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DP Design & Control Systems 1

An Overview of the Berkeley Mobile Offshore Base Dynamic Positioning Project

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Abstract

The Mobile Offshore Base (MOB) is a large, self-propelled, floating, pre-positioned ocean structure formed of three to five modules and reaching up to 1,500 meters in length. It must accommodate the landing and take-off of C-17 conventional aircraft, host 3000 troops, carry 10 million gallons of fuel and provide 3 million square feet of internal configurable storage. The alignment of the modules is maintained through the use of slew-able thrusters and/or connectors.

The University of California at Berkeley's involvement with the ONR Mobile Offshore Base project resulted in a three-year effort meant to provide insight into the design and architecture of coordinated DP systems (systems involving the DP of a structure or vessel relative to another floating ocean structure or vessel), a simulation environment in which different MOB concepts could be tested and evaluated, and an experimental scaled platform (1:150) on which the coordinated DP control algorithms were implemented and evaluated.

Introduction

The concept of a floating, at-sea base stems from the necessity for the United States to be able to stage military and/or humanitarian operations in any part of the world [7]. The Mobile Offshore Base is a very large floating ocean structure meant to provide the same capabilities as an on-land army base. It must accommodate the landing and take-off of C-17 conventional aircraft, host 3000 troops, carry 10 million gallons of fuel and provide 3 million square feet of internal configurable storage [8]. The modules forming the MOB must be able to perform long-term station keeping at sea, in the presence of waves, winds and currents. This is usually referred to as Dynamic Positioning (DP) control [5,6]. Dynamic positioning is further complicated in the presence of multiple ships whose operation has to be coordinated, thus extending the scope of DP with maneuvers under tight constraints. The breadth of potential applications has significantly increased the interest in this multi-disciplinary technology. Applications range from the Mobile Offshore Base (MOB), to cargo transfer between ships (with special interest to logistic fleets), to thruster assisted mooring and automated docking. In some concepts, the MOB is formed of multiple independent modules, which remain tightly aligned through the use of rotating thrusters. The DP system must maintain overall orientation and relative position between modules.

The CASSETTE (Development and Demonstration of Control And SyStem EvaluaTion TEchniques) project from PATH – University of California, Berkeley is part of the MOB technical base effort devoted to determining the feasibility of dynamic positioning of multiple MOB platforms. In this project we have developed an automated multi-module dynamic positioning control system for the MOB, and a simulation template to uniformly support DP control systems testing and evaluation. The virtual demonstration consisted of the simulation of several different MOB control methods under a set of environmental conditions, and we compared control system performances using an evaluation toolkit that was also developed during the project. Scale models of the MOB are being used to validate the key design issues and the results of the simulation.

In this paper, we address the general DP problem for standalone and multiple vehicles using an interdisciplinary approach that draws from ocean, electrical and mechanical engineering. In particular, we will consider dynamic positioning simulation and evaluation in the specific context of a MOB. A simulation framework has been implemented in SHIFT, a specification language for hybrid systems [9]. Libraries of mission scenarios, control techniques and strategies, platform and actuator models and disturbance models can be combined to create custom simulations. A laboratory testbed consisting of three scaled (1:150) models of MOB platforms has been developed and is used to evaluate concepts and validate simulation results.

The paper is organized as follows. We will start with a discussion of the adopted control architecture and coordinated DP strategy that were chosen. The control problem is complicated as the different structures must assemble at sea, station-keep, and disassemble. The assembly must also be able to rotate into the wind. These different problems were organized as maneuvers, and control algorithms switch from one maneuver to the next as needed or dictated by an operator [1].

One option for the DP control law itself is based on a variant of sliding mode control called "dynamic surface control" [2]. It commands a desired force system to the thruster allocation module, which uses dynamic programming methods to select an orientation and thrust level for each of the slewable thrusters [3]. The algorithms were simulated for different module configurations and environmental conditions up to sea state 6. The control system was then ported to a experimental setup consisting of three scaled modules, running in a basin at the Richmond Field Station facility. The scaled modules were equipped with scaled thrusters and laser and acoustic position sensors [4]. Simulation and experimental results will be presented in the paper, as well as the detailed control algorithms and a discussion of scaling effects in the test basin.

Control Architecture

This section presents a hierarchical architecture for Mobile Offshore Bases (MOB) control. By a control architecture we mean a specific way of organizing the motion control and navigation functions performed by the MOB, and the smooth switching between these functions. It is convenient to organize the functions into hierarchical layers. This way, a complex design problem is partitioned into a number of more manageable sub-problems that are addressed in separate layers. The decomposition also allows for modular design and testing and the incorporation of plug-and-play components.

We propose a hierarchical control architecture for control and maneuver coordination of multiple modules within the MOB. Example maneuvers include: forming or breaking connections between MOB components, and reorientation of the entire MOB string in the direction of the wind. The proposed architecture distributes information and control authority among modules and deals with exceptions and faults. It is organized hierarchically, with the lower layers of the hierarchy consisting of continuous controllers that interact with the sensors and actuators to produce the desired positioning and tracking performance. Higher layers of the hierarchy will be modeled by discrete event systems used for maneuver coordination, fault identification, and reconfiguration. These layers sequentially organize the generation of the optimal coordinated trajectories for all modules (global control), the optimal trajectories for each module (module control), the optimal trajectory tracking schemes, and the optimal motor controls (local control), to name a few. The de-coupling of optimization problems eventually compromises the overall optimality but makes the problem tractable. Hence, the architecture represents an empirical compromise between tractability and optimality. It will become apparent that the task is formidable, even in a reduced setting. Here we give an overview of what is involved, describe the key design concepts and establish a framework for tackling the problem. The interested reader is referred to [10].

One of the MOB mission requirement under analysis is the capability to support sea and air operations. In order to achieve this goal the MOB is required to:

- Be aligned with the dominant wind, local currents, waves, etc. that may introduce transverse perturbations.
- Remain operational for CTOL (conventional take-off and landing) aircraft through Sea State 6.
- Disassemble to survive worse environments, wind and wave drift forces, deriving from Sea State 7.
- Reassemble when the environment reduces to Sea State 6.

The availability for air operations is the single most important measure of effectiveness of this capability. The anticipated modes of operation are as follows:

- Unassembled mode: each individual module maintains a prescribed position and orientation.
- Assembled mode: the MOB assembly maintains a general position and orientation, and the individual modules maintain relative positions and orientations.
- Transitioning modules: independent modules are in preparation for mechanically connecting/disconnecting the modules end-to-end. Each transitioning mode corresponds to some prescribed sequence of operations. There are two major transitioning modes:
    - The normal mode where the assembling and disassembling operations are executed one platform at a time.
    - The emergency mode, where disassembling is executed as fast as possible under survival conditions deriving from Sea State 7.

The MOB operation requires adaptation to the environmental conditions. By adaptation we mean the downgrading of some specifications to be able to fully accomplish the operational requirements.

Mission Profiles

An example of a typical mission is presented below. In a first time, several independent modules assemble to form a MOB. This requires position and speed controllers for each module, a dynamic positioning controller for the immobile module(s) and a docking controller for the approaching module.

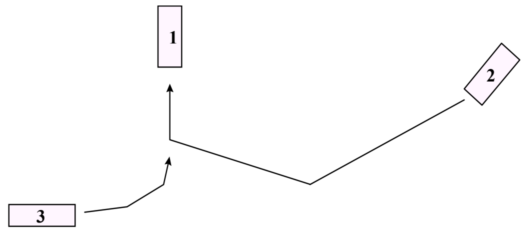

Figure 1. From Unassembled Mode to Assembled Mode.

Then, the group goes to and maintains a desired position while aligning with the wind. After a given period of time, the MOB breaks-up and the modules return to independent operation. This phase assumes that the assembled MOB will be able to perform dynamic positioning, alignment into the wind, and wind tracking. Also, individual modules need speed and position control for the disassembly phase.

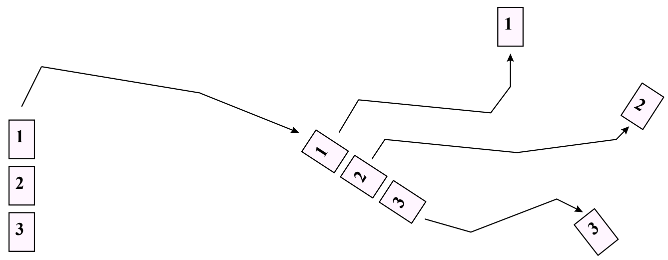

Figure 2. From Assembled Mode to Unassembled Mode.

Examining this profile, we extracted a finite, exhaustive number of maneuvers that can be used to form all MOB missions. Should the need for additional maneuvers arise, the architecture is sufficiently flexible to accommodate them with minimal changes.

Design Process

The control architecture design will consist of the following steps:
1) Deciding on the number of levels, their role, their descriptive language and the way they interact.
2) Identifying the information that is needed at each level to make meaningful decisions.
3) Designing interfaces to the sensing and communication architecture.

The design process benefited from the PATH experience in the motion coordination of multiple vehicles [11]. The PATH architecture design organizes individual motions into a small number of prototypical maneuvers that are used as atoms for more complex prototypical maneuvers involving the motion coordination of several vehicles. Prototypical motions can then be verified for safety and consistency as required by the safe operation of the whole system. This same organization was mapped onto the formal layered PATH architecture.

Although less structured than an automated highway, the control and coordination of the MOB can be decomposed according to the same principles. The movement of modules is realized through basic maneuvers (as described below) that are coordinated.

To complete a mission as described in the previous section, five separate controllers are necessary:
- go to a specified location (move MOB),
- assemble with other modules (assemble MOB),
- dynamically position (DP MOB)
- align in the wind (align MOB in wind),
- split up MOB.

Hence there are five different specific maneuvers for each module to perform. These maneuvers, in turn, require the consideration of a finite number of atomic control laws:

a) The "go to a point" law allows the module to move to a specified location.
b) The "trajectory tracking" law is a more refined version of the previous one, which allows you to track a trajectory. This is particularly useful for assembling and splitting up the modules of a MOB.
c) The "decelerate to assemble" law is used to control the speed of the platform accurately while assembling. This is necessary to avoid collisions and increase the precision of the assembling maneuvers.
d) The "dynamic positioning" law is used to maintain the alignment of the platforms and control their inertial and relative positions.
e) The "leaderless", "first as leader", "middle as leader" and "follower" laws all refer to different schemes to distribute the control between platforms. These are described in more detail in [11].

After identifying the atomic laws, the requirements in terms of actuator, sensor and communication capabilities were laid out, as shown in figure 3.

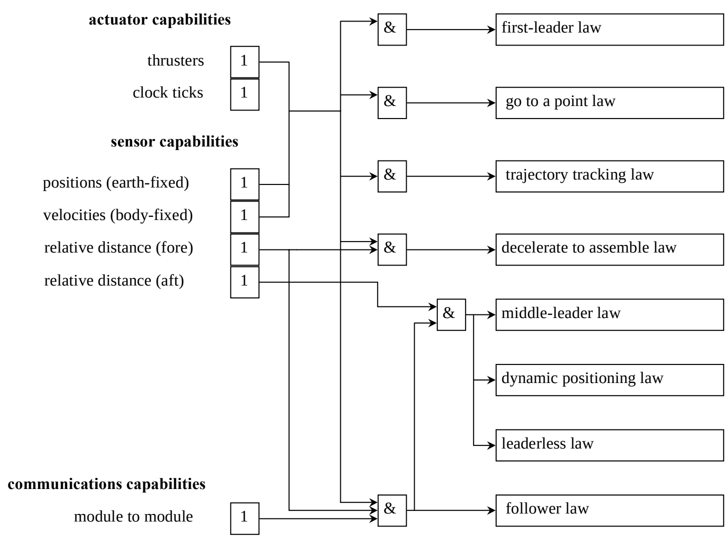

Figure 3. System Requirements for Atomic Laws.

The atomic laws can be combined to form all the basic maneuver laws, as illustrated in figure 4. A collision avoidance law is presented to make the set complete, but has not been implemented or tested yet.

Each basic maneuver is paired with a compatible reference generator.

At this point, a controller was designed for each of the basic maneuvers. Each basic maneuver requires a hybrid controller that coordinates the execution of the underlying atomic laws and the corresponding reference generator according to the logic encapsulated in a state machine. The controllers and reference generators all use the laws described in figures 3 and 4. A complete design for all layers and accompanying controllers is presented in [10].

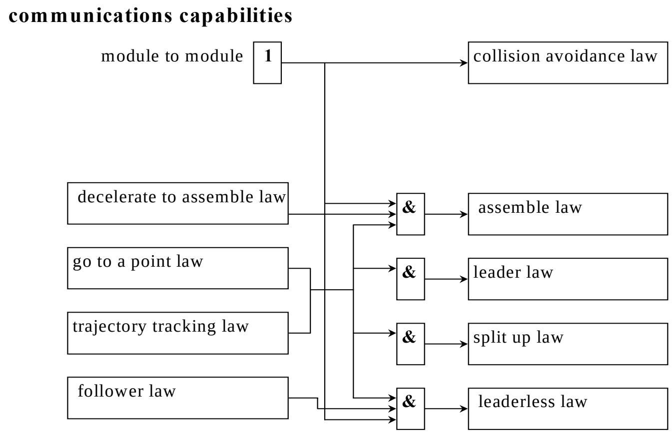

Figure 4. Combination of Atomic Laws to Obtain Basic Laws.

Control Algorithms

Dynamic Surface Control Approach

The equations of motion of a MOB module when derived in their complete form are quite complex, not only because of the sheer number of equations and forces, but also because the hydrodynamic force models are complex. In this section, we present the low frequency model of the platform dynamics that was implemented and used for the controller design. This model describes the motions of the dynamically positioned system.

The motion of the body-fixed frame is described relative to an inertial frame. The inertial frame is denoted (X_E, Y_E, Z_E) where the subscript "E" stands for "Earth-fixed". Typically the inertial frame is chosen so that X_E points north, Y_E points east, and Z_E points downward towards the center of the Earth. Consider for now the 2D problem. In the (X_E, Y_E, Z_E) frame, the platform has a position vector $\underline{\eta}$, with components [x, y, ψ], where x and y designate the position and ψ is the heading angle. In the inertial frame a velocity vector, $\underline{\dot{\eta}}$ can also be defined, with components $[\dot{x}, \dot{y}, \dot{\psi}]$.

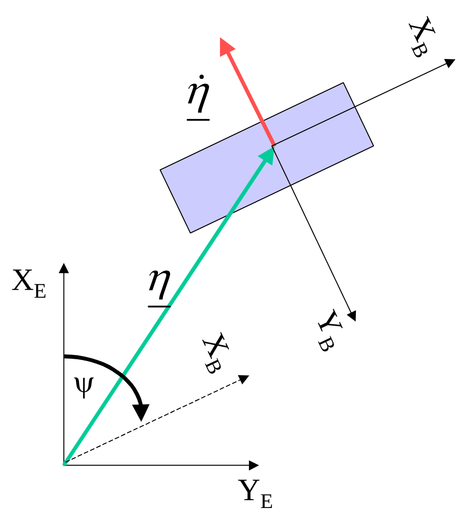

Figure 5. Inertial (Earth-fixed) and body-fixed frames for the derivation of the equations of motion.

The position and the velocity are vectors, and can be expressed in any basis. It is convenient when thinking about vehicles to define a body-fixed frame, say (X, Y, Z). The Society of Naval Architects and Marine Engineers (SNAME) has dictated standards for choosing the body-frame [6], so that the X-position is directed from aft to fore, the Y-position is directed to starboard, as shown in figure 5, and Z is pointing downward.

A free-floating body in the ocean moves in all six degrees of freedom. In dynamic positioning of vessels, we want to control a vessel (or platform) on the ocean surface with respect to the ocean floor. This is because traditionally, dynamic positioning is used to connect an oil well on the sea floor with a vessel on the surface using a pipeline. Dynamic Positioning vessels are not generally equipped with actuators in heave, roll or pitch. We consider the two-dimensional problem where we deal with the surge (X_B-position), sway (Y_B-position) and yaw (rotation about Z_B) motions.

The equations of motion which describe the low-frequency motion of a surface vessel can be written in the body-fixed frame as [12]:

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu = \tau + \tau_{env} \tag{1}$$

$$\dot{\eta} = J(\eta)\nu \tag{2}$$

where:

- $\nu = \begin{bmatrix} u & v & r \end{bmatrix}^T$ is formed of the body-fixed components of the Earth-fixed velocity vector of the platform,
- $\dot{\eta} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{\psi} \end{bmatrix}^T$ is the velocity of the platform in the inertial frame,
- M is the mass plus added mass matrix of the platform, (from the physical standpoint, the added mass represents the amount of fluid accelerated with the body),
- $C(\nu)$ is the Coriolis and centripetal matrix,
- $D(\nu)$ is the damping matrix,
- τ represents the body-fixed forces from the actuators,
- τ_{env} represents viscous drag and forces due to the environment (wind, waves and currents),
- $J(\eta)$ is a transformation matrix between the inertial and body-fixed coordinate frames, with:

$$J(\eta) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{3}$$

In these equations we have assumed zero current velocity as a simplification for controller design. Also, the equations are in two dimensions (that is, we consider three degrees of freedom). The thrusters only counteract the "horizontal" forces and act in surge, sway and yaw. The "vertical" motions, heave (Z_B position), roll (rotation about X_B) and pitch (rotation about Y_B), are not considered here. For conventional ships and platforms, rolling and pitching motions have zero-mean and limited amplitude.

The total motion of the ship in waves is given by the sum of a low-frequency component and a wave-frequency motion. The low-frequency component is separated out from the measured total ship motions by a wave filtering system. Attempting to control the oscillatory motion due to the waves causes wear and tear on the thrusters, and in general actuator bandwidth is insufficient to counter those motions efficiently. Several filters as well as a nonlinear observer have been developed for the filtering of these motions [13].

Non-Linear Control of One Vessel

The control problem is to choose the actuator forces to be applied such that the vessel reaches desired inertial coordinates,

$$\eta_d = [x_d, y_d, \Psi_d]^T . \tag{4}$$

We utilize the "Multiple Sliding Surface" (MSS) [14] and "Dynamic Surface Control" (DSC) [15] methods as well as the "Slotine and Li" algorithm [16], which was adapted to the control of underwater vehicles by [6].

The MSS controller involves two "sliding surfaces" [17]. The first surface defines the desired vessel position and orientation. The second surface defines a desired velocity, which, if maintained, will drive the vessel to its desired position. Thruster forces are chosen such that the second surface approaches zero.

The first surface is defined as:

$$s_1 = \eta - \eta_d . \tag{5}$$

Differentiating s_1 yields:

$$\dot{s}_1 = J(\eta)\nu - \dot{\eta}_d . \tag{6}$$

At this point a desired velocity, or "synthetic control", ν_d is defined as:

$$J(\eta)\nu_d = \dot{\eta}_d - \Lambda_1 s_1 , \tag{7}$$

where Λ_1 is a positive definite matrix. With this definition, if $\nu = \nu_d$, then:

$$\dot{s}_1 = -\Lambda_1 s_1 , \tag{8}$$

and $s_1 \rightarrow 0$ with a convergence rate determined by the choice of Λ_1. Because of the definition of s_1, this will also guarantee that $\eta \rightarrow \eta_d$.

The second sliding surface could be defined as $s_2 = \nu - \nu_d$, but computing the derivative of s_2 could lead to a very complex control law. A method called Dynamic Surface Control (DSC) [15] eliminates the need for model differentiation. First, we pass ν_d through a bank of first order filters:

$$T\dot{z} + z = \nu_d , \tag{9}$$

where T is a diagonal matrix whose elements, T_{ii}, are the filter time constants. These are chosen to be as small as possible, consistent with numerical conditioning problems. "z" now serves as an estimate of ν_d, with a derivative that is easily computed as:

$$\dot{z} = T^{-1}(\nu_d - z) . \tag{10}$$

Using z in place of ν_d, we now define the second sliding surface as:

$$s_2 = \nu - z . \tag{11}$$

At this point, a Lyapunov approach [16] can be drawn upon. We select a Lyapunov function candidate to be:

$$V = \frac{1}{2} s_2{}^T M s_2 \tag{12}$$

Differentiating V and using Equations (1) and (11) yields:

$$\dot{V} = s_2{}^T [M\dot{\nu} - M\dot{z}] = s_2{}^T [\tau_T - C(\nu)\nu - M\dot{z}] \tag{13}$$

where τ_T, the thruster force, is considered the only force acting on the vessel for the purpose of controller design. If τ_T is selected as:

$$\tau_T = C(\nu)\nu + M\dot{z} - K_D s_2 \tag{14}$$

where K_D is a positive definite, symmetric gain matrix, then:

$$\dot{V} = -s_2^T K_D s_2 \tag{15}$$

which guarantees that $s_2 \to 0$. This in turn implies that $\nu \to \nu_d$, $s_1 \to 0$ and $\eta \to \eta_d$. Using equation (10), the control law can be written in terms of z:

$$\tau_T = C(\nu)\nu + MT^{-1}(\nu_d - z) - K_D s_2 . \tag{16}$$

Control of Multiple Vessels/Modules

There are a great number of different possible strategies for coordinating MOBs. The goal of every strategy is to position the vessels in a straight line with tight relative spacing constraints. Three control strategies have been tested and implemented [11], using either the first or the middle modules as leaders in follow-the-leader type algorithms or using leaderless control where each module tracks an inertial reference and maintains a desired relative spacing with respect to the other modules. The best results were produced by the leaderless approach, using:

$$1^{st} \text{ vessel: } s_1^{\,1} = \eta^1 - \eta_d^{\,1} + \Lambda_r(\eta^1 - \eta^2 - \eta_d^{\,12}) , \tag{17}$$

$$2^{nd} \text{ vessel: } s_1^{\,2} = \eta^2 - \eta_d^{\,2} + \Lambda_r(\eta^2 - \eta^1 - \eta_d^{\,21}) + \Lambda_r(\eta^2 - \eta^3 - \eta_d^{\,23}) , \tag{18}$$

$$3^{rd} \text{ vessel: } s_1^{\,3} = \eta^3 - \eta_d^{\,3} + \Lambda_r(\eta^3 - \eta^2 - \eta_d^{\,32}) , \tag{19}$$

where η_d^{ij} is the desired relative spacing between modules i and j. The above notation allows us to see clearly the interactions of the two separate terms, with the first part of each s_1 surface dealing with tracking an inertial position, and the second part dealing with adjustments to the relative position. One reason to separate both terms so explicitly is that for the MOB, the absolute position of the assembled platforms does not have tight requirements, as pilots can easily spot the structure from the air or receive broadcasts giving the exact position of the floating runway. However, fuel economy is a significant issue, and the assembled MOB should be allowed to drift within reason. Yet the relative alignment of the platforms is of paramount importance for landing planes. The two-tiered control laws as presented in equations (17-19) allow us to make this distinction clear. If one only uses absolute positions, fuel consumption may be higher than needed. If one only controls relative platform positions, the assembly may drift significantly.

By adjusting the diagonal elements of Λ_r, the importance of absolute versus relative errors can be changed, with higher values corresponding to tighter relative position accuracy. Some of the attractive features of this approach are: 1) guaranteed string stability [18] since each vessel has an inertial reference, and 2) identical control structures can be used for both de-coupled and coupled maneuvers. If it is desired to de-couple the vessels and send them to arbitrary locations, then $\Lambda_r \equiv 0$ and η_d^{i} is defined for each separate vessel. Here by coupled we mean that the modules directly consider the position of their neighbors (coordinated positioning), and by decoupled we mean that the modules act independently of one another.

Simulation and experimental results are presented for the DSC approach.

LOS Approach

In this approach, the MOB assembly is modeled using a set of generalized coordinates that describe the location, orientation, and shape (relative positions) of the system, leading to a set of equations of the form

$$M\dot{\mathbf{v}} + C\mathbf{v} = \boldsymbol{\tau}$$

in which the left side includes forces due to both body inertia and added mass and the right side is a generalized applied force vector. This approach can incorporate both independent and connected modules. A feedback control law can be written in the form

$$\boldsymbol{\tau} = M\mathbf{v} + C\mathbf{v}$$

with the synthetic input chosen to provide suitable closed-loop error dynamics in location, orientation, and shape coordinates.

$$\mathbf{v} = \begin{bmatrix} \mathbf{v}_L & \mathbf{v}_O & \mathbf{v}_S \end{bmatrix}^T$$

Developing the controls in this way allows the rigid and flexible modes of the system to be tuned independently. This is important for a system such as the MOB, in which relative position and orientation need to be controlled more tightly than absolute position and orientation. Further details may found in [21] and in forthcoming publications.

Simulation Results

The feasibility of coordinated DP has to be evaluated under a representative sample of environmental disturbances in order to obtain statistically meaningful results. We ran Monte-Carlo simulations in a simulation environment to obtain these results. A model of the platforms has been developed using the standard equation of motion for ships [6, 12] and outputs from the WAMIT [19] software package. WAMIT generates the hydrodynamic parameters that are needed to model the platform dynamics and wave forces.

The objectives of the simulation are to evaluate different dynamic positioning control systems under a common set of platform models and environmental disturbances. MOB concepts were tested in a large range of scenarios with sea states ranging from 4 to 6, and in the presence of solitons.

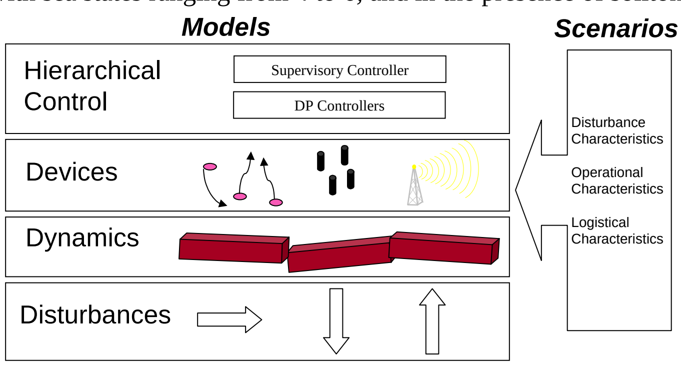

Figure 6. Design and evaluation perspective.

For the purpose of dynamic positioning control systems design and performance evaluation, the MOB system comprises a hierarchical control architecture and independent systems. Each independent system consists of a semi-submersible platform, a power plant, thrusters, sensors, flexible bridges and/or connectors. In the context of the feasibility evaluation of DP, the evaluation framework comprises:

1) A test plan and a set of evaluation criteria.
2) An Evaluation Toolbox that automates the execution of the test plan and the evaluation of the test runs.

The test plan, consisting of a set of test cases, is organized in terms of a combination of utilization environments (specified in terms of disturbances, including waves, wind and currents) and operational scenarios (module type and maneuvers). For each operational scenario there are several utilization environments [20].

The evaluation criteria consist of several measures of effectiveness that reflect the overall expectations. These include, among others, operability (uptime for air operations that is determined by the straightness and smoothness of the runaway) and performance.

In order to illustrate the coordinated control of the MOB under the control scheme discussed above, we have selected a representative test case from the simulations: reorientation of the string of modules in the direction of the wind. This is a non-trivial maneuver, which is generally not addressed in the literature, and where model nonlinearities and input saturation come into play.

In this maneuver, the vessels move from a horizontal alignment (the station keeping position) to a straight-line arrangement, rotated 10^o with respect to the x-axis, using leaderless control. This particular motion represents the rotation of the MOB into the wind. A string of three vessels is considered. Figure 7 displays the motions of all three vessels during this maneuver (note: the triangles representing the vessels are not drawn to scale). The second figure contains plots of the relative angular positions of the vessels. Clearly the controller helps to bring the MOB into alignment as the relative errors between vessels decrease with time and eventually go to zero (perfect angular alignment).

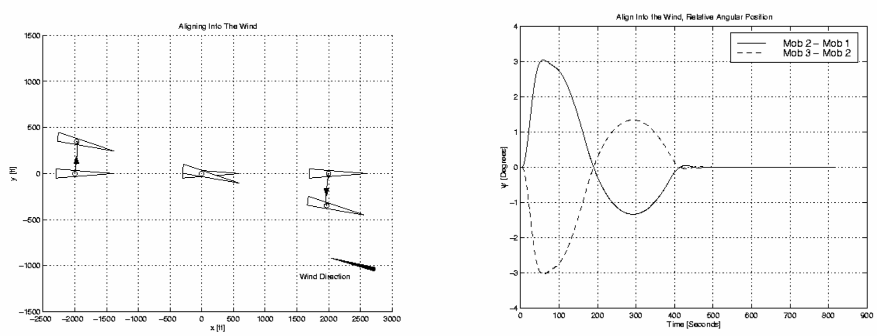

Figure 7. Aligning Into the Wind.

Experimental Setup and Results

In this section we discuss experimental results obtained with 1:150 scaled MOB modules. The modules were built as part of the MOB project. We discuss the setup first, then briefly consider scaling effects in the tank, and then show experimental results.

Setup

The PATH Program at UC Berkeley has developed a 1:150 scale physical model of a generic Mobile Offshore Base (MOB) concept. This concept utilizes three or more independently operable deep-sea going semi-submersible platforms that are used in conjunction with one another to create a stable sea-based runway for large cargo and other aircraft. The model consists of three 1.80m x 0.76m independent floating "modules", each equipped with four controllable (azimuth and thrust) thrusters and sensors that provide both inertial and relative position information. The models are operated in a 16m x 30m x 0.75m tank, located at the UC Berkeley, Richmond Field Station. The system is controlled by a real-time computer system located at the side of the tank.

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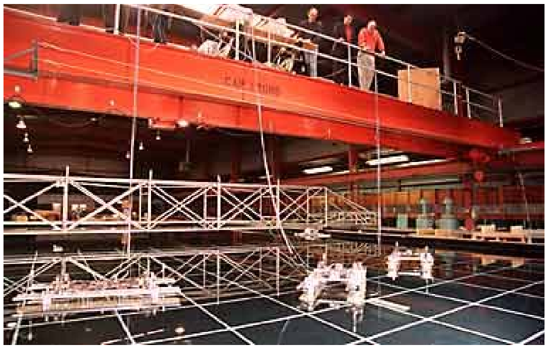


Figure 8. UCBerkeley Test Facility.

Scaled MOB Modules

The heart of the MOB physical model is the 1:150 scale module constructed from closed cell foam, acrylic plastic and aluminum tubing. The scale module is base on a full sized "generic" module developed by researchers at the US Naval Academy. The scale module is 1.8 meters long, 0.76 meters wide, has a draft of about 20 cm, and weighs close to 90 Kg. One module is shown in figure 9. Each module is equipped with four variable thrust, dirigible, ducted propellers; one mounted on each "corner". These thrusters were designed and fabricated at UCB and provide a true scale representation of the actual thrusters that would be used on full-scale modules [22]. The thrusters are electrically powered, with dc servomotors providing the variable thrust while stepper motors control the azimuth.

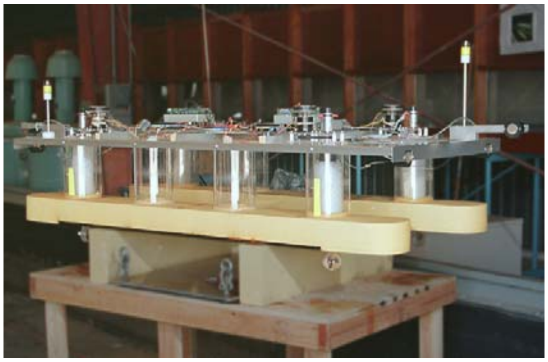
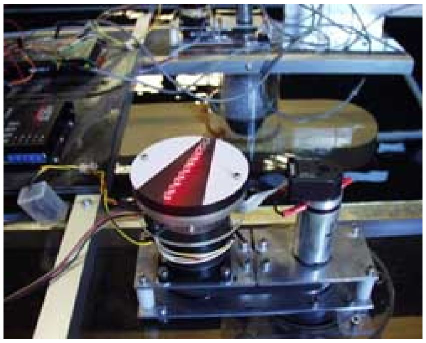


Figure 9. Scaled MOB module.

Visually, the most impressive feature of the models is the thruster indicator mounted on top of each of the thrusters. When in operation, a red LED "bar-graph" indicates the direction and magnitude of the thruster force vector. The tests are videotaped from above and the indicators will allow the video to be used as a first order of magnitude check of the system function. The indicators also give a quick visual reference as to what each module is doing and are quite useful for troubleshooting.



Figures 10 and 11. Scaled Thruster and Thruster Indicator.

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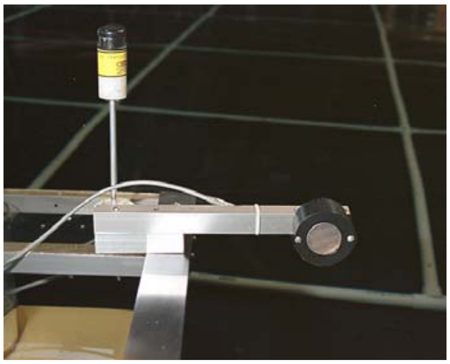
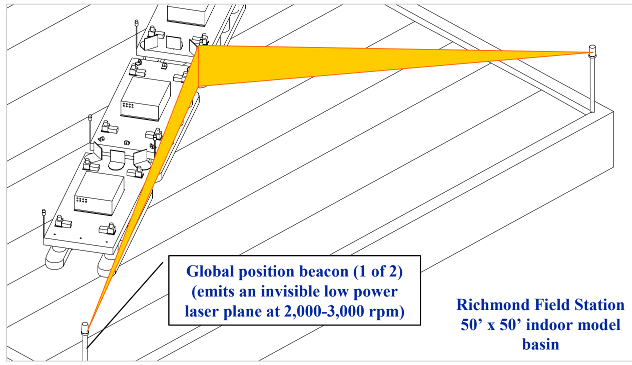
The modules are equipped with both absolute and relative position sensors. The absolute sensor system consists of a laser beacon/position transponder system using two “shore” mounted rotating laser beacons and two position transponders on each module. This system measures the position of transponders relative to the fixed beacon baseline on the side of the tank. Because there are two transponders on each boat, the position and orientation of each module can be determined in an inertial coordinate system. The accuracy of the system is approximately ±2 cm. The relative position measuring system consists of six ultrasonic sensors, three for each “gap” between the modules, which measure both longitudinal and lateral separation of the modules. The accuracy of this system is about ±2 mm.





Figures 12 and 13. Absolute and Relative Positioning Systems.

Computer Control System

The scaled modules are controlled from the “shore” of the tank by a network of computers. The control signals are passed to the modules via overhead “umbilical” cables one to each module. The computer system is composed of four computers, one that interfaces directly with the hardware and three that run the complex control algorithms. The interface computer is equipped with digital and analog I/O boards that connect to the modules via the umbilical cables; this computer in turn is connected to the other three computers with serial and Ethernet links. All of the computers run the QNX real-time operating system.

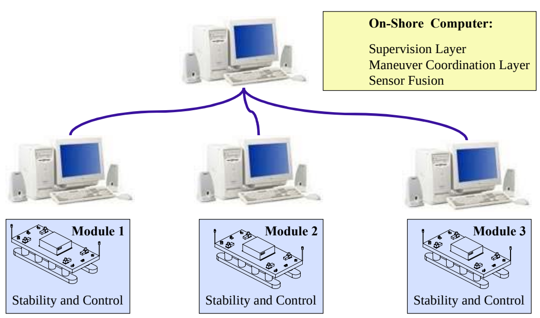
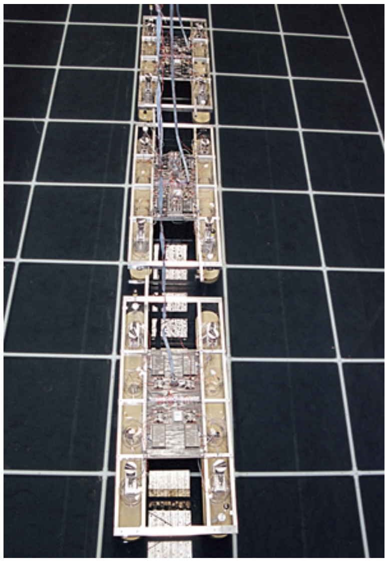
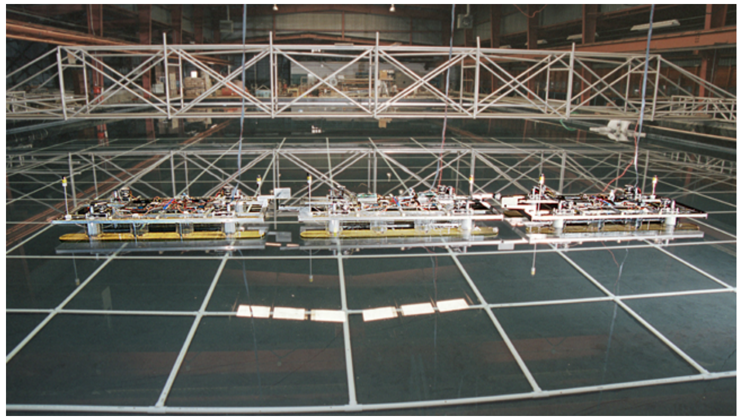


Figure 14. Computer Control System.

Test Facility

The system is operated in a large indoor tank of about 16m x 30m x 0.75m deep. This facility allows the testing of the small-scale models in the absence of external disturbances such as wind, but also provides the opportunity to introduce known disturbances into the system and measure the response.





Figures 15 and 16. Scaled Modules in Operation.

Goals of Model Testing and Scaling Effects

Because there is no experience base in the actual construction and operation of a MOB, the need to perform model tests during the various phases of the design process is more crucial than during the design of a conventional ship.

During the design of the MOB, a model of the behavior of the modules was required to select and optimize the various elements of the controller. Simulation was used, as it is impractical and overly time-consuming to expect to validate each variation of the design using model tests. To have reasonable confidence in the simulation tools, the behavior of the modules must be predicted adequately, in particular with respect to changes in performance with minor variations. The simulation tool developed during the project was discussed earlier. An important engineering goal of the experiments has been to validate that all of the important hydrodynamic phenomena have been identified and captured in MOB-SHIFT. This was accomplished by careful comparisons of MOB-SHIFT behavior predictions with the performance of the experimental models. This has allowed us to use MOB-SHIFT simulations with confidence to evaluate particular control system designs for the MOB through exhaustive simulation in a variety of environmental conditions and for a variety of operational scenarios.

One of the questions that is evoked during the planning and construction of physical models is that of scaling. Test basin considerations limit the range of possible scales to somewhere between 1:100 and 1:200. Dimensional analysis, through the use of the Buckingham-Pi theorem [12], guarantees that the physics for a model experiment will match that of the full-scale situation if and only if the dimensionless parameters formed from all of the governing variables are matched exactly. In practice, this condition is nearly impossible to meet, as it requires conflicting values for many of the test parameters. In particular, fixing the Froude number for the MOB guarantees that the physics of wave action at the model scale are identical those at full scale; matching the Reynolds number is functionally impossible for MOB testing, at the scales considered. On a small model scale, it is impossible to model the viscous effects (Reynolds number) and wave effects (Froude number) simultaneously. Further, because of the lack of viscous and surface tension effects, scale-model thrusters do not perform like the full-scale thrusters if the scaling calls for too small a thruster diameter. As a result, one usually needs to compromise between model scale (larger is better) and cost (costs for both construction and testing increase drastically with size).

When choosing the model scale for our experiment, we considered the purpose of the experiment, viscous drag forces, handling of the model, model function, and size of the test facility. In a first phase, we built relatively small models (1:150 scale). This choice allowed us to float three scaled MOB modules in the Berkeley basin, and each model is large enough to carry the appropriate control computers, thrusters and actuators. A model of this size is just large enough to be tested in a basin and avoid major surface tension and capillary wave problems. There are drawbacks to models this small, of course, with the main issues being propeller (thruster) scaling and viscous drag forces. As mentioned above, scaled thrusters do not perform like full-scale thrusters if viscous effects are not scaled, and scaling the viscous effects properly is functionally impossible. For our experiments, the thruster is approximately 4.7cm in diameter, and thrust characterization (that is, thrust versus propeller rpm) does not scale up correctly. However, the thrusters have been designed to have the correct scaled azimuth control (rotation speed and accuracy), and the correct thrust time constants. The only thing that does not scale correctly is the thrust to propeller rpm curve. This means that the thruster/thruster and thruster/hull interactions may not be the same as those in a full-scale module, and that the lowest-level control law for the scaled thruster would not be applicable to the full-scale units. Viscous drag forces are more difficult to characterize, but ship models are almost universally tested in water and theoretical methods exist for correcting the model scale results for the viscosity of water. In our case, the problem was slightly simpler as the MOB modules do not move through the water at any appreciable speed and effects due to improper scaling of the Reynolds number are greatly reduced.

The models built at Berkeley are small scale (1:150), economical models and have been designed to capture the basic hydrodynamic performance of the MOB modules and to allow a representative performance of the thrusters. The purpose of the models was to validate that all of the relevant hydrodynamic parameters had been captured in MOB-SHIFT, along with the demonstration of MOB control techniques for at-sea assembly of modules, multi-module dynamic positioning, alignment into the wind, and separation of modules. This has given credibility to the overall MOB concept. All of the above goals have been met. In this paper, we will concentrate on the validation of control maneuvers.

The Berkeley test basin does not allow for the generation of repeatable disturbances. Although disturbances were introduced at times for visual effect, in general, experiments in the basin did not include environmental disturbances. MOB-SHIFT was used to test the behavior of the MOB modules in control algorithms in severe environmental conditions.

Results

The user interface for the experiment is a menu offering a choice of several maneuvers. A maneuver coordinates the motion of one or several modules: legal maneuvers are shown in figure 17. They include moving one module to a new position and heading, assembling modules to form a bigger MOB, separating assembled modules, moving a string of modules to a new position and heading, and rotating a string of modules into the wind.

A typical mission would include: dynamic positioning at initial location, bringing the modules into far apart positions on a straight line, docking the modules to form a string, performing coordinated station keeping (DP), rotating the string 10 degrees and bringing it back, performing a coordinated lateral maneuver, and separating the modules. A full run takes about 20 to 30 minutes. Video showing all these maneuvers can be obtained from the PATH web page:

http://www.path.berkeley.edu

under the Publications and Video heading.

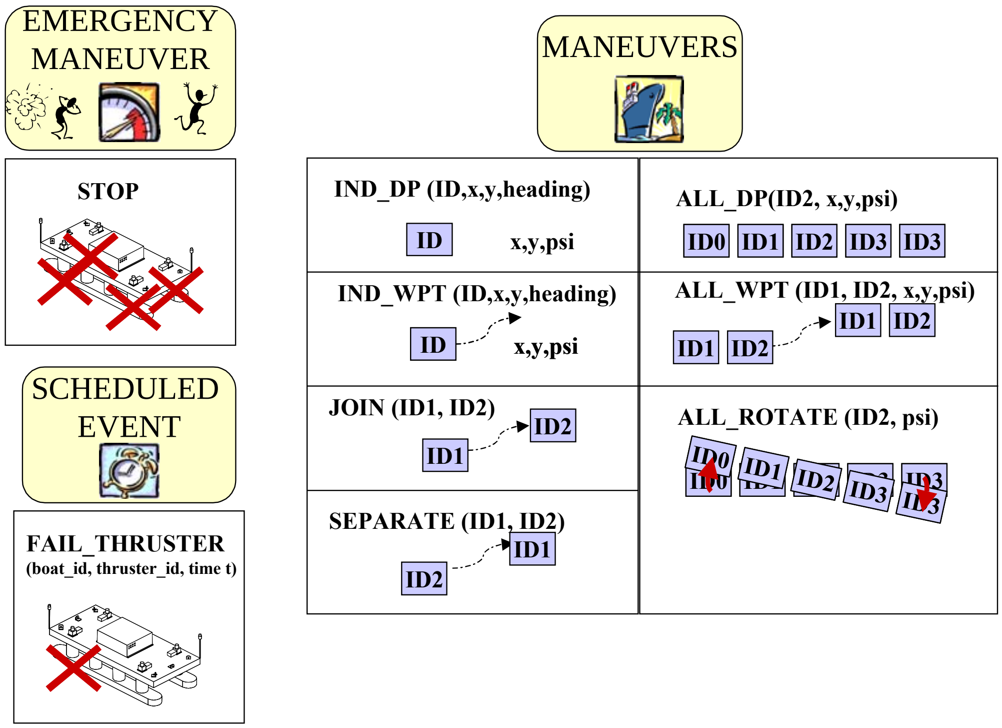


Figure 17. Maneuvers accommodated by the Scaled MOB Testbed.

For the purposes of this paper we will present logged data from an actual experiment. The data from the complete mission is difficult to interpret visually, so we will concentrate on the DP, docking, and coordinated rotation parts of the scenario. Figure 18 is an x/y plot of a module station keeping in the tank. It shows the motions of the center of gravity of the module in the x and y directions. The x and y position are given in meters, so the movements of the module's center of gravity are on the order of +/- 2 cm in either the x or y directions, which is about the accuracy of the absolute measurement system.

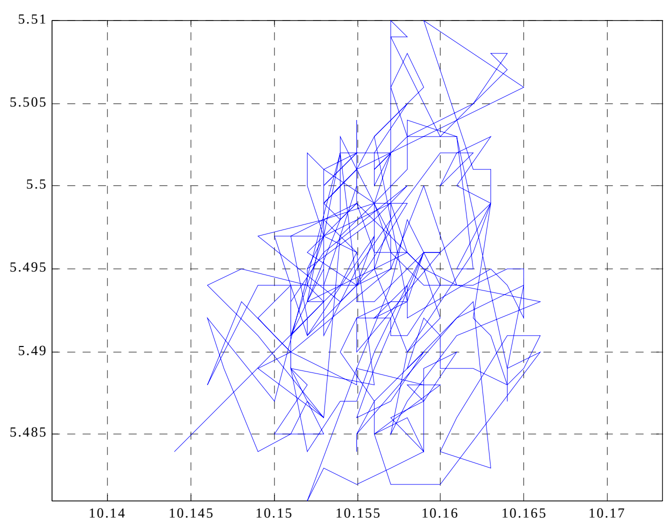


**Figure 18. Surge/Sway Measurements while Station-Keeping.
Setpoint is (10.15, 5.5). All units in meters.**

Figure 19 is a plot of the heading angle of the module shown in figure 18, during the same period of time. The desired heading angle is zero degrees.

Figure 19. Yaw Measurements (in degrees) while Station-Keeping. Setpoint is 0 degrees.

Usually, at the start of a mission the modules station-keep for some time, then assemble. The assembly maneuver is split into two parts: at first, the modules align, far away from each other. Then the two end modules come in and dock precisely. Figure 20 shows the x locations of the three modules forming the experiment during a precision docking maneuver. Module 1 is shown on top, module 2 in the center and module 3 in the lower plot. Initially, modules 1 and 3 are not exactly at their desired position because of umbilical forces. Module 2 station-keeps during the whole maneuver.

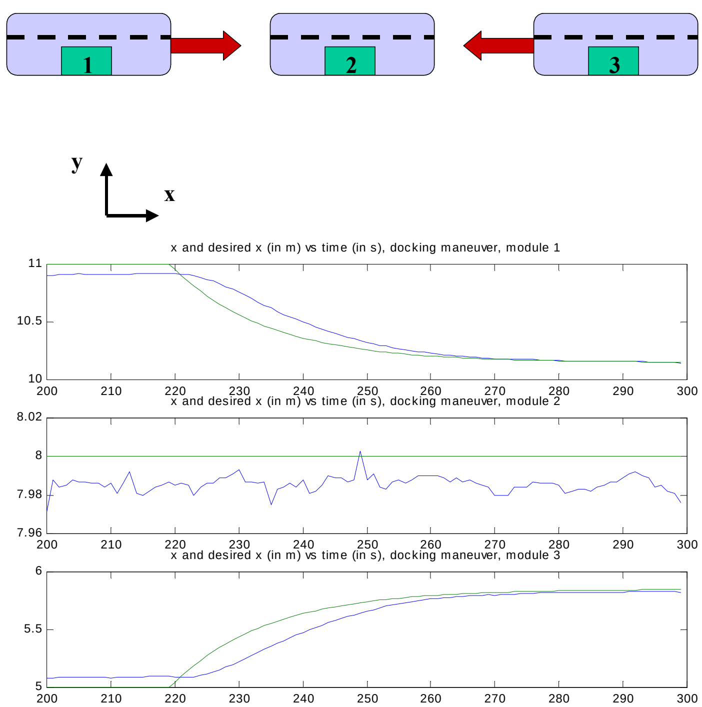


Figure 20. Docking maneuver.

Conclusions

This paper presents work on dynamic positioning control strategies for the Mobile Offshore Base that was conducted at the University of California, Berkeley and California PATH between 1998 and 2001. We discuss organization of different controllers and maneuvers in the context of coordinated dynamic positioning, control architectures, DP control strategies, and simulation results. The MOB control testbed is presented, goals of model testing and scaling effects are discussed, and experimental results are provided. Early experimental results obtained using the testbed have been encouraging. Improvements to the testbed could be made in two directions: the modules should be made wireless to extend their range and eliminate the forces exerted by the umbilical cables on the modules; also, the testbed would greatly benefit from an improved absolute position system.

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