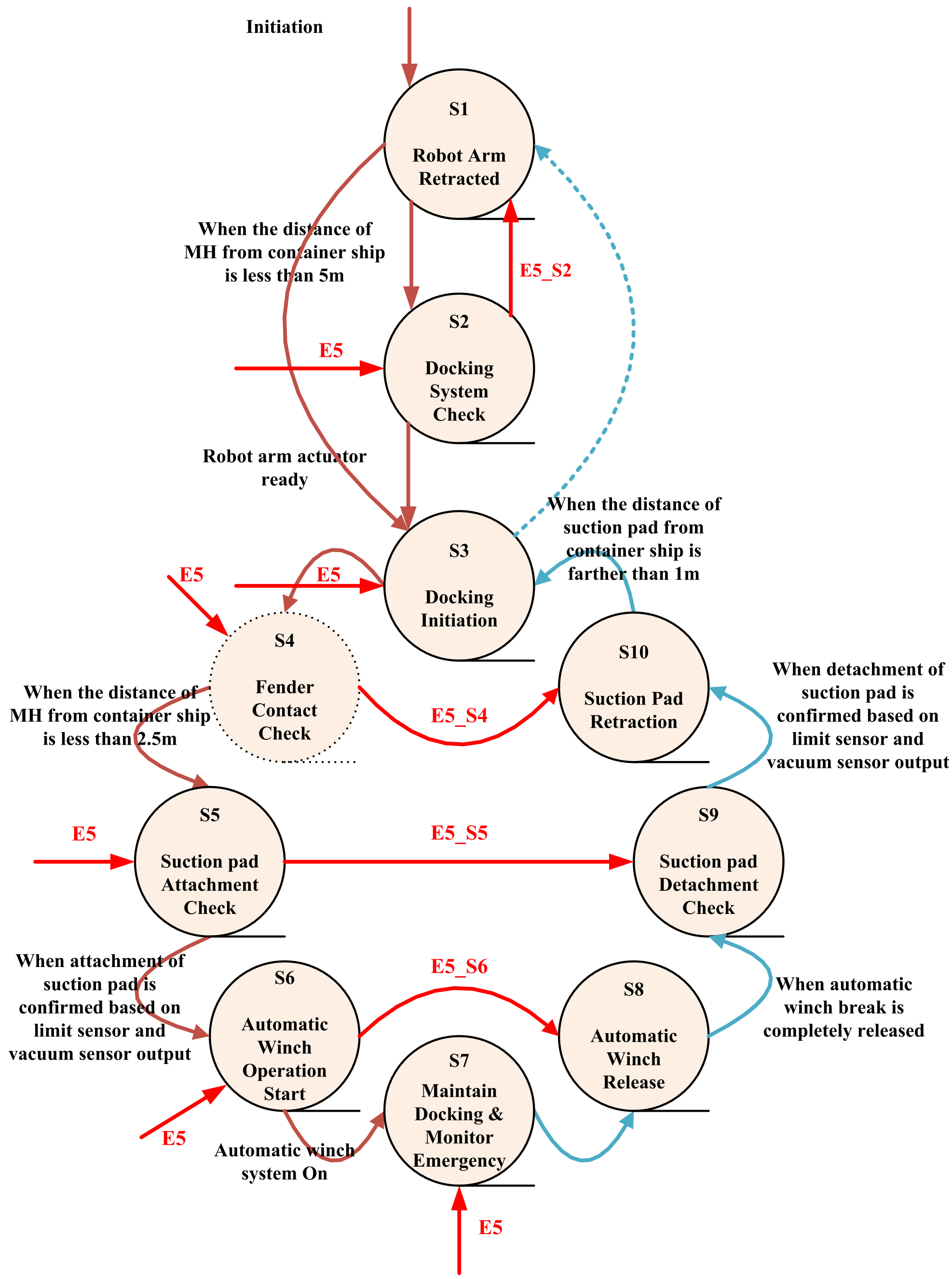


Fig. 13 The E5 emergency procedures from different control states (shown as *red arrows*)

MTi-G, XSENS Technologies B.V., Netherlands) mounted on the deck of the barge ship are summarized in Table 7 for the whole demonstration period. A more detailed relative six degrees-of-motion between the ships were precisely measured using a 3-D motion capture device that utilized a six degrees-of-motion marker attached on the hull surface of the target ship and a 3-D motion capture sensor camera mounted on the barge (Optotrak Certus, Nothern Digial Inc., Canada) as shown in Fig. 15b. The exemplary data on the detailed measurement of the relative six degrees-of-motions between the two ships from the tests conducted on 24 April 2011 are shown in Figs. 16 and 17. The trajectory of the marker point on a horizontal plane showing the shift of relative movement ranges from docking state to released state in Fig. 18. It shows that the range of horizontal displacement became much smaller in the docking state (docking state: 0.9 m; released state: 1.4 m) creating better environment for the crane operation.

In addition, it was also confirmed that other motions of the ships notably decreased after establishing docking, and that the maximum rolling angle was confirmed to have been reduced from ±1.0° before docking to ±0.3° after

Fig. 14 Open-water ocean demonstration of the ship-to-ship automatic docking system from a barge

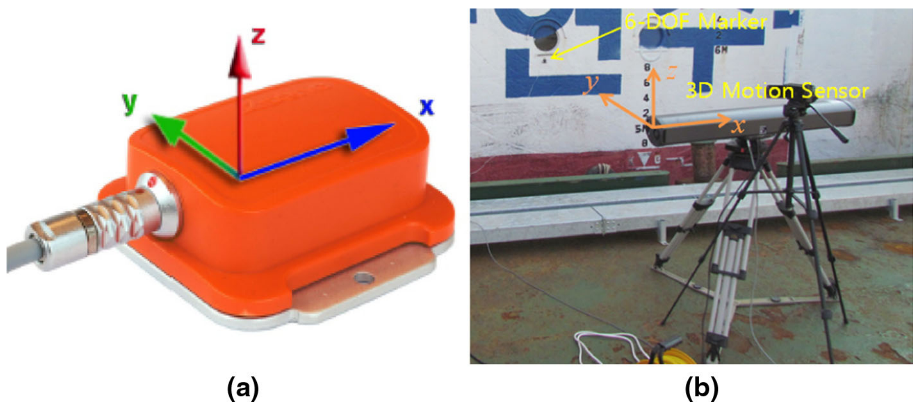


Fig. 15 Motion capture devices used for absolute roll motion of the barge and the relative six degrees-of-freedom (6-DOF) movements between the ships (**a**) gyro sensor (**b**) high precision six degrees-of-freedom motion capture device

docking, a decrease of 70 % based on the gyro sensor measurements. This indicates that the new automatic docking system can contribute to reducing the floating body motions in the ships, as well as accomplishing ship-to-ship docking. During the ocean demonstration, the docking condition was tested up to Sea State 3 and for the total of 12 h. The S2S-ADS thus successfully performed its intended functions.

The emergency operation was also tested during the ocean demonstration. While the docking state was maintained, an external emergency signal was randomly given to the docking system and the time required for emergency operation was verified. For every trial, it took less than 5 s for the vacuum pad to be detached and less than 15 s for the system to wind the cables and go into the storage mode for safety.

5 Concluding remarks

Loading and unloading cargo directly between two ships on the open-water area in ocean provide diverse advantages including the potential for providing port functions in areas that have poor facilities or shallow-water depths. However, under sea conditions affected by currents, waves, and wind; working with traditional cables not only consumes too much time and human labor, but also heightens the risk of accidents. To resolve such problems, the present study was focused on development of a S2S-ADS that can automatically perform docking between the two ships safely and quickly, even in sea states with considerable level of waves and winds, and maintain such conditions that cargo handling can be performed efficiently between the two ships. The outcomes of this work can be summarized as follows:

Table 7 Observations of the range of absolute roll angle measured by the gyro sensor mounted on the deck of the barge ship in the ocean demonstration

Date time	Sea state	Docking force (ton)	Docking time (min)	Maximum Roll angle before docking (°)	Maximum roll angle after docking (°)
04/18/2011 14:00	3	2	20	±1.5	±0.5
04/21/2011 15:00	2–3	5	20	±1.5	±0.5
04/24/2011 15:00	1–2	2	10	±2.0	±1.0
04/25/2011 14:00	2	2	60	±1.5	±0.8
04/26/2011 14:00	1	5	10	±1.0	±0.3

- A solution for ship-to-ship automatic docking operation is presented.
- A design process capable of determining the system specifications was established, and the number and the arrangement of the units required for the ship-to-ship automatic docking were determined.
- The detailed design of the automatic docking system for a 5000 TEU container ship and a 250 TEU MH was accomplished, and a prototype of the automatic docking system for the ocean demonstration was redesigned and developed in actual form.
- The measurement of the relative and absolute motions of the barge ship where the prototype of the developed S2S-ADS was mounted showed reduction of relative motion as well as the intended function of maintaining relative distance between the two ships up to Sea State 3.
- The emergency release and other key operation procedures of the automatic docking system were confirmed by measuring the separation time and the relative

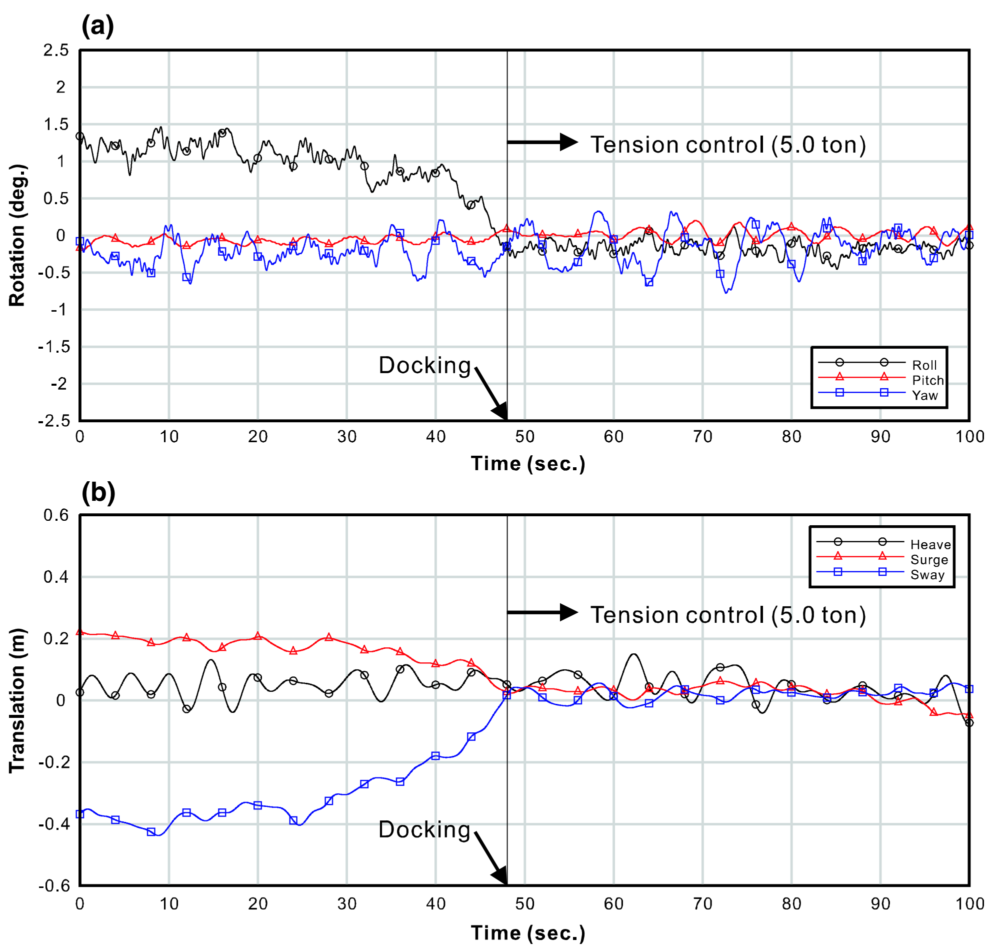


Fig. 16 Change in the relative motion of the other ship measured by a motion capture device mounted on the barge during docking engagement operation (24 April 2011): **a** roll, pitch and yaw; **b** heave, surge and sway

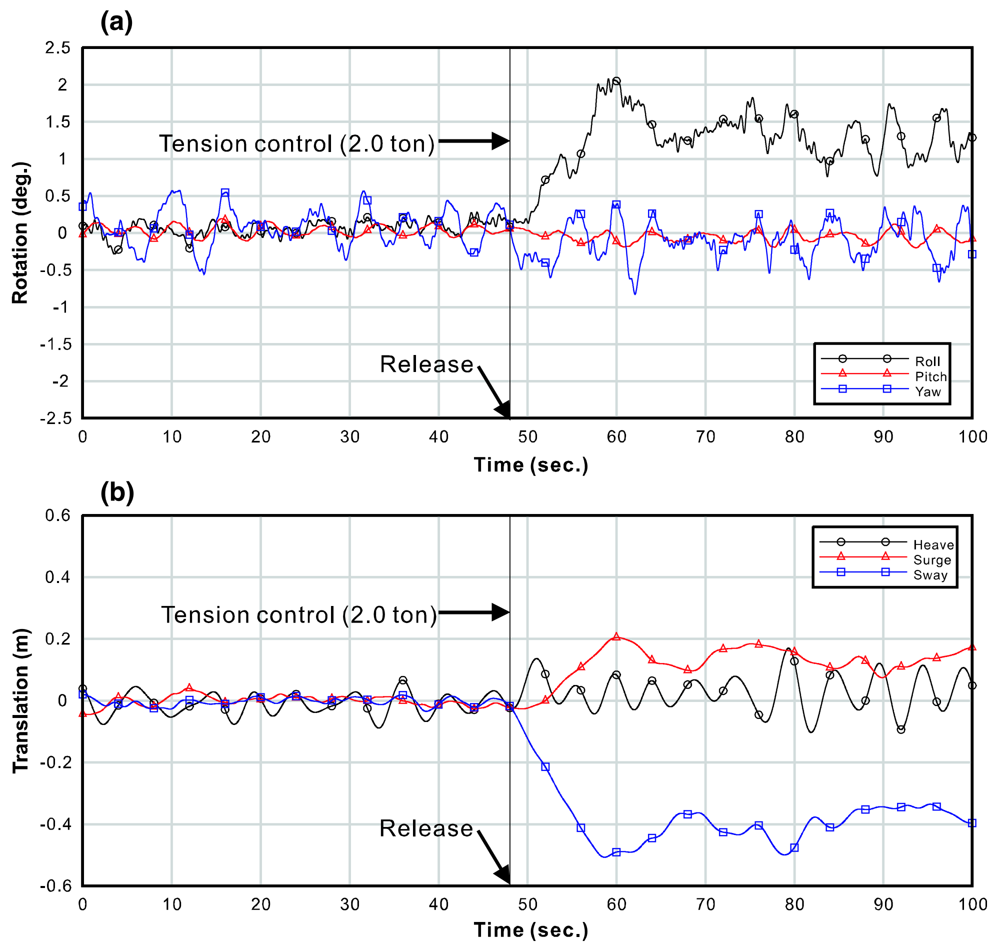


Fig. 17 Change in the relative motion of the target ship measured by a motion capture device mounted on the barge during docking release operation (24 April 2011): **a** roll, pitch and yaw, **b** heave, surge and sway

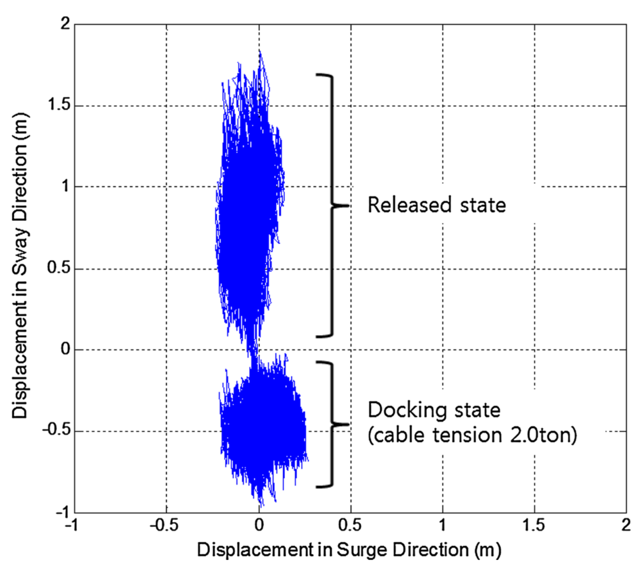


Fig. 18 The relative trajectory on a horizontal plane for a point on the 6-DOF marker attached to the hull surface of the target ship measured from barge ship showing different movement ranges in docking and released states

movements, thus verifying the key performance of the new S2S-ADS.

The first open-water S2S-ADS in the world has been developed, and confirmed to be applicable to actual MHs. In the future, the ship-to-ship automatic docking technologies may be extended to automatic tasks that requires docking in diverse conditions involving cargo transfers in ship-to-ship or ship-to-offshore situations, including LNG ships with FPSO vessels and LNG ships with offshore jetties, in addition to MHs. Furthermore, application of the automatic docking system to the quay docking of passenger ships, where docking time is considerable in proportion to lay time, is also possible. Moreover, diverse applications can be developed in the future using requirement analyses and necessary adjustments.

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