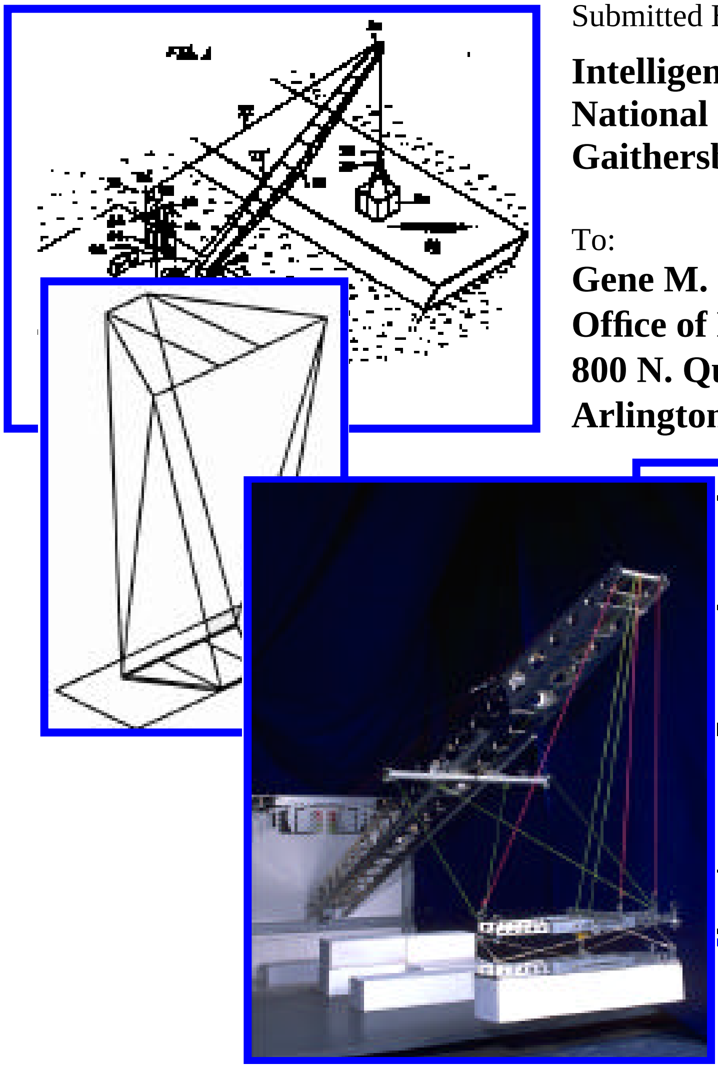
July 2, 1998

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology

Survey of Cargo Handling Research

Relative to the Mobile Offshore Base (MOB) Needs

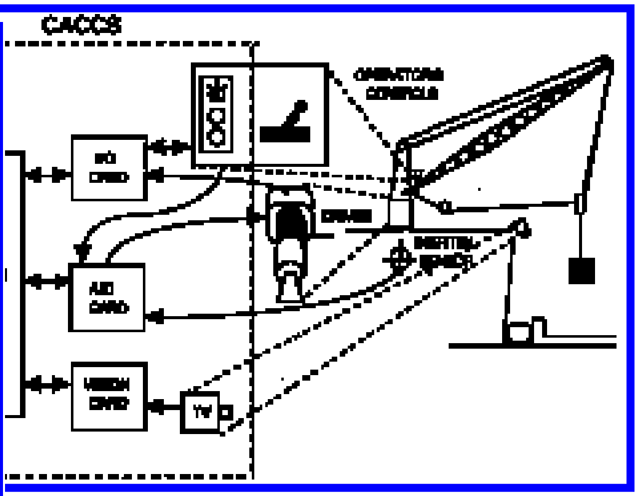


Submitted By:

Intelligent Systems Division
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

To:

Gene M. Remmers, Code 334
Office of Naval Research (ONR)
800 N. Quincy St.
Arlington, VA 22217-5666



ADMINISTRATIVE INFORMATION

Project Title

Survey of Cargo Handling Research Relative to the Mobile Offshore Base Needs

ONR Order No.

N00014-97-F-0196

Responsible Person / Organization

Gene M. Remmers, Code 334
Office of Naval Research (ONR)
800 N. Quincy St.
Arlington, VA 22217-5666

Performing Organization

National Institute of Standards and Technology
Intelligent Systems Division
Building 220/ Office B-127
Gaithersburg, MD 20899

Principal Investigators

Mr. Roger Bostelman	Phone: 301-975-3426 Email: rbostelman@nist.gov
Mr. Ken Goodwin	Retired

The authors would like to acknowledge critical contributors to this report including: Information providers, Debbie Russell for scanning many included images, NSWC Reviewers, MURI Reviewers, and ONR Reviewers.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Purpose

The Mission Need Statement for the Mobile Offshore Base (MOB) calls for a capability to perform full logistics support through Sea State 3, including waves of approximately 1.6 m (5 ft). However, a technical crane capability to do loading and unloading of cargo containers in Sea State 3 has not yet been demonstrated.

The Office of Naval Research (ONR) MOB program management team has recognized crane development as a critical technology that will be necessary for any feasible MOB. ONR has requested the National Institute of Standards and Technology (NIST) to assess the current state of practice in crane automation and motion compensation. This report is intended to establish a baseline and identify research needed to satisfy any gaps in the requisite technology.

Scope

The scope of this report will include cranes and other automation technology to achieve the lift on/lift off (LO/LO) transfer of cargo. This will include containers and break bulk cargo, such as tanks and causeway sections. Emphasis will be primarily upon the transfer of containers between the MOB and cargo container ships, landing craft, and lighters.

This report will not deal with loading and unloading cargo brought by aircraft to the flight deck. Such cargo will be handled by specialized forklifts, rolling equipment, ramps, and elevators.

Also, it will not address Roll On/Roll Off (RO/RO) cargo (such as trucks), nor bulk liquids transfer.

Background

The current need for off-loading ships where port facilities are not available or inadequate was recognized during the Vietnam war when cargo ships waited up to six months or more to unload.

Following the Vietnam war, the Navy undertook a search for at sea cargo handling alternatives. This led to the design, construction and deployment in the 1980s and 90s of a fleet of 10 Keystone State Class Auxiliary Crane Ships (T-ACS). These are container ships which have up to three twin-boom pedestal cranes to lift containers or other cargo from itself or adjacent vessels and deposit it on a pier or into lighterage.

To restrain horizontal pendulation (swinging) of the load, T-ACS cranes were equipped with a Rider Block Tagline system (RBTS) consisting of a rider block, which can be moved up and down the lift line, and two winch-controlled taglines. Crane operators control the height of the rider block and the pull of the taglines by foot controls. They control the slew and luff of the boom and the height of the hook with hand controls.

In Joint Logistics Over The Sea (JLOTS) exercises, it has been determined that the operators do not fully utilize the RBTS. As summarized in **[1]** [Bird], “a general consensus for sea state (SS) 3 is: maximum relative vertical displacements are approximately ±3 m (±10 ft) over the lighterage with maximum relative vertical velocities at approximately ±2m/s (±7 ft/sec) over the lighterage.” Crane ship roll is “the largest contributor to relative vertical displacement.” This concensus is based on motion studies conducted by the Naval Coastal Systems Center (NCSC), the Naval Civil Engineering Laboratory (NCEL), the Massachusetts Institute of Technology (MIT), the Stevens Institute of Technology, and others. **[1]** [Bird] Operators do not get an opportunity to practice under such conditions and consequently are not trained adequately for the task.

Current lighters can not operate in SS 3. The Navy does not have a current capability to off-load cargo containers in Sea State 3 or higher. A sea state 3 capable system (Joint Modular Lighterage System (JMLS)) is in development and is slated for procurement.

In the early 1980s the Navy undertook research to develop a Platform Motion Compensator (PMC) to deal with relative vertical motion. The original PMC design and concept was developed by EG&G. A prototype PMC was installed on the KEYSTONE STATE (T-ACS 1) and was used for a short time under SS 2 or less during the J-LOTS II exercise at Ft. Story, Virginia during the fall of 1984. While the PMC prototype was a technical success, the PMC was not implemented in the fleet because of its perceived cost and complexity.

Under the JLOTS Master Plan, three critical technologies are under development:

Rapidly Installed Breakwater (RIBS)

Joint Modular Lighter System (JMLS)

Sea State 3 Crane

The Sea State 3 Crane has been accepted as an Advanced Technology Demonstration (ATD) to start in FY00. Its objective would be to demonstrate shipboard crane pendulation control, for throughput of 300 containers per day per ship in sea state 3. It will employ non-linear, dynamic, control algorithms, some of which are now under development under ONR 6.2 supported research. The ATD is budgeted at approximately $9.9 million over 3 years.

Requirements

MOB crane requirements have evolved from NIST laboratory research and development of MOB cargo crane concepts. Additional input has been provided by several MOB concept developers also under contract to DARPA and the ONR.

The MOB cranes must be similar in size and capacity to the port cranes that load container ships. They must have similar reach, height, hook height, and lift capacity. They must be able to lift 23 t containers @ 36 m (from MOB), 72 t tanks @ 22 m, and 100 t causeway sections @ 11 m.

In addition, the MOB cranes must meet several special (currently assumed) requirements because of the operating conditions of the MOB. Cranes must traverse the length of container ships in order to reach all cargo cells. They cannot project above the plane of the flight deck during air operations. Because of this constraint, the cranes must be mounted on the side of the MOB, which may require a stronger structure to support the cranes. During transit and storms, it will be necessary to secure or stow the cranes, preferably where they can be easily maintained. In order to operate a majority of the time in many operating areas of interest around the world, the MOB must have the capability to load ships and lighters in Sea State 3. Sea State 4 capabilities for loading container ships would be highly desirable. Finally, the cranes must be capable of loading many containers in a single day to support various deployment missions.

Crane Technology

Crane technology relevant to the MOB needs has been developed in several streams of research, development, and demonstration.

A primary source of technology development has been the Joint Logistics Over the Shore (JLOTS) program to develop a capability to off-load cargo in Sea State 3, 1.6 m (5 ft) significant wave height, weather conditions.

Other major developments have come from the evolution of port cranes, resupply of off-shore platforms, and industrial, university, and government laboratory crane research.

Conclusions

Horizontal pendulation control has been demonstrated by the Rider Block Tagline System (RBTS), Integrated RBTS (IRBTS), feed forward control, and other methods.

Vertical motion compensation was demonstrated by NAVSEA/Coastal Systems Services (CSS) and EG&G on T-ACS 1, but not implemented in the T-ACS fleet.

MOB cargo container operations will require rapid, 6-D compensation of ship motions that are not as severe as lighter loading, but still on the order of ±1 meter for 5 second wave periods in sea state 3.

Enabling technologies for 6-D motion compensation have been developed and demonstrated in the laboratory and wave tank, but not yet demonstrated in full scale operations.

The Rider Block Tagline System could be significantly improved by the Craft Engineering Inc. IRBTS project, which will insert computer coordinated control of the rider block to constrain horizontal motions. A prototype system has been installed and demonstrated at dockside but has not yet been demonstrated at sea. However, vertical motion compensation will not be achieved by the Integrated RBTS.

The JLOTS Advanced crane control ATD, if developed successfully, could provide much of the technology needed for a MOB crane.

We believe that a compound control system, including wave sensing with feed forward control, combined with fast, closed loop control of relative motion between the load and lighter or container ship will be required. Sensors of incoming waves are critical to feed forward control.

Recommendations

Simulate and model the cranes required for cargo handling.

Develop the advanced computer control system necessary to achieve wave motion compensation.

Develop and demonstrate full scale integrated 6-D cargo container control for MOB operations.

PURPOSE

The Mission Need Statement for the Mobile Offshore Base (MOB) calls for a capability to perform full logistics support through Sea State 3, with significant wave height of approximately 1.6 m (5 ft). **[2]**[JPD]

However, a technical capability to load and unload cargo containers in sea state 3 has not yet been demonstrated.

The Office of Naval Research (ONR) MOB program management team has recognized crane development as a critical technology that will be necessary for any feasible MOB. ONR has requested the National Institute of Standards and Technology (NIST) to assess the current state of practice in crane automation and motion compensation. This report is intended to establish a baseline and identify research needed to satisfy any gaps in the requisite technology.

SCOPE

The scope of this report will include cranes and other automation technology to achieve the lift on/lift off (LO/LO) transfer of cargo. This will include containers and break bulk cargo, such as tanks and causeway sections. Emphasis will be primarily upon the transfer of containers between the MOB and cargo container ships, landing craft or lighters.

This report will not deal with loading and unloading cargo brought by aircraft to the flight deck. Such cargo will be handled by specialized fork-lifts, rolling equipment, ramps, and elevators.

Also, it will not address Roll On/Roll Off (RO/RO) cargo (such as trucks), nor bulk liquids transfer.

BACKGROUND

History does not tell us whether cranes were used to build the Egyptian pyramids around 2500 B.C. **[3]**[Wislicki] If we are to believe recent Hollywood movie makers, cranes were used to load stone blocks on barges to go up the Nile River.

The current need for off-loading ships where port facilities are not available or inadequate was recognized during the Vietnam war when cargo ships were kept waiting up to six months to unload.

T-ACS Ships

Following the Vietnam war, the Navy undertook a search for alternatives, which led to the design, modification and deployment in the 1980s and 90s of a fleet of 10 Keystone State Class Auxiliary Crane Ships (T-ACS) which are container ships which have up to three twin boom pedestal cranes to lift containers or other cargo from itself or adjacent vessels and deposit it on a pier or into lighterage.

Rider Block Tagline System

To restrain horizontal pendulation (swinging) of the load, T-ACS cranes were equipped with a Rider Block Tagline system (RBTS) consisting of a rider block with two pulleys, which can be moved up and down the lift line, and two winch-controlled taglines. Crane operators control the height of the rider block and the pull of the taglines by foot controls. They control the slew and luff of the boom and the height of the hook with hand controls. **[4]** [Cecce]

Joint Logistics Over the Shore

Joint Logistics Over-The-Shore is defined as “... the loading and unloading of ships without the benefit of fixed port facilities in either friendly or undefined territory and, in the time of war, during phases of theater development. LOTS operations are conducted over unimproved shorelines, through fixed ports not accessible to deep draft shipping, and through fixed ports that are not adequate without the use of LOTS capabilities.” **[5]** [Vaughters]

In Joint Logistics Over The Shore (JLOTS) exercises, it has been found that the operators do not fully utilize the RBTS. Operators do not get an opportunity to practice under high sea state (SS) conditions (e.g. SS 3) and consequently are not adequately trained for the task.

“The T-ACS demonstrated the capability to move containers in SS 3 as long as the sea conditions consisted of small period waves, i.e. wave/chop rather than long period ground swells. Navy lighterage did not demonstrate a SS3 capability. Whenever the T-ACS became exposed to ground swells on her beam she would begin to roll slightly, about 1 degree, which induced spreader bar pendulation. The controls for the RBTS were difficult to use and have an unacceptable time lag of 6 seconds in transitioning from raising the rider block to tensioning the taglines... As such, the crane and RBTS are not integrated and lack the control characteristics and functions needed for the operator to control the hook at all times so that load pendulation cannot start.” **[6]**[Department of Defense]

Current lighters can not operate in SS 3. The Navy does not have a current capability to off-load cargo containers in SS 3 or higher.

JLOTS Master Plan

The JLOTS Master Plan, jointly prepared by the Army and Navy, is the synthesis of critical, interdependent, enabling technologies, training, and command and control functions designed to meet Service and unified command Logistics Over-the-Shore (LOTS) and Joint LOTS (JLOTS) requirements. The CINC’s require a safe, sustained, service-interoperable LOTS/JLOTS operational capability through sea state 3 to support expeditionary, force reception, and theater sustainment logistics. Utilizing the “system of systems” philosophy, the JLOTS Master Plan defines the intricacies of heavy weather JLOTS operations and provides both a near-term solution to the sea state 3 problem to meet the CINC requirements and a link to the future. **[7]** [JLOTS Master Plan]

Under the JLOTS Master Plan, three critical technologies are under development:

Rapidly Installed Breakwater (RIBs)

Joint Modular Lighter System (JMLS) **[8]** [Webb]

Sea State 3 Crane

Advanced Technology Demonstration Proposal

The Sea State 3 Crane has been accepted as an Advanced Technology Demonstration (ATD). Its objective would be to demonstrate shipboard crane pendulation control, for throughput of 300 containers per day per ship in SS 3. It will employ non-linear, dynamic, control algorithms, some of which are now under development under ONR 6.2 supported research.

The current JLOTS 6.2 program includes the Applied Research Logistics Technology Program (PE62233N) Replenishment Project. The project includes: Advanced Shipboard Crane Technology, VLS At-Sea Rearming, Magnetostrictive Actuators for Weapons Elevator Applications, which are the topics relevant to this report. Objectives for the project are to improve performance, reduce total cost of ownership, and facilitate reduced manning initiatives of replenishment systems by application of science and technology. **[6]**

The Joint Logistics Over-the-Shore (JLOTS) executive plan through 1998 is to develop non-linear algorithms, evaluate control system concepts, perform concept trade-offs and model tests, and enhance the RBTS. This project links the container ship, shipboard cranes, lighterage, shore cranes, and beach clearance.

Future plans advance toward an At-Sea demonstration of the systems developed. The ATD is budgeted at $9.9 million over 3 years and is scheduled to start in FY00. **[9]** Rausch

REQUIREMENTS

The following requirements have been identified by NIST for MOB crane capabilities. These requirements are discussed in greater detail in a separate NIST report. **[10]**[Goodwin]

Two sets of requirements are discussed below. The first set are typical of a port crane for loading container ships. They include reach, height, and lift capacity at various distances.

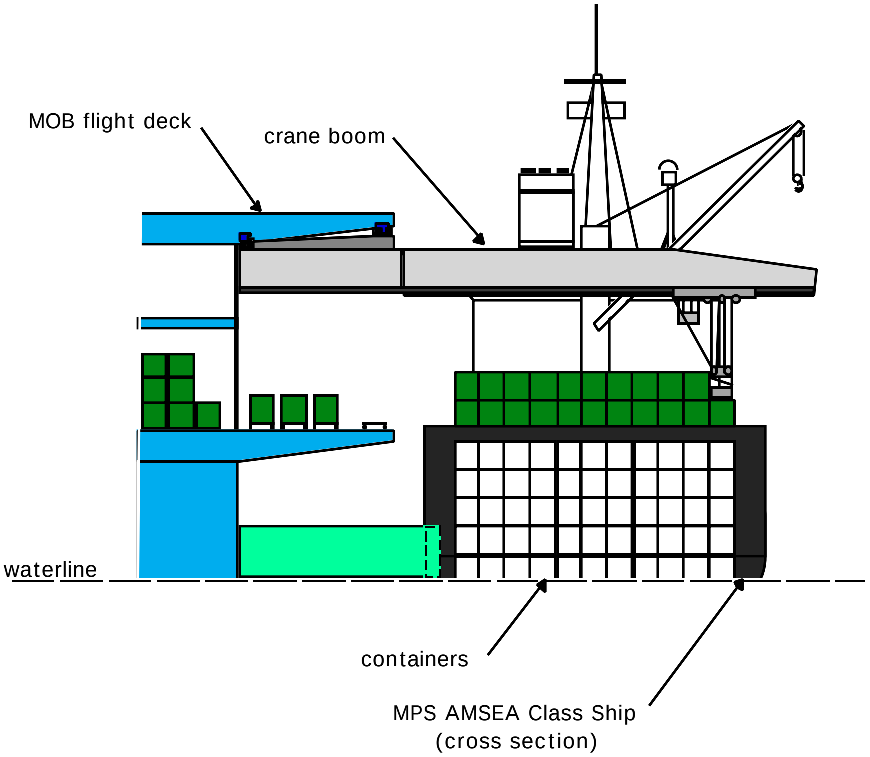
The second set of requirements are specific to the MOB because of its special characteristics. These include requirements to operate without intruding into airspace, to move along the length of a MOB section to reach the cells of container ships, structural support on the side of a MOB, operating in high sea states, and lighter loading.

Reach

Cranes must be able to reach the far side of the largest container ships currently in use (Panamax class ships).

This requires almost a 50 m reach when fenders are considered. The distance from the outer edge of the MOB to the ship wall berthed against the MOB will be 3 m (e.g. compressed fender) to 4.5 m (e.g. non-compressed fender). Figure 1 shows a Panamax ship berthed against the MOB with a compressed fender.

FIGURE 1. Cut-away view of a Panamax ship berthed against the MOB with a compressed fender



Height

Cranes must clear the superstructure of the ship and all shipboard obstacles.

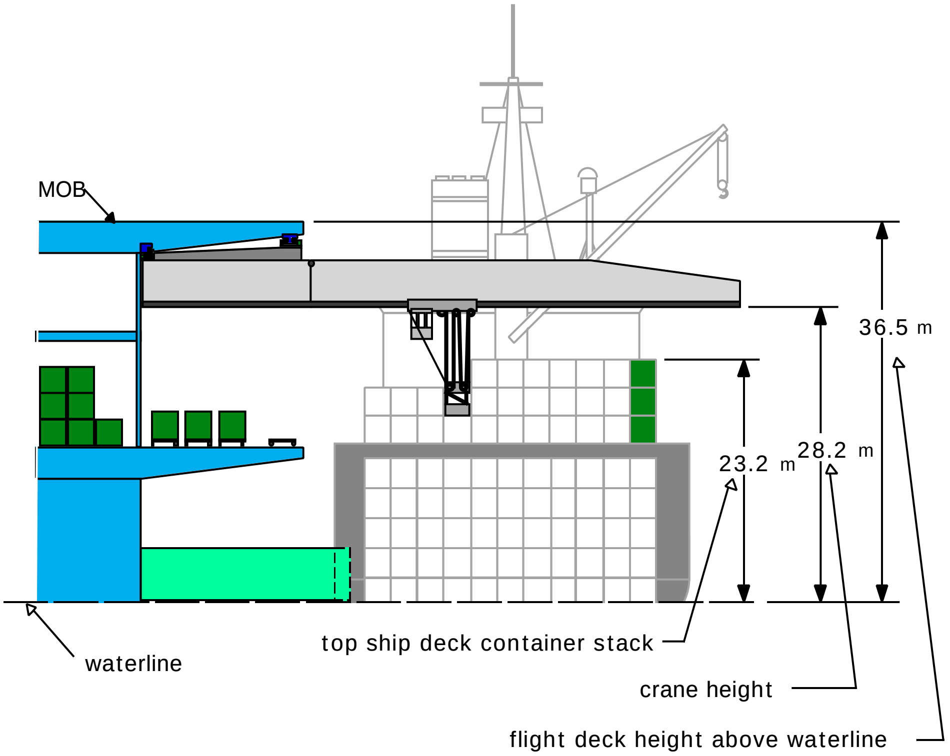
This means that the crane booms must be luffed or hinged so that they can be raised while container ships are docking.

The crane must have sufficient hook height to handle shipboard stacking of containers.

For the design shown in Figure 1, the MOB flight deck and top of the rail crane, will only be 36.5 m above the waterline during typical operations. The top container on a large, fully-loaded container ship may sit 23.2 m or more above the waterline (not considering vertical wave motion). This leaves only 13.3 m (= 36.5 m - 23.2 m) from the MOB flight deck to the top of the highest container. This means that the crane boom must be thin vertically to allow the highest possible hook height.

Figure 2 shows the crane (28.2 m above the waterline) and container stack height for 3 containers (23.2 m above the waterline). The minimum crane hook height is approximated at 25.8 m above the waterline. This allows retrieval of cargo containers stacked at most 2 high on the top deck of an MPS AMSEA Class Ship.

FIGURE 2. Height Restrictions of the rail crane for large ships (MPS AMSEA Class ship)



To unload containers stacked 3 high on this ship, the crane must retrieve the top containers in sequence from closest to farthest from the MOB. An additional 2.5 m hook height would be required to lift a container over the top stacked container.

To load or unload containers stacked higher than three levels on the MOB design shown, the MOB would have to ballast up to a higher level, or an alternative crane design, such as a luffing boom crane, would be required.

Crane Lift Capacity

Cranes must lift 23 t containers from the far beam of Panamax class ships (about 50 m from the MOB frame).

Cargo is containerized mainly in 6 m to 16 m long x 2.5 m wide x 2.5 m high (20 ft to 52 ft long x 8 ft wide x 8.5 ft high) standard ISO containers. LO/LO operations may also include break bulk and palletized cargo. Estimated, maximum, cargo weight positioned at a distance of 36 m (118ft) from the MOB edge is 23 t (25 tons).

Cranes should be capable of lifting break bulk cargo, vehicles, and barge sections.

This will provide lift of a 72 t tank at the center of a Panamax class ship (22 m) and lift of a 102 t causeway section at the near side of a ship (11m).

Cranes may be required to lift disabled RO/RO vehicles from ramps.

In the event that RO/RO vehicles or other equipment becomes immobilized, cranes may be required to remove such items (up to the maximum crane lift capacity) from ramps to continue cargo retrieval/loading operations.

MOB Container Storage/Stacking/Selective Retrieval

The MOB should have the capability to store and retrieve individual containers, remove pallets, and repackage containers on demand.

Although containerized cargo is simple and efficient for moving high volumes of cargo, Special Forces operations, OMFTS operations, and “marrying up” of MPF equipment with troops aboard the MOB will typically need cargo moved in smaller quantities, usually pallet sized loads. Therefore, an area for break-out, marshalling, and staging will be required. A capability to access multiple containers and load pallets and/ or containers is needed.

Longitudinal Crane Motion Along MOB

Cranes must access container cells at various positions along the length of container ships.

Fixed cranes would not be able to reach many cells of container ships moored alongside the MOB without warping the ship along the MOB. While moving the ship is technically possible, it is difficult and time consuming. Port cranes typically move on rails along the length of container ships. Similarly, it will be necessary for MOB cranes to move along the length of container ships.

However, if a container ship is longer than a MOB section, it may be necessary to warp the ship so that cranes can reach more cells. Some preliminary studies have shown that mooring lines can withstand the dynamic loads of container ships moored to the MOB in sea state 4. **[11]** [Seaworthy Systems]

Docking and Mooring to the MOB

The MOB must have a capability of docking and mooring container ships. Container ships typically do not have sufficient dynamic positioning capability to dock with a MOB. In harbors, container ships are assisted by tugs. It will be necessary for the MOB to have its own tugs, or some automated docking system to achieve docking and mooring.

Airspace Restrictions

Cranes should not interfere with airspace above the flight deck.

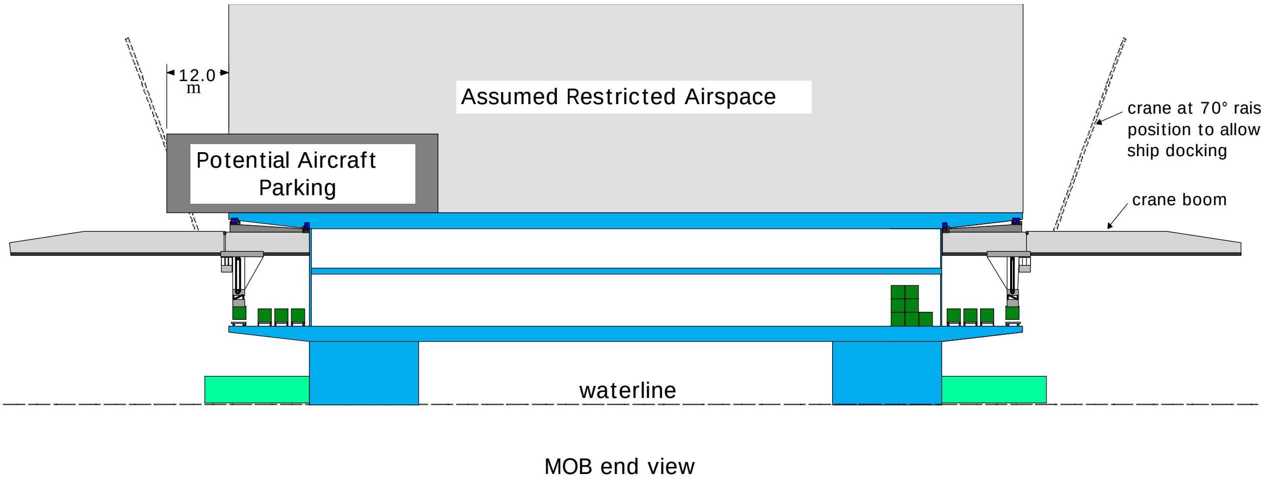
Cranes must not protrude into the airspace directly above the flight deck during air operations (see Figure 3). The vertical crane support tower commonly used to support and luff typical port rail or luffing cranes may not be feasible for the MOB, at least not on both sides of the flight deck. It might be feasible on one side where there are air control towers.

However, there are examples of low-profile, rolling boom cranes currently being used in ports. These low profile booms suggest a similar rail crane design. They have larger rail cross sections than the high profile cranes because they must support the weight of the boom and cargo as a cantilevered load.

Cranes should only rarely protrude above the plane of the flight deck.

Air operations may require parking of aircraft with wings or tails overhanging the edge of the flight deck. Figure 3 shows "potential aircraft parking" extending 12 meters beyond the MOB edge. This would interfere with luffing crane booms or their longitudinal movement along the length of container ships during crane operations. For larger aircraft, such as the C-17 transport, takeoffs and landings may be made with one wing tip beyond one edge of the flight deck. The degree of interference between aircraft operations and crane operations depends upon the air traffic to and from the MOB.

FIGURE 3. MOB Potential Airspace Restrictions



MOB Structural Side Loading

The MOB structure should support cranes mounted on the side of the MOB.

To avoid interference with aircraft operations above the flight deck, cranes must mount on the side of the MOB (see example in Figure 3). Therefore, the MOB structure must provide hard points that can support the load of the crane boom, the crane trolley, and a variety of cargos that are lifted at specified reaches. We have serious concerns about the forces that a fully loaded rail crane would exert on the MOB. A fully loaded luffing boom crane would generate much lower forces on the MOB than a rail crane, but would require the lowest deck to extend out beyond the flight deck. This is not provided in some current MOB designs.

Crane Stowage

The cargo cranes should be stowed for travel and excessive sea states.

When not in operation, the cranes should be stowed, preferably in locations that provide for convenient servicing. The preferred method of stowing a crane is to move it to a home position where it can be retracted into a compartment that is internal to the MOB (see Figure 4). This option places the crane inside where it can be easily serviced. An alternative stowage concept is to rotate the crane into a position beside the MOB, as shown in Figure 5. This method can be used for either rail or luffing cranes.

FIGURE 4. Crane Stow by Retracting the Minimum Length (shown in meters) of Crane Boom on rails and into the MOB

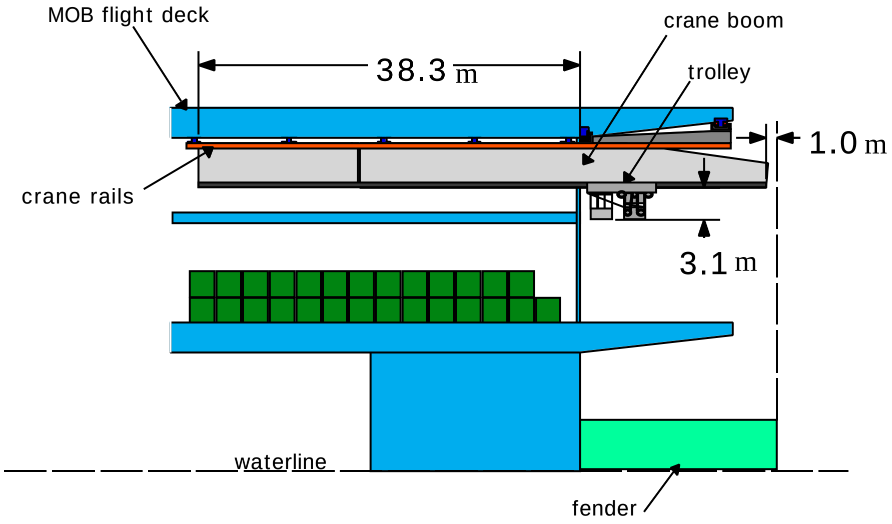
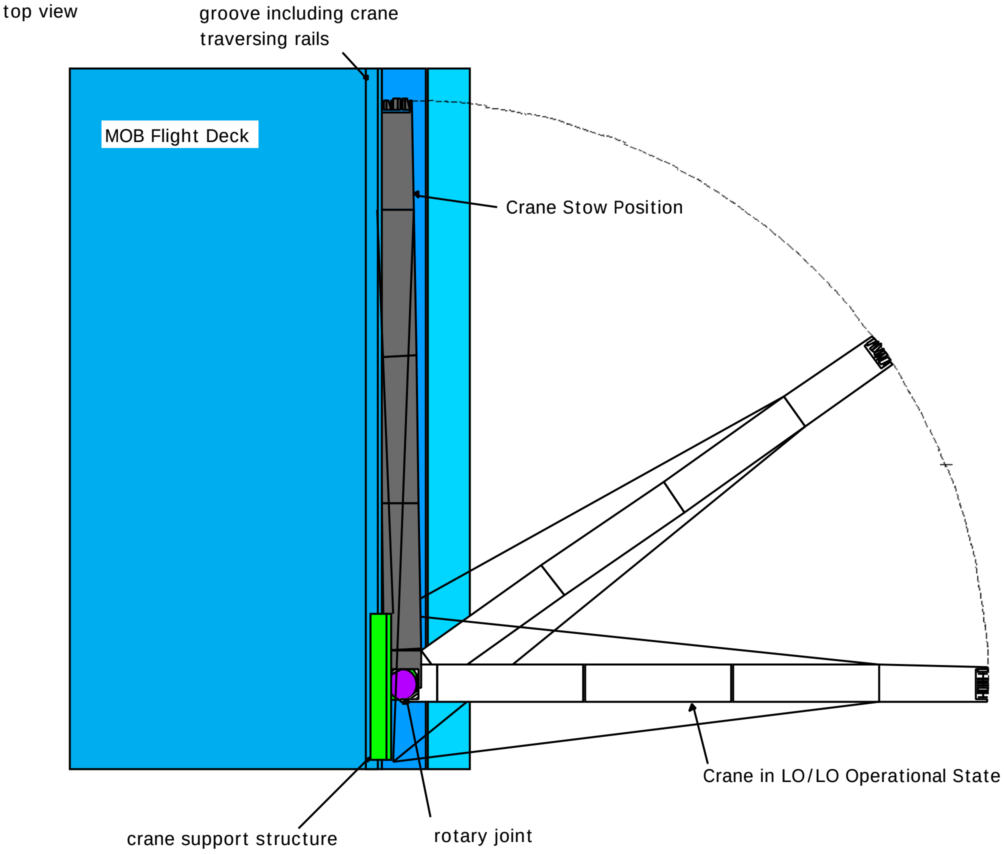


FIGURE 5. Alternative Stowage concept. The top view of a luffing crane is shown.



Operations in High Sea States

The MOB must be able to perform lift-on and lift-off (LO/LO) operations under weather conditions up to sea state 3, and preferably in sea state 4.

The Mission Needs Statement For the Mobile Offshore Base (MOB) calls for an operational capability in sea state 3. **[2]** It would be highly desirable to conduct cargo handling operations in sea state 4 allowing potentially increased operation time above lower sea states. The maximum operational sea state in which cargo loading or unloading operations are to be performed is estimated at sea state 4. Operations would be done only with large cargo container ships, since lighters would not be able to operate in sea state 4. Therefore, the design goal for cranes is to be able to perform lift-on and lift-off (LO/LO) operations under conditions up to sea state 4.

MOB Cargo Handling Requirements In Sea State 3

The MOB crane must compensate for longitudinal, lateral, and vertical ship motions relative to the MOB in high seas

Maximum motions for a T-ACS 4 Auxiliary Crane Ship relative to the MOB in sea state 4 are estimated to be: **[12]**[Cooper]

	Displacement	Acceleration
Longitudinal:	0.51 m (1.67 ft)	0.94 g x 100
Lateral:	1.12 m (3.69 ft)	2.16 g x 100
Vertical:	1.12 m (3.66 ft)	3.21 g x 100

Shipboard cargo motion compensation could be achieved by using automated rigging control as with the NIST RoboCrane technology. **[13]** [Albus]

This advanced technology would allow crane operators to retrieve cargo rapidly, even while at high sea states, by using an Intelligent Spreader Bar, with sensors and computer-assisted control that follows the cargo motion.**[14]** [Dougherty]

Lighter Loading

Loading containers from the MOB to lighters will be necessary.

The U. S. Marine Corps vision of Operational Maneuver from the Sea (OMFTS), if implemented, would eliminate the need for displacement hull lighterage by bypassing the beach and moving cargo by aircraft from the seabase. **[15]**[Krulak]

However, the Army will continue to require lighterage. The larger Army lighterage (LSV, LCU2000) and the proposed Joint Modular Lighter System (JMLS) are most likely to be used for lighterage operations from the MOB. **[8]**[Webb] Smaller lighters could potentially be used, depending upon shore to MOB distance and weather conditions.

Motions of lighters and other small ships in sea state 4 (assuming they are operable at this sea state) are expected to be considerably larger than motions of container ships. Wave motion compensation will require more horsepower since the smaller ships have greater relative motion, due to their size, than larger vessels.

It may be feasible for the MOB to replenish the Vertical Launch System (VLS) of DDG 51 ships, a capability that does not exist in the fleet now. **[16]**[Bouchoux]

Crane Throughput

Operational cargo container throughput requirements are mission dependent, but could be set as high as 30 containers per hour per crane.

Desired crane throughput rates have been estimated differently by different organizations. The following cargo retrieval rate estimates represent different views of what may be required of a MOB.

- The current JLOTS throughput target, using the NSWC Advanced Shipboard Crane Motion Control System, is to unload 300 containers in one day per T-ACS Ship (e.g. approximately 4 booms working simultaneously). Current capabilities are to make one lift about every 7 minutes.
- Brown and Root estimated that it would take 120 hours to load 1720 containers, at a rate of 8 minutes per container, to support an Army Division.
- McDermott estimated that, with more cranes, it would take only 24 hours to load 720 containers, at a rate of 6 minutes per container to support a Marine Expeditionary Force.
- The Center for Naval Analyses has estimated that support of a Maritime Prepositioning Force for 2010 (MPF 2010) will require off loading of 4,166 containers with no currently specified rate. **[17, 18]** [Nance] Containers are estimated to hold 16 pallets each. Without containers, typically 4 to 6 pallets can be crane-lifted using a net per lift.
- Approximate maximum port crane throughput is about 30 containers per hour (i.e. 2 min/container). While some port cranes are capable of unloading a maximum of 60 containers per hour, crane operation typically does not achieve this rate due to delays associated with ground transportation of cargo.

We believe that it is technically possible for MOB LO/LO operations to match port crane LO/LO rates (2 minutes per container) under conditions of SS 4, provided that an advanced crane control system is developed and used for the MOB. With advanced crane control on a minimum of seven cranes, each operating 20 hours per day, the MOB could meet the most stringent containerized, load-out requirement for the MPF 2010 in one day.

NIST ACTIVITIES

- Survey Crane Automation and Motion Compensation Relative to the MOB
- Develop Functional Criteria for MOB Cargo Container Handling
- Participate in MOB Mission Requirements and Performance Measures Working Group and Contractor Reviews

Literature and Patent Searches

Completed a literature search, interviews, site visits, and MOB contractor reviews as listed below:

Literature Search

- Literature search through NIST library, targeted at the following key words: Crane, Anti-sway, Control cable systems
- Government Reports Search through NIST library targeted at the following key words: Crane, Anti-sway, Control cable systems

Patent Search

- United States and International Patent Searches through NIST library targeted at the following key words: Crane, Anti-sway, Control, Cable Systems

Site Visits

- Ted Vaughters, Art Rausch, and Frank Leban, NSWC Carderock, Advanced Crane Research Program and to view current NRL experiments in crane load pendulation measurements using a scale T-ACS model in a wave tank.
- Rob Overton, Wagner Associates, and Anthony Simkus, Virginia International Terminal to discuss recent developments in anti-sway control as applied to port cranes.
- Dexter Bird, Craft Engineering, Hampton Virginia to discuss recent Rider Block Tagline System (RBTS) Developments
- Yvan Beliveau, Virginia Polytechnic Institute to discuss recent developments in anti-sway computer algorithms and mechanical enhancements. Also visited ONR Multi-University Research Initiative, Non-Linear Active Control of Dynamical Systems.
- Sandeep Vohra and Micheal Todd, Naval Research Laboratory for a demonstration of the 1/24 scale model T-ACS crane on a 6-axis motion simulator.
- Vito Milano, Center for Naval Analysis to discuss the Maritime Prepositioning Force 2010 study.
- Theodore Mordfin, Advanced Marine Enterprises to view and test the T-ACS crane simulator.
- Cdr. Lehr and Lt. Cdr. Dettbarn, N422-Navy Captain W. Lee Harris

- Max D. Weber, David Whalen, Steven Naud, Coastal Systems Station at Panama City, Florida, Dahlgren Division Naval Surface Warfare Center, Code A42, to discuss history of crane automation and current plans.
- Marty Fink, NAVSEA to discuss NAVSEA programs and other background information regarding crane/cargo handling research.

MOB Contractor Reviews

- Attended ONR MOB Contract Review meetings for the following companies:
    1. Kvaerner
    2. August Design Inc.
    3. Syntek Technologies, Inc.
    4. Atlantic Research Corp.

Other

- Presented Cargo Container Handling Requirements at MOB Contractor Conference, October 21-24,1997
- JLOTS Board Meeting, December 2, 1997
- Presented Cargo Container Handling Requirements at Requirements Working Group, January 29, 1998.

CRANE TECHNOLOGY DEVELOPMENT

Crane technology, which is relevant to meeting the MOB requirements, has been developed in several streams of research, development, and demonstration.

The primary source of technology development has been the Joint Logistics Over the Sea (JLOTS) program to develop a capability to off-load cargo in Sea State 3, 1.6 m (5 ft) waves, weather conditions.

Other major developments have come from the evolution of port cranes, off-shore drilling industry resupply of off-shore platforms, and industrial, university, and government laboratory crane research.

Following the war in Vietnam, the Navy undertook a series of studies for alternatives, which led to the design, construction and deployment in the 1980s and 90s of a fleet of 10 Keystone State Class Tactical Auxiliary Crane Ships (T-ACS). They are container ships to which have been added up to three twin boom pedestal cranes which will lift containers or other cargo from itself or adjacent vessels and deposit the cargo onto a pier or into lighterage. **[19]** [Jane’s Ships]

The T-ACS cranes were equipped with a Rider Block Tagline system with two winch-controlled taglines to restrain horizontal pendulation (swinging) of the load. Their crane operators control the height of the rider block and the pull of the taglines by foot controls; while they control the slew and luff of the boom and the height of the hook with hand controls. [**4]** [Cecce]

In the 1980’s the Navy undertook research to develop a Platform Motion Compensator (PMC) that was to stabilize suspended crane loads using the RBTS. The original PMC design and concept was developed by EG&G. A prototype PMC was installed on the KEYSTONE STATE (T-ACS 1) and was used during the J-LOTS II exercise at Ft. Story, Virginia during the fall of 1984. **[1]** [Bird] The Platform Motion Compensator was a technical success but, was not implemented because of its perceived cost and complexity. **[20]** [CNO]

Port Crane Anti-Sway Reeving

A variety of reeving and structural supplements have greatly reduced sway in port cranes.

Soest

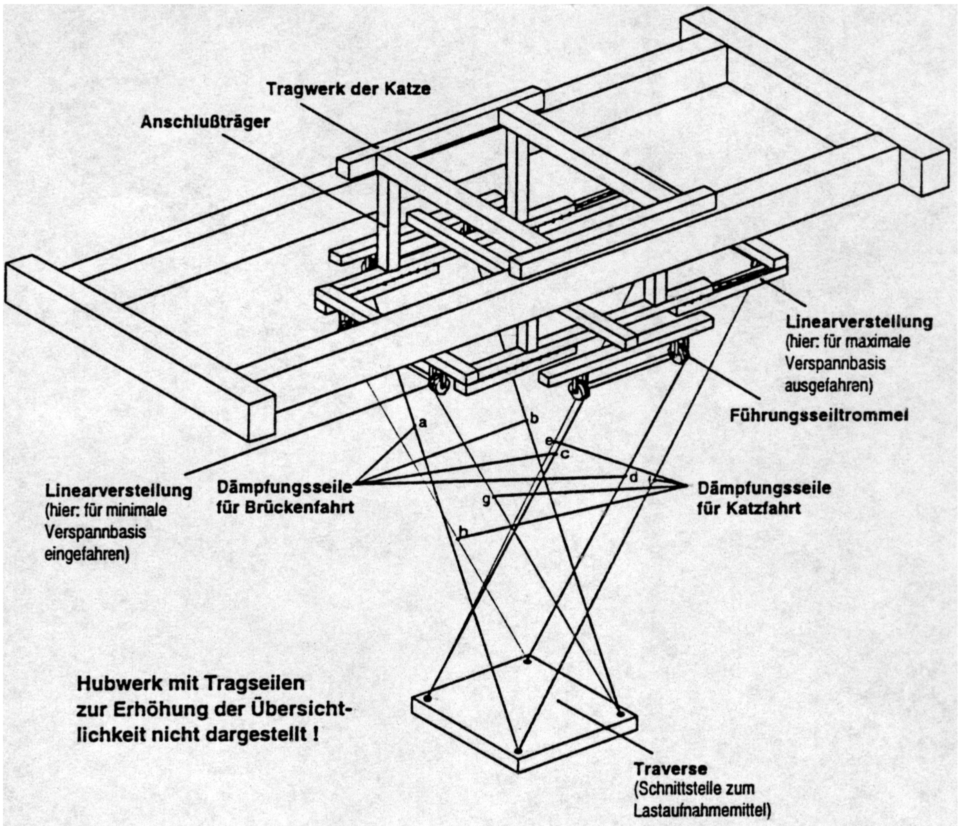
Cornelius Soest, et.al. filed a patent for an anti-sway, anti-rotation mechanism for crane reeving which comprises four spaced-apart overhead sheaves on an overhead support. A lifting beam assembly has four pairs of lifting beam sheaves also spaced apart. A tool is attached to the lifting beam. Cables connect between the sheave quads with a V-shaped arrangement to prevent sway and rotation while operating the crane. **[21]** [Soest]

Kleinschnittger

Andreas Kleinschnittger, University of Dortmund, Germany, proposed an eight-cable crane reeving system (see Figure 6) as part of his dissertation.

The system is composed of eight independently controlled cables attaching the trolley to a suspended, square platform. **[22]** [Kleinschnittger]

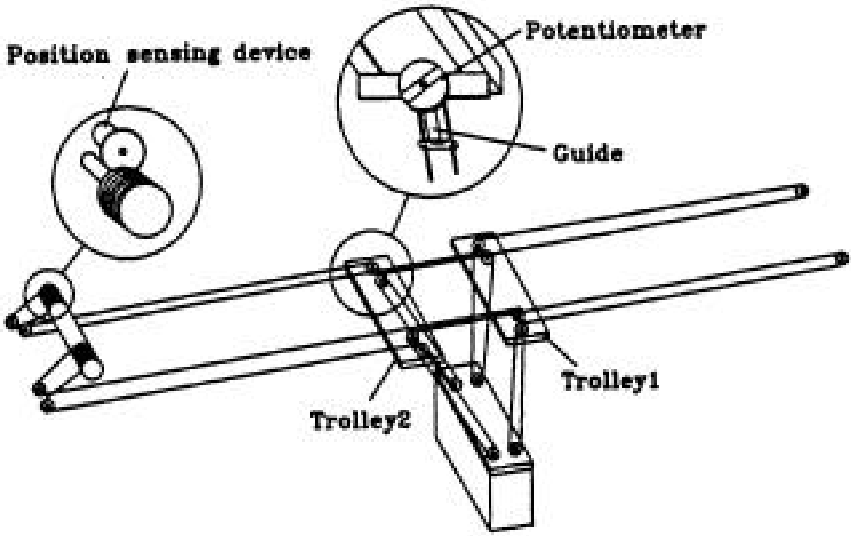
FIGURE 6. Eight Cable Crane Reeving configuration proposed by Kleinschnittger



National Fisheries University of Pusan, Korea

Kim, et. al. of the National Fisheries University of Pusan, Korea describes in their paper, “Development of a Crane System for High Speed Transportation in Container Terminal,” control of a container crane system with the use of two trolleys (see Figure 7). They state that with a single trolley, requirements for the typical accelerating, constant, and decelerating intervals of trolley motion cannot easily be satisfied. Therefore, they propose an independently controlled, dual trolley system. Based on experimental results, the proposed system addresses key issues of anti-sway, traversing time reduction and “swing of the grab” that is stopped at the end-point. **[22]** [Kim]

FIGURE 7. Dual trolley crane system configuration proposed by Kim



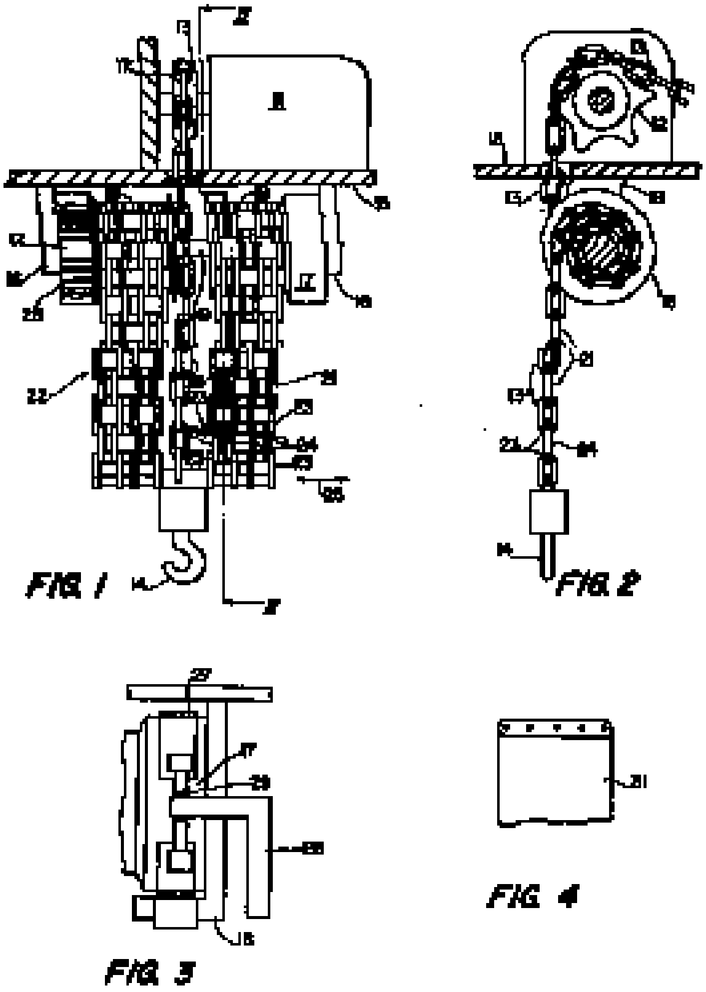
Shaper

Donald Shaper obtained a U.S. patent for an apparatus to stabilize against sway of a body suspended by cables from an overhead support. The apparatus includes first and second opposed rigid stabilizing members pivotally connected at the lower ends to the body. Also, guides carried by the overhead support are used for guiding the upper ends of the stabilizing members. Stabilizing members are used for pivotal and longitudinal movement relative to the overhead support and force transmission means interconnecting the stabilizing members. And also, for transmitting forces there between to generate substantially equal sway, without interfering with the raising and lowering of the body by the suspension cables. **[24]** [Shaper]

Bernaerts

Henry Bernaerts obtained a U.S. patent for an anti-sway device that uses roller chains (see Figure 8) to greatly restrict the lateral movement of the lifting lines suspended from hoists or cranes. The roller chain is suspended parallel to the lifting lines or lifting chains. The end is attached to the free end of the lifting lines. The other end of the roller chain is wound around a take-up reel that prevents the roller chain from going slack. Since the roller chains tend to be very stiff in a direction parallel to the pivotal axes of the roller links, the roller chain will tend to prevent the lifting lines from moving in the plane of the pivotal axes of the roller links. **[25]** [Bernaerts]

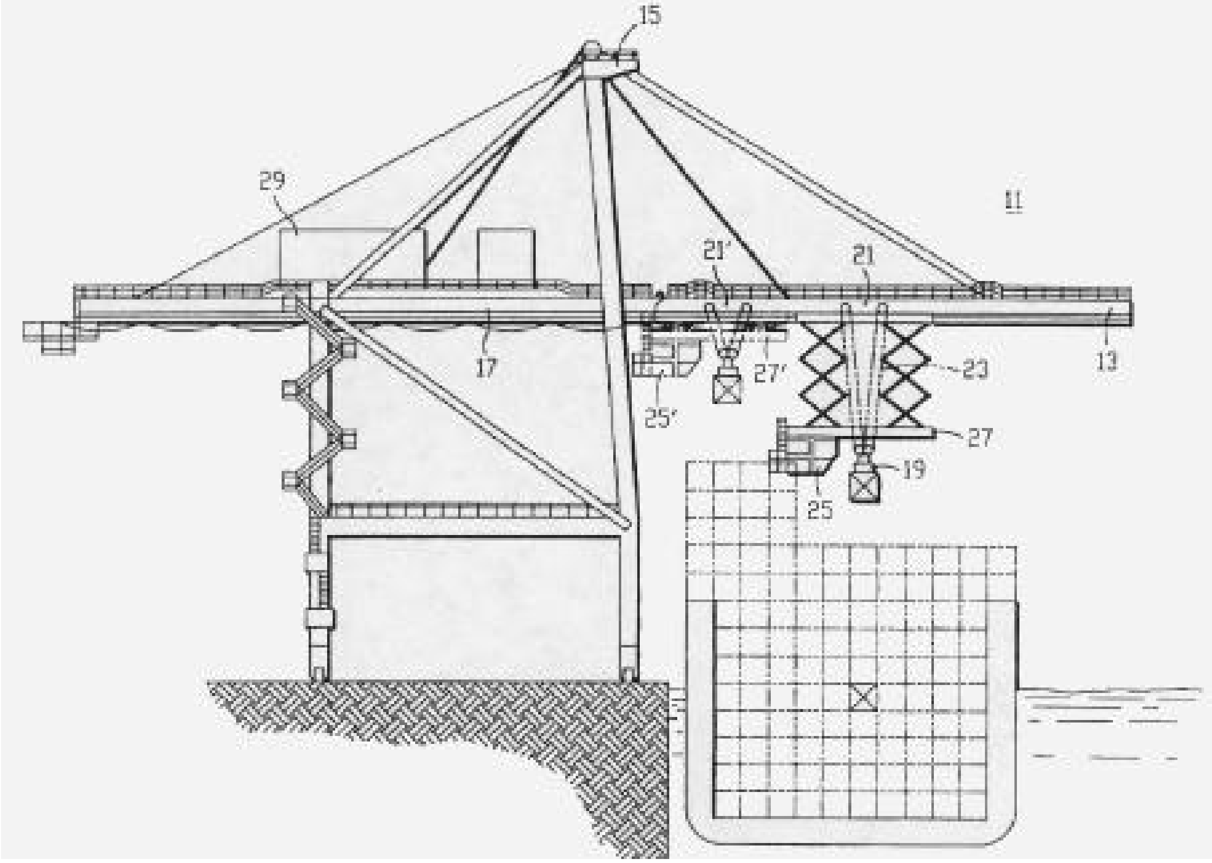
FIGURE 8. Graphics disclosed in Bernaerts patent (numbers are referenced in the patent).



Hasegawa

Shuji Hasegawa et.al. obtained a U.S. patent for a variable level platform suspended from the gantry of a cargo container handling gantry crane by a pair of scissors jacks (see Figure 9) with fleet through wire rope reeving for suspending a lifting spreader, whereby the platform effectively shortens the spreader lift lines for reducing container sway and container handling cycle times. **[26]** [Hasegawa]

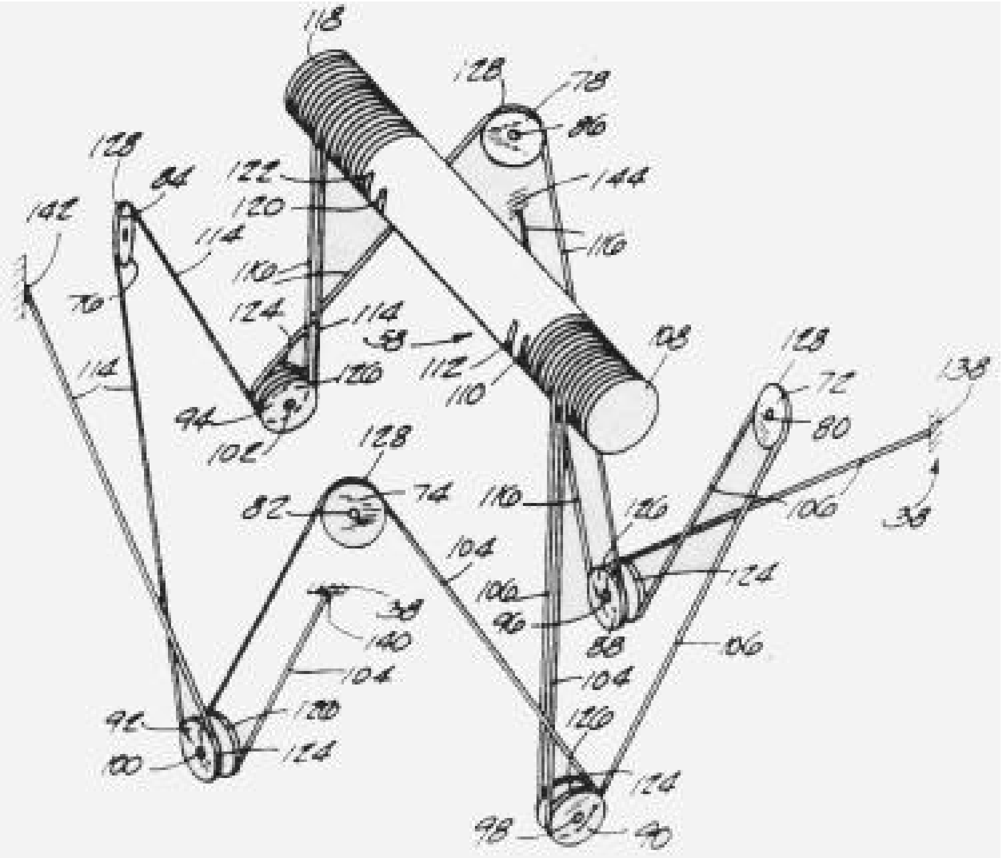
FIGURE 9. Graphics disclosed in Hasegawa patent (numbers are referenced in the patent)



Foit

Vilem Foit obtained a series of patents for anti-sway crane reeving, in which a winch drum is used to take up/payout cable through four separated snatch blocks, attached to an overhead frame, and suspend cables through four snatch blocks, attached to a spreader bar, to support and stabilize the load (see Figure 10). Two pairs of cables wrap around the same alternate snatch blocks to generate friction forces in response to swaying motions thereby dissipating swaying energy. The same anti-sway technique is applied for the other pairs of cables, also. **[27, 28, 29]** [Foit]

FIGURE 10. Graphics disclosed in Foit patent showing Anti-Sway Reeving



Port Crane Anti-Sway Control

Numerous advances have been made in port cranes and their control systems. This technology is available to be incorporated into any MOB crane design.

Anthony Simkus, at Virginia International Terminals, Inc. (VIT), together with Rob Overton, of Wagner Associates, have installed open loop, feed forward control on a port crane to reduce sway. This control provides smooth motions and increased throughput. It also

records motions taught by the operator and then allows playback for performing repetitive motions.

Simkus

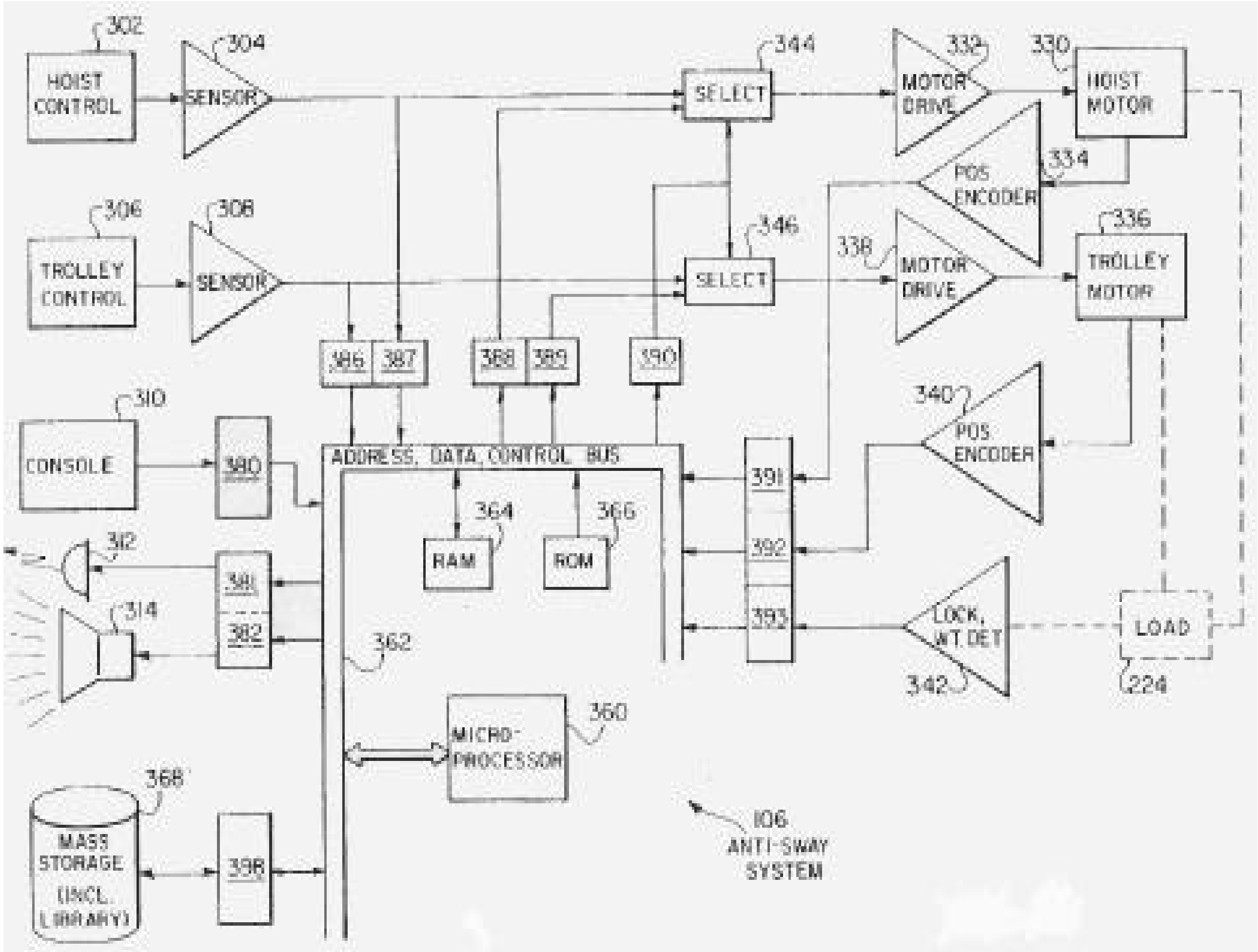
Tony Simkus and his associates at Virginia International Terminals have made a number of inventions to reduce sway and to optimize paths to provide smooth operations of port cranes. The crane has an elongated girder extending horizontally over the dock and the vessel. The crane can raise and lower the girder to change its elevation to minimize distance and time travel for the cargo. A trolley moves horizontally on the girder, and has a cargo engaging device that can be raised to become adjacent to the trolley. The cargo engaging device may be held rigidly against the trolley to permit large horizontal accelerations and velocities with virtually no attendant sway of the trolley or cargo. Paddles extending beneath the center of gravity can supplement the apparatus to further restrict sway. An operator cab moves independently of the trolley, allowing the operator several vantage points for viewing cargo movement.**[30]** [Davis]

Overton

Using a computer control system patented by Rob Overton, **[31]** [Overton] (see Figure 11), installed sensors on the winches are used to measure hook height and trolley position. The system then calculates velocity and acceleration of both. With a simulated model of the crane, it is able to predict load swing and use computer control to cancel sway of the load. The movements, load position as a function of time, and the weight are stored. Thereafter, in the Auto mode, the operator may entrust movement of the load to the control system, which causes the load to efficiently and safely traverse an optimum path (with minimum sway) in a minimum period of time. The operator is able to concentrate on movement of the load and the computer control virtually eliminates sway. Open loop, feed forward control in this situation provides fast and smooth operation.

Manual control can be attained at any point during load movement. The operator takes manual control at the end of every move.

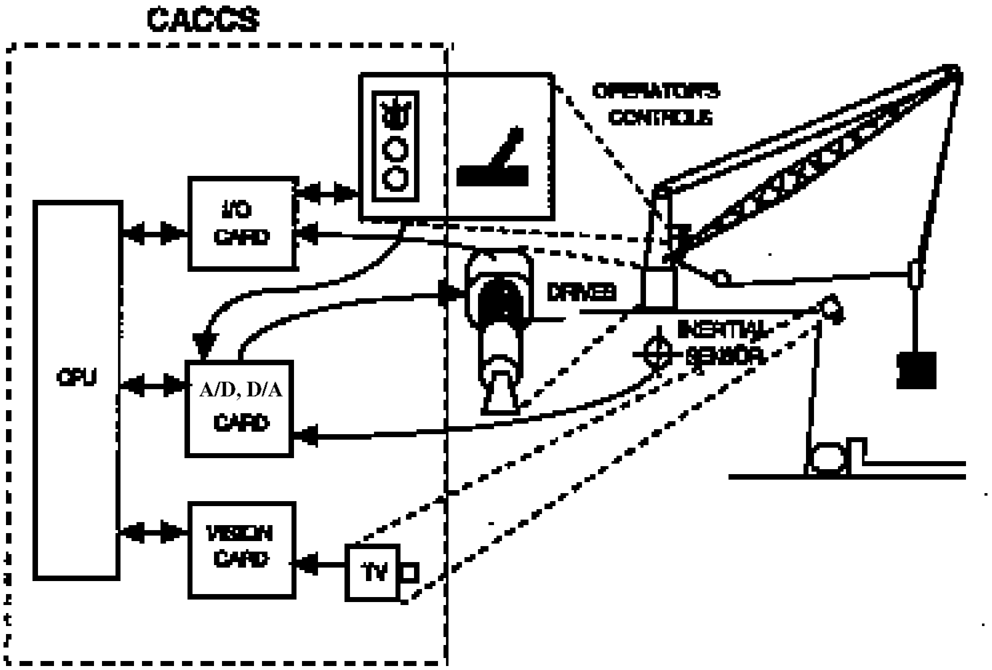
FIGURE 11. Learning Control System Block Diagram disclosed in Simkus patent (numbers are referenced in the patent)



Overton

Through an ONR SBIR (Small Business Innovative Research), Robert Overton (Daniel H. Wagner Associates, Inc.) addressed crane control in sea state 3, efficiency and safety, seamless position demand/manual operations, improving the Rider Block Tagline System (RBTS) effectiveness, and development of commercial applications. The Computerized Anti-sway Crane Control System (CACCS) approach was outlined (see Figure 12), including sensing the T-ACS motion, tracking a target on a lighter, calculating the path to the target, using modified 3-D double pulsed control and position demand to move the load, maintaining the load over the target, and maintaining the RBTS within its work volume. 3D pendulum simulation snapshots were displayed showing experimental evaluation. Phase 2 plans are proposed as part of a Phase 2 SBIR, including model crane building, specifications addressed, algorithms tested, coding software modules, integration of the system on a T-ACS, and test at sea.**[32]** [Overton]

FIGURE 12. Overton patented Anti-sway Control System



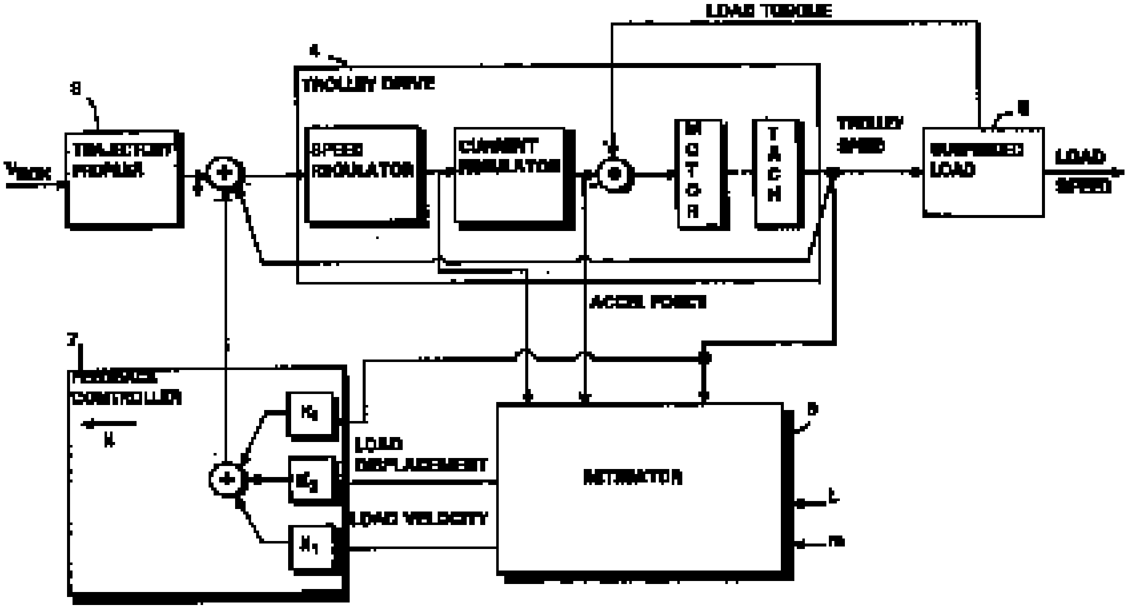
Sandia National Laboratories

Gordon Parker, Michigan Technological University and Rush Robinett, Sandia National Laboratories have developed a control algorithm for a bridge trolley crane that suppresses the load pendulation. The control system outlined uses a configuration-dependent blend algorithm, combined with two inputs (operator induced sway and base excitation (sea condition) induced sway) to form the crane actuator inputs. **[33]** [Parker]

Rushmer

Michael Rushmer obtained a patent on the use of the natural frequency Ω_n of a simple pendulum to estimate the velocity and displacement of the suspended load. A signal representative of measured load displacement is used to drive the estimated load displacement to the measured load displacement and modify the estimated velocity (see Figure 13). **[34]** [Rushmer]

FIGURE 13. Control System proposed in the Rushmer patent (numbers are referenced in the patent)

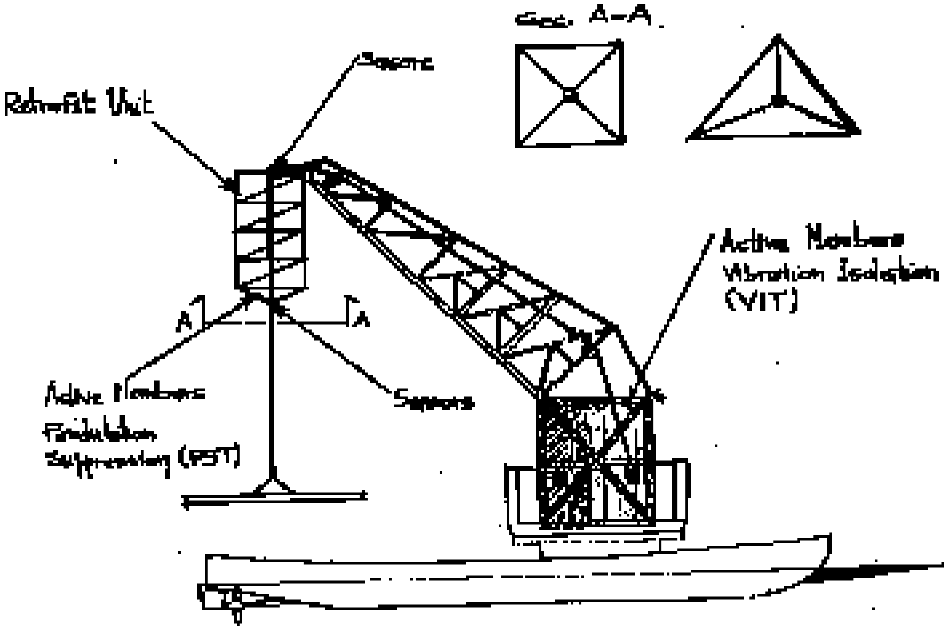


Lacarbonara

Lacarbonara, et. al. are studying new actuators for ship-mounted crane pendulation suppression under the ONR Multi-University Research Initiative Program at Virginia Polytechnic Institute. In the presentation, they offer four points including: Crane Actuation, Variable Geometry Trusses (VGT’s) (see Figure 14), Application to the Crane, and Preliminary Investigation of the Pendulation Suppression Truss (PST).

Under crane actuation, concepts considered are VGT’s, passive vibration isolation (base-mounted), nutation damping, tuned vibration absorbers (passive, semi-active, “virtual”), smart material (SM) cables, and a doubled pendulum (passive, semi-active, and sliding mass). **[35]** [Lacarbonara]

FIGURE 14. Variable Geometry Truss considered by Lacarbonara, Soper, and Pratt



Through the ONR MURI (Multi-University Research Initiative) Program, the Pendulation Suppression Truss (PST) has been investigated in a simplified model that shows the effect of a force applied to the crane load suspension cable to consider it as a means for dampening load oscillations. Equations of motions have been derived showing the constraints, analytical dynamics, and resulting motions. Open-loop resonance cancellation is currently being studied along with fixed-gain, nonlinear, state feedback, fuzzy, and neural strategies.

Rudnick

Siegfried Rudnick provides the details of cargo handling cranes self-optimizing digital control systems to move cargo quickly, precisely, and economically. Rudnick's paper describes standard high performance systems, automatic controller tuning, rotary digitizers that measure hoisting height, the stop and speed governed by crane load, and fast diagnostics. **[36]** [Rudnick]

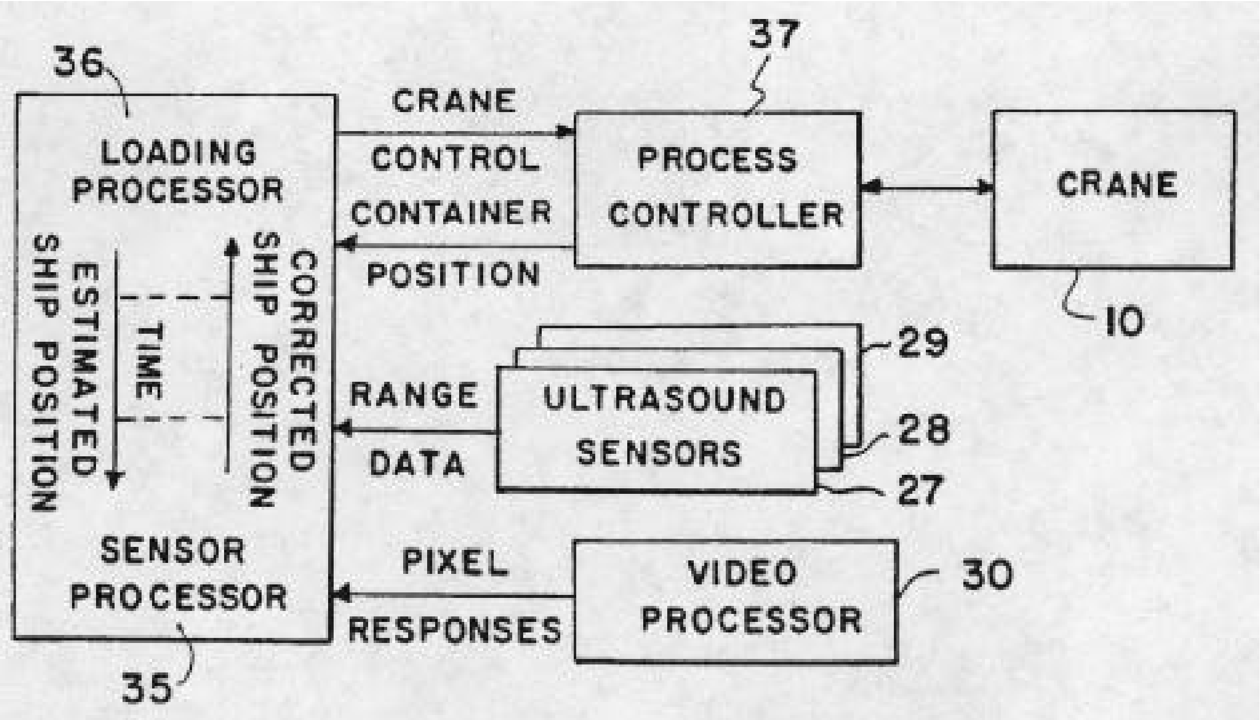
Sensors

Several sensor systems have been developed for real-time motion measurement of ships, loads, and cranes.

Overton

Rob Overton, at Wagner Associates developed a sensor system (see Figure 15) for accurately measuring the position of a moored container ship relative to a fixed pier. Measurement occures after loading or unloading each container on the ship and including a processor mechanism that combines the measured relative position with previously acquired data. This indicates the ship position prior to the loading and unloading of the previous container. Also, it utilizes the combined data to facilitate automatic control of placing or removing a subsequent container on the ship by a crane structure. The system is applicable for measuring movement of any large object in six degrees-of-freedom (6 DOF). **[37]** [Nachman]

FIGURE 15. Moored Ship Motion Determination System disclosed in Nachman patent (numbers are referenced in the patent)



August Design, Inc.

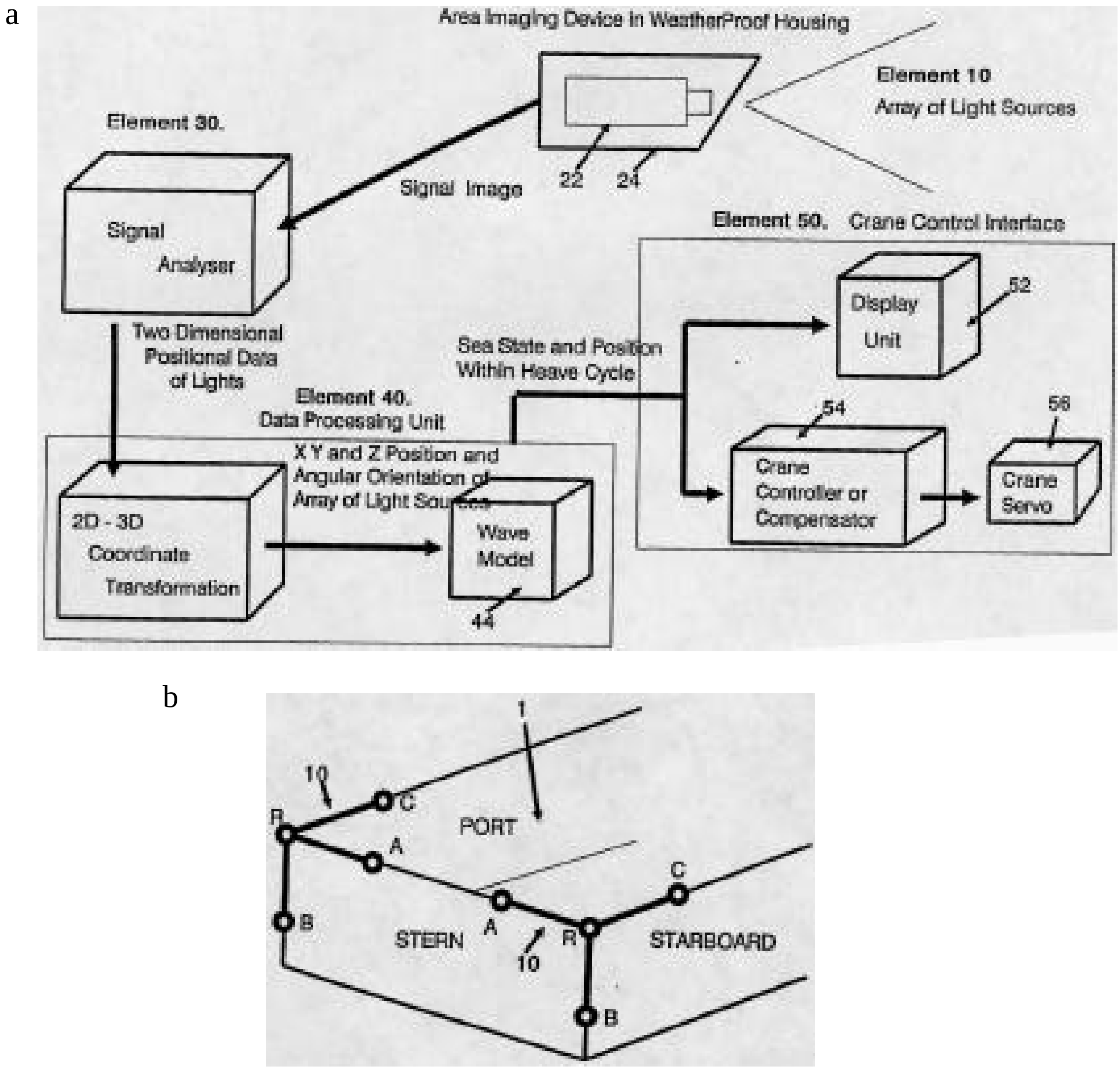
Ed Dougherty and his staff at August Design, Inc. have developed an Intelligent Spreader Bar (ISB) which includes a laser structured light sensor system to locate the corners of containers. With support from early DARPA funding in the MOB program, August Design and Bromma Inc., a major producer of spreader bars, are building a full size ISB and will demonstrate its performance this fall.

Under separate funding from Frank Leban, at Carderock, August Design has also been experimenting with stereo vision as an aid to crane operators in situations where the load is hidden from them. This is the case when reaching a container behind another one or when unloading a container over the side of a ship to a lighter. **[7]** In recent tests with 20 crane operators, there was enthusiastic agreement that stereo vision greatly facilitates such tasks.

Bonsor

Nigel Bonsor, et.al. of the UK, claimed a patent for a machine vision system (see Figure 16) that could be used to co-ordinate the interaction between a floating object (ship) at sea and a reference object (platform). The floating body is measured in real-time directly relative to the reference object using three visible non-aligned points on the floating object and using imaging to capture the points for feedback information to control the crane or other device**. [38]** [Bonsor]

FIGURE 16. a) Machine Vision System and b) Cargo Measurement points shown in Bonsor patent (numbers are referenced in the patent)



Akos

Crane sensing developments have also taken place in other industries, such as nuclear power. For example, Gy Akos has developed and installed telemetric position sensing equipment in the nuclear power station of Paks, for accurate monitoring of the crane position during reactor maintenance. The equipment utilizes high-resolution line scan cameras and special bar-codes. **[39]** [Akos]

Similar encoding has been installed on a bridge crane at NIST as part of the National Advanced Manufacturing Testbed Construction Automation project for determining precise crane positioning.

Motion Prediction

Various groups have studied, modeled, and measured crane and load motions.

Several universities have done research on crane motion prediction within the Office of Naval Research MURI (Multi-University Research Initiative) Program under the topic of Ship-Mounted Cranes. These studies are described below:

Todd

The Naval Research Laboratory (NRL) and Carderock Naval Surface Warface Center (NSWC), under the Office of Naval Research (ONR) Multi-University Research Initiative (MURI), combined theoretical and experimental study of a spherical pendulum placed upon a Stewart Platform - a dry test bed for simulating six-axis motions. When the platform was programmed to provide relatively simple roll motions, itindicates a likely presence of complex, amplitude-modulated oscillations (including chaotic modulations) at a very slow time scale relative to the primary roll frequency. These complex, slow-time oscillations can be isolated in an experimental or real system by means of a phase-sensitive detection-demodulation scheme. The fast-time “carrier” driving frequency dynamics are stripped off by tuning to a reference signal at the driving frequency and low-pass filtering similar to AM radio operation. Theoretical and experimental analyses of the slow-time dynamics have revealed a rich Hopfand flip bifurcation sequence as load swing resonance is approached, leading to large-scale out-of-plane load oscillations.

In addition to the spherical pendulum studies, a 1:24 scale model crane was fabricated and placed upon the Stewart Platform. The crane retained most functionality of real T-ACS ship cranes, including motorized slew, luff, and hoist motions, as well as a rider block tag line (RBTS) control system. Roll-forced studies of the model crane revealed dynamical features very similar to the spherical pendulum, including slow-time chaos near resonance. A wave tank test consisting of the model crane, along with a 1:24 scale T-ACS crane ship, container ship, and lighter barge, was conducted at the NSWC-Carderock facility. The test parameters inluded sea state, ship heading, crane geometry and configuration, ship configuration, and load type. All together, almost 250 different experiments were completed with each run approximately 8 min long, over 30 measurands, such as ship motions, load motions, and sea spectrum, were obtained in each run. Preliminary analysis of some data sets again indicates behavior similar to what was observed in both the spherical pendulum and the crane on the Stewart platform. **[40]** [Todd]

Kimiaghalam - NASA and North Carolina A&T State University

Kimiaghalam, et. al. use the relatively new method of Genetic Algorithm (GA) to provide control and motion planning in the test case of the nonlinear dynamics of a crane. There are several approaches to solving a dock-mounted, container crane control problem using optical control methods. Usually the necessary conditions for solving this problem require finding the initial co-states vector. In the research, real value GA is used to optimize the initial values of the sea states of the system. Each individual gene has its own fitness value based on its ability to move the system to desired final states after a given time. In order to evaluate the fitness, a system simulator is used to simulate systems trajectories continuously. The dynamics of the crane and GA approach is reported to have solved two-point boundry value problems. Application of the steady-state GA and different crossover operators to speed up the process are tested to maintain the diversity of the individuals in a population and to improve the convergence. **[41]** [Kimiaghalam]

Baptista - University of Maryland

Baptista studied the quantitative results for the cargo pendulation amplitude in a large number of simulations of rolling crane ships. Results for ships equipped with the existing rider block tag line system (RBTS) to those of the Maryland rigging are compared. A variety of roll-motion data sets measured in the field are used. In the Maryland rigging, the pendulation is damped by applying a combination of dry and viscous friction to a moving pulley. Optimal coefficients for the frictional terms are determined and, without any active control, a reduction of pendulation amplitude is possible by more than a factor of ten compared to the RBTS.**[42]** [Baptista]

Chin and Nayfeh - Virginia Polytechnic Institute

A simplified model of a cargo container motion while at sea was studied by Chin and Nayfeh in **[43]**. The study illustrates how the instabilities could arise due to the combination of a one-to-one internal resonance and a primary (additive) resonance or a parametric (multiplicative) resonance. The method of multiple scales is use to drive four ordinary-differential equations describing the amplitudes and phases of the two modes. The resulting two sets of modulation equations are used to study the equilibrium and dynamic solutions and their stability. The response could be a single-mode solution or a two-mode solution. A combination of a shooting technique and Floquet theory is used to calculate limit cycles and ascertain their stability. The numerical results indicate the existence of a sequence of period-doubling bifurcations that culminates in chaos, multiple attractors, intermittency of type I, and cyclic-fold bifurcations. The excitation parameters that lead to complex motions, including chaos, are identified in the study. In **[44]** [Chin], an elastic spherical pendulum subjected to parametric excitations is used to model the load pendulations. Derived equations are used to investigate the instabilities of the load motion and to provide information for controlling load pendulations. The analytical results are verified by numerical simulations of the original, full, nonlinear equations.

Horizontal Motion Control

Simkus

As discussed in the previous section on port-crane anti-sway control, Tony Simkus and Rob Overton have studied the instinctive concerns about open-loop control, the operators perspective, and the anti-sway, closed-loop control system including sway sensor requirements and the control system based on trolley response and cycle. An integrated crane model is stated as the only way to optimize trolley cycle. Conclusions suggest that closed-loop control has the best control of the sway and handles wind. Also, open-loop is the fastest and smoothest and operators take manual control at the end of every move.**[45]** [Simkus]

Control of containerized cargo suspended by a port crane is improved substantially with integrated, feed-forward control. Load sway is decreased when moving it from, for example, the ship to a transport vehicle on the ground. The typical operator controls are augmented with transparent computer controls so that minimal control complexity is added. Rapid cargo retrieval and placement does not affect the operator since the control cab is driven independently from the crane trolley. Endpoint locations can be taught so that the spreader bar can move at maximum speeds to the taught locations where an operator interjects additional commands, such as move slowly to acquire the target container and grip/ungrip the spreader.

Clarke Chapman Marine Crane Testbed

A 13.6 t (15 ton) Clarke Chapman Marine Pedestal crane was mounted on a 16.4 m x 48.7 m (54 ft x 160 ft) barge to act as a testbed for the T-ACS 1 crane-system, motion-compensation studies. The testbed RBTS served the dual purpose of providing a scale model to evaluate the performance and effectiveness of the T-ACS 1 RBTS and permitted safe at-sea operations of the testbed crane. The RBTS on the Clarke Chapman crane was approximately a 5/8-scale model of the full scale T-ACS 1 RBTS, which was installed later on the six cranes aboard the KEYSTONE STATE. The testbed crane and its RBTS functioned well and demonstrated that the RBTS concept could be applied successfully to level luffing and marine pedestal cranes. **[1]** [Bird]

EG&G -Rider Block Tagline System

The first, full-scale Rider Block Tagline System (RBTS) (see Figure 17) was installed on a T-ACS 1 crane built by Lakeshore.

The T-ACS 1 crane with the RBTS has the following characteristics:

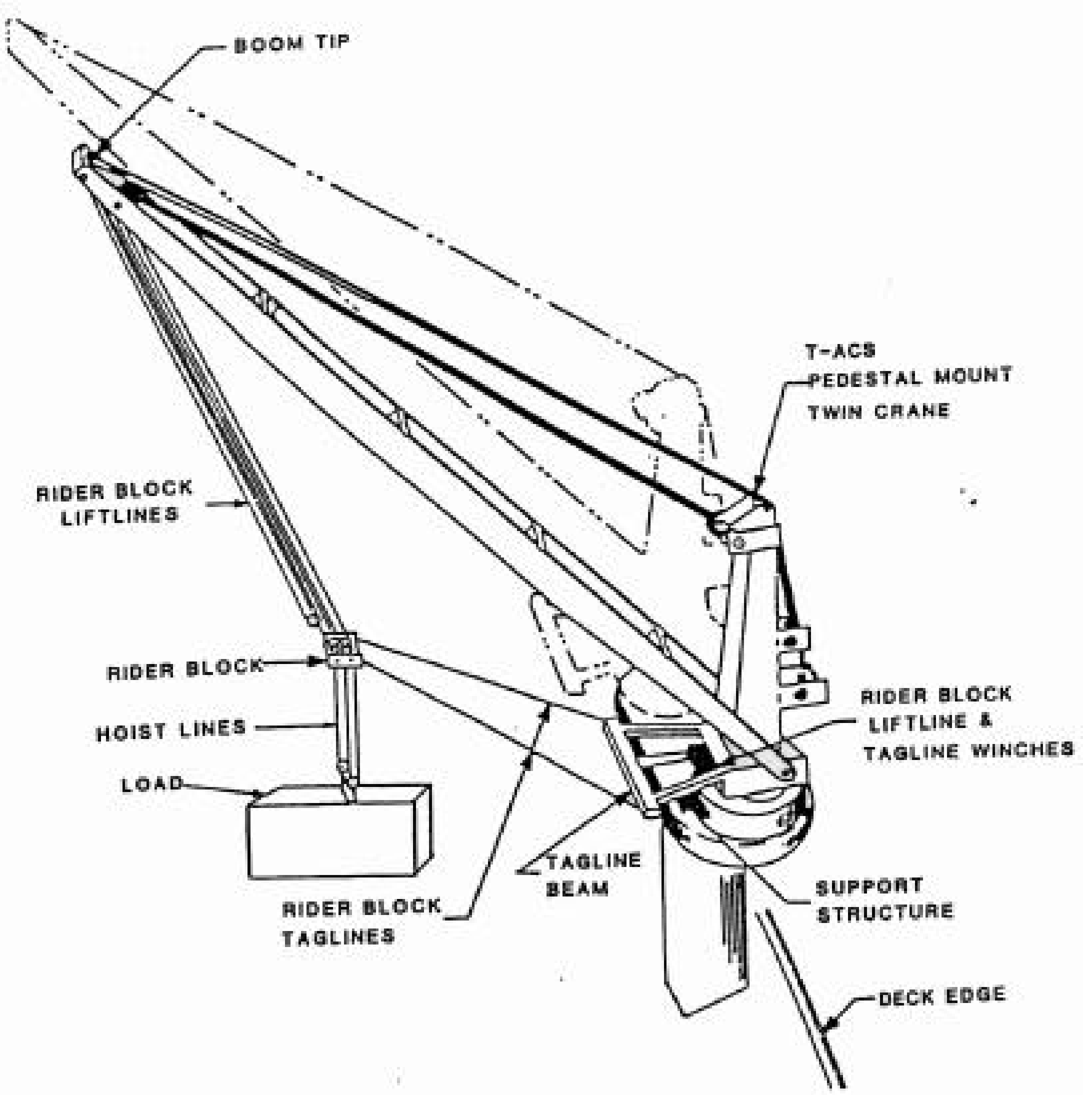
Rated Load:	36 t (40 tons =33 tons and spreader bar)
Boom Length:	39 m (129 ft)
Tagline Beam Length:	7.6 m (25 ft)
Hoist Reeving:	2x2 part 34 mm (1 3/8 in) wire rope
Rider Lift Line:	1 part 34 mm (1 3/8 in) wire rope
Taglines:	1 part 34 mm (1 3/8 in) wire rope

Tagline and Rider Lift Winch: SCR electric driven, single controller

The T-ACS 1 RBTS was a primary test item during the JLOTS II exercises off Ft. Story, Virginia during September 1984. Evaluation of the RBTS on the T-ACS 1 disclosed design problems that greatly reduced its effectiveness during these exercises. The problems were primarily in three areas: structural (several tagline beams showed signs of structural inadequacy), controls (delays in prioritizing control to the RB lift and tagline winches), and human factors (operator training on the new, unique RBTS is necessary for effective, efficient operation at sea).

The RBTS has been installed on 10 different cranes over a 6 year development period, including both Lakeshore and Haglund manufactured cranes. It has demonstrated repeatedly that it can be a simple and effective deterrent to dangerous, uncontrollable pendulation during container handling operations at sea **[1]** [Bird]

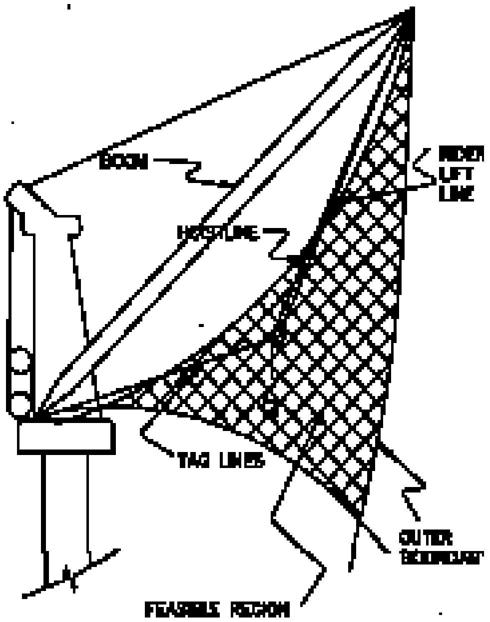
FIGURE 17. Rider Block Tagline System used on T-ACS Cranes



Craft Engineering (Dexter Bird III) - Integrated Rider Block Tagline System

The Rider Block Tagline System (RBTS) was developed by the Navy for use in mitigating the effects of pendulation when handling cargo at sea. Primarily, the RBTS permits control of the pendulum length by allowing the operator to select the position of the rider block in the vertical boom plane. This, however, increases the complexity of the crane control problem by the addition of two or more degrees-of-freedom (tagline and rider liftline) to the existing three degrees-of-freedom problem (hoist, boom and slew). This increased complexity places additional decision-making and physical-dexterity requirements upon the crane operator. The rider block must be maintained within a feasible region (see Figure 18) for it to be effective. Control functions and algorithms have been designed to facilitate the Integrated RBTS (IRBTS) control that reduces operator control complexity. **[46]** [Craft Engineering Assoc.]

FIGURE 18. T-ACS Crane Feasible Region (Dexter Bird, Craft Engineering)



Rosenfeld - **Virginia Polytechnic Institute**

Yehiel Rosenfeld, converted a full-scale 4.5 t (5 ton) payload crane into a semi-automatic “Handling Robot” that scale-models typical construction cranes. The control system allows operation of the crane in either a manual or a semi-automatic mode, and it can be taught to memorize up to 50 different benchmarks. Tests of performance, accuracy, repeatability, and safety aspects were completed and demonstrated a 15% to 50% reduction in typical work cycles, high accuracy and repeatability, and a generally safer operation resulting from anti-sway of suspended loads. **[47]** [Rosenfeld]

MURI

Several universities have performed crane motion control research within the ONR MURI Program under the topic of Ship-Mounted Cranes. These studies are described below:

Li and Balachandran - University of Maryland

Li and Balachandran studied a mechanical filter concept to control pendulation. A filter was incorporated at the pivot point about which the crane load oscillates. In the considered filter, the pivot point is constrained to move in a circular track in a two-dimensional space. It was demonstred that large crane-load responses excited by ship-roll motions and other disturbances can be suppressed effectively by using a passive filter as well as an active filter. In the active filter, a static feedback control law was used. In the current work, the active filter has been explored further and this filter has been extended to a three-dimensional case. The authors show that this filter is effective in suppressing responses of a crane load that is allowed to oscillate in a three-dimensional space. Relevance of the filter concept to crane systems on fixed platforms has also been considered. **[48]** [Li]

Dadone and Vanlandingham - Virginia Polytechnic Institute

Dadone and Vanlandingham studied control of pendulation of ship-mounted crane loads by separating control effort into several levels. First, effort must be expended to minimize the rolling motion of the ship itself. Second, an effective design for the crane must include an adequate control authority. And finally, full use must be made of this control capability through the use of intelligent control methods (since conventional techniques are incapable generally of dealing with complex, nonlinear models). In the study, the use of neural-fuzzy control techniques are applied to the crane control problem in the separate levels mentioned. Using a simple model of the ship rolling dynamics (provided by Professor Saad Ragab and his students) the effect of active (pumping) control of liquid ballast is studied for both single-frequency and multi-frequency wave motion. Using an augmented “Maryland rigging” crane design, some simulations are studied that offer evidence of a feasible design, in that load transfers can be made in relatively high sea states. The “golden thread” for all the control action is Fuzzy Logic Control (FLC), which is an approach that permits the use of both “human” knowledge about the system and data-training methods in which control can be improved online. Future work will utilize more complex dynamic models, including 6

DOF coupled motion, and elaborate on the necessarily more complex control algorithms required. **[49]** [Dadone]

Wen, et. al. - NASA and NCA&T State University

Wen, et. al. consider the Maryland Rigging mechanism for pendulation control where the load is connected at two different points on the crane boom. Equations of motion are derived that consider an active suppression method. Based on angle measurement and angular velocity of the roll motion of the boom attained by the rate gyro, the control action used to suppress the swinging consists of changing the length of the rope on which the pulley slides. The complete system has been simulated with the ability to change the boom angle, the amount of friction and/or length of the rope with no simplification. Moreover, the simulater requires control inputs and their derivitives as well as, rolling angle and its derivitives. The full, nonlinear model is used to test control design based on a linearized system. Also, dynamic friction is applied to improve performance. **[50]** [Wen]

Lacarbonara, et. al. - Virginia Polytechnic Institute

Lacarbonara, et. al. studied a modified, variable-truss-geometry architecture (refer to Figure 14) for pendulation control in ship-mounted cranes. A progressive approach to developing a hybrid control strategy is followed by the design methodology applied to a mechanical filter. The two limiting cases, a fully-active and fully-passive control, are considered using a planar control architecture. The 3D version is envisioned for future research. The fully-active control law is designed using Linear Quadratic Regulator theory. The system is linearized around the operating equilibrium, and a cost function penalizing pendulation and actuator stroke is employed. The fully-passive system makes use of a linear spring, a viscous damper, and an intermediate mass. The number of parameters associated with the passive design is reduced to two by assuming that the optimal combination of mass and stiffness is that of Den Hartog vibration absorber. Using the results of the fully-active and fully-passive analyses, a starting point for hybrid or semi-active design is obtained. Further, results provide a base line for comparing the performance of these more sophisticated control architectures. **[51]** [Lacarbonara]

Soper, et. al. - Virginia Polytechnic Institute

Soper, et. al. developed a new, open-loop control strategy applied to a planar pendulum subjected to the most severe combination of base excitations - horizontal motion at the primary-resonance frequency and vertical motion at the principal-parametric resonance frequency. The actuator architecture is that of the planar pendulation suppression truss developed at Virginia Polytechnic Institute. The control action is typical of many single-input control systems - the control authority in one direction is high and the control authority in the orthogonal direction is zero in a linear sense. Although the action of the controller is linearly decoupled from part of the system dynamics, effects are transferred to the orthogonal direction through nonlinear coupling. Proper detuning of the control input allows the nonlinear coupling to provide control action in the direction that is uncontrollable in a linear sense. The maximum pendulation angle of the steady-state motion system is one of the appropriate system response metrics. It is used as the cost function for evaluation of the optimal detuning gains. Transfering energy to uncontrollable modes via nonlinear coupling through either plant or actuator action is recognized and explored for control objectives. The control strategy is refered to as “open loop” because neither the system state nor a measured output are employed in direct feedback. However, the approach tactily assumes direct availablity of the disturbance levels and relative phases. **[52]** [Soper]

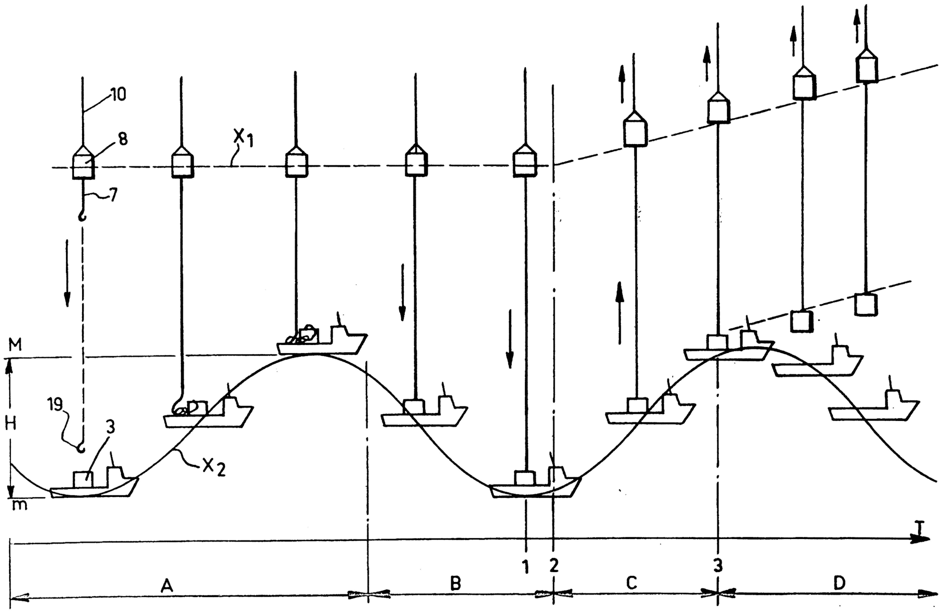
Offshore Platform Resupply

In the 1970s and early 1980s, several systems were developed to compensate for heave of boats engaged in offshore oil platform replenishment.

Cojean

In 1978, Maurice Cojean obtained a patent for removal and deposition of loads between two supports in repeated, relative, vertical movement (see Figure 19). The device consists essentially of a crane close to the high point of the support on which the load rests in its rising movement for lifting the load. To do this, the lifting device, which is suspended from the hook of a crane, includes a structure supporting a winch, a detection device for the winding in or out of cable wound by the winch, and brakes adapted to block the cable pay-out when its crane lift speed is equal to the decreasing support heaving speed. The device is applicable to the unloading of ships supplying off-shore platforms.**[53]** [Cojean]

FIGURE 19. Graphics from the Cojean patent (numbers are referenced in the patent)



Wudtke

Donald Wudtke obtained a patent in 1979 for a motion compensator for a crane to assist the operator in safely lifting loads from the deck of a heaving work boat (see Figure 20). The crane hook follows the motion of the load because a level of pre-tension is maintained on the line by use of a counterweight connected to the reeving system. A hydraulic cylinder is connected to the counterweight and also provides a cushion at both ends of its travel. **[54]** [Wudtke]

FIGURE 20. Graphics from the Wudtke patent (numbers are referenced in the patent)

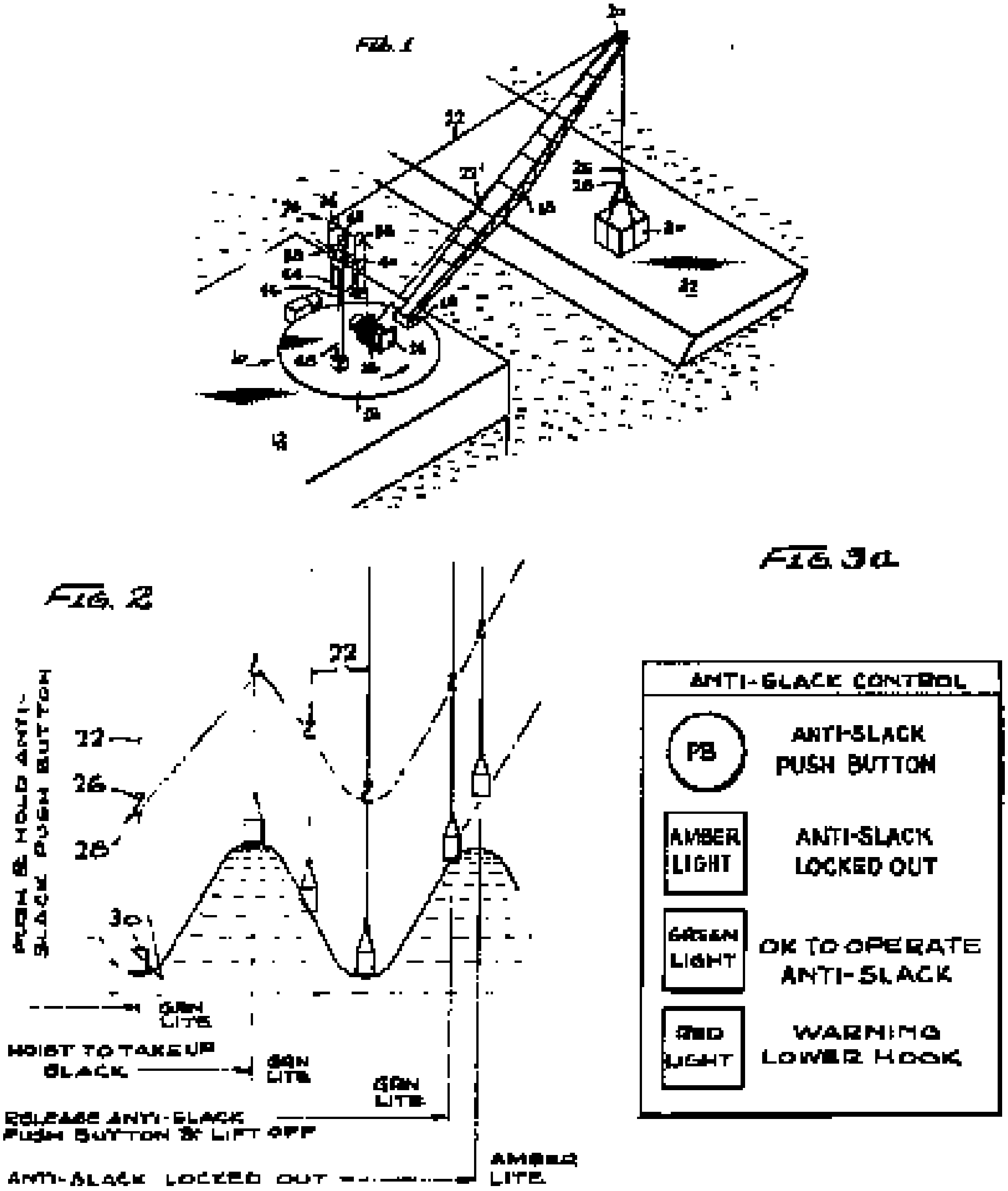


FIG. 1

FIG. 2

FIG. 3a

Archibald

Archibald, et.al. of the U.K., patented a concept in 1982 for a hoist or crane incorporating a hydraulic compensator to provide heave compensation when installed at either end of two stations or at a single station. Pressured by gas-loaded accumulators and including a sector for achieving either bi-directional hydraulic fluid flow between accumulators and the compensator (to compensate for load position movements) or a unidirectional flow (permitting heaving in but preventing subsequent paying out) whereby the load is removed from the sea at the wave crest level. **[55]** [Archibald]

Vertical Motion Compensation

Rucker Transloader

In 1968, Rucker Control Systems delivered the Rucker Transloader to the Navy. It consisted of a hydraulic ram tensioner that could be placed in the load line of a crane cable system to provide for adjustment in cargo position. This system was operated hydraulically and was designed to heave a 2.7 t (3 ton) capacity and linear displacement capability of ±2.4 m (±8 ft) while responding to a maximum velocity of 1.2 m/sec (4 ft/sec). Testing was conducted by the David Taylor Naval Ship Research and Development Center during 1970 on a land based mock-up of a crane boom.The Transloader functioned satisfactorily with a load of 172 kg (380 Lb) attached, but when the 1542 kg (3400 lb) load was lifted, oscillations began that soon reached violent proportions. Extensive analysis was performed and hydraulic valves were replaced with hydraulic servo valves to permit easy adjustment of the system feedback gain. Enhanced performance resulted, but with overdamped control of heavier loads and with too slow response times for practical use. **[1]** [Bird]

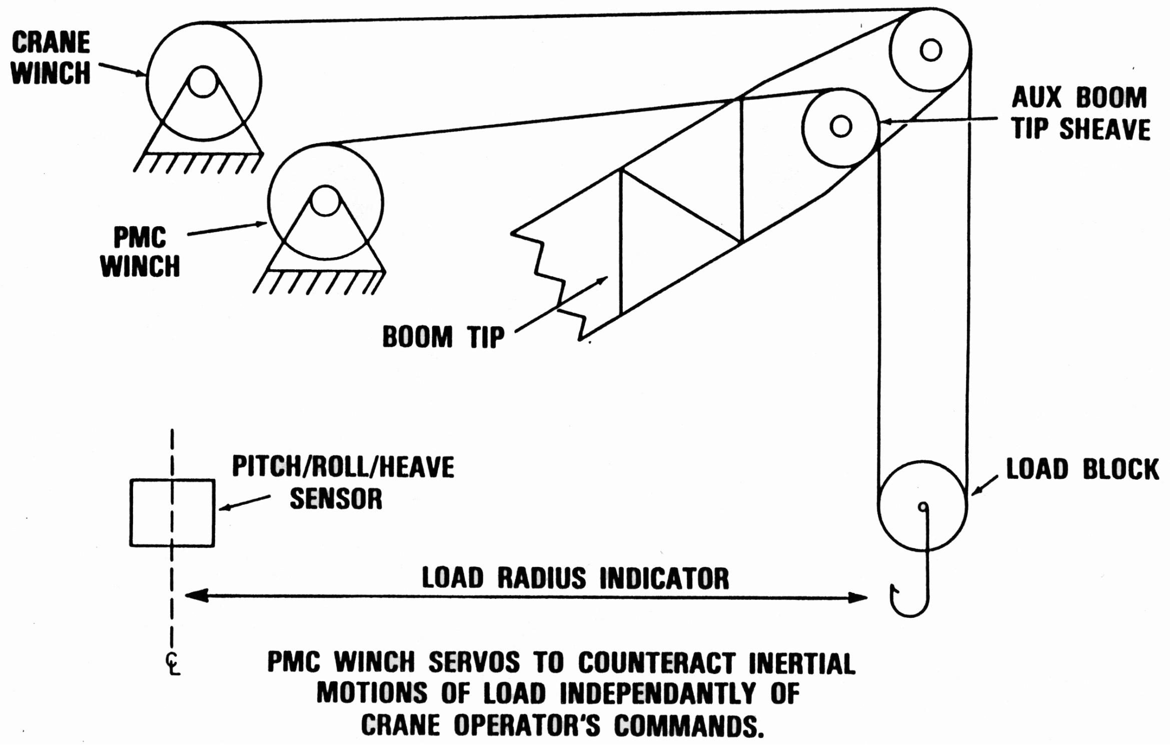
EG&G Platform Motion Compensator

In the 1980’s the Navy undertook research to develop a Platform Motion Compensator (PMC) to deal with relative vertical motion. The original PMC design and concept was developed by EG&G. A prototype PMC was installed on the KEYSTONE STATE (T-ACS 1) and was used during the J-LOTS II exercise at Ft. Story, Virginia during the fall of 1984. While the PMC prototype was a technical success, the PMC was not implemented in the fleet because of its perceived cost and complexity.

The PMC was designed specifically to remove the vertical component of the load motion induced by the crane platform’s motion. The PMC is an electro-hydraulic mechanical device that, without the aid or attention of the crane operator, moves the hook load in a velocity and direction equal and opposite to the vertical motion imparted to the load by the crane platform as it rolls, pitches, and heaves during offshore cargo off-loading operations.

The PMC includes primary power supplied by four 74.6 kW (100 Hp) electric motors, a pair of accumulators and pressure sensors (for tension control), main winch modification with increased torque and double grooving (two part line reeving), modified controls (built-in microcomputer, sensor displays, diagnostic lights). Components were installed above the operators cab. A PMC block diagram is shown in Figure 21.

FIGURE 21. Platform Motion Control Basic Schematic Diagram



An inertial ship motion sensor, a crane load radius, and slew angle sensors are all that is needed to provide inputs for the calculation of the instantaneous vertical velocity of the load. Basic design goals were limited to: 36 t (40 tons). maximum crane load, ±1 m/s (3.5 ft/s) maximum compensated hook speed, and ±3.7 m (±12 ft) maximum compensated amplitude.

Prototype testing was performed at dockside and at-sea. At dockside, containers were landed repeatedly on the dock successfully. The closeness of the operators cab and the hydraulic pumps resulted in excessive noise in the cab. The at-sea testing was conducted during JLOTS-II exercises. Crane operators commented that the difference with and without the PMC was significant. Consensus on the exercise was that the operation could not have been accomplished without the PMC. **[1]** [Bird]

Draper Laboratory Automatic Touchdown Algorithm

Instead of following the motion of the entire wave period, C.S. Draper Laboratory was commissioned by the Naval Coastal Systems Center to investigate adaptive loading strategies by attempting to land the cargo at the wave peak. The result was an adaptive automatic touchdown algorithm developed in 1980. The function of the algorithm is a velocity control with higher gain as the load approaches the deck, i.e. if the load and the lighter deck are not in danger of high velocity collision, do not attempt to get out of the way. The automatic touchdown algorithm was developed and tested on the Manitowac 4100W Ringer Crane at Port Hueneme, California in 1980. The basic system components were an ultrasonic range measuring device mounted on the spreader bar, a crane winch controller including a tachometer on the winch and potentiometers on the torque converters as feedback, and a desk-top computer to implement the touchdown algorithm. An on-deck control unit, to be replaced by automatic controls, allows an operator, stationed at the rail of the ship, to switch the unit from automatic landing to constant tension when the load touches the lighter deck.

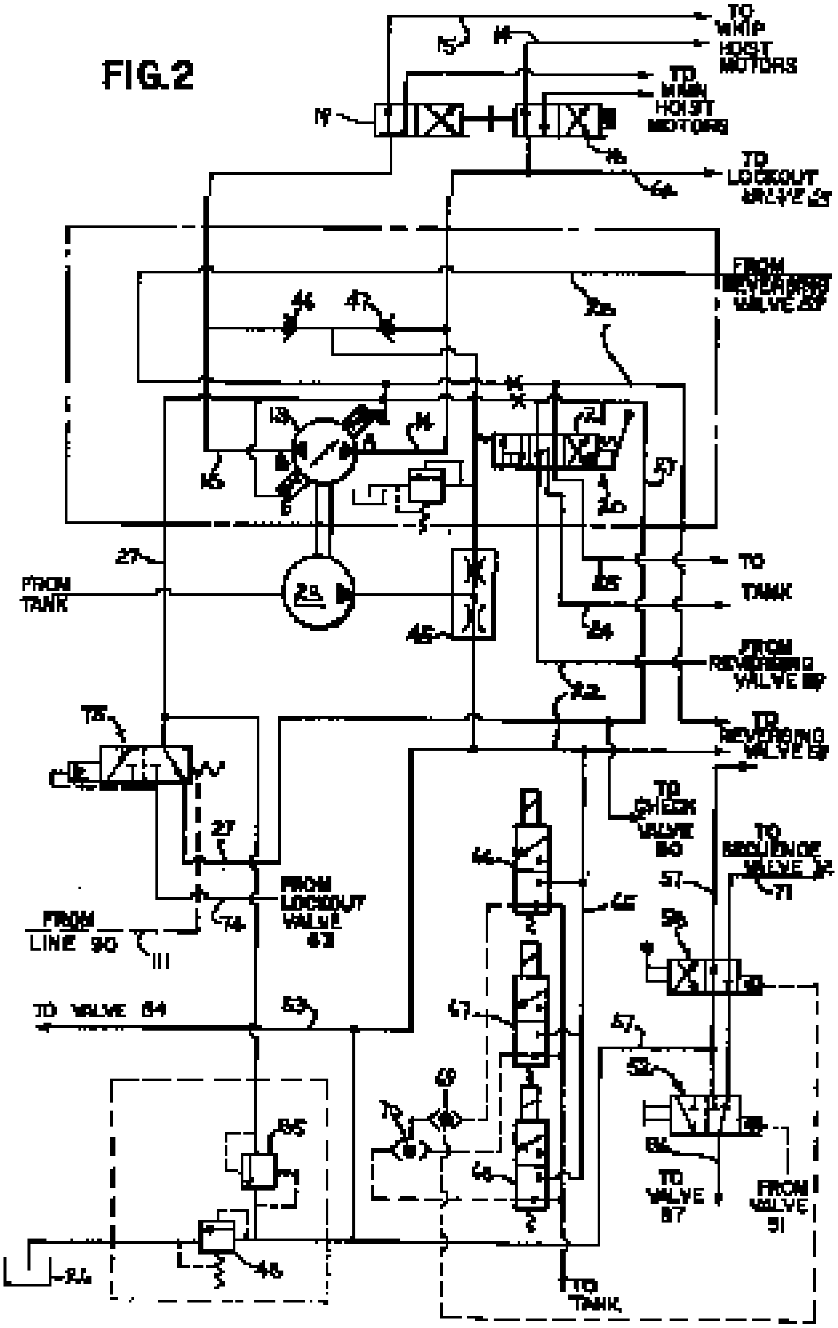
With less than one-foot amplitudes, the demonstration of the system was sufficiently successful to indicate that the concept was viable and had the potential to enhance greatly the container handling operation at the lighter interface. **[1]** [Bird]

Dummer

Robert Dummer obtained a patent for a heave compensating system (see Figure 22) in 1980. A marine crane, including a high-speed winch having a hydraulic heave compensating system, automatically controls the crane winch to compensate for the vertical movement of the load during offloading operations. The heave compensating system includes a reversing valve for overriding manual control and for directing control pressure to stroke the pump of a hydrostatic winch drive into its raise mode of operation. Also included is a compensating valve that regulates the displacement of the pump, permitting it to develop and maintain only a predetermined pressure in the high pressure main fluid line. The heave compensating system preferably includes a lift control system for automatically hoisting a heaving load only at or near the crest or trough of a wave.**[56]** [Dummer]

FIGURE 22. Hydraulic Schematics showing the drive system for a boom crane disclosed in the Dummer patent (numbers are referenced in the patent)

FIG.2

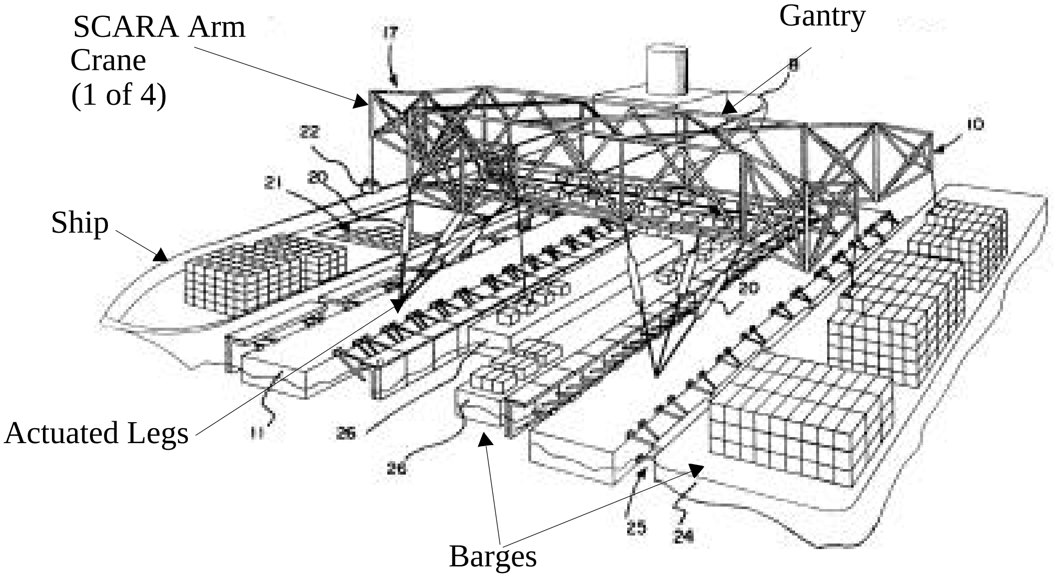


Crane Designs-Structures and Reeving

Lee - AACTS

Don Lee, at the Franklin Institute, conceived **[57]** [Lee] and together with August Design **[58]** [Dougherty], built a working scale model of an advanced, automated, vessel cargo transfer system for loading and unloading of ships and lighters (see Figure 23). It includes an articulated manipulator arm mounted on a frame. The arm is provided with a spreader bar at the distal end. The spreader bar is provided with facilities for grasping cargo. Sensors track the movement of the vessel, and automatically responsive controllers adjust the motion and position of the spreader bar to follow the motion of the vessel. Berthing modules are provided to aid in controlling the motion of the vessel. In a major embodiment (of the patent), the manipulator arm is mounted on a transverse frame that bridges spaced apart floating barges, and provisions are made for serving vessels both on the outboard and inboard sides of the barges. In another embodiment, the manipulator is shore-based. The figure shows applications for flexible truss bumpers, also.

FIGURE 23. AACTS graphic from Lee Patent



Liebherr

Liebherr’s new (CBS) crane designs include a series of new cranes intended specifically for multi-purpose vessels, with higher capacities (25 t to 100 t) and outreach (22 m to 45m). **[59]** [Liebherr]

Wave Motion Damping

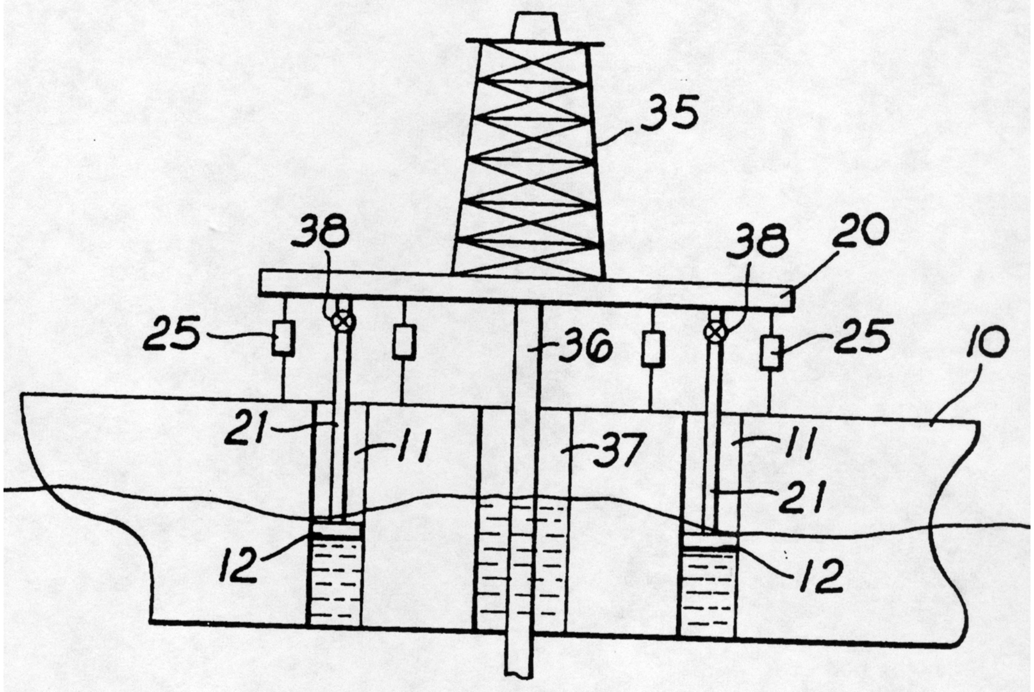
JLOTS - Rapidly Installed Breakwater

The RIB (Rapidly Installed Breakwater) System is a SS3 enabler. It will allow JLOTS cargo transfer operations to continue through sea state 3. The RIB system is a V-shaped floating structure consisting of two legs joined at the front and anchored at each end such that the legs form a 45° angle. Each leg of the RIBs acts as a diffraction element for obliquely-incident waves, leaving relatively calm water inside and behind the structure. A stiff curtain with triangular elements at each end extends through the water column to a depth sufficient to deflect most of the wave energy. Most applications would include a depth of 6 m (20 ft), have 2.4 m (8 ft) of structure above the waterline, with each leg on the order of about 305 m (1000 ft) in length. Scientists believe that the RIB has the potential to dramatically increase throughput, for a relatively small cost, in some locations by a factor of more than 1000 percent. Obstacles to completion include its deployment and employment, mooring, repositioning, recovery, and survivability. Initial conclusions suggest that there are no insurmountable problems. **[7]**

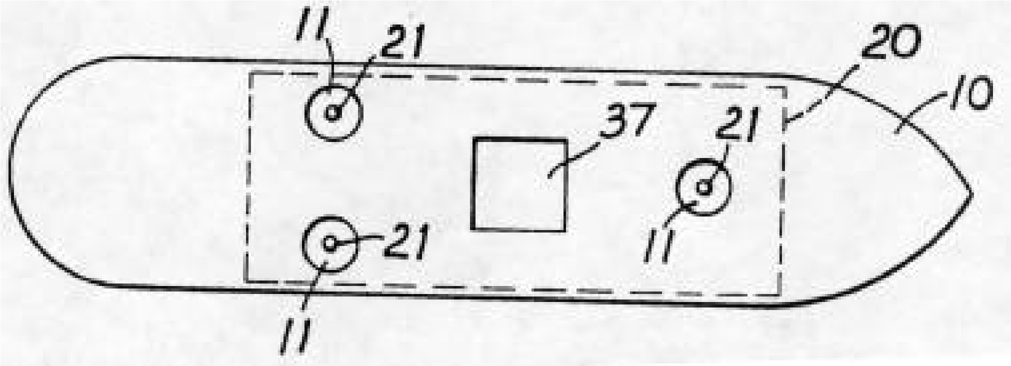
Kuo

Chengi Kuo filed a UK patent that proposes that marine vessels be equipped with moonpools (see Figure 24) in a way to isolate the motion of a crane from a ship’s motions. A moonpool is a vertical passage within a vessel, in this case closed at the upper end and open at the lower end to the sea, to provide a column of sea water within the vessel. Moonpools as proposed, allow small motions in heave, roll, and pitch and, when equipped with controlled air pressure at the upper end and a pontoon work area, provide a controlled means of supporting, for example, a crane that is vertically steady with the sea bed and independent of the vessel motion. **[60]** [Kuo]

FIGURE 24. Top and Side views of the Moonpool concept proposed in the Kuo patent (numbers are referenced in the patent)



side view



top view

Blood - Float, Inc.

Howard Blood developed a concept called PSP (pneumatically supported platform) that is a modular floating platform composed of a number of cylindrical shaped components. Each cylinder is sealed at the top with an end cap and open to the ocean at its base. Each cylinder contains air at a pressure greater than atmospheric pressure. This compressed column of air supports the platform in a manner that reduces the wave induced forces acting on the PSP structure as compared to a platform with a closed bottom. This cushioning effect of the air column is expressed by the air pocket factor. Another aspect of the PSP design is that air is allowed to flow from each cylinder to its neighbors through connecting orifices. The air flow provides a mechanism to help level out highs and lows in the pressure distribution beneath the structure and provides an additional mechanism for dissipating wave energy. **[61]** [Blood]

World City

World City conceptualized a floating city called the Phoenix World City. It would be the first in a generation of cruising resorts and floating cities of the future. It would be nearly a quarter-mile long, accommodate 6,200 guests in 2,800 staterooms and suites, offer a variety of facilities, restaurants, and shops. The floating city would include massive portals in the stern of the vessel that open to reveal a large marina within the hull and a lively seaport. Four 400-passenger day cruisers, ships themselves, would dock inside the marina and be deployed at high speeds to and from ports and a variety of destinations within a fifty mile radius of the city. **[62]** [World City Corp.]

McDermott

The McDermott MOB concept conceptualized an artificial beach to land LCAC (Landing Craft Air Cushion) vehicles and, potentially, other lighterage with this “beach” capability. This would essentially eliminate the wave effects on the lighterage.

Integrated Motion Control

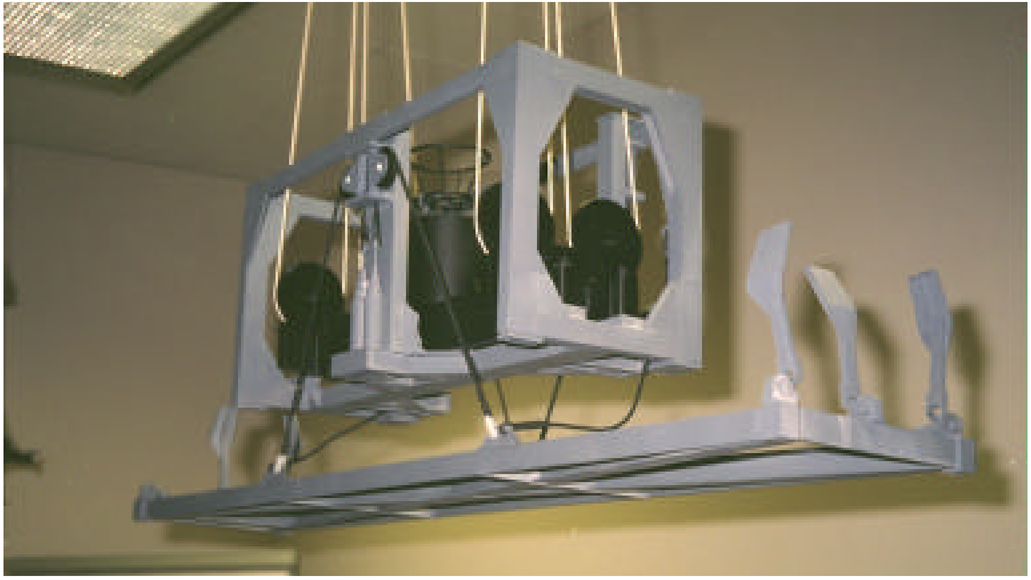
August Design

As part of the Carderock NSWC JLOTS Advanced Crane Technology Program (initiated by the DARPA MOB Program), a 6 DOF spreader bar, called the Intelligent Spreader Bar (see Figure 25), is being developed by August Design, Inc. The technology includes a two-part container spreader bar with an automated, 6 DOF positioning system that manipulates the spreader bar relative to the container and maintains the container’s motion and orientation relative to a selected frame of reference (such as the deck of a lighter). It also manipulates the connection part of the spreader relative to a container during latching. **[7] [63]** [Dougherty]

The system includes six, computer-controlled rotary actuators mounted in a headblock. Cables connect the rotary actuators to a lower spreader bar and provide six-axis motion compensation between the crane, suspending the ISB, and the cargo. The six cables then provide 20.4 t (22.5tons) maximum lift for container loads using electrical or hydraulic power. Sensors for measuring container position relative to the reference are proposed to be ultrasonic or optical range finders. Processing of sensor and position data occurs onboard the ISB in a microprocessing unit.

Benefits from the ISB are that container pitch, roll, and heave motions will be compensated for during latching and set-down. The ISB could eliminate the need for tagline handlers aboard lighters while increasing the speed of engaging and placing containers.

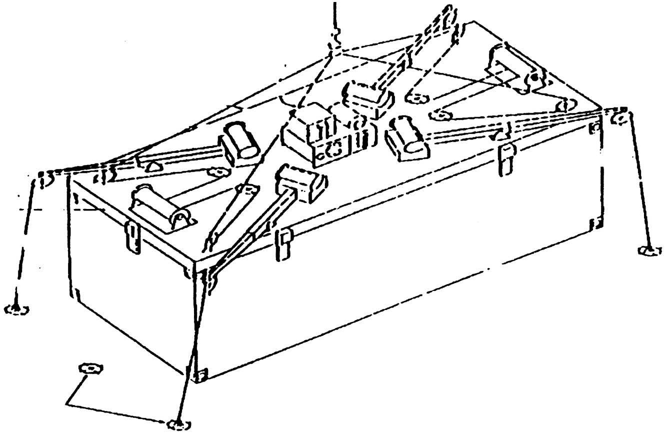
FIGURE 25. I/16th scale model of the August Design Intelligent Spreader Bar



JLOTS - Spreader Bar Tagline System

Also within the JLOTS Core SS3 Project, a Spreader Bar Tagline System (see Figure 26) is being studied. This technology provides automated, powered taglines to control cargo pendulation and cargo spotting during cargo handling operations. The current procedures for using taglines are hazardous since they rely on personnel to maintain continuous tagline control. The hardware for this technology relates to a set of powered taglines located on the spreader frame and belayed to hard-points on the lighters. **[7]**

FIGURE 26. Spreader bar Tagline System



JLOTS - Remote Crane Control Station

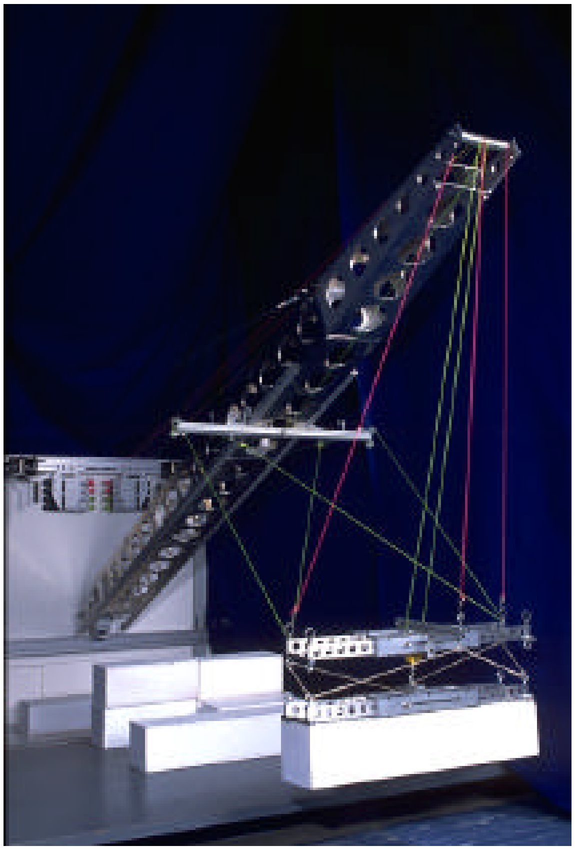
Within the JLOTS Operational Enhancement Program, a remote crane control station has been proposed. This mature technology includes a second crane operator who would be located at the ship bulwark and have a close and direct view of the lighter deck. The operator based in the crane cab would transfer crane control to the mobile crane operator at a non-critical point in the lift. The mobile crane operator would use the remote control to spot and land the cargo. Upon completion of the move, and with the spreader bar or hook safely hoisted, the control would be reverted to the cab-based operator for another cycle. **[7]**

Albus - NIST RoboCrane

During the late 1980's, DARPA contracted NIST to study robot cranes. In this study, a revolutionary crane design evolved by James Albus, et. al., based on the Stewart-platform, parallel-link manipulator. NIST turned this configuration upside-down, used cables as the parallel links, winches as actuators, and gravity as the vertical force component. This allows a lower platform to be suspended from an upper (reference) frame and maneuvered with full 6 DOF capability. Multiple adaptations to the original design, now trademarked as the RoboCrane, have been studied. **[64, 65, 66]** [Albus]

In 1996, NIST was contracted by DARPA, followed by ONR, to study the RoboCrane applied to LO/LO operations for the MOB. Several concepts were developed, including a rail crane that is similar to a port crane and a luffing crane as shown in Figure 27. A final project report includes these and other concepts that NIST developed**. [67]** [MOB RoboCrane] In the final report, detailed descriptions of the RoboCrane reeving and control are explained.

FIGURE 27. Photograph of a 1/16th scale model luffing crane configured with RoboCrane cabling.

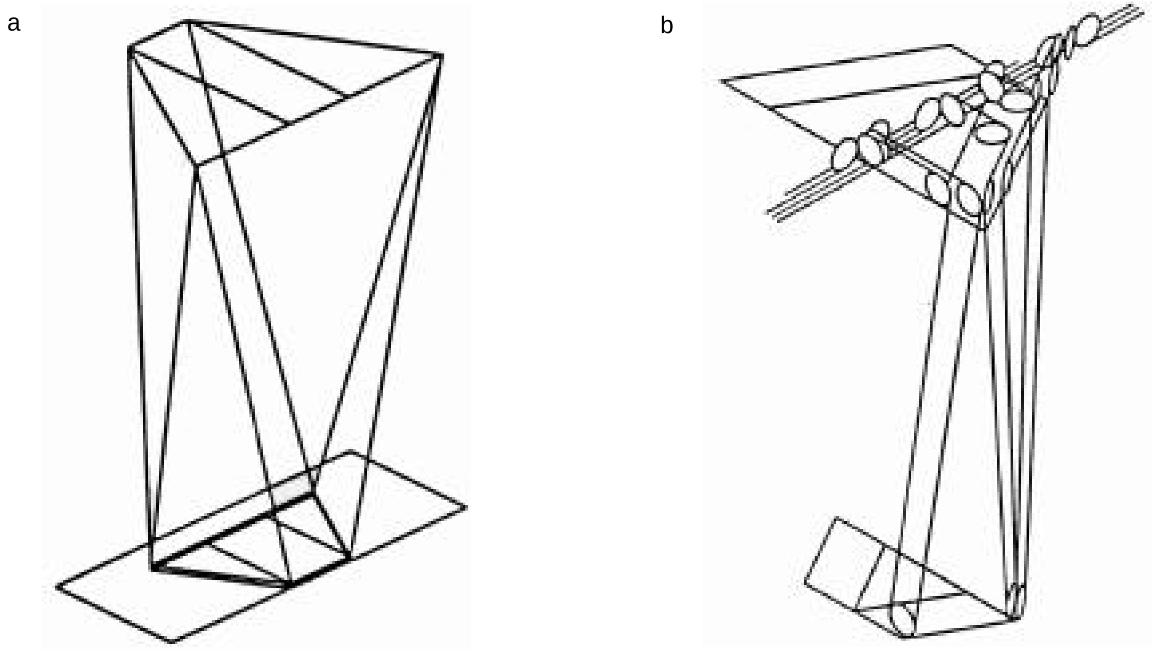


The concept includes the use of upper and lower Stewart Platform-reeved spreader bars, that augment the typical heavy lift lines, and provide sufficient constraint in 6 DOF to compensate for relative ship motions. The two spreader bars can be joined to minimize power and maximize control speed. Also, the spreader bars can be separated with the lower spreader joining the upper spreader with an additional Stewart Platform reeving. This allows the lower spreader to enter ship cells, reach between stacks of ship deck containers, and reach over container stacks blocking the upper spreader bar access to the targeted container.

Dissanayake and Durrant-Whyte - University of Sydney Australia

Dissanayake and Durrant-Whyte of the University of Sydney Australia have described the design and implementation of a semi-autonomous and, ultimately, fully-autonomous, container quay-crane. The new crane is based on a novel, reeving arrangement (see Figure 28), similar to the NIST RoboCrane, which allows both fast and accurate gross motion as well as fine micropositioning. Their paper, “Towards Automatic Container Handling Cranes,” describes the essential theory behind this design and presents experimental results from a 1/15th scale model. The proposed instrumentation of this crane is also briefly described as are key elements of the operator interface. **[68]** [Dissanayake]

FIGURE 28. a) Kinematic structure of the trapezoidal reeving arrangements b) Arrangement of sheaves on the trolley and the head-block.



Dynamical Systems

Dadone

Paolo Dadone, through the MURI Program at Virginia Polytechnic Institute, is studying a three dimensional crane model pendulum that uses fuzzy logic to reduce pendulation while incorporating the “Maryland Rigging” scheme with variable friction. Simulation of this model shows fuzzy control of trolley motion and enhanced anti-sway load positioning control.

Also, using a neural (fuzzy) model reference, adaptive-control technique, Dadone does not model the crane first. Instead, using the adaptive control technique, the neural model is to learn (identify) what the crane actually does to reduce errors between output from the crane and a reference model (goal point).**[69]** [Dadone]

Winches and Drives

Electric drives with direct frequency converters (DFC) have been developed to “modernize” crane and ship controllable ac drives.

Feldman

I. Yu Feldman has pointed out recently that electric drives of crane and ship winch mechanisms utilize not only relay-contact control systems but also systems with TTS direct frequency converters (DFC). Frequency converters may be used to modernize crane and ship-controllable ac drives, as well as new developments (i.e. removing deficiencies of the DFC by increasing grid frequency). **[70]** [Feldman]

Podobedov

E. G. Podobedov, et.al, have described automatic electric drives with frequency converters for hoist and deck mechanisms. They provide the technical characteristics, circuitry, and basic data and for electric drives with direct frequency converters. **[71]** [Podobedov]

Allen

Richard Allen, at Ship’s Equipment Centre, a firm specializing in turnkey contract, electro-hydraulic, SEC Ten Horn winches, provides a compact, self-contained unit that is filled with lubricant and mounted on an enclosed foundation framework. Rapid installation and simple connect enable turnkey operation. **[72]** [Allen]

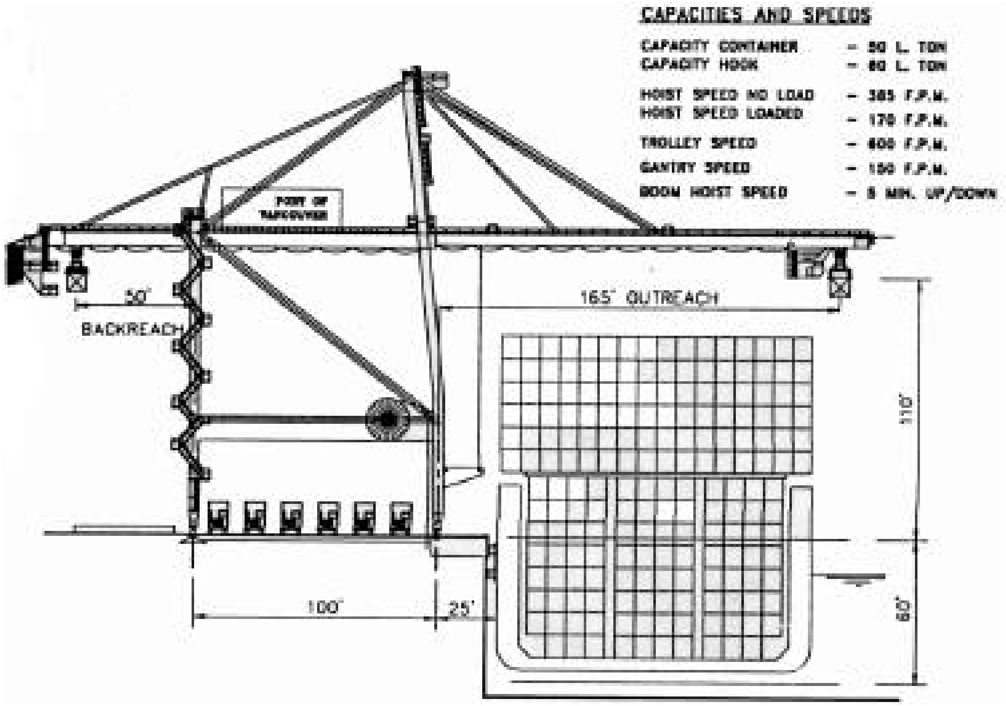
Container Terminal Automation

Many new ports have been expanded and modernized in the last decade. Several of these utilize advances in anti-sway control to achieve semi-automatic control and consequent improvements in operating efficiency.

Barker - Deltaport

Ann Barker has described the development of Deltaport and the key operating features such as berth design, on-dock intermodal yard, container storage yard, infrastructure improvements and cranes (see Figure 29). Cranes will be equipped with an electronic anti-sway system. The system will detect spreader sway in relation to the trolley. There will be a corresponding trolley movement to dampen the spreader sway. This semi-automatic operation and other features, such as enhanced crane monitoring and maintenance system (advanced diagnostics, crane production monitor, data logging, and preventive maintenance data logging).**[73]** [Barker]

FIGURE 29. Graphic showing Deltaport Terminal Crane



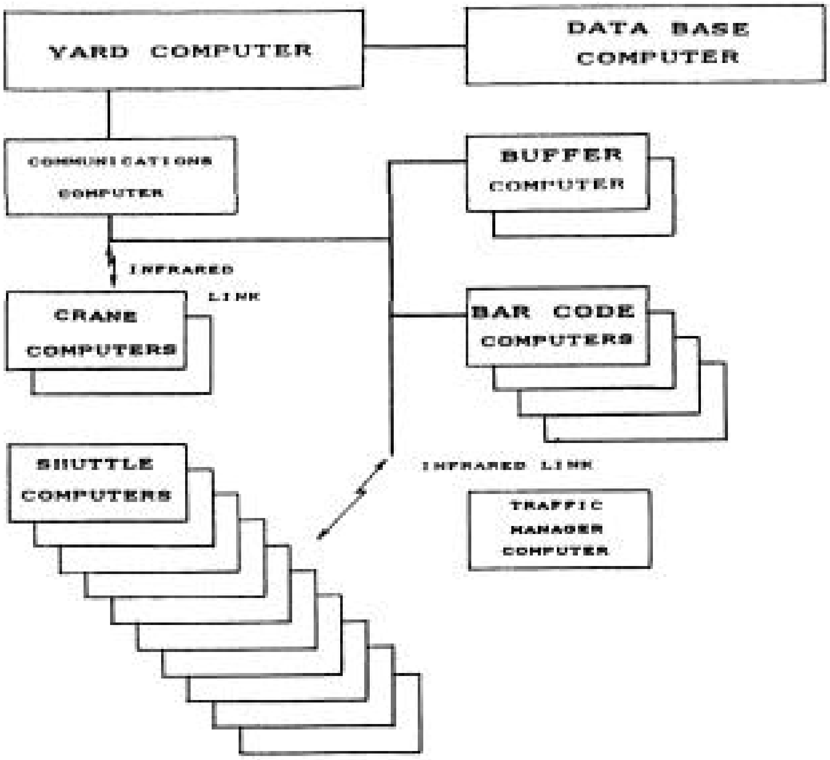
Reiss - Advanced Research Projects Agency

Daniel Reiss describes recent advances that can be used to design a fully-integrated, automated container terminal (IACT) capable of providing order of magnitude improvements in operating efficiencies, life cycle costs, and land utilization. Specifically, high capacity Rail Mounted Gantry designs including spans greater than 100 m and direct drives and controls (high-precision, static, stepless drives and controls allowing precise positioning and computer control of large devices over long distances. **[74]** [Reiss]

GRAIL - August Design

August Design designed and constructed a working 1:100 scale model of the GRAIL robotic container handling facility (see Block Diagram in Figure 30) for Sea Land Service. The system manages and controls the movement of cargo containers throughout a shipping facility - from the time a container arrives at the container yard to the time it is placed onboard ship. The system features traffic management, redundant collision avoidance systems, fail safe design, an expert system for placement of containers in the yard (fully automated shore cranes and container accumulators (for queuing below the cranes)), a unique data management system that uses color graphics to display the entire yard, an efficient network control system and a number of autonomous mobile robots. The robots include a highly reliable end effector, infrared communications, accurate positioning, extensive mobility, speed control, and onboard collision avoidance. **[75]** [Dougherty]

FIGURE 30. GRAIL System Block Diagram



Material Handling Alternatives

Naval Architect

Sources, such as Naval Architect, describe new developments in shipboard cargo handling equipment, particularly so where future reefer ships are concerned, including: automatic pallet lifting in reefer ships, the S-Loader System (Mark IV), knuckle-boom deck crane for container handling, KSW system automatic pallet handling, and MacGregor-Hagglunds LC Cylinder-Luffing Cranes. **[76]** [Naval Architect]

Material handling alternatives to cranes include: conveyors, mono-rails, footed bridge boom, AGV, forklifts, elevators, air bearing pallets, and stackers. All alternatives to cranes would require ramps or connections with motion compensation.

Simulation

Simulators have been developed to facilitate design, testing, development of operator interfaces, and operator training.

Virginia International Terminals

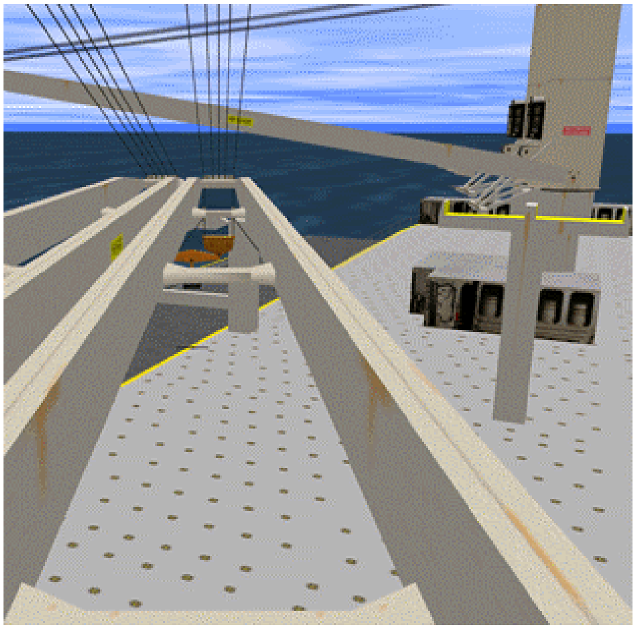
Implementation of an advanced operator interface has been integrated on cranes at VIT. Three cranes have been equipped with an electronic anti-sway system, which involves two modes: a “Learn” mode and an “Auto” mode. In the Learn mode, an experienced operator operates the crane manually while his specific control movements are observed by the invented system. The movements, load position as a function of time, and the weight are stored. Thereafter, in the Auto mode, the operator may entrust movement of the load to the present system, which causes the load to traverse an optimum path efficiently and safely (with minimum sway) in a minimum period of time. Manual control can be attained at any point during load movement.**[77]** [VIT]

Advanced Marine Engineering and Jason Associates Corp.

Advanced Marine Engineering and Jason Associates Corp. have both built crane simulators that respond to joystick and foot pedal commands while updating crane and cargo motion representing actual crane operations. The load pendulation on the crane simulator is typical of cranes and, therefore, provides an education tool for crane operators. **[78]** [Mordfin] The RBTS has also been programmed into the simulator and the operator can view the effect of the rider block in controlling the load without using the actual crane. Various lighting and wave motions can be set to simulate varying conditions at sea. Jason Associates has developed similar trainers called Crane Operators Training Systems, which also include a “universal crane cab” mounted on a motion base. **[79]** [Jason

Associates] Figure 31 shows a snapshot of the LMSR operator cab simulator by Jason Associates.

FIGURE 31. Snapshot of LMSR Crane Operator Cab Simulator by Jason Associates



Craft Engineering

The RBTS permits control of the pendulum length by allowing the operator to select the position of the rider block in the vertical boom plane. This, however, increases the complexity of the crane control problem by the addition of two more degrees-of-freedom (tagline and rider liftline) to the existing three degree-of-freedom problem(hoist, boom, and slew). The Integrated RBTS (IRBTS) allows simultaneous control of the tagline and rider liftline without the additional complexity of their independant functional controls. Dexter Bird developed a PC-based simulation of the IRBTS to facilitate development of the actual control algorithms and operator command set.

CONCLUSIONS

Horizontal pendulation control has been demonstrated by the Rider Block Tagline System, IRBTS, feed forward control and other methods.

Vertical motion compensation was demonstrated by EG&G on T-ACS 1, but not implemented in the T-ACS fleet.

MOB cargo container operations will require rapid, 6-D compensation of ship motions. These motions are not as severe as lighter loading but are still on the order of ±1 meter for 5 second wave periods in sea state 3.

The Rider Block Tagline System could be significantly improved by the Carderock NSWCCSS/Craft Engineering Inc. project to insert computer coordinated control of horizontal motions.

Vertical motion compensation will not be achieved by the improved RBTS.

Enabling technologies for 6-D motion compensation have been developed and demonstrated in the laboratory and wave tank, but not yet demonstrated in full scale operations (e.g. Intelligent Spreader Bar, RoboCrane, U-Sydney trapezoidal reeving).

The JLOTS ATD, if developed successfully, could provide much of the development needed for a MOB crane.

Sensors of incoming waves are critical to feed forward control. Large waves actually occur rather infrequently. If they can be sensed and anticipated, then operations can be conducted during the lulls between major waves or motions.

A compound control system, including wave sensing with feed forward control, combined with fast, closed-loop control of relative motion between the load and lighter or container ship may be required.

RECOMMENDATIONS

- **Simulate and model the cranes required for cargo handling.**

Scale models of a rail crane, luffing crane, triangular crane, and box crane have been constructed at NIST. These have provided some insight into the crane requirements for the MOB concepts developed by Brown and Root and McDermott. For other concept developers, it would be very useful to simulate and build a scale model of proposed container cranes and their interface to the MOB. The models could be used to verify the concept design, such as the pulley and winch locations, the stability of the cargo as a two or three stage compensation system attached to this model, actuated boom raise, crane traversal along the MOB, and computer controlled cargo acquisition. Cargo motion simulation and/or hydrodynamic response with crane model control should follow.

- **Develop the advanced computer control system necessary to achieve wave motion compensation.**

Upon construction of a representative rail crane as described in [67], the model will demonstrate static control of the spreader bar and verify stability requirements. Additionally, the crane model must also demonstrate, under computer control, the synchronized winch control that will be required of a full-scale version of the crane to achieve relative motion compensation. Algorithms must be designed and demonstrated to achieve continuous servo control of the trolley and the taglines for full operator assisted/monitored six degree-of-freedom spreader bar and cargo control during high sea state conditions.

- **Develop and demonstrate full scale integrated 6-D cargo container control for both MOB and JLOTS operations.**

In order to minimize crane power during operations, especially including high sea states, smart control of the crane operations is necessary. We believe that a compound control system, including wave sensing with feed forward control, combined with fast, closed-loop, 6 DOF control of relative motion between the load and lighter or container ship will be required. Sensoring of incoming waves is critical to feed-forward control. To investigate this control concept, we recommend a joint proposal be submitted to the Navy, including industry and government experts in these areas, targetting both the MOB and JLOTS LO/LO operations challenge.

Also, we recommend that the joint ARMY/NAVY lighter project include research complementing MOB LO/LO operations whereby lighter usage at high sea states be considered.

And, we recommend that the Army crane operator simulator at Fort Eustice be studied and modified to include operator training on six degree-of-freedom motion compensation systems, such as the dual or triple stage systems modeled in [67]. This will provide direct information from potential crane operators regarding the use of six-degree-of-freedom motion compensation systems through high states (i.e. SS3 or above).

REFERENCES

References are listed in order of their occurence. If a reference is previously cited, it will not appear again in another section.

Executive Summary

1. Bird, J. Dexter, III, Motion Compensation for Offshore Container Handling, EG&G Washington Analytical Services Center, Inc. February, 1986.

Purpose

2. JPD, Mission Need Statement For The Mobile Offshore Base (MOB), ACAT Level, September 15,1995.

Background

3. Wislicki, Alfred; Cohrs, Heinz-Herbert; Bachmann, Oliver; and Whiteman;Tim; The History of Cranes, International Cranes, UK, October 1997.
4. Cecce, Robert, Antipendulation Crane, U.S. patent 4,171,053.
5. Vaughters, T.G., Mardiros, M.F., Joint Logistics Over the Shore Operations in Rough Seas, Naval Engineer Journal, May 1997, pp. 385-396.
6. Department of Defense, Analysis and Evaluation Report - JLOTS II Throughput Test, August 1985, section 3.2.1.1.4 Sea State 3, Ground Swells, and Load Pendulation, pp. 3.69-3.76.
7. JLOTS Master Plan, December 1997.
8. Webb, Bob, Naval Facilities Engineering Command, draft RFP for the Joint Modular Lighter System (JMLS) Mission Need Statement, Civil Engineering Support Office (CESO), http://199.123.61.61.
9. Rausch, Art, Advanced Technology Demonstration Proposal, Naval Surface Weapons Center-Carderock, CDNSWC 293, November 1997.

Requirements

10. Goodwin, Ken; Bostelman, Roger; Cargo Container Transfer Requirements for the Mobile Offshore Base, NIST Internal Report (draft), March 1998.
11. Wood, William, Seaworthy Systems, Inc., Preliminary Design Mobile Offshore Base Ship Interface, (draft), April 1, 1997.
12. Cooper, Kelly, “Motion Responses for Selected Cargo Location Points on a T-ACS Auxiliary Crane Ship in an Open Seaway,” Carderock Naval Systems Warfare Center, Sept. 1996: Tables 3 and 4: Ochi-Hubble Spectra Corresponding to Natural Roll.
13. Albus, James; Bostelman, Roger; Jacoff, Adam; MOB RoboCrane Final Report, Mobile Offshore Base Project, Vol. 1, 2, NIST Internal Report (draft), 1997.

14. Dougherty, E.J.; Lee, D.E.; Shively, P.D., Automated All-weather Cargo Transfer System (AACTS), Society of Naval Architects and Marine Engineers, STAR Symposium, pp S2-3-1, S2-3-6, April, 1989.

15. Krulak, General Charles, MPF 2010 and Beyond, December 30, 1998, reprinted in Inside the Navy, January 12, 1998.

16. Bouchoux, Donald; The MOB as a Supplement to the CVX, Whitney, Bradley & Brown, Inc.BB, January 29, 1998.

17. Nance, John, Jr.; Milano, Vito R.; Souders, Robert M.; and Bowditch, Thomas A., Mission Area Analysis (MAA) for Maritime Prepositioning Force (MPF) Future Seabasing Concepts Phase 1 Summary Report, Center for Naval Analyses, CRM 97-102.09, 26 Sep 1997.

18. Nance, John, Dry Cargo and Vehicle Lift Requirements, MPF MAA Study Notice #23, Center for Naval Analyses, 29 Sep, 1997.

Crane Technology Development

19. Janes's Ships, USA/Amphibious Warfare Forces, page 846.

20. CNO Strategic Sealift Division (N-42), Cargo Off-load and Discharge System (COLDS), October 1992.

Port Crane Anti-Sway

21. Soest, Cornelius; et. al., Anti-sway, Anti-rotation mechanism for crane reeving, U.S. Patent 4,376,487, filed Jan. 22, 1981.

22. Kleinschnittger, Andreas, University of Dortmund, Germany.

23. Kim, Sang-Bong, et. al, Development of a Crane System for High Speed Transportation in Container Terminal, Sixth (1996)-International Offshore Polar Engineering Conference Proc., Los Angeles, CA, May 26-31, 1996, pp. 542-547.

24. Shaper, Donald, Stabilizing Device, U.S. Patent 4,273,242, filed May 18, 1979.

25. Bernaerts, Henry, Anti-sway device for hoists and cranes, U.S. Patent 4,227,677, filed Mar. 26, 1979.

26. Hasegawa, Shuji; et. al., Variable level lifting platform for a cargo container handling crane, U.S. Patent 5,538,382, filed June 3. 1994.

27. Foit, Vilem, Anti-sway crane reeving apparatus, U.S. Patent 4,949,854, filed Dec. 9, 1988.

28. Foit, Vilem, Anti-sway crane reeving apparatus, U.S. Patent 4,949,855, filed Dec. 9, 1988.

29. Foit, Vilem, Anti-sway crane reeving apparatus, U.S. Patent 4,953,721, filed Dec. 9, 1988.

30. Davis, Rudolf, C. III; Simkus, Anthony P. Jr., Method and apparatus for moving containers between a ship and a dock, U.S. Patent 5,478,181, filed Jan. 26, 1994.

31. Overton, Robert; Anti-sway control system for cantilevering cranes, U.S. Patent 5,526,946, filed Dec. 5, 1994.

32. Overton, Robert, Shipboard Crane Control, presentation at NSWC Carderock on July 24, 1996.

33. Parker, Gordon; Robinett, Rush; Ship-based Crane Payload Sway Control, Sandia National Laboratories.

34. Rushmer, Michael; et. al, Electronic Anti-sway Control, U.S. Patent 5,443, 566, filed May 23, 1994.

35. Lacarbonara, Walter; Soper, R. Randall; Pratt, Jon; Nayfreh, Ali; and Mook, D.T.; MURI Seminar, July 24, 1997.

36. Rudnick, Siegfried, Container Cranes: Top Performance with Standard Systems, Energy and Automation XII, No. 2, 1990, pp. 4-7.

Sensors

37. Nachman, Marcus; Overton, Robert, Moored ship motion determination system, U.S. Patent 5,089,972, filed Dec. 13, 1990.

38. Bonsor, Nigel; et. al., Method and system for interacting with floating objects, UK patent GB-2,267,360B, filed May 22, 1992.

39. Akos, Gy, et. al., Development of an Optical Telemetric Position Sensing Equipment for Nuclear Power Station Reactors, 16th Congress of the International Commission for Optics, Budapest, Hungary SPIE Volume 1983, part 2 of 2, Aug. 9-13, 1993, pp. 971-972.

Motion Prediction

40. Todd, Micheal; Vohra, Sandeep; Leban, Frank, Studies of Crane Load Pendulation: Stewart Platform Testing and Wave Tank Model Testing, Third Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, April 13-14, 1998.

41. Kimiaghalam, Bahram; Homaifar, Abdollah; Bikdash, Marwan, Optimal Control for Gantry Crane Two Point Boundary Value Problem by Genetic Algorithm, Third Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, April 13-14, 1998.

42. Baptista, Murilo da Silva; Hunt, Brian R., A Comparitive Study of Cargo Pendulation on Rolling Crane Ships, Third Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, April 13-14, 1998.

43. Chin, C; Nayfeh, A. H., Nonlinear Dynamics of Crane Operation at Sea, American Institute of Aeronautics and Astronautics, AIAA-96-1485, 1996.

44. Chin, C; Nayfeh, A. H.; Mook, D. T., Dynamics and Control of Ship-Mounted Cranes, American Institute of Aeronautics and Astronautics, AIAA-98-1731, 1998.

Horizontal Motion Compensation

45. Simkus, Anthony, Jr.; Rudolf, Chester, System for learning control commands to roboticly move a load, especially suitable for use in cranes to reduce load sway, U.S. Patent 5,117,992, filed Jan. 28, 1991.

46. Craft Engineering Associates, Inc., Integrated RBTS Control System for T-ACS Crane, A preliminary Design Study for the Coastal Systems Station NSWC, Dahlgren Division, May 1997.

47. Rosenfeld, Yehiel, Automation of existing cranes: from Concept to Prototype, Automation in Construction 4, Elvesier Science, 1995, pp. 125-138.

48. Li, Y.-Y.; Balachandran, B., Dynamics, Stability, and Control of Cranes, Third Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, April 13-14, 1998.

49. Dadone, Paolo; VanLandingham, Hugh, Intelligent Control Methods for Ship-Mounted Cranes, Third Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, April 13-14, 1998.

Offshore Platform Resupply

50. Wen, Bing; Kimiaghalam, Bahram; Momaifar, Abdollah; Bikdash, Marwan, Control and Simulation of Ship Crane with Maryland Rigging, Third Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, April 13-14, 1998.

51. Lacarbonara, Walter; Soper, R. Randall; Pratt, Jon; Nayfeh, Ali H.; Mook, D.T., New Actuators for Ship-Mounted Crane Pendulation Suppression, Second Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, July 29, 1997.

52. Soper, R. Randall; Lacarbonara, Walter; Chin, Char-Ming; Nayfeh, Ali H.; Mook, Dean T., Nonlinear Resonance-Cancellation of a Base-Excited Planar Pendulum, Third Semi-Annual MURI Meeting Nonlinear Active Control of Dynamical systems, Virginia Polytechnic Institute , Blacksburg, VA, April 13-14, 1998.

53. Cojean, Maurice; Colin, Jean-Paul, Device for removing and depositing loads between two supports in repeated relative vertical movement, U.S. Patent 4,324,385, filed Aug. 30, 1978.

54. Wudtke, Donald, Motion compensator and control system for crane, U.S. Patent 4,354,608, filed June 8, 1979.

55. Archibald, et. al., Sea Swell and Shock Load Compensator, UK Patent Application, GB-2,096,563A, filed Mar. 31, 1982.

Vertical Motion Compensation

56. Dummer, Robert, Marine Crane Lifting Control, U.S. Patent 4,304,337, filed May 29, 1980.

Crane Designs

57. Lee, Donald, Automated all-weather cargo transfer system, U.S. Patent 5,154,561, filed April, 11, 1990.

58. Dougherty, E.J., Lee, D.E., Shively, P.D., Automated All-weather Cargo Transfer System (AACTS), Society of Naval Architects and Marine Engineers, STAR Symposium, pp S2-3-1, S2-3-6, April, 1989.

59. Naval Architect Journal, New Designs at Liebherr, May 1996 Issue, pp. 36-40.

Wave Motion Damping

60. Kuo, Chengi; Marine vessels and moonpool structures therein, UK patent GB-2,150,516B, filed Nov. 30, 1984.

61. Blood, Howard, Conceptual Design Report of the Pneumatically Stabilized Platform, Report Number FI-TR-09-96, Float Incorporated, December 1996.

62. World City Corporation, Phoenix World City Update, Fall 1993.

Integrated Motion Control

63. Dougherty, Edmond, Intelligent Spreader Bar Quarterly Presentation to NSWC: Contract #N00167-95-C-0088, August Design, Inc. Merion, PA, November 20, 1996.

64. Albus, James; Bostelman, Roger; Dagalakis, Nicholas, The NIST RoboCrane, Journal of Research of the National Insitute of Standards and Technology, Vol. 97, Number 3, May-June 1992.

65. Bostelman, Roger; Albus, James; Dagalakis, Nicholas; Jacoff, Adam; Gross, John, Applications of the NIST RoboCrane, 5th International Symposium on Robotics and Manufacturing Proc., Maui, HI, August 14-18, 1994.

66. Bostelman, Roger; Albus, James; Dagalakis, Nicholas; Jacoff, Adam, RoboCrane Project: An Advanced Concept for Large Scale Manufacturing, Association for Unmanned Vehicle Systeems International (AUVSI) Proc., Orlando, FL, July 15-19, 1996.

67. Albus, James; Bostelman, Roger; Jacoff, Adam; MOB RoboCrane Final Report, Mobile Offshore Base Project, Vol. 1, 2, NIST Internal Report (draft), 1997.

68. Dissanayake, Durrant-Whyte, Towards Automatic Container Handling Cranes, University of Sydney, Australia.

Dynamical Systems

69. Dadone, Paolo, Interview at Virginia Polytechnic Institute, July 29, 1997.

Winches, Drives

70. Feldman, Yu. I., et. al., Automated Electric Drives with Frequency Converters for Crane and Ship Winch Mechanisms, Russian Electrical Engineering, Vol. 66, No. 10, pp. 1-5, 1995 (Allerton Press, Inc. 1996).

71. Podobedov, E. G., et. al., Automatic Electric Drives with Frequency Converters for Hoist and Deck Mechanisms, Elektroteknika, Vol. 64, No.8, Aug. 8, 1993, pp. 24-28.

72. Allen, Richard, Winches and mooring equipment from Ship’s Equipment Centre, The Naval Architect, Sept. 1995 Issue, p. E474.

Container Terminal Automation

73. Barker, Ann, Deltaport: A new Container Terminal for Vancouver Port Corporation, Ports ‘95 Proc., Tampa, FL, Mar. 13-15, 1995, pp. 37-48.

74. Reiss, Daniel, Advanced Container Terminal Design, Ports ‘95 Proc., Tampa, FL, Mar. 13-15, 1995, pp. 652-664.

75. Dougherty, Edmond, J; Lee, Donald E.; Shively, Paul D., Automated All-Weather Cargo Transfer System, Society of Naval Architects and Marine Engineers, Sprint Meeting/STAR Symposium, New Orleans, LA, April 12-15, 1989.

Material Handling

76. Unknown Author, New Developments in Reefer Cargo Handling, Naval Architect, Feb. 1995, E99-E102.

Simulation

77. Simkus, Anthony, Interview and Site Visit to Virginia International Terminals, July 1997.

78. Mordfin, Theodore; Interview and Site Visit to Advanced Marine Enterprises, 1997.

79. Jason Associates Corp., Crane Operator Training System White Paper, San Diego, CA.

BIBLIOGRAPHY

The following literature citations have not been specifically referenced in this report but provide information that may be of interest to workers in crane technology. Abstracts or patent claims are included.

Control

- Jorge Angeles, Evtim Zakhariev, Computational Methods in Mechanisms, NATO, Advanced Study Institute, Volume 2, Varna, Bulgaria, June 16-28, 1997 [c/o Prof. Dr.-Ing.habil.Christoph Woernie, Universitat Rostock]

Deals with the direct and inverse kinematic problem of cable suspension robots that belong to the class of under constrained structural systems (Kuznetsov, 1991). [This work is contributed by Prof. Dr.-Ing. habil. Christopher Woernie, Universitat Rostock]

- Shu-Zi Yang, et. al. (Editors), Weiping Li, et. al. (Paper Author), Precise Positioning Control of Overhead Traveling Cranes, International Conference on Intelligent Manufacturing Proc., Vol. 2620, pp. 792-797, June 14-17, 1995, Wuhan, China.

A new control design is presented for precisely controlling overhead traveling cranes using microprocessors using state feedback control algorithms to guarantee stability of the crane, a trajectory planner to avoid saturation, and an additional integral term to eliminate steady-state error. Theoretical analysis and experimental implementation on a laboratory crane verifies the effectiveness of the approach.

- Yang, Li-Farn, Mikulas Jr., Martin M., Mechanism Synthesis and Two-Dimensional Control Designs of an Active Three-Cable Crane, Spacecraft and Rockets Journal, Vol. 31, No. 1, Jan.-Feb. 1994, pp. 135-144.

The vibrational characteristics of a three-cable suspension mechanism is investigated by comparing a simple two-dimensional suspension model and a swinging pendulum in terms of their analytical natural frequency equations. Also, a study of active control is made of the crane dynamics using two different actuator concepts. Two regulator-type control laws based on Lyapunov control are determined to provide vibration suppression for both dynamic systems. Simulations including initial-valued dynamic responses as well as active control performances are also presented.

- Armstrong, N.A., Moore, P. R., A distributed control Architecture for Intelligent Crane Automation, Automation in Construction 3, Elvesier Science, 1994, pp. 44-53.

Design and implementation of a modular distributed control system for crane and hoist automation in manufacturing and construction. Technology was evaluated on a gantry crane which embodies control structures such as anti-sway, condition monitoring, tele-operation, automatic load coupling/decoupling, and automatic cycling.

- Itoh, Osamu, et. al., Application of fuzzy control to Automatic Crane Operation, International Conference on Industrial Electronics and Instrumentation Proc., Vol. 1: Plenary Session, Emerging Technologies, and Factory Automation, pp. 161-164.

Crane outline showing overhead-trolley drive and the factors that cause swing such as delay and friction of the crane even if controlled along a pattern. Conformation using computer simulation and practical machine show the effect of the fuzzy control method which combines the means of the control of positioning and swing pendulation.

- Murata, Istuo; Nakajima, Masamichi; Automatic Control System of Container Crane, Transactions of the Japan Society of Mechanical Engineers, Aug. 1993, pp. 137-143.

Explains the automated container crane system within the total management system of a container yard. The system includes: anti-sway control, position control, optimum route control, container stacking profile recognition, and management of operation. (in Japanese).

Heave Compensation

- Kerr, Andrew; McGill, William; Crane cable tensioning arrangement, UK Patent Application, GB-2,045,196, filed Mar. 31, 1979.

A cable-tensioning, piston-actuated pulley and another similar arrangement but with full-load capacity, maintains relative heave compensation between floating vessels.

Container Terminal Automation

- Unknown author, Watching over the Weight: Automation for a Taipei Cargo Terminal, Airport Forum, Weisbaden, West Germany, June, 1993.

Modern cargo terminals need comprehensive container handling with a sophisticated control system that can guide and monitor the mechanical handling equipment, track every single shipment, and command handling and inventory functions. This automated system was being built by ICM of Germany for Everterminal in Taipei.

POINTS OF CONTACT

Phillip Abraham
Office of Naval Research
ONR 331
800 N. Quincy St.
Arlington, VA 22217-5660
703-696-4307
703-696-6887 FAX

LTC Christopher Barbour
Logistics Directorate, J-4
4000 Joint Staff, Pentagon
Washington, DC 20318-4000
703-697-6155
703-614-1076 FAX
barbourcr@js.pentagon.mil

Roderick Barr
Hydronautics Research, Inc.
7210 Pindell School Road
Fulton, MD 20759
301-369-4201
301-470-3427 FAX

Yvan J. Beliveau
Dept. of Building Construction
122H Burruss Hall
Virginia Polytechnic Institute
Blacksburg, VA 24061-0156
540-231-5948
540-231-7339 FAX
yvan@vt.edu

Dexter Bird, III
Craft Engineering Associates, Inc.
2102 48th Street
Hampton, VA 23661
757-825-1516
757-827-5097 FAX
crafteng@erols.com

Howard Blood
Float Incorporated
1660 Hotel Circle North, Suite 725
San Diego, CA 92108
619-299-9231
619-299-8878 FAX

Donald R. Bouchoux
Whitney, Bradley & Brown, Inc.
1600 Spring Hill Road
Suite 400
Vienna, VA 22182
703 448 6081 ext. 154
703-821-6955 FAX
dbouchoux@wbbinc.com

Kelly Cooper
Naval Surface Warfare Center
Carderock Division
David Taylor Model Basin, Code 29
9500 Mac Arthur Blvd.
West Bethesda, MD 20817-5700
301-227-5429
301-227-1041 FAX
cooperkb@nswccd.navy.mil

Richard Currie
McDermott International, Inc.
P.O. Box 11165
Lynchburg, VA 24506-1165
804-522-5656
804-522-6933FAX
richard.l.currie@mcdermott.com

M.W.M.G. Dissanayake
Dept. of Mechanical and Mechatronic Engineering
The University of Sydney, 2006, NSW. Australia

Edmond J. Dougherty
August Design, Inc.
120 West Lancaster Ave., 3rd Floor
Ardmore, PA 19003-1305
610-642-4000
610-642-5137 FAX
www.august-design.com

Martin D. Fink
Naval Sea Systems Command
Strategic Sealift Program Office
PMS 385, PEO CLA
2531 Jefferson Davis highway
Arlington, VA 22242-5160
703-602-0920 ext 109
703-602-5385 FAX

Len Haynes
Intelligent Automation Inc.
2 Research Place, Suite 202
Rockville, MD 20850
301 590-3155
301-590-9414 FAX

J.L. Korenek
Brown & Root Energy Services
PO Box 4574
10200 Bellaire Blvd.
Houston TX 77072-5299
281-575-4371
713-575-3227 FAX

Frank Leban
Naval Surface Warfare Center
Carderock Division
David Taylor Model Basin, Code 2930
9500 Mac Arthur Blvd.
West Bethesda, MD 20817-5700
301-227-4698
301-227-1041 FAX
leban@oasys.dt.navy.mil

CDR Steve Lehr
N42
OPNAV
Crystal City Square 2, Room 1002
1725 Jefferson Davis Highway
Washington DC 20350
703-602-7305

Vito Milano
Center for Naval Analyses
4401 Ford Avenue
P.O.Box 16268
Alexandria, VA 22302-1498
703-824-2684
703-824-2949 FAX

Ted Mordfin
Advanced Marine Enterprises, Inc.
1725 Jefferson Davis Highway
Suite 1300
Arlington, VA 22202
703-413-9200
703-413-9221 FAX
mordfin_ted@advmar.com

Jack Nance
Center for Naval Analyses
4401 Ford Avenue
P.O.Box 16268
Alexandria, VA 22302-1498
703-824-2204
703-824-2949 FAX
nancej@cna.org

Prof. Ali Nayfeh
Dept. of Engineering Science and Mechanics
Virginia Polytechnic Institute
Blacksburg, VA 24061-0219

John Nicholson
Float Incorporated
1660 Hotel Circle North, Suite 725
San Diego, CA 92108
619-299-9231
619-299-8878 FAX

Clyde Nolan
Brown & Root Energy Services
PO Box 4574
10200 Bellaire Blvd.
Houston TX 77072-5300
281-575-4370
713-575-3227 FAX
cnolan@b-r.com

Rob Overton
Wagner Associates
Suite 500
2 Eaton Street
Hampton, VA 23669
757-727-7700
757-722-0249 FAX
rob@va.wagner.com

Gordon Parker
Sandia National Laboratories
P.O. Box 5800, MS 0949
Albuquerque, NM 87185

Art Rausch
Naval Surface Warfare Center
Carderock Division
David Taylor Model Basin, Code 293
9500 Mac Arthur Blvd.
West Bethesda, MD 20817-5700
301-227-4590
301-227-1041 FAX
rausch@oasys.dt.navy.mil

Gene Remmers
Office of Naval Research
ONR 334
800 N. Quincy St.
Arlington, VA 22217-5660
703-696-0814
703-696-0308 FAX
remmerg@onr.navy.mil

Don Resio
EDRC
3909 Hallsferry Road
Vicksburg, MS 39180
601-634-2018
d.resio@cerc.wes.army.mil

L.CDR Thomas Satterly
N422
OPNAV
Crystal City Square 2, Room 1002
1725 Jefferson Davis Highway
Washington, DC 20350

Curtis E. Schelle
MAR, Incorporated
6110 Executive Blvd., Suite 410
Rockville, MD 20852
301 230-4595
301-770-2680 FAX

William E. Schulz
John J. McMullen Associates, Inc.
Century Building, Suite 715
2341 Jefferson Davis Highway
Arlington, VA 22202
703-418-0100
703-418-4269 FAX

Anthony P. Simkus, Jr.
Virginia International Terminals, Inc.
P.O. Box 1387,
Norfolk, VA 23501
757-440-2878
757-440-2879 FAX
simkus-t@vit.org

Randy Tagg
University of Colorado
1250 14th St.
Denver, CO 80202-1712
303-556-2293

Robert Weibel
McDermott Shipbuilding, Inc.
160 James Drive East
St. Rose LA 70087
504-471-4067
504-471-4103 FAX
bob.weibel@mcdermott.com

Mike Todd
Naval Research Laboratory
Room 127, Bldg. 215
4555 Overlook Ave., S.W.
Washington D.C. 20375-5338
202-767-1480
202-404-8645 FAX

Jack Turner
Syntek Technologies, Inc.
4301 North Fairfax Drive
Suite 850
Arlington, VA 22203
703-525-3403
703-525-0833 FAX
jturner@snap.org

Ted Vaughters
Naval Surface Warfare Center
Carderock Division
David Taylor Model Basin, Code 29
9500 Mac Arthur Blvd.
West Bethesda, MD 20817-5700
301-227-4591
301-227-1041 FAX
vaughter@oasys.dt.navy.mil

Sandeep T. Vohra
Naval Research Laboratory
4555 Overlook Ave., S.W.
Washington D.C. 20375-5338
202-767-9349
202-404-8645 FAX
vohra@ccfsun.nrl.navy.mil

Jim York
University of Maryland
4201 Computer Science Bldg.
IPST
College Park, MD 20742
301-405-4875
301-314-9363 FAX
york@ipst.umd.edu

Max Weber
Steven Naud
Coastal Systems Station
6703 West Highway 98
Panama City, FL 32407-7001
904-235-5445
904-235-5443 FAX
weber_max@ccmail.ncsc.navy.mil

William Wood
Seaworthy Systems, Inc.
P.O. Box 975
Barnegat, NJ 08006
609-361-0479
609-361-0802 FAX