# Vessel Positioning Project

# Proyecto de Posicionamiento de Buques

## Texas A & M University

**30 de junio de 1999**

**Contrato No. PAP-3926**

**Introducción y Conclusión**
**(No existe Resumen Ejecutivo)**

# Panama Canal Commission
# Final Report

## Vessel Positioning Project

Contract No. PAP-3926-BGP

http://pcc-tamu.tamu.edu

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**PCC Final Project Report**

# INTRODUCTION

## Project Description and Tasks

This final report presents the results of Contract No. PAP-3926-BGP entitled "Project to Identify and Evaluate Alternative Concepts for Vessel Positioning at the Locks." This study was conducted for the Panama Canal Commission's Canal Capacity Projects Office by the Texas Engineering Experiment Station, which is the Engineering Research Division of the Texas A&M University System. The period of this conceptual design study was January 1, 1999 to June 30, 1999.

The objective of the project is to brainstorm a variety of possible alternative techniques for dynamic centering, towing and stopping vessels that transit the system of locks at the Panama Canal. From these possible approaches six of the most promising ideas are to be chosen and analyzed to the extent possible in the time period. The analyses are to include operational descriptions, preliminary designs and cost considerations. The alternative systems can either be applicable to the current system of locks or to possible larger additional new locks that are under consideration by the Panama Canal Commission. Almost no constraints are stipulated except only minimum modifications to vessels are allowable; for example some modifications to the vessels' existing attachment points are feasible, but hull modifications or attachments are not feasible. Also economic considerations are to be secondary to effectiveness, feasibility, practicality, and reliability aspects of the concepts.

This interdisciplinary study is to be conducted by undergraduate and graduate students and faculty from a variety of engineering disciplines at Texas A&M University in close cooperation with Panama Canal Commission Engineers and Pilots. This approach was stipulated, as opposed to the traditional research project, because it was felt that a group of students often can be very creative in envisioning possible solutions that might not be identified in another setting.

## Current Positioning System and Motivations for the Study

The current system uses special purpose locomotives operating on tracks on the lock walls to tow, stop, center and hold vessels throughout the locks. These functions are accomplished through the use of winches and cables attached to the mooring points on the vessels, and traction is achieved via electric power driving a pinion gear engaged with a rack that runs the length of the locks. An onboard pilot achieves vessel control through visual sensing of vessel lateral and longitudinal position and velocity. Precise control is critical since there is only two feet of clearance between the lock walls and the hulls of the larger vessels, and wall contact is undesirable. Effective dynamic control is required due to inevitable external disturbances such as water turbulence and wind.

This system has worked fairly well for many years and is generally reliable and safe. However the large shear forces inherent in the system have resulted in heavy wear on the rack and pinion, winch systems and locomotives that require costly and frequent maintenance and replacements. This has accelerated as traffic and the size and weight of vessels have increased, and this trend is expected to continue. Thus the main motivation for the identification of alternative positioning systems is to reduce the wear, maintenance and manpower requirements and associated costs while increasing throughput in a safe and reliable fashion.

## Excessive Wear

The first observation that we have made in the study is that the wear on the current system is excessive for several reasons. A primary reason is due to the positioning system configuration. If there are locomotives with flexible attachment cables only on one lock wall for towing and stopping, then because the cable is never parallel to the vessel an undesirable lateral force is created that tends to pull the vessel into the lock wall. Consequently additional locomotives must be used on the opposite walls whose functions are not only to tow and stop, but also to counteract the opposite lateral forces so centering can be achieved. Thus "wasted forces" and associated excessive wear and necessary over design of system components are inherent. On the other hand, this lateral stretching action provides a built-in impediment to external disturbance forces to some degree, and thus enhances lateral control. In an ideal *minimum wear* configuration that only applies forces that are necessary and no more, the longitudinal and lateral forces should be uncoupled. That is, longitudinal towing and stopping forces should only be directed from the centerline of the locks to the centerline of the vessel. On the other hand, lateral-positioning forces should only be directed perpendicular to the vessel and never applied unless needed due to external disturbances arising from water turbulence, wind etc. An alternate system that achieves or reduces this longitudinal and lateral applied force coupling would be desirable from the viewpoint of minimizing wear, but lateral position control may or may not require more complexity than in the current system. This would depend entirely on the nature of the positioning system used.

Another observation related to excessive wear in the current system is that a rack and pinion cannot effectively accommodate large shear loading. Shear loading is inherent in the current configuration and cannot be avoided except through an alternate design.

Also, it appears that unnecessary over control is occurring in the current process, resulting in more shear loading than is necessary to effectively laterally position the vessels. The over control that is occurring is due to the uncoordinated action of the various locomotive operators. Maximum winch forces are being applied at times when less force would be adequate. Another factor affecting the over control is the time delay that occurs between the time a vessel begins to lose its centerline position (due to disturbances) and the time this error in position is noted by the pilot, corrective action is determined, communicated and actuated by the locomotive operators.

The time delay or lag between an error in vessel position and applied control action is particularly detrimental and often occurs to varying degrees in any system that relies on human operators in a feedback control loop. This is due to the fact that humans lose attention easily, grow weary of repeated tasks, and the fact that visual sensing is often imprecise, particularly in poor visibility conditions.

To demonstrate the effect of excessive time delay and other phenomena in the system we have developed a simulation (see Appendix) using MATLAB SIMULINK of the lateral and longitudinal motion of any vessel in water subject to any type of forces, disturbances or initial conditions. Using SIMULINK the vessel can also be coupled to a "perfect" lateral positioning control system. The control system employed receives sensed lateral position error information in real time and automatically applies appropriate lateral corrective forces using an industry standard Proportional-Integral-Derivative (PID) controller.

As an illustration of the detrimental effect of time delay in control actuation, consider a 65,000 ton vessel, 600 feet long with a 12 foot draft, an aspect ratio of 12.5 and a freeboard height of 24 feet. The PID control system can supply lateral forces on the vessel up to a maximum of 140,000 pounds on either side. Suppose the vessel is for some reason positioned laterally one foot from its desired position and is moving at that instant laterally at a rate of 0.1 feet per second further away from the desired position. This deviation is sensed at that time and appropriate control action is automatically applied without delay to restore the vessel to the desired position as indicated in Figures I.1 and I.2.

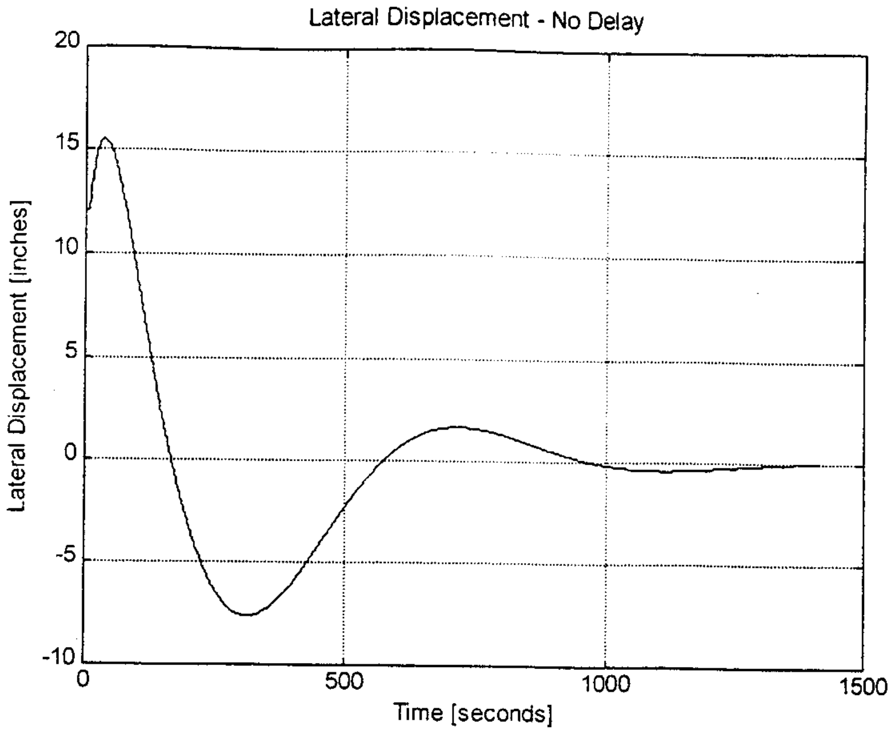


*Figure I.1*

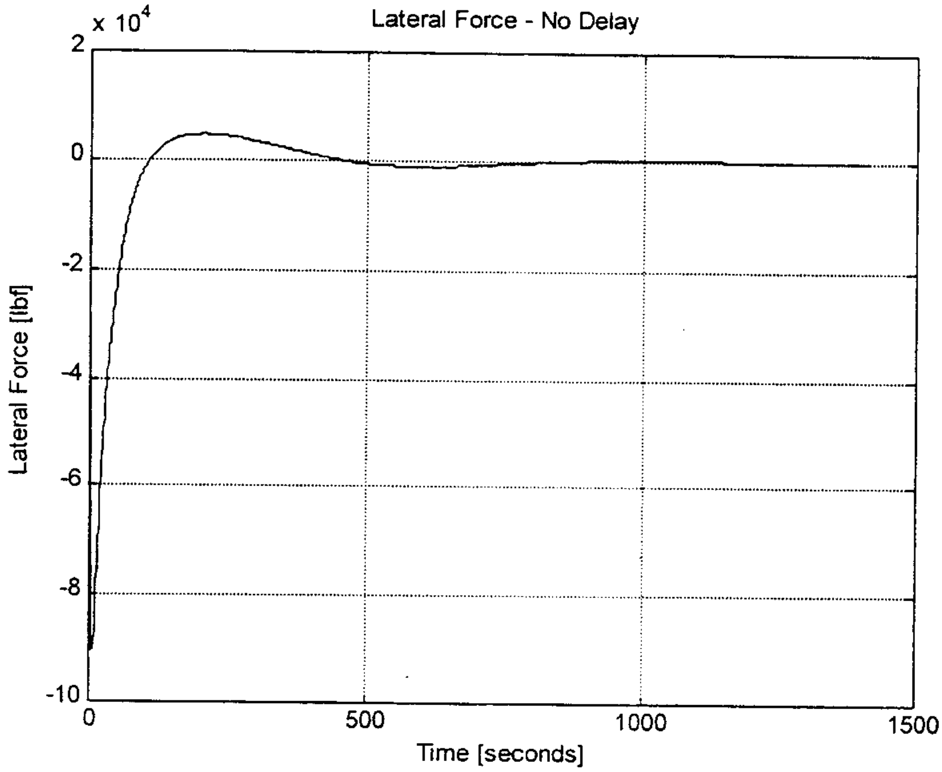


*Figure I.2*

Notice that the control system is very stable, it easily and smoothly accomplishes the centering task, and no control saturation occurs.

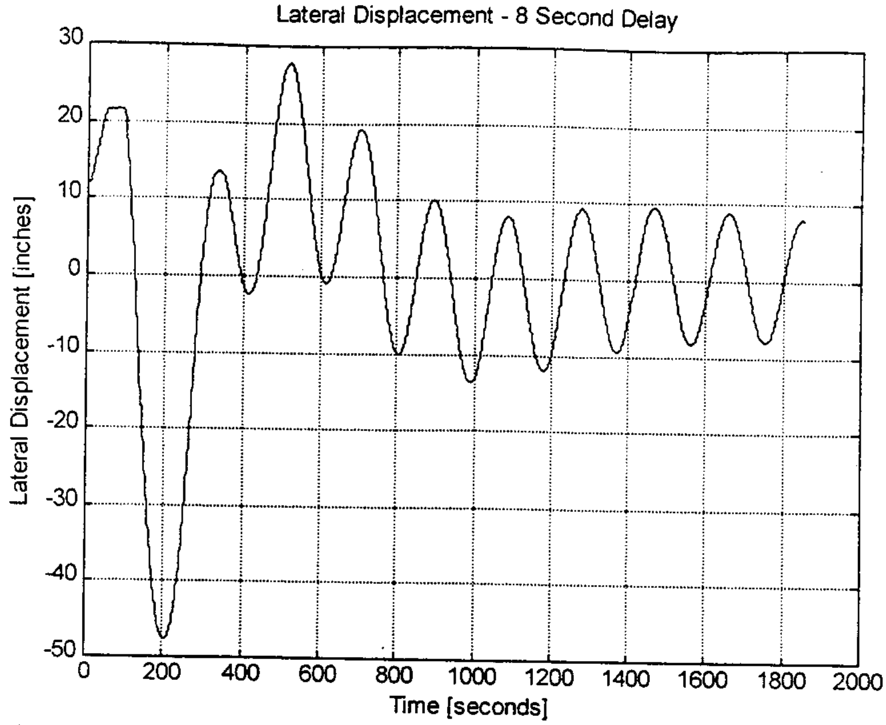


*Figure I.3*

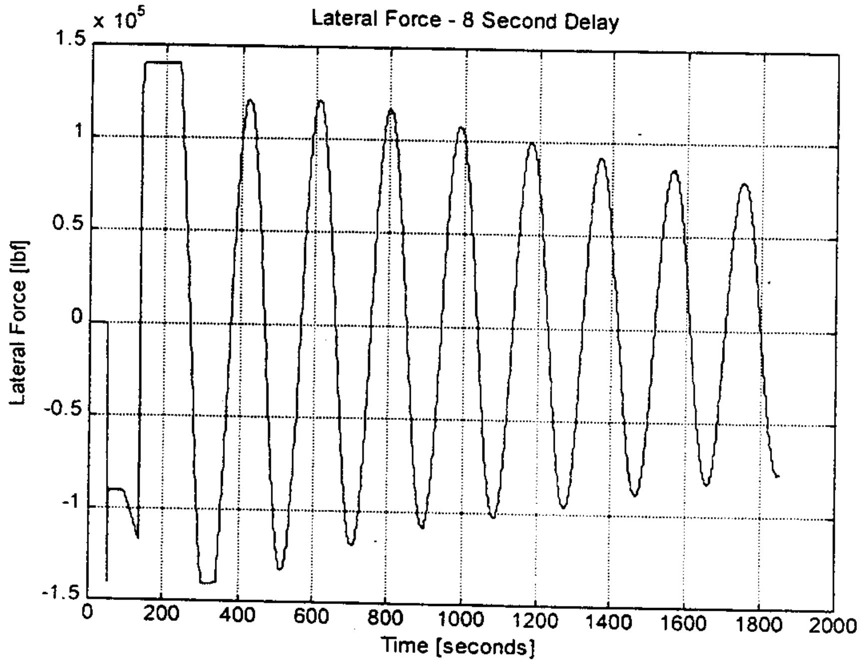


*Figure I.4*

Now consider the same vessel under the exact same control system and with the same initial perturbation, but with an 8-second delay before any control action is applied (Figures I.3 and I.4).

Because of the time delay the response is highly oscillatory and large control forces are applied over a long time period causing excessive wear on the system that is unnecessary. An eight-second delay is probably extreme, but serves to illustrate what can happen in a worst case scenario. In addition, when there is time delay even more control force occurs when the control system is not perfect, for example using "bang-bang" control whereby only maximum forces are applied, similar to the current positioning system.

The point of this simulation and discussion about control actuation time delay is to point out that in order to minimize system wear it is very important to accurately and rapidly detect vessel deviations from the desired lateral position and apply corrective restoring forces as soon as possible. This has been one of the guiding principles in the identification of alternate positioning systems in this study.

## Class and Process

To accomplish the study a new course entitled "Creative Solutions to Engineering

Systems Problems" was created, and 12 graduate and undergraduate students were selected from mechanical, electrical, industrial and ocean engineering. The course began with discussions of the brainstorming and creative processes, the "systems engineering" process, on working in groups effectively, and of course on the nature of the problem. An essential aspect was a class trip to the Panama Canal early in the semester to gain first hand knowledge of the operation and issues. Equally important was a visit to Texas A&M University later in the semester by Mr. Boris Moreno Vasquez and Mr. Juan Wong H. from the Canal Capacity Office and Captain Raul Brostella for further understanding and guidance.

Approximately two thirds of the semester was spent in developing a function structure, brainstorming a multitude of possible approaches, and selection of six of the most promising approaches. The remainder of the semester was dedicated to further development and design of these selections. An important tool in the whole process was a dynamic Web Page (http://pcc-tamu.edu) that served as a central location for information and activity for the class as well as a vehicle for featuring the project.

## Function Structure

The problem is very challenging due to the fact that there are a multitude of functions that must be effectively accomplished. First, a critical task is to initiate control at the lock entrance. This is a difficult task because of the severe currents and tides that are often present, and the necessity of connecting cables to the vessels in the current process. Next the system must provide effective centering throughout the lockage, towing, stopping and holding at the lock gates, and accommodation of the inherent level changes. The system must be able to accommodate a large variety of vessels and operate in rain, fog and poor visibility. A critical element is failsafe operation, particularly with respect to stopping at the gates in the event of failure of any part of the system. The design should provide maximum throughput and exhibit minimum wear, maintenance, manpower and energy requirements. In addition a desirable feature is a system that will ameliorate the so called "piston effect." Finally the importance of capital costs is evident.

In the initial brainstorming process for concepts it is important to identify only the basic required system functions and associated parameters without influence from the additional desirable features. For example, if cost is allowed to be an initial important factor, it is very likely that some idea that might possibly evolve into a practical solution would never surface or receive adequate consideration. The Project Objective Statement and Function Structure that was used to guide the initial brainstorming process follows in Figure I.5.

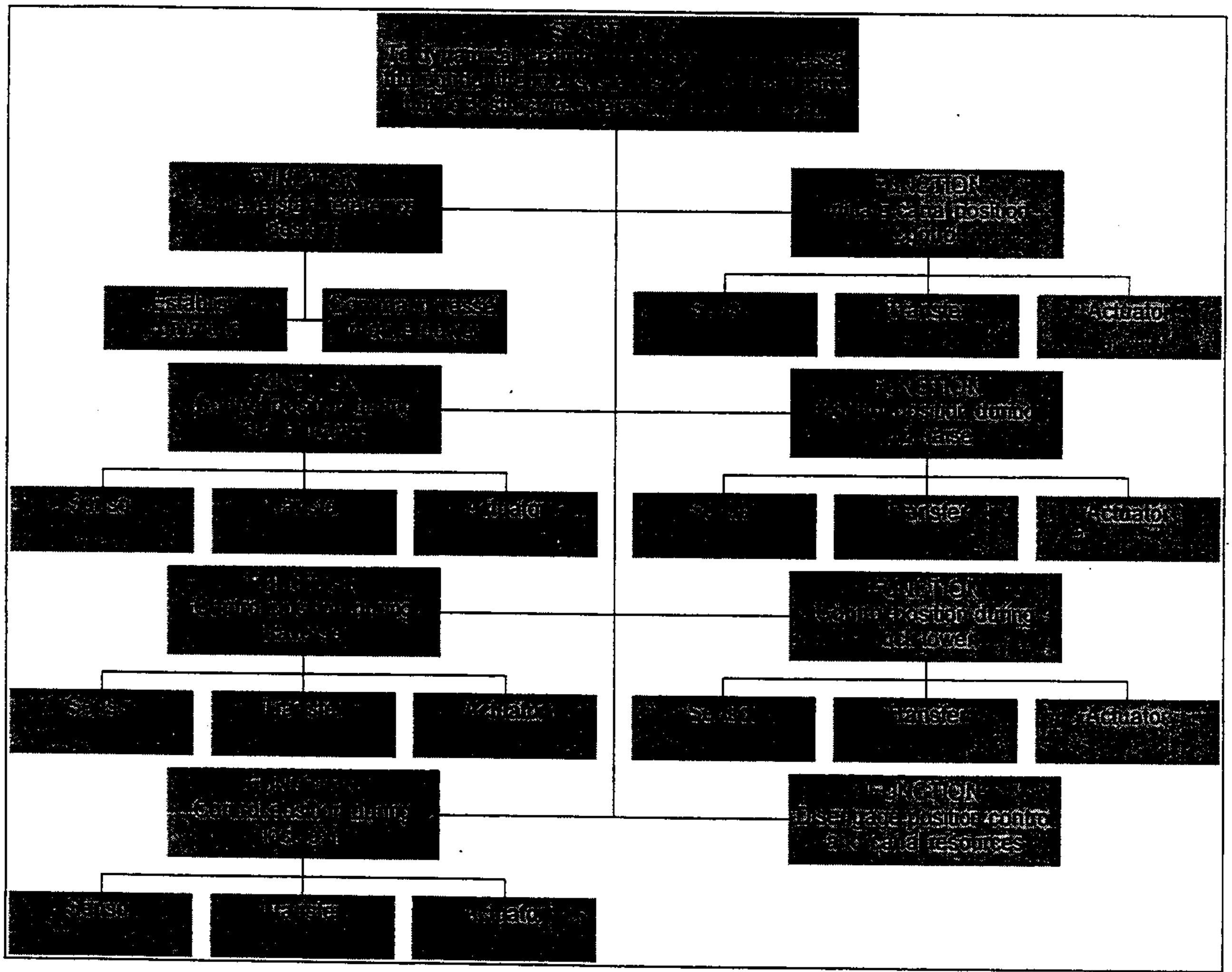

***Figure I.5: Function Structure.***

## Brainstorming and Evolution of Ideas

Following the identification of the problem, the brainstorming process was carried out. Starting with a list of basic natural and technological phenomena capable of providing and imposing forces on a vessel (see Appendix for the list), several conceptual ideas were proposed. The research group was divided into small teams of four members each to do a preliminary study on the feasibility of the ideas. All these ideas were documented (see Appendix) and discussed with the representatives of the Panama Canal Commission. Some of the initial ideas were farfetched, but such thinking was encouraged to engender creativity. The research team then developed a matrix consisting of the most important factors. The matrix was then used, along with feedback from the representatives from the Commission, to select the ideas that the research group felt were worth exploring in more detail (refer to the Appendix for the complete matrix). For every concept that was determined improbable, the team took on the challenge of "how to make the idea work." It should be noted that while reviewing the ideas, Dr. Len-Rios' idea for a magnetic self-centering mechanism was reviewed (see Appendix).

As a result of this process, the following ideas were selected:

***Integrated Robot Winch*** – This is similar to an automated version of the current system but does not use locomotives.

***Rack and Pinion*** - A pinion gear is attached to the ship and a rack along the lock wall.

Two Degree of Freedom Winches - Uses a winch on a vertical structure to provide the longitudinal and lateral forces while optimizing cable angles.

***High Tension Tight Rope*** - Uses a cable stretched across the lock with a winch attached to the ship to provide lateral forces.

***Spring System with Natural Equilibrium*** - A truss system that uses springs to passively provide centering forces on the ship.

***Lateral Forces Using Counter Weights*** - Cables attached to the vessel are connected to a counter weight mechanism to passively provide centering forces.

***Hydraulic Actuated Side Cars*** - Provide longitudinal and lateral forces using hydraulic pistons attached to a cart that moves along the side walls.

***Truss*** - Use a telescoping truss to obtain a rigid push pull connection. This connection allows lateral, longitudinal and angular correcting forces.

***Floating Lock*** - Use a floating structure to provide a consistent interface between the stationary lock structures and varying ship geometry.

*Synchrolift* – Use a conformable cradle to control the ship motion by imparting forces directly on the hull.

***Magnetic Systems*** - Use magnetic forces to control the position of the ship inside the lock. This is the combination of many magnetic conceptual ideas.

***Bumper Systems*** – Use a bumper system to protect the ship from damage caused by lock wall interactions. This is a combination of the many bumper conceptual designs.

***Traveling Bit*** – Attach Cables of fixed length to the vessel and to carts that are propelled by a mechanical drive system mounted on the lock wall.

***Floating Approach Wall*** - Allow any position control system to initiate control before the ship enters into proximity of the non-compliant concrete lock structure by using two floating structure.

***Viscous Cells*** – Hydraulic bumpers along the lock walls provide passive cushions; pulling and stopping are achieved using fixed winches at the gates with long cables.

The research team was then sub-divided into three new groups of 4 people. Each of these four groups then selected four ideas to explore in more detail. The reason for the re-shuffling of the groups was to ensure the best-suited mix of backgrounds to explore the specific ideas the group was assigned. As the groups explored the feasibility of each one of these ideas, some of them were dropped or combined with other concepts to be able accomplish the different tasks required by the traverse process. From the original 12 selected ideas, the list of ideas that were discarded by the research team along with reasons for dismissal follows.

| **Conceptual Idea** | **Reason for Dismissal** |
|---|---|
| Rack and Pinion | Several shortcomings due to having to mount a large device on hull of the vessel. |
| Two Degree of Freedom Winch | Including a vertical degree of freedom below the lock wall would reduce the maximum size of ships that could traverse the lock. The benefits provided by this design could not justify this "waste" of space |
| High Tension Tight Rope | Many of the features of this design were used to make the Traveling Bit concept feasible. |

| | |
|---|---|
| Spring System with Natural Equilibrium | This concept is very similar to the Truss idea. They have so many features in common that the spring system could be implemented in the Truss design by replacing the hydraulic cylinders with springs. |
| Hydraulic Actuated Sidecars | This idea was found to be very similar to the truss idea. Many of it unique features were incorporated into the Truss design. Therefore, further development was not pursued. |
| Magnetic Ideas | This concept's ability to impart a physical force is inversely proportional to the square of the separation distance from the hull of the vessel to the magnet. This was a fundamental physical handicap for this idea. Additionally, any magnetic idea would not be able to control the traverse of any vessels with hulls non-ferrous. |
| Bumper Systems | Capital intensive system with limited benefits. Though these systems minimize the potential for damage, they must be supplemented by other systems (e.g. cable/locomotives) |
| The Synchrolift | The inherent complexity of the linkages associated with conforming to any arbitrary hull geometry and the number of parts that would need to be underwater made this concept unattractive. |

***Figure I.6: Concepts discarded by the design teams***

After the different design groups decided which ideas they wanted to pursue, the final design phase started. Focus was set on exploring the following six ideas:

Integrated Robot Winch

Traveling Bit

Lateral Forces Using Counter Weights

Truss

Viscous Cells

Floating Lock

## Designs

The major portion of this report consists of further development of each of the six ideas. Each idea is summarized and represented graphically. Operational descriptions of the concepts which include pilot interface, human elements. lock entrance aspects, centering capabilities, accommodation of elevation changes, towing and stopping are included. System requirements, for example power, sizes, weights, configurations, etc. are presented resulting from design calculations that appear in the Appendix. The main assumption used in the development of these specifications is that the system must be able to apply a lateral force of 140,000 lb. to each side of a vessel and a longitudinal towing/stopping force of 200,000 lbf. Description of maintenance, system reliability and required infrastructure and vessel modifications are presented, and applicability to the existing locks versus potential new locks is addressed. Finally the concept is compared to the "datum" locomotive system currently in use.

## Additional Concepts

In the brainstorming process and in the process of understanding the operation of the locks and the positioning system, two additional ideas not specifically related to the project scope were generated that could potentially enhance lock operations. These include a modification of the gate sill configurations to reduce the severe turbulence that is present in the locks, and an innovative water conservation concept that resulted from discussions regarding the concern over the water supply.

Finally, a system that involves a pivoting entrance and exit wall to enhance control initiation, and a description of the simulation used to test and evaluate several concepts are included in the Appendix.

# CONCLUSIONS

This has been an ambitious challenging project that has been very beneficial to us in the engineering education process. It is fairly unusual for a class to have the opportunity to work as a group on a real multifaceted interdisciplinary problem that involves numerous objectives, creativity, brainstorming, design and tradeoffs, all in an international setting. The fact that the Panama Canal is one of mankind's engineering marvels that exemplifies creative design is particularly motivational. From our perspective it has been a tremendous learning experience and we are very appreciative of the opportunity.

We hope that we have been able to contribute some useful new concepts that may not have been previously considered, not only for the vessel positioning process, but also through the additional ideas that arose regarding turbulence and water conservation. Also we hope that the understanding and expression of the problems from our viewpoints have been beneficial to Panama Canal Engineers as they continually search for ways to improve the Canal operations. It is important to point out that our study has only been at the conceptual level, and that numerous issues and open questions exist before any of the concepts could ever be practical. In addition we are reluctant to prioritize the six new positioning systems that we have presented because we are not aware of all the issues that might strongly influence choices. Perhaps a hybrid version of the concepts could be the best approach.

We offer the following general conclusions.

A positioning system that uncouples longitudinal and lateral forces as much as possible is desirable from the viewpoint of minimizing wear, maintenance and component load capacities. Excessive wear and unnecessarily large forces and associated over design of components is present in the current locomotive system because of the strong coupling of forces that exists.

Automation of a positioning system requires sensing, signal processing and computing systems. These components are much more reliable presently than in the past as evidenced by their critical and extensive use in harsh environments, for example down hole drilling where there is extreme temperature and pressure, and in the outer space radiation environment. It is felt that the benefits of automation far outweigh the objections relating to complexity and potential unreliability, particularly if redundancy is used.

We feel that active positioning systems that rely on distributed hull forces, for example electromagnetic forces and water flow forces, to achieve centering are much less viable than positioning systems that rely on vessel attachments and point forces applied to bits.

All of our six ideas rely on attachments and point forces except the viscous cell idea, which is a passive, (no external power required) bumper system with point forces for longitudinal control. The attractive feature of distributed force systems is that no attachments are required, but this gain is substantially offset with problems associated with possible detrimental hull interactions, difficulty of precise control, nonlinear scaling issues, difficulty of towing and stopping, excessive power and complicated infrastructure requirements.

The rack and pinion system in use is not designed to easily withstand the shear loading that is present.

Time delay in control actuation is very detrimental to effective control and wear; every effort should be made to minimize it.

In the current system there is no feedback to Pilots regarding the amount of longitudinal and lateral force each locomotive is applying at any instant. This information could be invaluable to the current positioning operation in terms of reducing wear and more effective centering.

Finally there are a number of important tasks that remain to be undertaken. An optimal design will require a much better knowledge of the magnitudes of the disturbance and hydrodynamic forces on various classes of vessels in the restricted locks, the required longitudinal towing and stopping forces, and the lateral positioning forces that are required for a variety of vessel classes. Once a design concept is chosen for further development, this information coupled with simulation and scale models could be invaluable in design optimization. In addition there are many open issues in the design of any automated aspect of the system that requires sensing, information processing and feedback controls.

We are very interested in the next stages of the research and design processes associated with this project and would like to undertake the responsibility. There is very broad capability along these lines at Texas A&M University, and we are certain that we could develop this project to fruition.