AUTOMATIC POSITION CONTROL OF A 30,000 TONS SHIP DURING OCEAN MINING OPERATIONS

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ABSTRACT

Extensive computer simulation and performance analysis and assessment have been carried out for the dynamic positioning control of a large, commercial ocean mining ship/pipe system, and selective results are presented. It is tentatively concluded that automatic position control, with a manual override option, of a 300,000 tons ship with 18 thrusters of 4,500 hp and an 18,000 feet long lift pipe system would be feasible for commercial operations of a preliminary mining system in the Pacific Ocean. The preliminary system employs a self-propelled miner similar to the one having been tested in the Pacific Ocean. For the feasibility study, we have performed the following; the thruster power estimate, a subsequent selection of an azimuthing ship thruster system configuration, steady-state and dynamic motion of the ship-pipe system, track-keeping, turning and station-keeping control, design of an automatic control system, and nonlinear control simulation during mining operations and selective contingency situations. For the development of commercial systems, the small-size, test-mining system does not provide all the design data. It is much larger, and subsequently, requires development of more sophisticated technology and engineering capabilities. The present method of analysis and simulation can be applied to many other mining system analyses. Furthermore, it can be directly applied to the station-keeping control of deepsea drilling or ocean margin drilling systems.

INTRODUCTION

Ocean mining research and development have been active for more than ten years. Major effort of such R & D works has been placed on the deep ocean mining of manganese nodules from the seafloor of water depth, ranging from 12,000 to 18,000 feet, near the equatorial zone in the Northeast Pacific Ocean. For the past few years, major R & D activities at various consortia have been the at-sea test mining with small mining systems which may have checked out a few subsystems and concepts. However, a commercial production system, of which operation may be realized within the next ten years, requires design and operation of much larger (perhaps by an order of magnitude) mining system (ship, lift pipe, buffer, miner) and subsequent development of more sophisticated technology and engineering capabilities. For the mining system and operations to be economical at this time, the ship size can be from 70,000 ton to 300,000 ton, depending on the market of various metals out of the manganese nodules, on the transhipment plan and on other parameters. So far, no commercial mining system of such size has been designed for hardware fabrication or tested by any of the mining consortia. For the development of a commercial system, it further requires reliable, more advanced technology development, individual subsystem design, fabrication and checkouts, and importantly, the scale-up technology of the small mining systems, which may have been previously tested in the Pacific Ocean, to the size of commercial systems.

One of the comprehensive system analyses required for the mining system concept trade-off study and design is the overall dynamic positioning of an entire mining system (Fig. 1). Design of a commercial system, of which the ship size can be an order of magnitude larger than the test-mining ship, requires an extensive computer position control simulation and hydrodynamic and structural dynamic analyses. The computer control simulation tool for such purpose should be developed so that it can be applied regardless of the system size for the system analysis and parametric study. The "deepwater" drilling system technology for the 1,000-3,000 feet water depth can not be directly applied to the deep ocean mining system design for the 12,000-18,000 feet water depth. For such drilling systems, the ship or platform size and water depth are an order of magnitude smaller than for the mining subsystems.

This order of magnitude increase in ship size and water depth for the deep ocean mining brings in many new complex problems which would require subsequent technology development for the design as well as operation of the mining systems. A few examples of the new considerations are as follows. The drag of the lift pipe system can become a significant portion of the ship thrust power, and it can have an important
influence on dynamic positioning control of the continuously moving mining ship and the "free-bottom end" of the pipe. Vertical variation of the subsurface physical environment and its seasonal or daily variation are great near the equatorial zone. It affects significantly the pipe motion along its length and the subsequent mining system control operation. The dynamic interaction of the pipe motion with the physical environment and ship motion and control is very sophisticated [1, 2, 3]. Also, the position control of the mining system is more sophisticated than that of the drilling systems even for the same deep water depth. The present mining system would require less stringent constraints on the position control accuracy for high nodule sweep efficiency than many other mining systems, by allowing much freedom for the miner to move around the seafloor. But the continuously moving or track-keeping requirement of the mining system still places stringent requirements on the accuracy of the ship and/or pipe positioning control. Each mining consortium has been developing its own unique mining system to fit the individual mining requirements.

Therefore, instead of approaching this problem from the "deepwater" drilling technology to an order of magnitude deeper water depth, we have looked at this problem from the deep ocean depth to identify new problems, including the problems as identified above. The thruster size and system configuration of the ship are determined through extensive hydrodynamic and structural analyses of the ship/pipeline system and thruster efficiencies. On this basis, a nonlinear control model was designed. The bottom end of the pipe, or the buffer, is automatically controlled in coordination with the ship and miner control. The mining system control simulation has been performed in time domain in order to simulate the operations, which would be more critical than the design.

Although very comprehensive, sophisticated hydrodynamic and structural analysis [1, 2, 3, 4] and position control simulation and performance analyses and assessment have been carried out for details of each mining subsystem and each control subsystem, the present paper presents only overall aspects of the commercial mining system position control. Since the present mining system is unique and is the first of its kind, the mining system, operational and environmental requirement are described first.

PART I
MINING SYSTEM, REQUIREMENTS, AND THRUSTER SYSTEMS ANALYSES

DESCRIPTION OF THE MINING SYSTEM AND OPERATIONAL REQUIREMENTS

Each ocean mining consortium has been developing or testing different mining systems: towed-line system, continuous-line bucket system, self-propelled miner system, and others. For the present study, a preliminary commercial mining system concept (ship, pipe, (buffer), miner) of Ocean Minerals Company, has been investigated for the feasibility of automatic position control with manual override option. The present system (Fig. 1) uses a self-propelled miner. The miner maneuvering motion on the seafloor can be nearly independent, with certain operational constraints, of the free-bottom end motion of the 18,000-ft. long, lift pipe, thus greatly increasing the nodule sweep efficiency for a given seafloor surface area of manganese nodules.

During deployment and retrieval of the lift pipe and bottom mining equipment, the ship is controlled to station-keep about a stationary point on the seafloor. During normal mining operations, the ship and/or pipe are controlled to maneuver continuously or track-keeping, turning etc. following the self-propelled miner on the seafloor which follows the mining track, and maneuvers for bottom situations. The nodules collected by the self-propelled miner are in a form of mixture of nodules, some bottom soil particles and subsea water. The mixture is transported as two-phase flow vertically ("lifted" or "hoisted") by various means to the ship through the miner-to-buffer linkage, the buffer, and a 18,000 feet long, nearly vertical lift pipe string which carries a buffer attached to its free bottom end [1, 2]. If an air-lift system is used, it becomes a three-phase fluid flow. The buffer weight can vary during the mining operation. Nodule transshipment is beyond the scope of this paper, and is not discussed. The miner propulsion and maneuvering are controlled by miner control subsystem onboard ship. The ship is required to maintain the most favorable heading to keep the thruster power consumed to a minimum during normal mining operation. This means the ship would have to perform a grabbing motion. During normal mining operation, the ship with or without the assistance from the buffer control is controlled to have the pipe-buffer system follow the self-propelled miner within the envelope permitted by the linkage, which is assumed to be completely flexible in this study. During the buffer or ship control, the current flow velocity would continuously vary. The envelope permitted by the linkage is defined as the steady state and dynamic motion displacement of the free bottom end of the pipe or the buffer relative to the instant miner position on the seafloor. It is a function of operational system design parameters. A method to determine this on the basis of nonlinear steady-state and transient motion responses of the bottom end of the pipe can be found in [1, 2].

The mining system and its position control system must be designed to minimize their possible adverse dynamic influence on the miner track-keeping ability in order to achieve economical nodule sweeping efficiency. The pipe motion responses are coupled with or greatly influenced by the nonlinear dynamic behavior and control of the ship and buffer, and by the variation of the subsurface physical environment such as current flow velocity. Time lag between the initiation of ship motion and the effect at the bottom end of the pipe, or vice versa, is very substantial. The position control should be well coordinated with the dynamics of the ship/pipeline system. Also, the large static horizontal excursion of the bottom end of the pipe [2] can substantially vary the vertical pipe bottom-end clearance relative to the seafloor. Theoretically, there exists pipe vibration possibility beyond a certain mining velocity, which can be induced by vortex shedding from the pipe [4]. This is outside the scope of the present paper and is not discussed any further.

As for the station-keeping requirement about a seafloor point such as for the drilling and production systems, the ocean mining system must be controlled to be stationary about a point on the seafloor.
Additionally, it must be controlled to move or maneuver continuously along the seafloor mining track, following the bottom or seafloor mining plan. Furthermore, the mining system should be able to maneuver around, when encountering situations such as stopping due to subsystem failure, a sudden encounter of obstacles and adverse bottom topography. The position control system design is subject more to the operational (time-domain) aspects than to the design aspects. The entire position control system of the mining system is onboard the ship.

Some small-size test mining systems have been tested at sea of various depths. They include tow-sled system and continuous line-bucket system. The track-keeping ability of the miner or nodule collector of the tow-sled system is directly subject to the steady-state as well as dynamic bottom end motion of the lift pipe for which the only miner position control is usually through the ship's positioning control. Also, the continuous line-bucket system is subject to similar constraints. It can be controlled only through the ship's positioning control. One of the advantages of the present system having the pipe bottom end "free", the linkage between the buffer and the miner, and a self-propelled miner is to achieve high nodule sweep efficiency. The high efficiency can be achieved by providing the self-propelled miner free to move or sweep the bottom nodule track according to the bottom mining plan, freeing the miner from the dynamic motion of the pipe bottom end and ensuring higher nodule recovery within given seafloor surface area. The buffer weight reduces the steady-state horizontal excursion of the pipe bottom end.

The Characteristics of a Lift Pipe/Buffer System used in the present simulation are shown in Table 1. The pipe is tapered in three sections, with its top end connected to a heave compensator system and hanging vertically from the moon-pool of the mining ship. A buffer is attached to the free bottom end of the pipe, theoretically not restrained by the linkage connected to the miner on the seafloor. For the present study, a buffer weight of 150 dry tons, a locked heave compensator system and a gimbal on the pipe top end are used. The characteristics of linkage system and the self-propelled miner are only slightly relevant to the present simulation and are not described.

The Mining Ship size was determined on the basis of a set of preliminary system requirements for a commercial mining operation. Principal characteristics of the ship are given in Table 2. The ship size is approximately 300,000 L ton in displacement and 960 ft in length and has a large moonpool to handle the pipes and the bottom mining equipment including the miner. The propulsion or thruster systems are to be determined on the basis of the hydrodynamic analysis of the preliminary mining ship, which is discussed later.

PHYSICAL ENVIRONMENTAL CONDITIONS

The Maximum Operating Physical Environmental Conditions used for the present study are determined on the basis of the statistical wave data [8] and other subsurface environmental data [2] for the potential mining site near the equatorial zone in the Northeast Pacific Ocean and are given in Table 3. Environmental data in Table 3 are constructed as conservative values in order to establish the ship thruster power requirements and extreme cases of the mining system operational simulation. The subsurface current velocity and fluid properties [2] are a realistic representation of the potential mining sites in the Pacific Ocean. They vary monthly and often daily. They vary significantly with distance from the surface, which can greatly affect the variation of the pipe drag along its length and the resultant ship/pipe system control (see [2] for details). One of the composite (swell plus wave) spectrum [6, 7, 8] for \( H_{1/3} = 13 \) ft, which gives one of the largest mean wave drift forces for the station-keeping mode of the mining ship in the beam sea, is used.

Among the physical environmental data required for the mining system control simulation and analysis, the wave spectrum model and the subsurface current profile [2] were established on the basis of very limited measured data. Measurements of more such data on a long term basis is desirable.

LIFT PIPE MODELS

A simple lift pipe model is used for the present simulation. It consists of the equation of motion of discrete number of pipe elements. For the discretization of the pipe string, a finite difference method is used. For the pipe string modelling, bending stiffness and torsional characteristics are ignored. The hydrodynamic forces consist of the inertial forces, which account for the added mass, and the drag forces, and additionally the body force is accounted for. The equation of motion for a pipe string element is nonlinear in the velocity-squared term of the drag force. It is solved with the Newton-Raphson method. Numerical integration has been carried out by Milne method [5].

The present simulation method is different from the three-dimensional beam, nonlinear finite element model of a lift pipe which has been developed to simulate and analyze nonlinear static and transient motions of an 18,000-ft pipe [1, 2]. The latter accounts for coupled axial, bending and torsional deformations. Position control simulation with this new computer program may be reported in the future.

HYDRODYNAMIC FORCES FOR SHIP THRUST POWER

For the purpose only of determining the ship thruster power, the following three requirements for the maximum physical environmental conditions are considered,

- the ship can be steered along the heading which would require minimum thruster power consumption during track-keeping
- during station-keeping and turning, sufficient thruster power should be available for any chosen heading
- the ship can cruise at 12 knots velocity

Hydrodynamic force and moment components being accounted for in the thrust estimate are:

- mean low frequency wave drift forces (\( F_{wd} \)) on the ship hull
current wave drift forces are computed as a transfer function, induced by the relative current velocity ($V_c(z)$)

current force (dominantly drag force) on the ship hull ($F_{cp}(z)$), induced by the relative current velocity

aerodynamic force or wind force ($F_a$) on the ship hull and superstructure

The relative current velocity is defined as the ship or pipe element velocity ($V_e$) relative to the surface or subsurface current velocity profile. Hydrodynamic forces for the maximum ship thruster power is determined for the maximum operational environmental condition (Table 3), under the assumption that all force components are coplanar;

$$F_{max} = |F_a| + |F_{cs}| + |F_{wd}| + |F_{cp}|$$

As will be shown later, the position control simulation and performance assessment show that the ship thruster power as determined above is adequate to operate the mining ship/pipe system within the operational and environmental requirements.

Pipe Drag. Among the force components for the given operational and environmental (Table 3) requirements, the $F_{cp}$ and $F_{wd}$ are the largest force components and are in the same order of magnitude for the station-keeping mode with no choice of headings. For the given requirements, the $F_{cp}$ remains the same regardless of the ship heading. The $F_{cp}$ values vary along the pipe length as a function of $V_c(z)$ and the vertical variation of the subsurface water properties. The assumed mining velocity range of $0 < V_m < 3.5$ ft/sec can place the pipe drag coefficients ($C_p$) along the pipe near the subcritical to critical Reynolds number (Re) range. In other words, the $C_p$ values can be quite different at an instant between the top- and bottom-end sides of the lift pipe. Furthermore, steep slope and ambiguity of the $C_p$ versus Re curve in this Re range can pose problems for accurately estimating the contribution of total pipe drag at different ship velocities to the ship thrust allocation (see [2] for details) and possibly for the ship thruster control. The latter will be further discussed in conjunction with the control simulation results.

If the top end of the lift pipe is connected to a point far from the ship e.g., the pipe drag vector can require significantly large restoring moment in the ship thrust allocation.

Wave Drift Forces. Although the prediction accuracy may not be sufficiently reliable for practical application, the wave drift forces are assumed to consist of two components; mean low-frequency force component and slowly oscillating component. First, the mean wave drift forces are computed as a transfer function, using the methods in [9] for beam seas and in [10] for head seas. The wave-induced ship motions are computed on the basis of Vugts [11]. Through proper relation between the transfer function and wave energy spectrum, the mean wave drift force spectrum is obtained. This analytically computed spectrum is empirically corrected, mainly shifting the frequency for the maximum energy density to the experimental value from a similar ship hull model test. The statistical values of the mean drift forces are obtained for Sea State 6 ($H_{1/3} = 4$ m or 13 ft). The slowly oscillating components are additionally accounted for later in the thruster analysis.

The largest mean wave drift force occurs for the beam sea condition with $H_{1/3} = 4$ m, for which case the mean wave drift force is larger than the pipe drag. If the ship can have favorable headings during station-keeping, the mean wave drift force can be much smaller than the pipe drag. For deepwater drilling, usually, the pipe drag is small compared to the ship drag, and has been ignored. However, for a very long vertical pipe such as deep ocean mining pipe or drilling riser in the present water depth range, the pipe drag as a fraction of the total ship/pipe system drag is very substantial. It can be larger than the total ship drag e.g., for head seas [2].

Maximum Hydrodynamic Forces. For the purpose of determining the number and size of the ship thrusters, the maximum hydrodynamic forces for the beam sea condition are used. In this case, it is assumed that waves (swell and wind waves), wind and current profile are colinear.

**THRUSTER SYSTEM CONFIGURATION**

Thruster Configuration Selection and Maximum Power. Based on the evaluation of two thruster configurations, the azimuthing thruster system configuration was chosen. The restoring forces to be generated by the thrusters are calculated for two types of thruster system configurations:

1. Azimuthing thrusters, fore and aft,
2. Fixed or (X,Y) thruster system (or a longitudinal thruster and transverse thrusters, fore and aft)

For the purpose of determining the maximum thruster power, it is assumed that (1) the top end of the pipe is located 36.4 m aft of the ship e.g. and (2) groups of thruster units are located at two points along the longitudinal (x-) axis of the ship at $x = 117$ m and $-129$ m, respectively. In the case of azimuthing thrusters, the required restoring force per thruster group is calculated in the direction opposite to the total force on the ship, which include the pipe drag.

These two thruster system configurations are evaluated for operational modes of the station-keeping, track-keeping, and transit cruising for the operating requirements and the maximum environmental conditions as previously described. Upon extensive computations and analysis, the results are summarized in Table 4 as maximum total thrust force. Table 4 shows that the azimuthing thruster configuration requires the least power consumption. However, if the ship is able to maintain the favorable heading within 5 to 10 degrees, performance of the (X,Y) thruster configuration system becomes nearly equal to that of the azimuthing system. The thruster force requirements for the transit cruise can be easily met with the power for the azimuthing system.

Table 4 also shows that the station-keeping mode of operation requires more total thrust force than the track-keeping mode. If the no-choice of heading requirement for the station-keeping mode is removed, then the azimuthing system requires only 1,719 KN total thruster force, and the (X,Y) system requires...
2,390 KN. In this case the track-keeping mode would require more total thruster forces. However, the no-choice of heading requirement has been maintained for the present simulation in order to compensate for the additional thruster force needed for the transshipment operation.

**Thruster Configuration Analysis.** The two thruster groups, which were located at x = 117 m and -129 m for the determination of the maximum thruster power, are replaced by a real azimuthing thruster configuration for the analysis. Total thruster requirements are determined by adding an allowance for the dynamic control of the ship to the steady state thrust requirements, accounting for thruster efficiencies. This allowance consists of allowances for the low frequency variation of the wave drift forces and for the dynamic controlling forces to correct position or track errors.

On the basis of internal company data, the thruster efficiency is realistically estimated, accounting for the following: (1) thruster force-power ratio of 11 to 14 kgf/hp, (2) influence of inflow velocity, which varies as a function of modes of operations, and (3) thruster interactions, including thruster-thruster interaction and thruster-hull interaction. The maximum steady state force required for the maximum operational requirements and environmental condition is 4,604 KN as shown in Table 4. The allowances for the low-frequency variation of wave drift forces and for the dynamic controlling forces of the ship are determined according to the experimental data and experience records, which are available internally. These allowances can slightly differ between experiment and experience. The total allowances used are about 34 percent of the maximum steady state forces for the track-keeping mode and about 60 percent for the station-keeping mode.

During track-keeping operations, the maximum required power using a minimum thruster force-power ratio is 68,891 hp. It is 75,000 hp for the station-keeping mode. When 4,500 hp thruster units are installed, this leads to total 18 thrusters. For the transit cruise mode, only 13 thrusters would be required.

Additionally accounting for the thruster efficiencies as previously discussed, preliminary locations of the thrusters are determined as shown in Fig. 2. Thus, it is tentatively concluded that the present preliminary mining ship/pipeline system can consist of 18 azimuthing thrusters of 4,500 hp (at the propeller) with controllable propellers in asymmetric nozzles, or 13 thrusters of 6,000 hp. Although thrusters of such size can be manufactured at this time, the reliability and the handling problems remained to be proved. It is reminded that if the no-choice of heading requirement is removed for the station-keeping mode, the number of thrusters can be reduced.

**PART II**

**POSITION CONTROL SIMULATION, PERFORMANCE ANALYSIS AND ASSESSMENT**

**SIMULATION OBJECTIVES**

The first part of the paper presented a general introduction to the mining system and operational procedure, a description of the main system components and of the operational requirements, and thruster system configuration analysis.

The second part of the paper concerns the simulation and control performance analysis and assessment. The main simulation objectives are:

1. to establish the feasibility of automatic position control of the ship-pipe-buffer system during station-keeping and mining, while following the miner in such a way that the buffer-to-miner slant range does not exceed the linkage length during all specified operational and environmental conditions
2. to investigate if Active Buffer Control would be necessary to meet the stated requirements.

One of the basic questions to be answered is how detailed and accurate the simulation model should be to obtain a sufficiently high level of confidence and to be able to draw substantial conclusions. In a feasibility study, the model accuracy will inherently be limited. Nevertheless, the accuracy should be sufficient for the present analysis.

**SIMULATION MODEL AND COMPUTER PROGRAM**

All relevant system components are represented by mathematical models as detailed as strictly necessary in view of the simulation objectives.

The block diagram of Figure 3 shows the modeled system components for the present simulation:
- ship and ship thruster system
- lift pipe and buffer
- miner and linkage between miner and buffer
- environment of wind, waves and current
- measurement system
- digital control system.

The mathematical models are set up to simulate the low frequency motions of the ship, the pipe and the buffer due to the environment and due to the thruster action. For the ship, also the high frequency wave induced motions are simulated [11]. The necessary quantitative data, such as hydrodynamic and wind force coefficients and thruster data are calculated or estimated, as described in Part I.

The nonlinear ship equations of motion are set up to allow for zero or low speed maneuvering in any direction. The forces in longitudinal and lateral directions and the moment about the ship's c.g. include the following contributions:
- hydrodynamic forces and moment
- wind or aerodynamic forces and moment
- low frequency wave drift forces and moment
- forces and moment due to the pipe response
- forces and moments developed by the 18 thrusters

The thruster forces and moments are calculated taking into account the influence of the incoming water velocity (speed and direction) on the nominally developed thrust of each individual thruster. The incoming water velocity is defined to be a function of the ship motion relative to the water and of the interference with nearby thrusters. The thruster force is the vector sum of all individual thruster forces. The model is capable of simulating the
failure of any thruster. More detailed discussions and other force components can be found in Part I. The environment is modeled to include the random characteristics of wind and waves. The model of the surface and subsurface current represented a two-dimensional current velocity profile: The current speed is a function of distance from the free surface, while the direction is kept a constant.

The simulation computer program is written in Fortran language and implemented in two EAI Pacer-100 computers for the present simulation. The two computers are used in parallel with the lift pipe simulation program run on one computer and the remaining part on the other computer. Appropriate sampling periods for pipe, ship and control system were chosen. Due to the complexity, the ratio of computation time to real time is almost one.

CONTROL CONCEPT AND SYSTEM DEVELOPMENT

The control concept was defined in view of the requirement that the combined ship-pipe-buffer system must be positioned in such a way that the buffer position be maintained close to the miner, both during station-keeping (miner at rest) and during mining operation, while following the self-propelled miner. The miner is steered from the ship along a predetermined track, unless it must avoid an unexpected obstacle.

To illustrate the types of problem encountered, when controlling the buffer position, Figure 6 shows schematically what would happen when the ship-pipe-buffer starts moving from rest up to a certain steady state velocity: At time \( t_0 \) the ship starts. Due to the characteristics of the pipe, the buffer starts at rest until time \( t_1 \). From then, both ship and buffer accelerate (the buffer lags behind-time \( t_2 \) until the ship reaches the steady state velocity. At some time \( t_3 \), both ship and buffer have reached the steady state velocity, the ship then is far ahead of the buffer.

The example clearly indicates that the behavior of the pipe has a large impact on the control of the buffer. The idea, therefore, arose to distinguish two ways of controlling the buffer position;

1. Passive Buffer Control: the buffer motions are entirely determined by the ship and pipe motions.
2. Active Buffer Control: the buffer motions are partly determined by the ship and pipe motions and partly by thruster units, mounted on the buffer or the bottom end of the pipe. Installation of buffer thruster units can imply power and control cables, potential failures and necessity of maintenance. The buffer should always be positioned close to the miner. As a consequence, the ship should anticipate steady state as well as transient motions of buffer and miner, since the example showed that the motions of the buffer lag behind the ship motions. Especially when the miner track includes turns, the anticipation is important because then the ship must travel a much longer distance, due to the steady state buffer–ship offset.

The transient characteristics of the pipe clearly indicate that control of the ship-pipe-buffer system would require foreknowledge of the miner track pattern, while also at least the pipe behavior under steady state conditions should be known. Foreknowledge of the miner track pattern (i.e. miner position and velocity as a function of time) is feasible since the miner follows predetermined tracks, which should be determined on the basis of detailed terrain surveys. The behavior of the real pipe may deviate slightly from the prediction model, thus affecting the guidance function of the control system.

As a result, the control concept distinguishes a guidance and a control function both split up into two tasks, as shown in Figure 5:

1. The Measurement Data Processor (MDP) filters and smoothes the incoming measurement data. A Kalman-filter forms part of the MDP.
2. The Set point Management (SM)-module performs the essential guidance functions, being the calculation of the set points for ship and buffer (in case of Active Buffer Control) during all applicable modes. The SM-module integrates the foreknowledge of the miner track pattern with the known pipe behavior to arrive at position and velocity set points for the ship. A long term error compensator based on integrated miner-buffer distance corrects the calculated set points for steady state errors. The ship heading set point is the so-called favorable heading, unless the operator selects an off-optimum heading set point. The favorable heading is calculated at specified intervals.

3. The thrust, required to follow the set points, is determined by PID-controllers with gain factors and time constants, which are automatically adapted as function of the ship velocity relative to water. The function of the ship PID-controllers is alleviated by Wind- and Current Feed Forward Compensators. These compensators counteract directly the wind and hydrodynamic forces and moments, exerted on the ship by wind and water. The required buffer thrust—under conditions of Active Buffer Control— is determined by PD-controllers.

4. Last but not the least, the Thrust Allocation Logic (TAL) distributes the control forces and moment among the individual thrusters. The generation of the moment has priority, so that the ship can always assume the favorable heading. This is of particular importance, in case of (temporary) thrust saturation. The TAL automatically adapts its function, in case one or more thrusters are out of operation.

SIMULATION PROGRAM SET-UP

To meet the simulation objectives, the simulation is split up into two parts:

1. Verification of the control concept, improvement of the control system, if necessary, and tuning of the control parameters.
2. Assessment of the performance of the controlled ship-pipe-buffer system for the relevant tasks under the specified operational and environmental conditions.
The relevant tasks are distinguished, being station-keeping, track-keeping including turning, and operation during contingency situations, such as emergency stops.

The basic miner track, used in the simulation, is as presented in Fig. 6, which combines several modes of mining operation. Table 5 specifies the track sections 1-15 and lists the duration. Note that during the sections 6 and 7 the ship moves backwards. During sections 8 through 13, the miner maintains a constant speed \( V_0 = 1.04 \) kts, also during the 90°-turns! Other track patterns include obstacle avoidance patterns and an unexpected sudden miner stop, followed by an emergency stop of the ship.

Most simulation runs have been made with the buffer in the Passive Buffer Control-mode, because that condition would provide the most significant information about the functioning of the control system.

Each run is defined by a number of conditions and parameters, such as:

- miner track pattern and operating speed (between 0-3.5 ft/sec)
- environmental conditions (calm-moderate-design weather)
- buffer control mode (passive or active)
- guidance and control parameters
- special events

RESULTS OF THE SIMULATION

The first series of runs indicated that the control concept was adequate. Nevertheless, a few important modifications were deemed necessary to improve the Set point Management (SM) and Thrust Allocation functions. Having implemented these modifications, the guidance and control parameters are tuned again.

The results are summarized here. The discussion concentrates on track keeping and turning; the station-keeping did not cause any significant problem. The most important variable, being the buffer-to-miner slant range is shown as function of time in Figs. 7 and 8. The corresponding miner tracks are also indicated.

The runs indicate very clearly that the performance deteriorates significantly at the higher mining speed, if turning at the full speed. At the 1.04 kts mining speed, the performance was quite good, apart from the turns. The third turn with a 100-ft turn radius caused the largest temporary increase of the slant range, as shown in both Figs. 7 and 8. Active Buffer Control improves that situation significantly: comparing Run CB with Run CO (Fig. 8), the effect is clearly demonstrated. Maximum buffer thrust is estimated to be 20 tonf.

For two runs (run BS and CB), also the projected tracks of ship, buffer and miner are presented (Figs. 9 and 10). An interesting aspect is that the current causes a considerable offset of the ship track relative to the miner track, especially in case of a cross-current \([1]\). As anticipated, current is apparently an important factor, also because of the effect on the steady state buffer-ships offset: A favorable current direction reduces this offset, while an adverse direction increases the offset significantly. See for example the lower track legs. Due to the offset, the ship must travel a much longer distance than the buffer, particularly during and after the third 90°-turn.

Interestingly, the performance during both moderate and design weather conditions compared favorably with the calm weather performance. The average power consumption was higher. Figure 11 presents power consumption time histories for Run BR, BS and CA and CB. From these time histories, the effect of the mining speed (compare BR with CA) and the effect of the weather (compare BS, CA with CB) can be deduced. It also becomes evident that the power requirements on the average are far below the maximum available power of 61 Mega Watt (about 80 KHP), owing to the favorable heading concept. Only during and after the 90°-turns, full power is demanded during some time.

The same is true for the conditions, during which the ship has to maneuver relatively fast for the cases such as obstacle avoidance maneuvers or emergency stops:

1. Effect of Thruster Failure. The effect of thruster failure on the average is small. Obviously, during full power conditions, failure of any thruster is noticed, although the performance degradation was less than expected.

2. Effect of Differing Pipe Characteristics. The results which have been discussed so far, are obtained assuming that the pipe behavior characteristics are exactly known. This assumption is important, because the SM function is dependent on the reliability of the pipe behavior data. A significant difference between the real pipe response behavior characteristics and those used in the SM-module might therefore very well affect the control system performance. The way to check this was to keep the SM-module unchanged, while the (simulated) pipe response characteristics were altered significantly. One simulation run was sufficient to show that the performance got indeed worse: The slant range (Fig. 12) must be compared with run BR. The deterioration would require long linkage, at least with Passive Buffer Control. Nevertheless, the SM-module needs the steady state pipe behavior data to calculate the set points. It means that more realistic pipe response characteristics should be determined with more accurate methods (e.g. \([1]\) and \([2]\)) and after the full-size pipe is tested at sea and the SM-module updated accordingly, if necessary.

3. Performance During Emergency Stop. An important event is the unexpected, sudden miner stop, caused for example, by a miner propulsion failure and followed by an emergency stop of the ship. Two runs illustrate what would happen, in case of Passive Buffer Control (Fig. 13-a) and in case of Active Buffer Control (Fig. 13-b). Figure 15 shows the distance traveled by the ship, the buffer and the miner since the start of the run. The miner stop took place during the steady part of the run. Once the miner stop was recognized, the ship reversed its direction as fast as possible. Nevertheless the buffer overshot the miner by about 850 ft. (260 m), in case of Passive Buffer Control; Active Buffer Control reduced the overshoot to about 290 ft. (88 m).
CONCLUSIONS AND RECOMMENDATIONS

Within the limited scope of the present study for the preliminary concept, the following conclusions are tentatively drawn:

1. Automatic control of the 300,000 DWT mining ship-buffer system is feasible during station-keeping as well as during mining.

2. The position control performance depends very much on the miner operating speed.

3. Active Buffer Control would improve the performance significantly at the higher mining speed.

4. At the lower mining speed of 1 knot, the performance is quite good, even with Passive Buffer Control. At the maximum mining speed of 2 kts, the overall performance, if turning at the full speed, may require Active Buffer Control, or long buffer linkage.

5. The weather is not of significant influence on the performance for the present simulation.

6. The most critical phases of the normal mining runs are the 90°-turns at full operating speed.

7. Maximum power consumption of the ship thruster system occurs only during and after sharp turns

8. Sufficiently accurate knowledge of the steady state and transient pipe response behavior is necessary, to guarantee a reliable set point calculation of the ship’s control system. This problem has already been considerably overcome by the sophisticated methods in [1] and [2]. Simulation with the latter methods may be reported in the future.

9. For the present sample mining track, it is recommended to adopt a mining procedure with smooth miner track patterns (no sharp turns), with a miner operating speed of 1 knot maximum, to reduce the ship and miner speeds during turns, or to increase the linkage length.

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REFERENCES


TABLE 1

PHYSICAL CHARACTERISTICS OF AN 18,000 - FT LONG PIPE

<table>
<thead>
<tr>
<th>Pipe Section</th>
<th>Length (ft)</th>
<th>Wall Thickness (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>2,000</td>
<td>.635</td>
</tr>
<tr>
<td>Middle</td>
<td>3,000</td>
<td>.500</td>
</tr>
<tr>
<td>Bottom</td>
<td>13,000</td>
<td>.438</td>
</tr>
<tr>
<td>Total</td>
<td>18,000</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 2

THE MINING SHIP CHARACTERISTICS

Length overall (LOA) 293 m (961.3 ft)
Length between perpendiculars (LBP) 288 m (944.9 ft)
Molded beam (B) 68.5 m (224.7 ft)
Molded draft midship 20 m (65.6 ft)
Trim 0 (0)
Displacement 340,888 m³
Ship's weight 349,760 m.T
C.G. forward of midship 1.81 m (5.9 ft)
C.G. below waterline 7.29 m (23.7 ft)
C.B. below waterline 9.55 m (31.3 ft)
TABLE 3
MAXIMUM OPERATING ENVIRONMENTAL CONDITIONS:

Mean Wind Speed, $U_a$ \hspace{1cm} 30 kts
Wind Gust (60 sec. duration) \hspace{1cm} 3σ
Surface Current Speed, $V_c$ \hspace{1cm} 1.6 kts
Subsurface Current Profile \hspace{1cm} [2]
Composite (Swell + Waves) Spectrum, $S(\omega)$ \hspace{1cm} $H_{1/3} = 13$ ft
Max. Ship Speed, $V_s$ \hspace{1cm} 3.5 ft/sec

TABLE 4
MAXIMUM TOTAL THRUSTER FORCES (KN) FOR THE MAXIMUM ENVIRONMENTAL AND OPERATING CONDITIONS

<table>
<thead>
<tr>
<th>Mode of Operation</th>
<th>Max. Total Thruster Force (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(X, Y)$ System</td>
</tr>
<tr>
<td>Station keeping</td>
<td>4,723</td>
</tr>
<tr>
<td>Track keeping</td>
<td>5,810</td>
</tr>
</tbody>
</table>
Table 5
Simulated Miner Track Pattern for \( V_s = 1.04 \text{ kts} \)

<table>
<thead>
<tr>
<th>MINER TRACK SECTIONS</th>
<th>START OF MANEUVER (seconds after start of run)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. station keeping</td>
<td>0</td>
</tr>
<tr>
<td>2. acceleration to mining speed (1.04 kts)</td>
<td>600</td>
</tr>
<tr>
<td>3. stable run</td>
<td>1202</td>
</tr>
<tr>
<td>4. deceleration to slow speed</td>
<td>3002</td>
</tr>
<tr>
<td>5. reversal turn (miner makes 180° turn, ship stops and moves backwards)</td>
<td>3452</td>
</tr>
<tr>
<td>6. acceleration to mining speed (1.04 kts)</td>
<td>3812</td>
</tr>
<tr>
<td>7. stable run</td>
<td>4262</td>
</tr>
<tr>
<td>8. turn 1, 90°, radius ( R_1 = 152 \text{ m} ) (500 ft)</td>
<td>5762</td>
</tr>
<tr>
<td>9. stable run</td>
<td>6204</td>
</tr>
<tr>
<td>10. turn 2, 90°, radius ( R_2 = 91 \text{ m} ) (300 ft)</td>
<td>8604</td>
</tr>
<tr>
<td>11. stable run</td>
<td>8868</td>
</tr>
<tr>
<td>12. turn 3, 90°, radius ( R_3 = 30 \text{ m} ) (100 ft)</td>
<td>11268</td>
</tr>
<tr>
<td>13. stable run</td>
<td>11356</td>
</tr>
<tr>
<td>14. stopping</td>
<td>13756</td>
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<tr>
<td>15. station keeping</td>
<td>14206</td>
</tr>
<tr>
<td>end of run</td>
<td>15000</td>
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</tbody>
</table>
Fig. 1 - Configuration of a Preliminary Mining System Concept.

Fig. 2 - Preliminary Azimuthing Thruster Configuration.
Fig. 3 - Block Diagram of the Present Simulation Model.

Fig. 4 - Ship-Pipe-Buffer Motion from Start to Steady State Motion.
Fig. 5 - General Block Diagram of Control System.

Fig. 6 - Basic Miner Track Pattern for 1.04 Kts Mining Speed.
Fig. 7 - Buffer-to-Miner Slant Range (Run BR and BS).
Fig. 8 - Buffer-to-Miner Slant Range (Run CB and CO).
Fig. 9 - Track of Ship, Buffer and Miner (Run BS).

Fig. 10 - Track of Ship, Buffer and Miner (Run CB).
Fig. 11 - Power Consumption of Ship Thruster System (Run BR, BS, CA and CB).
RUN CM
Passive Buffer Control
Miner speed - 1.04 kts
Miner track - basic track
Environment - calm weather
Achenbach pipe drag coefficient

Fig. 12 - Buffer-to-Miner Slant Range (Run CM).
Fig. 13 - Emergency Stop of Ship after Miner Stop (Run BY and CD).