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Skin-to-Skin Replenishment

ABSTRACT

The possibility of resupplying the Maritime Prepositioning Force (Future) [MPF(F)] "Sea Base" at-sea directly from commercial containerships would add a new dimension to the force projection equation. Provided that the operation could be regularly and safely conducted in the open ocean, reliance on a nearby friendly port would be lessened or eliminated. Additionally, since the commercial vessels would supply the MPF(F) directly, the USN vessels which would otherwise be required to shuttle cargo from a friendly port would be reduced or eliminated.

Recent studies conducted by JJMA and NIST for the ONR indicate that such an operation may become feasible in the near future. Current commercial tanker lightering operations have proven the concept of skin-to-skin open-ocean transfer of liquid cargo. Unlike hanging a hose between two moving vessels, however, handling containerized cargo would require a revolutionary new 6 degree-of-freedom motion-compensated crane with controls accurate enough to lift and lower containers in cell guides without jamming in sea-states up to SS 5.

The paper presents a concept that the authors believe could result in achieving a transformation in logistics support. Such a new concept of operations could allow support of US forces in areas of the world where the nearest friendly port is hundreds or thousands of miles from the battle. Furthermore, the new agility could result in net savings in both logistics forces and logistics support vessels.

INTRODUCTION

While the concept of skin-to-skin connected replenishment of fully loaded ISO containers at-sea could take on a number of potential missions, the mission that this study focused on was one of a future MPF(F) Sea Base receiving containers from commercial container ships. Such a mission, if it could be accomplished, would provide a significant logistic benefit.

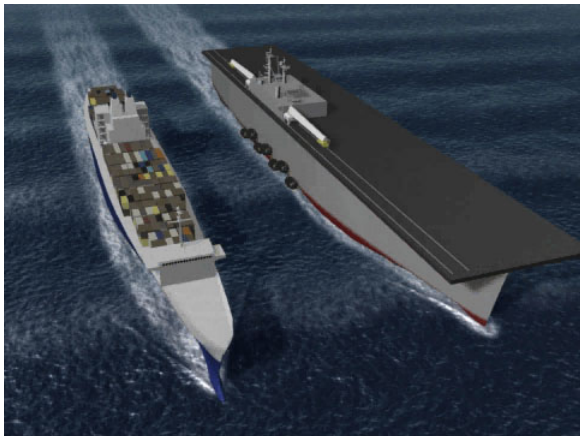

Figure 1 – Notional Sea Base Approaching a Commercial Container Ship

Without a skin-to-skin connected replenishment of the sea base directly from commercial container ships, material would have to be shipped break-bulk on shuttle ships equipped with handling gear and Underway Replenishment (UNREP) gear adequate to at least receive the sea base's UNREP rig. These shuttle ships would be required to make round trips either from the US, or from the nearest friendly port. The seabasing concept is intended to preclude the dependence on nearby friendly ports. In order to plan for this contingency, the shuttle fleet required to support the sea base would have to be large enough to provide continuous support – assuming that the sea base theater of operations is halfway around the world from the US. Once the shuttle ships were in-theater, conventional or the new heavy UNREP method would be used to transfer the cargo. Current plans call for heavy UNREP to be able to transfer loads up to 5,443 kg (12,000 pounds).

With a skin-to-skin connected replenishment capability, the fleet of special-purpose shuttle ships would not be required. Instead, commercial container ships would be used to shuttle the cargo directly to the Sea Base. This is exactly how a land base is currently supplied. The difference is that sea base is exactly where you want it, but is operating in the open ocean and subject to wind and wave forces that will affect both ships.

The question that this paper examines is: Can a sea base be designed with the capability to be resupplied like a land base in spite of the effects of open ocean wind and wave forces? In attempting to answer this question, we will

- Examine the motions of the two vessels moored together with existing technology fenders and mooring lines
- Discuss ways to minimize the relative motions
- Propose a six-degree-of-freedom crane concept that could potentially control the container load, withstand the forces imposed, and compensate for the relative motions
- Analyze the dynamics of the proposed crane concept
- Propose a crane control approach that has the potential of taming the relative motions in conditions up to Sea State 5 (SS5).

It should be noted that this paper does not examine and is not proposing the replenishment of combatant ships with the skin-to-skin method. It is likely that UNREP will continue to be the best option for combatants due to small size, hull form, and inability to handle ISO containers. While there may be other applications and extensions of the technology proposed, this paper focuses on the Sea Base resupply issue.

SHIP MOTIONS ANALYSIS

The initial investigation into the skin-to-skin replenishment sea-keeping presented several problems. The operation could clearly be separated into four stages as follows:

1. Approach – Maneuvering the ships into close proximity
2. Connecting the Ships
3. Cargo Transfer Operation
4. Separation.

The primary focus of the analysis was the third stage, the cargo transfer operation. The core issue with the cargo transfer operation is the relative motions of the two ships. The principal elements of the cargo transfer operation are the ship connection system and cargo transfer cranes. The connection system consists of fenders, winches, and mooring lines. A feasibility study was undertaken to analyze a connection system that could withstand the objective SS5 and potentially be 'tuned' to reduce ship relative motions thereby reducing the performance requirements of the six degree-of-freedom motion compensated cargo transfer crane.

The approach, connection and separation are closely related ship controllability issues that rely heavily on seamanship and human factors. Ship controllability is discussed and qualitatively reviewed, but is not the primary subject of this sea-keeping analysis. It remains a subject of future study.

Ship Approach, Separation & Connection

Experience in tanker lightering has shown that the approach and separation phases may become critical in planning the operation, establishing constraints on forecast weather and sea conditions, and selecting speeds and headings for skin-to-skin transfer operations. This is especially true when considering the likelihood of continuing operations as weather and sea conditions degrade. For example, in offshore tanker lightering, cargo transfer operations have often been continued into substantially worse sea conditions than would have been accepted for an approach and connection.

However, the approach and separation phases are of limited duration, perhaps on the order of an hour, while the alongside phase may last for a day or more. For this reason, the effects of ship motions, especially with regard to expected extreme values, are of greatest concern during the cargo transfer operation. By contrast, the approach and separation phases are governed mainly by ship-handling and line-handling problems, although ship motions can obviously have some effect as well, particularly if low-speed ship controllability is not adequate for the wind and sea conditions. Low speed must be assumed for skin-to-skin operations because of the need to make a controlled contact on the fenders, without hull interaction forces or moments taking charge at small separations. Low speeds also permit lateral thrusters to be used effectively.

Typically, ship forward speeds at the time of fender contact are below 4 or 5 knots. The standard of ship-handling which is routinely exercised in making a safe and expeditious approach is quite impressive. It involves the fine use of thrusters, rudder and propeller forces, and ultimately the mooring lines as well, to manage the closure rate while maintaining the required relationship between the headings of the two ships, so as to contact on the main sea fenders.

The ship controllability challenges presented by prevailing wind and seas must be overcome without using excessive ship speed, since this would lead to hull interaction forces and moments that could exceed available control authority in the final stage of the approach to fender contact.

However, these aspects of the design requirements were not analyzed quantitatively in this study. For the present, based on the experiences of both UNREP and lightering ships, it is anticipated that a safe approach to contact with fenders for skin-to skin transfer can be made, under a range of conditions of wind and waves. A key element of future analysis will be to show that approach speeds and headings can be selected to produce satisfactory course-keeping and control of both ships, under given conditions of wind and waves.

Connected Ship Modeling

Engineering simulations were used to evaluate the global and relative motions during the skin-to-skin cargo transfer operation. The simulations used consisted of five elements; the ships, fenders, mooring winches, mooring lines, and the environment.

NOTIONAL SHIPS

For the purposes of this study, it was necessary to make some assumptions with regard to the kind of ships that may be used in logistic operations. The Sea-Base concept has formed a part of several recent Maritime Pre-Positioning Force (Future) [MPF(F)] studies. Because of this, a notional MPF(F) was selected as the Sea Base.

It is assumed that a Sea Base ship would be equipped with the sea fenders, possibly under davits for ease of deployment and recovery, as is used on advanced lightering tankers. In all likelihood, the Sea Base ship would be equipped with significant lateral thruster capacity. It is possible that it would be twin-screw, although many modern lightering tankers are single-screw with electric drive or controllable pitch propellers.

By contrast, a typical modern containership, for example, would be powered by a direct-coupled diesel, single-screw, fixed-pitch. For such a ship, minimum engine revolutions would tend to dictate the minimum controllable speed in a moderate wind and sea. A typical approach procedure might be as follows:

The commercial container ship would hold course and speed, following or head seas being preferable, whichever provides better control and line-passing opportunities under the existing wind and wave conditions. The Sea Base ship would take station abreast, judge the relative leeway being made by each ship, and then approach at a fractional knot of transverse closure. Forward mooring lines would typically be passed and connected first. These lines would be hauled in as required to help counteract any bow-out hull interaction moment.

Once sufficient lines were connected, the Sea Base ship, MPF(F) in this study, would use winches and thrusters to control the final closure, to a square contact on the fenders. Finally, towing lines (spring lines) would be tensioned and the commercial container ship would stop engines or assume a minimum rpm. The Sea Base ship would then provide the forces for propulsion and course control during the alongside phase.

For separation, the procedures would be reversed. The commercial container ship would start engines slow or dead slow ahead, holding course. Towing and mooring lines would be cast off, with the bow mooring lines last. Meanwhile, using thrusters, rudder, and screws, the Sea Base ship would draw away from the commercial container ship laterally until enough separation was obtained to allow a gentle turn away without bringing the sterns too close.

Having described the over-all concept, we should return to detailed assumptions about the ships, which are required for the hydrodynamic analysis of the steady alongside phase of the evolution.

The Sea-Base ship used in this study is a notional 90,000-ton MPF(F) [1]. The commercial container ship hull form selected was the high-speed containership, SL-7 class. These 55,000 ton, PANAMAX beam ships were converted to vehicle cargo ships, T-AKR 287 – 294, and are operated by the Military Sealift Command (MSC).

Table 1– Notional Ship Parameters

	MPF(F)	SL-7
Length (WL), m	305	275
Beam (WL), m	40.8	32.2
Draft, m	10.5	9.20
Depth, m	35.4	19.5
Freeboard, m	24.9	10.0
Waterplane Area, m^2	10.11×10^3	5.732×10^3

For skin-to-skin operations the sea fenders are positioned to prevent steel-to-steel contact or collision. The two ships are positioned longitudinally so that the centers of the parallel middle bodies coincide. The working fenders are all arranged in the parallel middle body area to make them most effective. Figure 2 shows the fender arrangement between the two notional ships.

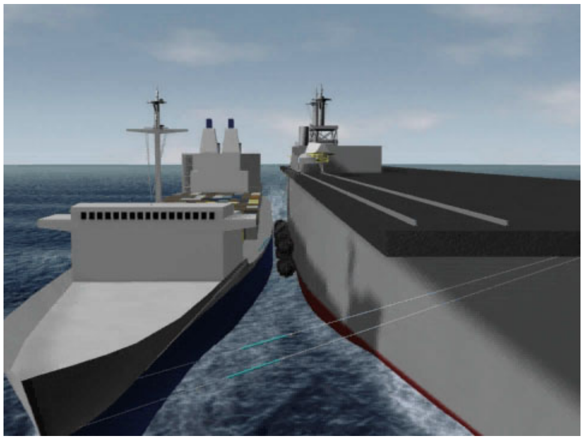

Figure 2 – Fenders Arranged Between Notional Sea Base and Commercial Container Ship

As in current tanker lightering arrangements, there will be auxiliary fenders positioned outside the parallel middle body to prevent accidental contact at bow and stern. These are to provide a modest level of protection during the last part of the approach and line passing stage, and again at the start of separation. However, these fenders would not be in contact during normal operations in the alongside phase, and consequently they were not included in the motion simulation model.

FENDERING

The assumed fender characteristics are those of Seaward 28-ft (length) foam filled Sea Cushion fenders. Figure 3 depicts the foam-filled fender construction. This class of fender is about the largest foam-filled size in current use, and it is assumed that the largest stand-off distance will be required for safety and to expand operability in a seaway.

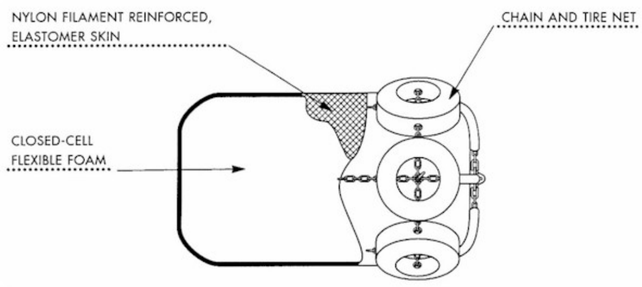

Figure 3 – Foam-Filled Fender Construction

The fenders are rigged in longitudinal fender strings. This configuration has been found to be the best scheme to maintain the longitudinal location of the fenders while permitting them to ride vertically in response to relative vertical motions due to roll, heave, and pitch. There are four fenders rigged afloat at the waterline between the two ships. To protect the topsides three additional fenders are suspended above water with motion-compensating davits.

MOORING WINCHES AND LINES

Two types of mooring winch and line combinations were studied; constant tension cable lines and locked mooring lines. The tension of a constant tension winch is controlled in order to maintain mooring line tension within reasonable limits.

A locked mooring arrangement is often controlled by hand and monitored in such a way that the lines are set to an approximate tension, and then locked. The deck watch resets the line tensions periodically as the ships change draft during the operation. Therefore, the line stretch is the only dynamic part of the mooring line system.

The locked mooring lines require more compliance. Synthetic hawsers (often nylon) are used. A conventional mooring winch will be enough to provide initial tension. The winch is then locked, permitting the mooring line to act as a spring when stretched. In practice, a softer spring constant is often desired, and this can be obtained by using a nylon grommet (a loop of nylon hawser, laid to untwist with increased tension) as the standing part of the line. The stiffness of the nylon grommet is related to the stiffness of the Nylon line, the length of the grommet and the initial twist of the grommet.

At the winch drum end and the mooring end on the other ship, steel cable, or high modulus synthetic ropes such as Kevlar or Spectra can be used so that the ends of the grommet can rotate as the mooring works, and is not subject to chafe. The Nylon grommet is the compliant part of the mooring, and basically determines the over-all stiffness of the mooring.

Systems using constant tension winches can also make use of the grommet in order to reduce peak system loads and minimize the reactions of the winch.

ENVIRONMENT

The effectiveness of the connected replenishment system will degrade as sea state increases. So in order to evaluate level of effectiveness or diminishing performance, the skin-to-skin connected replenishment system was examined in a range of sea states.

Sea states 3, 4 and 5 based on STANAG 4194 for Open Ocean North Atlantic were modeled. The Bretschneider spectrum, long crested, was used. This spectrum is designed to model wind-driven seas, rather than swell. It is a 2-parameter spectrum. The wave height and zero up-crossing period are specified.

Wind forces can be quite significant on high-freeboard ships. The sustained wind speed was associated with the wave height according to STANAG 4194. Wind was considered from the same direction as the waves. The American Petroleum Institute (API) method for calculating gust velocity was applied.

Current and current vertical gradient effects, which can result in different drift forces acting on two ships of different draft, were neglected in the analyses.

Simulations Performed

Once the general viability of the system was established, runs were made to evaluate which variables and elements of the mooring system had an effect on the global and relative motions of the two ships, since reduction of the motions would increase crane operability. The sensitivity studies investigated:

- Heading Relative to the Environment
- Ship Speed
- Fender Stiffness
- Winch Mechanism
- Winch Tension
- Line Stiffness
- Line Arrangement

The system, including the two ships, fenders, mooring lines and winches, and cargo-transfer gear, was modeled using the Atkins Quantitative Wave Analysis (AQWA) suite of programs. The responses of the moored floating bodies at wave frequency and drift frequency in a random sea, subject to forces imposed by waves and wind were calculated. Results were generated as a time history of the relevant responses, which were then visualized and statistically summarized for further analysis.

The system was modeled in the time domain because the non-linear behavior of the mooring lines and fenders cannot be correctly accounted for in the frequency domain. After running a series of time-domain realizations, spectra were constructed from the aggregate time history for the processes of interest: mooring line tensions, fender compressions, roll amplitudes, vertical and transverse relative motions, etc. Extreme and average loadings, compressions, and motion amplitudes for the required exposure time were estimated from the spectra, a Weibull analysis or a statistical analysis.

Computer Simulation Results

To minimize the impact load on the fenders and mooring lines, it is desirable to keep the ships' heading aligned with the predominant wave/wind heading, either head seas or following seas. It is also desirable that the smaller ship and the fenders should be sheltered somewhat from the direct effects of incident and reflected waves between the ships, and from the wind.

For this study, headings of –170 deg (10 deg off the exact head sea) and –10 deg (10 deg off the exact following sea) were considered in order to introduce relative roll motions. For each of the two headings, three operating ship speeds, 3, 6 and 9 knots, are considered. To investigate the effect of fender stiffness, the regular fender stiffness was reduced by half in some cases. Both CT and locked mooring lines of different tension levels and line stiffness are studied.

A total of 26 different combinations of the above factors have been simulated in SS5, each for a 33.3 minute duration. The number of fenders (7) and mooring lines (10), and their arrangements remain the same for most of the cases. A different arrangement is assumed in one of the cases for comparison.

In addition to the 6 DOF ship motions of each ship, the fender compression, mooring line tension, relative ship motion and the required crane power for cargo transfer are also of interest. Limited by the size of this paper, only a summary of the sensitivity study results is described herein.

MOTION SUMMARY OF INDIVIDUAL SHIP

Heave and pitch motions of the two ships are not affected by the mechanical connections between the ships. The wave excitation forces, inertia, and hydrostatic restoring forces are too dominant, and there can be no significant effect on tuning from the relatively small (and nearly horizontal) forces placed on the ships by fenders and mooring lines. Heading and speed are the only control variables at the operator's disposal to alter the vertical responses.

In roll, alteration of course and speed can be used to affect the wave encounter frequency. In addition, altering course and speed will lead to a different amplitude and period of rudder application on the towing ship, and this in turn will affect the ships roll response. The ship's roll natural frequency, which is primarily governed by its metacentric height, inertia, and added mass properties, can be altered to some extent by the mooring cable (locked) stiffness, fender stiffness, and the cable/fender configuration. Simulations also showed that the stiffness of the present Seaward fenders can be optimized to reduce roll motion. Softer fenders produced lower roll motions in the simulated cases. However, the optimum combination of cable/fender stiffness and configuration to reduce roll motions is believed to be case specific.

Sway and yaw motions are primarily affected by the ship heading and forward speed. Head seas tended to produce more sway and larger yaw angle than following seas for the same forward speed. Even though locking the cables can prevent excessive sway and yaw motions, excessive mooring line loads may occur if the mooring lines and fenders are not carefully designed. However, it is possible to design a combination of optimum cable and fender stiffness to minimize the sway and yaw motions without producing excessive cable loads. In SS5, with constant tension lines, the ship heading must be kept in following seas, and the speed can not exceed 6 knots. Otherwise, excessive sway and yaw motions are inevitable and the envisioned skin-to-skin cargo-transfer operations would not be able to continue. A wider range of ship headings, as well as higher speeds, would be possible in lower sea states, but the precise dependency has not been investigated here.

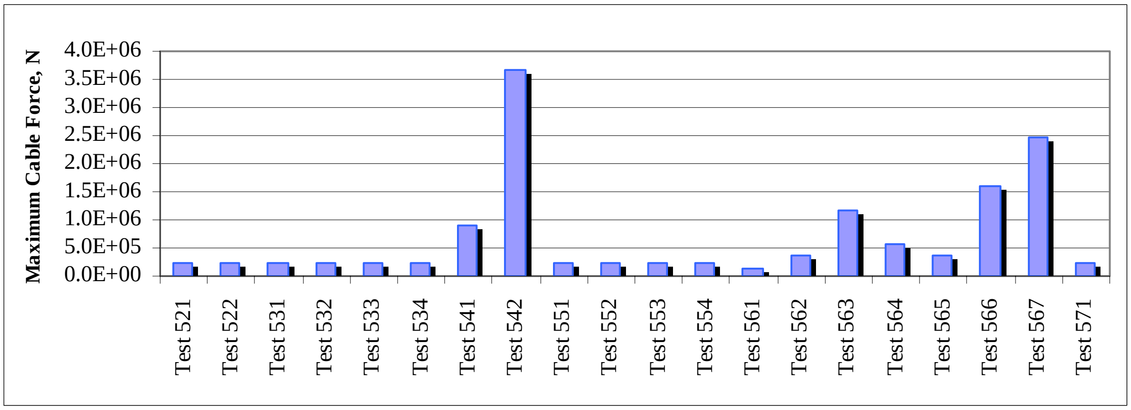

Figure 4 – Maximum Mooring Cable Force in 30 Days of Continuous SS5 Operation

MOORING LINE TENSION AND FENDER COMPRESSION

Locking the mooring cables will reduce sway and yaw motion but excessive cable loads may occur in SS5 even at the most benign headings and speeds, if these locked cables are not allowed to slip after a certain level of tension is reached. The slip mechanism limits the tension, and helps prevent line parting, but after the line has been paid out by slipping, the winch must be powered up, generally manually, in order to pull the cable back in. If the cable is not pulled back, it will remain slack as the two mooring points move closer again.

In all the simulations done for this study, the locked lines are not set to slip so that the magnitude of the mooring cable tension could be compared as shown in Figure 4.

In cases where the cable tension is held constant, the cables are considered safe if the tension is kept below 20 percent of the cable’s breaking strength. In other words, the allowable stress is 20% of its breaking strength. Since the tension is controlled, there is virtually no line breaking risk if constant tension winches are used.

Locked cables, which rely on the grommet to provide responsive extension will much better restrain sway and yaw motions but may incur excessive loads if not carefully designed. Simulation shows that the locked mooring lines will easily break in SS5 head seas even at a low speed of 3 knots. At the same speed and sea state in following sea, the mooring line tension is much lower but still much higher than the 2.5 inch grommet’s allowable stress. In Figure 4, all of the cases with a higher than 500kN maximum tension have locked mooring lines. If the grommet stiffness is softened by half (from Test

563 to Test 564), the maximum mooring line tension can be reduced by almost 50%, with only slight worsening of sway and yaw motion, but well within an acceptable range.

With softer lines, the predicted maximum mooring line tension in 30 days of continuous operation in SS5 following sea at 3 knots is well below the 63.5mm (2.5 inch) grommet's allowable stress. If the speed increases to 6 knots (Test 564 in Figure 4), the maximum tension will exceed the allowable by only 15%.

It is anticipated that the maximum cable tension may be further reduced if the fender stiffness is also reduced. For this reason, operating at 6 knots in following seas with locked cables is believed to be possible with properly selected cable and fender stiffness.

The present Seaward 14 x 28 ft fenders can provide a maximum of 1,100,000 lb (4900 kN) of reaction force at the allowable 60 percent compression. Only two of the 26 cases exceed this level and excessive sway and yaw motions already rule out these two cases. If the excessive motions in these cases were reduced by improvements to the over-all dynamics of the system, the fender strength would not be a limiting factor even in these two worst cases. In the cases where ship motions are acceptable, the maximum fender load is less than 20% of the capacity of the regular Seaward fenders. Therefore, the fender strength is not anticipated to be a problem except for a very poorly designed system.

THE RELATIVE MOTIONS OF THE TWO SHIPS

To perform container transfer operations safely, limits must be placed on the relative motions between the MPF(F) and a commercial container ship. A crane specifically designed for container transfer between two ships in a seaway has yet to be developed; consequently, the relative motion limits for skin-to-skin operations of the ships cannot be derived from the capabilities of an existing system. However, it is safe to conclude that the smaller the relative motions, the less demanding the operation will be for the crane, both in technology, and in power.

Relative motions of two pairs of points were calculated. The first point of each pair is crane boom tip (attached to the Sea Base) when the boom is reaching out to the far side of the commercial container ship to pick up a container. The second point of each pair is the point straight down from the first on the container ship's deck, where the container sits. The first pair of points represents the crane operating at the foremost cargo area while the second pair represents the aft most cargo area.

Excessive relative surge motion occurs mostly in head seas at all speeds and following seas at 9 knots. In following seas at 6 knots or slower, the relative surge motion is, in general, not of concern even though some cable/fender combinations provide larger relative surge motions than others. Likewise, excessive relative sway motions are also primarily caused by the head seas and high speeds. Head seas tend to induce larger sway motion than following seas for the same forward speed. The higher the forward speed, the more difficult it is to control the relative sway motion. Employing softer cables (for example, by using twisted grommets) and/or softer fenders can reduce relative sway motions. It is believed that there exists an optimum combination, specific to the two ships involved, of cable stiffness, fender stiffness and cable/fender arrangement, in which the relative sway motion is minimum.

Even though the mechanical connections between the two ships do not affect the heave or pitch magnitudes in any significant way, they do affect the relative phases of the heave and pitch of the two ships, and therefore the relative motions. This makes it more difficult to draw conclusions on how the mechanical connections and their properties affect the relative vertical motions. Nonetheless, the large vertical motions again seem to occur more in the head seas and/or 'high' speed cases than in following seas at 6 knots or lower. Figure 5 shows the comparison of the maximum relative vertical motion between boom tip and commercial container ship deck point in 30 days of continuous SS5 operation. The relative motion of 2.0 meters or greater all occur in head seas or following seas in excess of 6 knots, regardless of the mechanical connections.

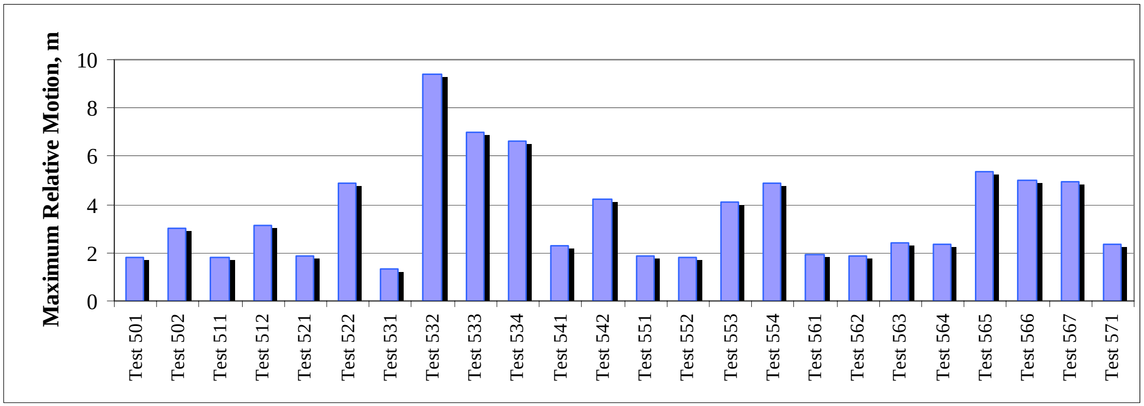

Figure 5 – Maximum Relative Vertical Motion Between Boom Tip and Commercial Container Ship Deck Point in 30 Days of Continuous SS5 Operation

MAXIMUM CRANE POWER REQUIRED FOR MOTION COMPENSATION

This section is to compare the crane power required to compensate the relative ship motion at the moment when the crane lifts up the container. To avoid the possibility of a lifted container impact with the deck or the cargo on deck, the crane must be powerful enough to compensate the relative motion between the boom's end and the container. It is not intended to estimate the actual crane power requirement for the whole operation cycle. It is understood that the power for lifting a container at a desired speed after the container is lifted off the deck may be more demanding than that required for the motion compensation at the moment of pickup.

Once again, the ship heading and forward speed seem to be the dominant factors. In head seas of any speeds and following seas in excess of 6 knots, the maximum required crane power all exceed 500 kW. In following seas at 6 knots, the maximum required power at the aft most position is around 460 kW if constant tension lines are used, around 510 kW if locked cable lines are used. Likewise, in the foremost position, the power requirement is 400 KW and 455 KW respectively. The stiffness of locked cables and the stiffness of fenders do not seem to affect the power requirement in any noticeable way. Changing the arrangement of the cables and fenders may change the power requirement. For the two different fender/cable arrangements being considered in this study, the crane power could differ 12 %.

CRANE CONFIGURATION

Research in the Intelligent Systems Division and Structures Division at the National Institute of Standards and Technology has explored innovative ways to use sensors, computers, and light-weight tensioned cable structures for heavy manufacturing and construction tasks such as lift and position of heavy loads and manipulation of tools and parts for assembly, fixturing, welding, cutting, grinding, machining, macro stereo-lithography, and surface finishing. Recent research has developed novel concepts for movable scaffolding and worker positioning systems that enable workers to maneuver themselves and parts and tools throughout a large work volume for tasks such as ship repair and aircraft de-painting.

There are two basic principles: one is the use of multiple cables maintained in tension and configured to rigidly support a work platform, the second is the use of winches to control the lengths of the cables so as to maneuver the work platform. The initial concept was to use six cables arranged as a Stewart Platform [1] to stabilize a work platform and use six winches to maneuver the work platform through a work volume. Figure 6 depicts a basic (Stewart Platform) configuration.

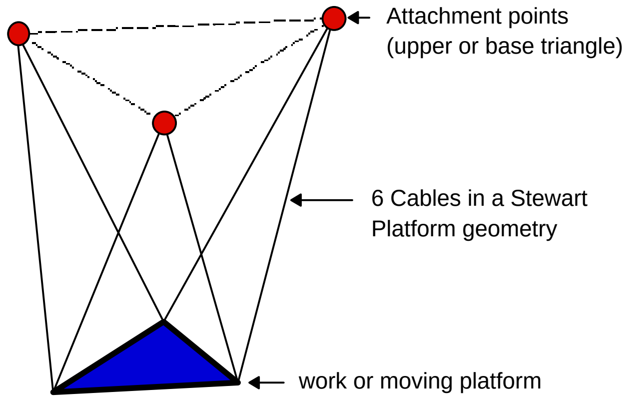

Figure 6 – Basic Stewart Platform

Stewart platforms are in common use as motion simulators for pilot training and amusement rides. In these applications, the arrangement is inverted, and hydraulic cylinders are used.

The "RoboCrane" uses cables rather than hydraulic cylinders. Provided that the cables do not go slack from excessive vertical acceleration, the RoboCrane can achieve the same six-degree-of-freedom control.

For the proposed application, several adaptations to the basic RoboCrane concept were necessary. These adaptations include:

- Rotator – Required to obtain higher rotation angles without causing suspension cable contact
- Upper Spreader – Required to keep the suspension cables from contacting containers in stacks adjacent to the target container, and also used to increase system redundancy as well as improve winch responsiveness by reducing the individual winch peak power requirements
- Lower Spreader – Required to engage the container

Figure 7 shows the proposed rigging arrangement. Each of the spreader platforms will be controlled in six degrees-of-freedom by twelve cables.

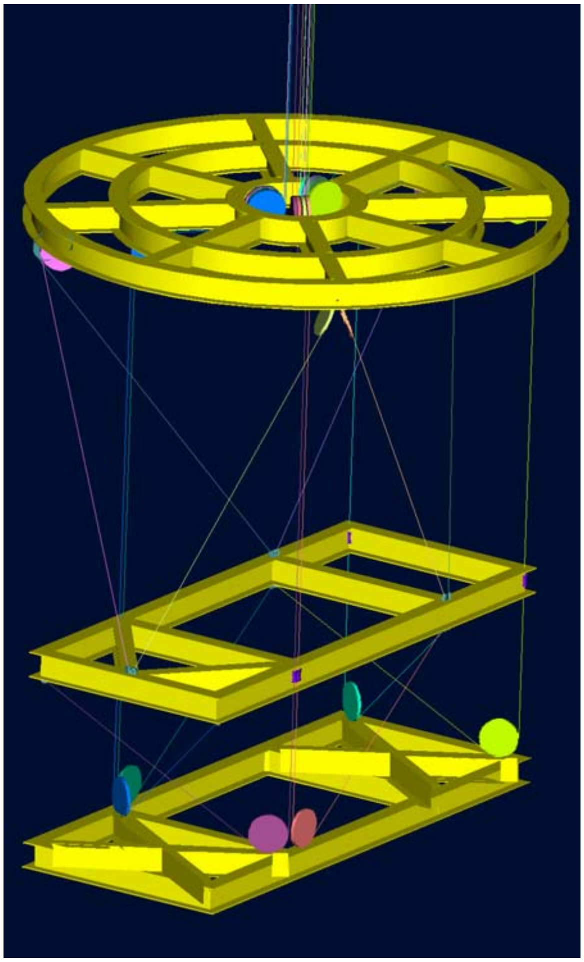

Figure 7 – Proposed Crane Rigging Arrangement

A number of alternate crane structural configurations were considered. The authors conducted a formal trade study to evaluate seven different crane arrangements. The approach shown in Figure 8 is a traveling crane with a box girder boom. Winches would all be located inside the boom, close to the traveling carriage. This approach was evaluated as having the highest performance/cost ratio. However, ship configurations could drive crane arrangement. Many other arrangements are possible.

Figure 9 shows an artists concept of the proposed crane on the Sea Base unloading a commercial container ship alongside, skin-to-skin.

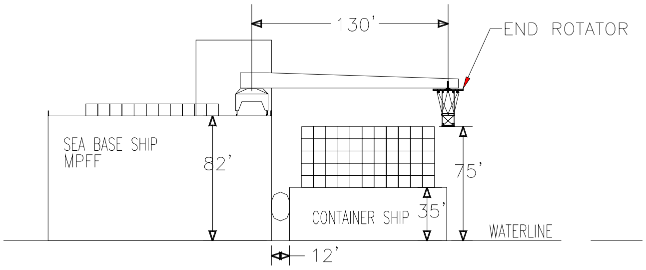

Figure 8 – Sea Base Crane Looking Forward

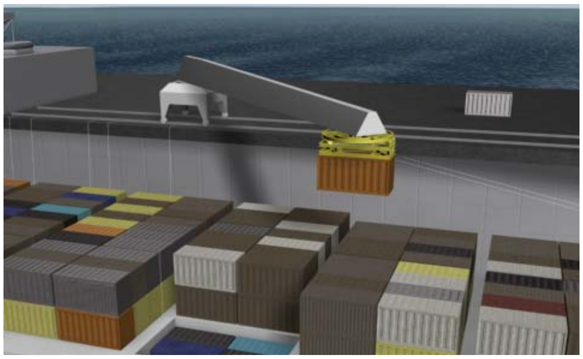

Figure 9 – Artists Concept of Proposed Crane

CRANE DYNAMICS

The dynamic responses of the cargo transfer system, specifically the behavior of the load that the crane is transferring, is of paramount importance in determining the feasibility of the skin-to-skin transfer operation. The seaway excites the MPF(F) ship motions which in turn causes the load of a crane to pendulate relative to the MPF(F) ship. Additionally, the commercial container ship will be responding to the same seaway with different ship motions, which in some cases can be completely out of phase with the MPF(F). To perform the replenishment operation safely with low probability of damage to the ships and the crane, the load must move with very little relative motion to the containership when the crane is picking up the load, and then move with little relative motion to the MPF(F) ship when the crane is setting down the load. A crane can be designed to have small load pendulation relative to its own platform, but for small relative motions to a second platform a control system must be used that can excite motions in the load as desired, resulting in a low relative motion to that platform.

Dynamic, physics-based simulations were performed on the crane system defined above to:

- Verify the feasibility of the crane rigging configuration
- Determine the motion of the crane load relative to the MPF(F) ship and the commercial containership, with the cables locked, in a given seaway
- Determine if it is theoretically possible for a control system to maintain zero relative motion between the load and the commercial containership
- Determine the pay-out and haul-in rates and corresponding winch power required to excite the load to zero relative motion to the containership

Simulation Software

The software package used to develop, simulate, and analyze the dynamic models is ADAMS by MSC Software. A model is developed by defining all the parts of a system, including masses and inertial properties, defining forces acting on or between these parts, and constraining the motions of the parts to each other (or not at all). ADAMS develops the equations of motion of the system from the model and then solves the equations numerically in the time domain. The output of the program is the solution of the equations, from which any force acting through the system or motion of any part in the system can be obtained.

Model Description

The selected seaway case for the dynamic simulation is one that is expected to create the greatest accelerations of the load, and relative motions between the load and the containership. The selected case is SS5, slightly off head seas, with the crane boom end extended to the container furthest away from the MPF(F) and containership centers of gravity.

The model of the transfer system was made of the crane rigging defined above, supporting a forty-foot container weighing 30 metric tons. The upper spreader is located 24 m below the boom tip and the load is an additional 20 m below that. All the parts of the system are treated as rigid bodies, except for the cables, which are modeled elastically. The simulations are utilized to examine the forces in the system from the load being held at a single position; that is, the operation of picking up and setting down the load has not been examined. This was done so that the maximum loads throughout the system could be identified for the given sea conditions.

Verification of Crane Rigging

The first purpose of the dynamic model is to verify that the crane rigging is feasible. If a cable in the rigging system becomes slack at any time, that cable cannot be used to control the container motion during that time. Also, when a cable becomes slack and then is impulsively tensioned, shockwaves will be sent through the system that will require a stronger, heavier, more costly crane system to withstand. For this reason, the rigging system is judged to be feasible only if all crane cables remain tensioned with the crane winches set in the ‘locked’ position (and of course, the crane needs to work as anticipated!). Figure 10 shows the cable tensions over a segment of the 2000 second simulation.

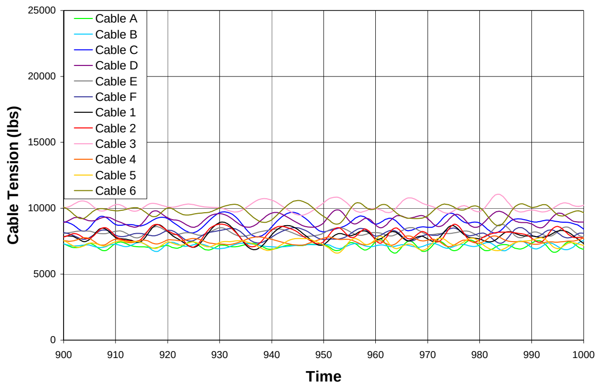

Figure 10 - Cable Tensions, Winches 'Locked'

As can be seen the cable tensions stay in a relatively narrow band oscillating between 26.7kN and 53.4 kN (6000 and 12000 lbs) of tension. In this rigging configuration, it appears there is no danger of the cables going slack, and therefore is a feasible rigging configuration for holding the load. This particular simulation with the crane winches ‘locked’, allowing no pay-out or haul-in of the cables, was also used to determine the relative motion of the load with respect to both ships. The relative motion is examined by comparing two points in space. One point is rigidly fixed to the containership, and the other is rigidly fixed to the container. Both points are initially at the same position, at the center of the container. The displacement, velocity, and acceleration between the two points can be used to compare their relative motions. Figure 11 shows the displacement magnitude of the container relative to the containership, and Figure 12 shows the velocity magnitude.

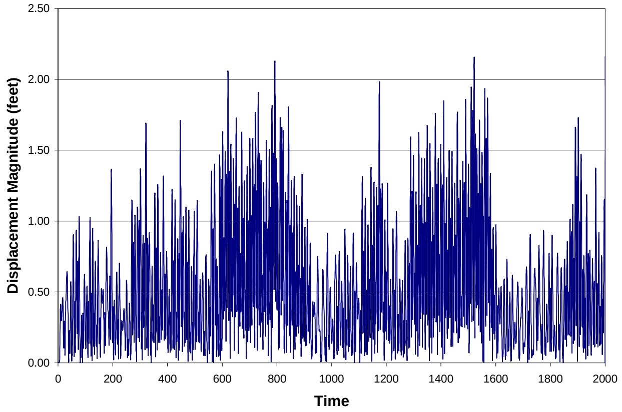

Figure 11 - Relative Displacement Magnitude Between Load and Containership

Oscillations of greater than 1.2 m (4 ft) are observed with relative speeds up to 0.3 mps (1 fps). This is a large enough relative motion to cause damage to the containership and pose a safety risk.

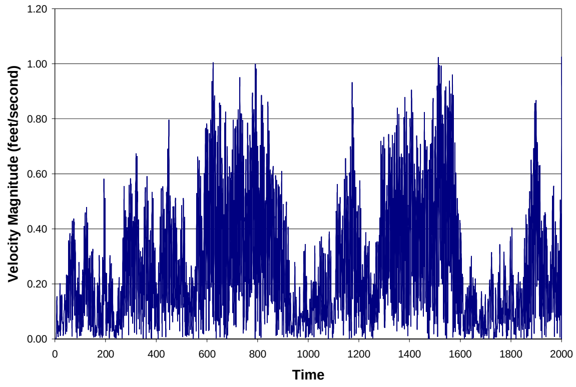

Figure 12 - Relative Velocity Magnitude Between Load and Containership

Active Motion Control

The model is altered slightly to determine if it is possible for a control system to excite the load to move with zero relative motion to the containership, and also to determine the pay-out and haul-in required of the crane cables.

An artificial constraint is added to the load, which forces it to move with the containership. Six of the twelve winches are unlocked (the cables connected to the load) such that the cables do not exert a force on the load, and the pay-out and haul-in required of the cables geometrically to stay attached to the container are recorded.

It will be theoretically possible for a control system to control the motion if the system is not over constrained and doesn't 'lock-up' while the load is moving with the containership, and if the pay-out and haul-in rates of the cables really will move the container with zero relative motion to the containership.

The results of this simulation are displayed in Figure 13 shows the haul-in and pay-out displacements of the cables required and Figure 14 shows the rates. The system did not lock-up, and no excessive forces were seen.

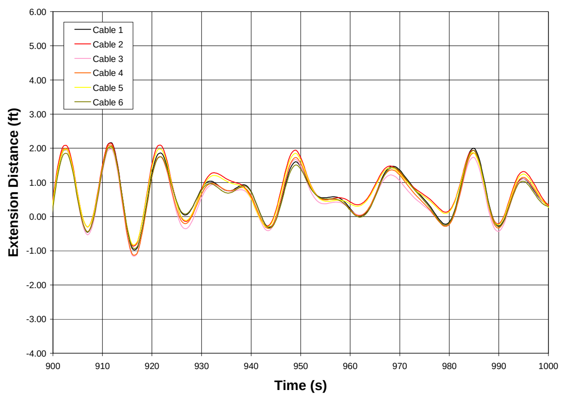

Figure 13 - Required Cable Pay-out and Haul-In Displacement

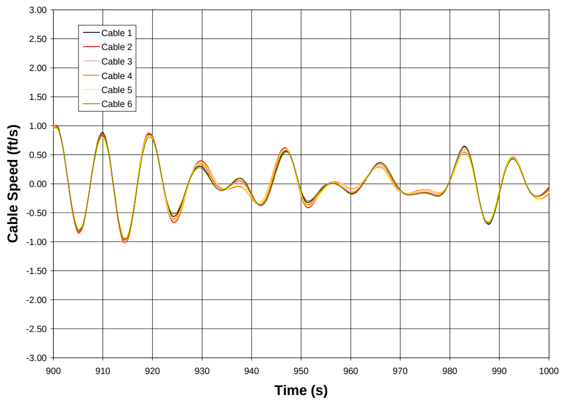

Figure 14 - Required Cable Pay-out and Haul-in Speeds

To create zero relative motion, the cables are required to move in very close phase with each other at similar pay-in and haul-out rates. Cable extensions up to 1.5m (5 ft) are seen with a rate of 1 mps (3 fps).

Next, the model was altered again and the constraint fixing the container to the containership was removed. The pay-out and haul-in rates determined in the previous simulation are now used as inputs to see if the container can indeed be excited to move with zero relative motion to the containership.

Figure 15 displays the displacement magnitude of the container with this active control, compared to the winches locked case shown above. As can be seen, there is a significant relative motion reduction from the theoretical control system, but there is still some relative motion. The velocity magnitude plot shows similar results.

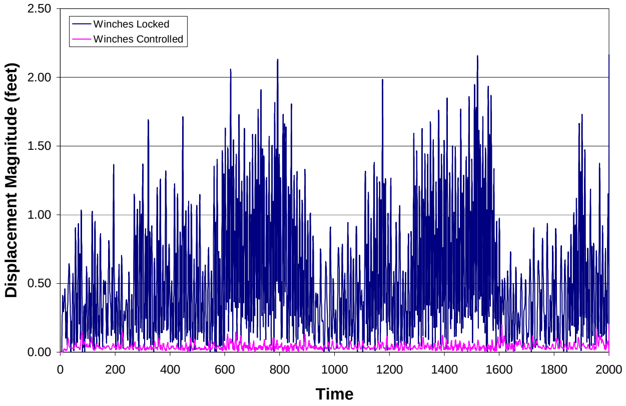

Figure 15 - Relative Container Motion to Containership with Active Control

The tensions of all the rigging cables are shown in Table 2. The results are similar for all the system cables, not just the actively controlled cables. Tensions have increased dramatically but not catastrophically, with a peak in the 2000s simulation at 11,340 kg (25,000 lbs). The range in the time period shown runs from 0 kg (0lbs) to 7,711kg (17,000 lbs), and high frequency oscillations are more prominent.

During the simulation some of the cables do go slack. For a cable to go slack, the connection point on the container must be moving up faster than necessary for zero relative motion, or more realistically, the container is not falling fast enough to maintain zero relative motion. The geometry of the cable attachment points to the load and the pay-out and haul-in of some cables may limit the loads' 'drop speed' at the cable that goes slack from trying to push the load down. It is possible that changing the geometry of the connection points on the load or on the upper spreader may reduce this 'slackening'. even given geometry causing the cable slackening. The relative motion of the container stays at some mean level even with cable slackening. This encouraging fact suggests that the container motion is not highly sensitive to past motion history; a large percentage of the container motion is dependent upon the current ship motion. This conjecture certainly needs additional examination and confirmation, but if true will lead to a control system which is less complex than initially anticipated.

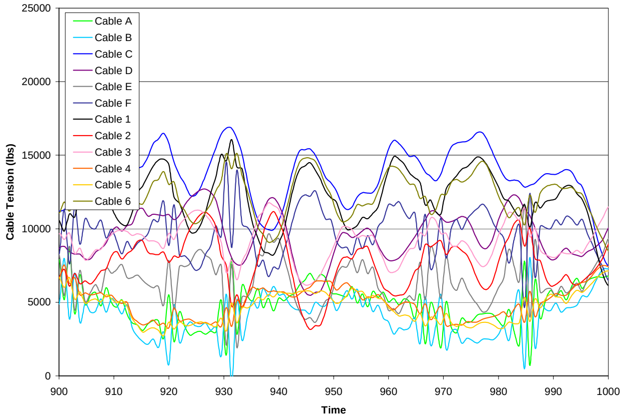

Figure 16 - Cable Tensions with Active Control

The power required to control the cables is not untenable either. Table 2 lists the maximum power output required at the cable wrap from the winches.

Table 2 - Required Winch Power

Winch Cable	Maximum Power Required
Cable A	113 hp
Cable B	128 hp
Cable C	271 hp
Cable D	217 hp
Cable E	123 hp
Cable F	178 hp

It has not been shown that zero relative motion can be obtained for this case, but it has been shown that very small relative motion can be obtained with a reasonably sized system.

This analysis is far from complete. Investigations of the system operation need to be examined in additional seaways and at additional ship headings. The location of the boom tip should be adjusted as well to verify that the worst relative motions are seen at its current position. This simulation technique was utilized to help design the crane rigging concept configuration geometry. The geometry should be further examined to identify relationships between cable connection points and load variation in the cables when under active control. Actual control systems need to be implemented in to the simulation to determine their effectiveness.

CRANE CONTROL

The RoboCrane® is a trademarked control system and rigging configuration developed by the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. Over the past 15 years, the NIST Intelligent Systems Division has studied a variety of rigging configurations that apply the basic geometry (see Figure 6) and kinematic control of the Stewart platform, parallel-link manipulator. [2] The RoboCrane cable-controlled manipulator was developed during a project for the Defense Advanced Research Project Agency that studied crane suspended load control. Since the DARPA project, a series of rigging and platform geometries have also been studied to fit current reconfigurable, cable-drive system needs. [3,4,5] Applications beyond Stewart's original control and rigging configuration are explained in [6] for ship repair, in [7] for underwater use, and in [8] for space use.

While RoboCrane can lift large, heavy and awkward loads, its stability and maneuverability allow advanced programming techniques more analogous to robots than cranes. The RoboCrane combines sensors, a computer, a platform and tensioned cables to perform heavy manufacturing and construction tasks, such as: lifting and positioning heavy loads and manipulation of equipment, tools and parts. The RoboCrane manipulator can improve performance for such tasks as: assembly, fixturing, welding, cutting, grinding, machining, surface finishing, inspection, and cargo handling.

For skin-to-skin and other at sea cargo-handling needs, the rigging geometry is required to fit within the footprint of the containers and spreader bars being handled. Standard ISO containers and spreader bars measure approximately 6 m to 12 m (20 ft to 40 ft) or more in length by 2.4 m (8 ft) wide and do not touch adjacent containers while stacked onboard ship or during handling. Rigging between spreader bars therefore, must also fit within this geometry and requires a slightly different configuration as shown in Figure 17. Also, spreader bars must retract as close as possible to the crane tip to provide minimized crane structure height relieving wind forces as well as minimizing crane cost. The upper frame attaches to crane via a rotary joint while lower spreaders are suspended by cables from the frame This design allows the spreader bars to retract against one another.

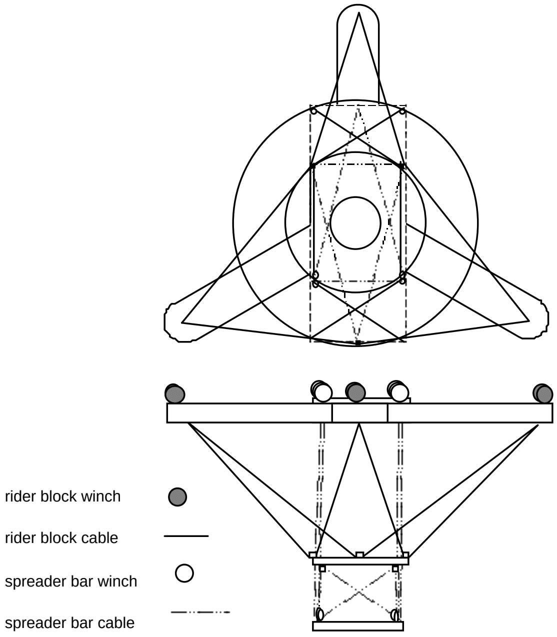

Figure 17 – Top and Side Views of the Proposed Cable Rigging

Control

The RoboCrane moves in cartesian and joint modes. Cartesian control allows crane operators to intuitively move and/or the control computer to move the platform front-to-back, side-to-side (see Figure 18), up-and-down, roll, pitch, and yaw about cartesian axes, as well as combinations of these motions. Joint mode allows single-hoist motion for setup or cable replacement for normal maintenance.

The RoboCrane rigger must measure the anchor points with respect to a ground-based coordinate system (crane). The anchor points of the cables platform origin relative to the ground origin, to their sheaves on the platform (spreader bar) must likewise be measured with respect to a which moves around as the cables lengthen and shorten. These calibration measurements need only be done once, when the platform is installed at the facility. Velocity servo amplifiers will power the hoist motors. The amplifiers will provide a serial interface over which velocity commands and position feedback are sent. Depending on the configuration, a single RS-485 serial link can connect to a single amplifier serving a single motor, or several amplifiers each controlling several motors can share a single serial link.

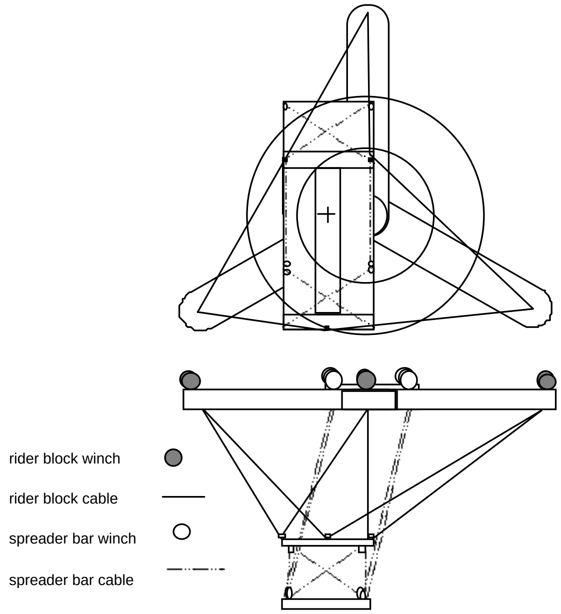

Figure 18 – Spreader Bars Shifted From Center Position While Under Full 6 DOF Control.

Control Method

As experienced on the Flying Carpet RoboCrane and is expected for the skin-to-skin application as well, the controller implements resolved-rate teleoperation or autonomous motions, in which an operator controlled joystick or computer generates the desired velocity of the moving platform in Cartesian space (X, Y, Z, roll, pitch, and yaw). This desired velocity is transformed into cable speeds through the inverse Jacobian function:

$$W = J^{-1} V \qquad (1)$$

where W is the 6x1 cable speed vector, V is the 6x1 Cartesian velocity vector, and J^{-1} is the 6x6 inverse Jacobian transform matrix that depends on the current Cartesian position of the moving platform.

The Jacobian is an instantaneous relationship. In a sampled system, where some time elapses between successive recalculations of the inverse Jacobian matrix, the cable speeds will be constant during this interval. As a result, the moving platform will accumulate position errors and require correction by sensory devices viewing a known scene, such as containers on a ship. Laser ranging (Ladar) devices are expected to be used for this purpose.

It is possible to correct these minimal errors automatically, since the actual Cartesian position is continually computed by reading the cable lengths from the motor encoders and running these through the forward kinematics function:

$$C = T\o \qquad (2)$$

where C is the actual 6x1 Cartesian position vector, ø is the 6x1 cable length vector, and T is the 6x6 matrix for the forward kinematic transform.

In the case of the Stewart Platform, the inverse Jacobian transformation J^{-1} is closed form. However, the forward kinematic transform T is not closed form, and iterative calculations estimate the true Cartesian position C. The iterative algorithm requires an initial estimate of the Cartesian position in order to converge. During normal operation, this estimate is simply the last Cartesian position computed, which changes little from cycle to cycle. However, initial computations need a matched pair of cable and Cartesian positions in order to begin the iterations. A short, four step homing procedure generates the matched pair. [9] If the controller can preserve its last Cartesian position upon shutdown and restore it when starting up later, then the homing procedure need be done only once when the system is first set up and calibrated. This has been demonstrated with the full-scale prototype Flying Carpet and is easily transferable to this project.

Motion Compensation

For motion compensation, a laser scanner (Ladar) unit can be attached to the spreader bar and point downward toward the containers. The crane and spreader configuration is expected to be sufficiently rigid to allow this operation. Initially during cargo retrieval from the container ship (or during loading), the crane can scan the container ship for container and cell position and orientation information. Ladar range information is received and stored in controller memory for the entire crane work volume. Once scanned, the Ladar is used to locally servo position and orientation of the spreader bar to the target container as it comes in view of the container to pick-up or the cell to place a container. Outriggers on the spreader allow the Ladars and cameras to look past the spreader (see Figure 19). The crane control computer uses the Ladar data to servo position and orientation of the spreader bar to the container or cell while keeping a safe distance to the container or cell until ready to retrieve or place the container.

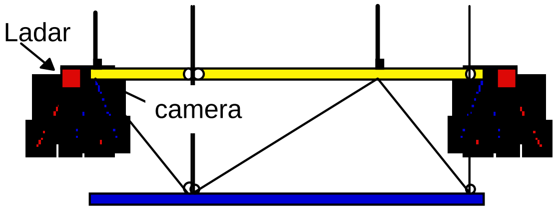

Figure 19– Ladar and camera mounting to upper spreader bar for motion sensing of containers relative to lower spreader bar.

An operator can use the cameras to provide close-proximity views of the containers, lower spreader bar and ship deck. The camera view looking down on the containers would appear as shown in Figure 20.

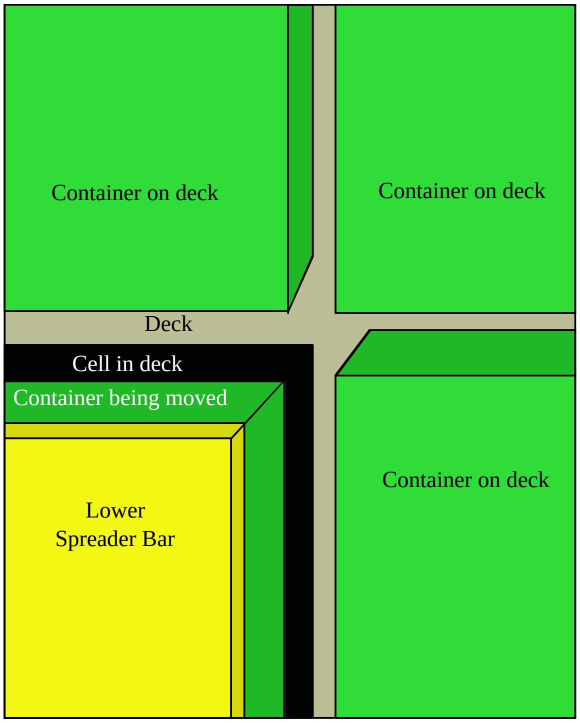

Figure 20 – Camera view looking down on containers..

CONCLUSION

The proposed approach of resupplying the Sea Base may be unconventional from current US Navy operational methods, but is not without precedent in current commercial tanker operations. Super tankers are lightered on a regular basis in many parts of the world. These operations have taken place in higher sea states than those envisioned for the Sea Base. There are, however, obvious differences between the current commercial lightering operations and the proposed Sea Base resupply. These include:

- Vessel Sizes – Typical tanker sizes are 300,000 DWT lightering to a 150,000 DWT. The sizes envisioned for the MPF(F) Sea Base are 90,000 DWT with the container ship a 55,000DWT vessel. This means that the ship motions of the Sea Base / container vessel will be higher than the tankers, but will have lower kinetic energy.
- Vessel Windage Area – The wind will play a greater role on the proposed “sea base”

resupply operation than will be the case for the tanker operation. Additionally, high vessel sides and deckhouse structure would be in a greater risk of steel–on-steel contact than the tankers.

- Cultural Resistance – US Navy ship handlers, brought up on UNREP, where maintaining at least 100 feet of ship separation is paramount, have a hard time imagining intentionally bringing two large ships together in a SS5. Tanker masters, on the other hand, have a hard time imagining driving two vessels for hours on end in close proximity, with no large fenders to protect them.
- Cargo Handling – It is obviously more difficult to handle containers than it is to handle liquid cargo. Once a hose is connected, and secured with adequate slack, the hose centenary provides all of the motion compensation that is required.

In spite of these differences, the authors have not seen, and do not envision any insurmountable obstacle to achieving the Sea Base resupply method proposed. Certainly, more work needs to be done. Additional hydrodynamic studies are planned, and at-sea tests need to be conducted on vessels of the size proposed. The major effort, however, should be focused on the development and test of a suitable six-degree-of-freedom crane. In a parallel effort, the authors recommend that MPF(F) concept designs be developed to fully take advantage of this transformational approach

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ACKNOWLEDGMENTS

This feasibility study was sponsored by the Office of Naval Research, under the direction of Ms. Lynn Torres. We thank Ms Torres for her support and encouragement. Sincere thanks are also expressed to VADM Jim Amerault, USN (retired), Frank March of Seaward International, Joshua Miller of JJMA and Dr. Robert Scher of JJMA who all contributed to the successful completion of this investigative phase. Additionally, thanks is given to JJMA for continuing to support the study after the government funded portion of the work was completed.

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2. *Intelligent Systems*
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