Sampled data adaptive digital computer control of surface ship maneuvers.

Uhrin, John Joseph
Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/17932
SAMPLED DATA ADAPTIVE DIGITAL COMPUTER CONTROL OF SURFACE SHIP MANEUVERS

John Joseph Uhrin
NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

SAMPLED DATA ADAPTIVE DIGITAL COMPUTER CONTROL OF SURFACE SHIP MANEUVERS

by

John Joseph Uhrin III

June 1976

Thesis Advisor: George J. Thaler

Approved for public release; distribution unlimited.
**REPORT DOCUMENTATION PAGE**

1. **REPORT NUMBER**

2. **GOVT ACCESSION NO.**

3. **RECIPIENT'S CATALOG NUMBER**

4. **TITLE (and Subtitle)**
   Sampled Data Adaptive Digital Computer Control of Surface Ship Maneuvers

5. **TYPE OF REPORT & PERIOD COVERED**
   Engineer's Thesis; June 1976

6. **PERFORMING ORG. REPORT NUMBER**

7. **AUTHOR(s)**
   John Joseph Uhrin III

8. **CONTRACT OR GRANT NUMBER(s)**

9. **PERFORMING ORGANIZATION NAME AND ADDRESS**
   Naval Postgraduate School
   Monterey, California 93940

10. **PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS**

11. **CONTROLLING OFFICE NAME AND ADDRESS**
    Naval Postgraduate School
    Monterey, California 93940

12. **REPORT DATE**
    June 1976

13. **NUMBER OF PAGES**
    371

14. **MONITORING AGENCY NAME & ADDRESS (IF different from Controlling Office)**
    Naval Postgraduate School
    Monterey, California 93940

15. **SECURITY CLASS. (of this report)**
    Unclassified

16. **DISTRIBUTION STATEMENT (of this Report)**
    Approved for public release; distribution unlimited.

17. **DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)**

18. **SUPPLEMENTARY NOTES**

19. **KEY WORDS (Continue on reverse side if necessary and identify by block number)**
    Underway Replenishment, Ship Dynamics, Hydrodynamic Interaction, Destroyer Maneuvering, Simulation, Ship Propulsion, Hydrodynamics, Sea State, Low Order Models, Ship Speed Control, Optimal Control, Ship System Modeling, Replenishment At Sea, Nonlinear Control,

20. **ABSTRACT (Continue on reverse side if necessary and identify by block number)**
    The replenishment at sea (RAS) maneuver is studied in detail for heading and speed control. Design of purposefully nonlinear control laws is accomplished for the Mariner hull using the linearized equations of motion in three degrees of freedom. Extensive use of low order modeling and optimal control theory was made. Procedure steps are presented in detail to facilitate redesign for other ship types. The results are verified using...
20.
DSL simulation for a number of possible RAS scenarios. The control systems are also tested in a sea state to insure proper operation in the presence of external perturbations.

19.
Automatic Control, Control System Design, Adaptive Control, Automated Ship Control, Digital Computer Control
Sampled Data Adaptive Digital Computer Control of Surface Ship Maneuvers

by

John Joseph Uhrin III
Lieutenant, United States Navy
B.E.E., Villanova University, 1967
M.S., Naval Postgraduate School, 1975

Submitted in partial fulfillment of the requirements for the degree of

ELECTRICAL ENGINEER

from the

NAVAL POSTGRADUATE SCHOOL
June 1976
ABSTRACT

The replenishment at sea (RAS) maneuver is studied in detail for heading and speed control. Design of purposefully nonlinear control laws is accomplished for the Mariner hull using the linearized equations of motion in three degrees of freedom. Extensive use of low order modeling and optimal control theory was made. Procedure steps are presented in detail to facilitate redesign for other ship types. The results are verified using DSL simulation for a number of possible RAS scenarios. The control systems are also tested in a sea state to insure proper operation in the presence of external perturbations.
TABLE OF CONTENTS

FOEM DD 1473 ................................................................. 1
APPROVAL FORM ............................................................. 3
ABSTRACT ................................................................. 4
TABLE OF CONTENTS ......................................................... 5
LIST OF TABLES .......................................................... 7
LIST OF FIGURES ........................................................ 8
TABLE OF TERMS AND ABBREVIATIONS .................................. 14
ACKNOWLEDGEMENTS ...................................................... 16
I. INTRODUCTION .......................................................... 17
II. MCRELING ............................................................... 19
   A. MAFINER DYNAMICS ................................................ 19
   B. RULER RESPONSE .................................................. 32
   C. ENGINE RESPONSE ................................................ 38
   D. EXTERNAL FORCES ................................................. 43
      1. Two Ships in Proximity ....................................... 43
      2. Waves ............................................................ 48
III. REELENISHMENT AT SEA ................................................. 63
   A. HEADING CCNTROL ................................................ 63
      1. Control Choice .................................................. 63
      2. Control Method ................................................ 64
      3. Optimization ................................................... 74
         a. Technique ...................................................... 74
         b. Cost Function ................................................. 76
         c. Results ........................................................ 77
         d. Control Testing .............................................. 85
         e. Second Optimization ....................................... 89
         f. Continued Control Testing ................................ 97
         g. Varying Initial Conditions ................................ 112
         h. Performance in Sea State .................................. 138
   B. VEICCITY CONTROL ................................................ 156
      1. Type of Control ................................................. 157
      2. Optimization ................................................... 159
# TABLE OF CONTENTS (cont.)

3. Control Testing ........................................ 163
4. Longitudinal Position Offset ....................... 173
5. Wave Effects on Velocity Control .................. 194

IV. CONCLUSIONS AND RECOMMENDATIONS .................. 199
   A. CONCLUSIONS ........................................ 199
   E. RECOMMENDATIONS .................................... 201

APPENDIX A .................................................. 203
APPENDIX E .................................................. 289
APPENDIX C .................................................. 298
COMPUTER PROGRAM #1 ....................................... 320
COMPUTER PROGRAM #2 ....................................... 324
COMPUTER PROGRAM #3 ....................................... 327
COMPUTER PROGRAM #4 ....................................... 329
COMPUTER PROGRAM #5 ....................................... 332
COMPUTER PROGRAM #6 ....................................... 338
COMPUTER PROGRAM #7 ....................................... 344
COMPUTER PROGRAM #8 ....................................... 350
COMPUTER PROGRAM #9 ....................................... 356
COMPUTER PROGRAM #10 ..................................... 362
BIBLIOGRAPHY ................................................ 368
INITIAL DISTRIBUTION ...................................... 370
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>II-1</td>
<td>Symbols and Nomenclature</td>
<td>25</td>
</tr>
<tr>
<td>II-2</td>
<td>Characteristics of Mariner-type Ship</td>
<td>27</td>
</tr>
<tr>
<td>II-3</td>
<td>Non-dimensional Hydrodynamic Coefficients</td>
<td>28</td>
</tr>
<tr>
<td>II-4</td>
<td>Rudder Command and Response</td>
<td>35</td>
</tr>
<tr>
<td>II-5</td>
<td>Wave Simulation Listing</td>
<td>56</td>
</tr>
<tr>
<td>III-1</td>
<td>Approach Phase Optimization Results</td>
<td>78</td>
</tr>
<tr>
<td>III-2</td>
<td>Turn Phase Optimization Results</td>
<td>90</td>
</tr>
<tr>
<td>III-3</td>
<td>Initial Condition Simulation</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>Crss Reference</td>
<td></td>
</tr>
<tr>
<td>III-4</td>
<td>Optimization Results</td>
<td>161</td>
</tr>
<tr>
<td>III-5</td>
<td>Polynomial Curve Fit Results</td>
<td>164</td>
</tr>
<tr>
<td>III-6</td>
<td>Position Offset Testing</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td>Crss Reference</td>
<td></td>
</tr>
<tr>
<td>C-1</td>
<td>Interactive Curve Fit Polynomial Coefficients</td>
<td>299</td>
</tr>
<tr>
<td>C-2</td>
<td>Interactive Curve Fit Error Analysis</td>
<td>303</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>II-1</td>
<td>Direction and Sense of Hydrodynamic Terms</td>
<td>21</td>
</tr>
<tr>
<td>II-2</td>
<td>Rudder Step and Ramp Model Geographic Comparison</td>
<td>30</td>
</tr>
<tr>
<td>II-3</td>
<td>Rudder Step and Ramp Model Yaw Difference vs. Time</td>
<td>31</td>
</tr>
<tr>
<td>II-4</td>
<td>Rudder Block Diagram</td>
<td>33</td>
</tr>
<tr>
<td>II-5</td>
<td>Rudder Responses</td>
<td>36</td>
</tr>
<tr>
<td>II-6</td>
<td>Rudder Responses</td>
<td>37</td>
</tr>
<tr>
<td>II-7</td>
<td>Gas Turbine Propulsion Plant Block Diagram</td>
<td>39</td>
</tr>
<tr>
<td>II-8</td>
<td>Propulsion Plant High Order Model Step Response</td>
<td>40</td>
</tr>
<tr>
<td>II-9</td>
<td>Propulsion Plant Low Order Model Block Diagram</td>
<td>38</td>
</tr>
<tr>
<td>II-10</td>
<td>Step Response Comparison of Low and High Order Propulsion Plant Models</td>
<td>42</td>
</tr>
<tr>
<td>II-11</td>
<td>Family of Interactive Y Force Curves</td>
<td>45</td>
</tr>
<tr>
<td>II-12</td>
<td>Family of Interactive N Moment Curves</td>
<td>46</td>
</tr>
<tr>
<td>II-13</td>
<td>Interactive Forces Effect on the Geographic Plot</td>
<td>52</td>
</tr>
<tr>
<td>II-14</td>
<td>Lateral (Y) Forces</td>
<td>53</td>
</tr>
<tr>
<td>II-15</td>
<td>Rotational (N) Moments</td>
<td>54</td>
</tr>
<tr>
<td>II-16</td>
<td>Interactive Forces Effect on Yaw of the Control Ship</td>
<td>55</td>
</tr>
<tr>
<td>II-17</td>
<td>Wave Simulation Run #1</td>
<td>57</td>
</tr>
<tr>
<td>II-18</td>
<td>Wave Simulation Run #2</td>
<td>58</td>
</tr>
<tr>
<td>II-19</td>
<td>Wave Simulation Run #3</td>
<td>59</td>
</tr>
<tr>
<td>II-20</td>
<td>Wave Simulation Run #4</td>
<td>60</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>II-21</td>
<td>Wave Simulation Run #5</td>
<td>61</td>
</tr>
<tr>
<td>II-22</td>
<td>Wave Simulation Run #6</td>
<td>62</td>
</tr>
<tr>
<td>III-1</td>
<td>Measurement Technique</td>
<td>65</td>
</tr>
<tr>
<td>III-2</td>
<td>Alternate Method of Measurement</td>
<td>67</td>
</tr>
<tr>
<td>III-3</td>
<td>Distance Logic</td>
<td>69</td>
</tr>
<tr>
<td>III-4</td>
<td>Heading Difference Calculation</td>
<td>70</td>
</tr>
<tr>
<td>III-5</td>
<td>Rudder Control Block Diagram</td>
<td>73</td>
</tr>
<tr>
<td>III-6</td>
<td>Optimization Flow Chart</td>
<td>75</td>
</tr>
<tr>
<td>III-7</td>
<td>Approach Phase Yaw Result</td>
<td>79</td>
</tr>
<tr>
<td>III-8</td>
<td>Approach Phase Y Forces</td>
<td>80</td>
</tr>
<tr>
<td>III-9</td>
<td>Approach Phase N Moments</td>
<td>81</td>
</tr>
<tr>
<td>III-10</td>
<td>Approach Phase Geographic Plot</td>
<td>82</td>
</tr>
<tr>
<td>III-11</td>
<td>Approach Phase Lateral Distance DY</td>
<td>83</td>
</tr>
<tr>
<td>III-12</td>
<td>Approach Phase Rudder Response</td>
<td>84</td>
</tr>
<tr>
<td>III-13</td>
<td>Turn Phase Rudder Action of Reference Ship</td>
<td>86</td>
</tr>
<tr>
<td>III-14</td>
<td>Turn Phase Rudder Response</td>
<td>87</td>
</tr>
<tr>
<td>III-15</td>
<td>Turn Phase Lateral Distance DY</td>
<td>88</td>
</tr>
<tr>
<td>III-16</td>
<td>Turn Phase Yaw Response</td>
<td>91</td>
</tr>
<tr>
<td>III-17</td>
<td>Turn Phase Y Forces</td>
<td>92</td>
</tr>
<tr>
<td>III-18</td>
<td>Turn Phase N Moments</td>
<td>93</td>
</tr>
<tr>
<td>III-19</td>
<td>Turn Phase Geographic Plot</td>
<td>94</td>
</tr>
<tr>
<td>III-20</td>
<td>Turn Phase Lateral Distance DY</td>
<td>95</td>
</tr>
<tr>
<td>III-21</td>
<td>Turn Phase Rudder Response</td>
<td>96</td>
</tr>
<tr>
<td>III-22</td>
<td>Approach Phase Lateral Distance DY</td>
<td>98</td>
</tr>
<tr>
<td>III-23</td>
<td>Approach Phase Yaw Response</td>
<td>100</td>
</tr>
<tr>
<td>III-24</td>
<td>Approach Phase Y Forces</td>
<td>101</td>
</tr>
<tr>
<td>III-25</td>
<td>Approach Phase N Moments</td>
<td>102</td>
</tr>
<tr>
<td>III-26</td>
<td>Approach Phase Geographic Plot</td>
<td>103</td>
</tr>
<tr>
<td>III-27</td>
<td>Approach Phase Lateral Distance DY</td>
<td>104</td>
</tr>
<tr>
<td>III-28</td>
<td>Approach Phase Rudder Response</td>
<td>105</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>III-29</td>
<td>Turn Phase Yaw Response</td>
<td>106</td>
</tr>
<tr>
<td>III-30</td>
<td>Turn Phase Y Forces</td>
<td>107</td>
</tr>
<tr>
<td>III-31</td>
<td>Turn Phase N Moments</td>
<td>108</td>
</tr>
<tr>
<td>III-32</td>
<td>Turn Phase Geographic Plot</td>
<td>109</td>
</tr>
<tr>
<td>III-33</td>
<td>Turn Phase Lateral Distance DY</td>
<td>110</td>
</tr>
<tr>
<td>III-34</td>
<td>Turn Phase Rudder Response</td>
<td>111</td>
</tr>
<tr>
<td>III-35</td>
<td>Approach Phase Run #1 Yaw Response</td>
<td>114</td>
</tr>
<tr>
<td>III-36</td>
<td>Approach Phase Run #1 Geographic Plot</td>
<td>115</td>
</tr>
<tr>
<td>III-37</td>
<td>Approach Phase Run #1 Rudder Response</td>
<td>116</td>
</tr>
<tr>
<td>III-38</td>
<td>Approach Phase Run #2 Yaw Response</td>
<td>117</td>
</tr>
<tr>
<td>III-39</td>
<td>Approach Phase Run #2 Geographic Plot</td>
<td>118</td>
</tr>
<tr>
<td>III-40</td>
<td>Approach Phase Run #2 Rudder Response</td>
<td>119</td>
</tr>
<tr>
<td>III-41</td>
<td>Approach Phase Run #3 Yaw Response</td>
<td>120</td>
</tr>
<tr>
<td>III-42</td>
<td>Approach Phase Run #3 Geographic Plot</td>
<td>121</td>
</tr>
<tr>
<td>III-43</td>
<td>Approach Phase Run #3 Rudder Response</td>
<td>122</td>
</tr>
<tr>
<td>III-44</td>
<td>Approach Phase Run #4 Yaw Response</td>
<td>123</td>
</tr>
<tr>
<td>III-45</td>
<td>Approach Phase Run #4 Geographic Plot</td>
<td>124</td>
</tr>
<tr>
<td>III-46</td>
<td>Approach Phase Run #4 Rudder Response</td>
<td>125</td>
</tr>
<tr>
<td>III-47</td>
<td>Approach Phase Run #5 Yaw Response</td>
<td>126</td>
</tr>
<tr>
<td>III-48</td>
<td>Approach Phase Run #5 Geographic Plot</td>
<td>127</td>
</tr>
<tr>
<td>III-49</td>
<td>Approach Phase Run #5 Rudder Response</td>
<td>128</td>
</tr>
<tr>
<td>III-50</td>
<td>Approach Phase Run #6 Yaw Response</td>
<td>129</td>
</tr>
<tr>
<td>III-51</td>
<td>Approach Phase Run #6 Geographic Plot</td>
<td>130</td>
</tr>
<tr>
<td>III-52</td>
<td>Approach Phase Run #6 Rudder Response</td>
<td>131</td>
</tr>
<tr>
<td>III-53</td>
<td>Turn Phase Run #4 Yaw Response</td>
<td>132</td>
</tr>
<tr>
<td>III-54</td>
<td>Turn Phase Run #4 Geographic Plot</td>
<td>133</td>
</tr>
<tr>
<td>III-55</td>
<td>Turn Phase Run #4 Rudder Response</td>
<td>134</td>
</tr>
<tr>
<td>III-56</td>
<td>Turn Phase Run #6 Yaw Response</td>
<td>135</td>
</tr>
<tr>
<td>III-57</td>
<td>Turn Phase Run #6 Geographic Plot</td>
<td>136</td>
</tr>
<tr>
<td>III-58</td>
<td>Turn Phase Run #6 Rudder Response</td>
<td>137</td>
</tr>
<tr>
<td>III-59</td>
<td>Approach Phase Run #4 Lateral Y Forces</td>
<td>139</td>
</tr>
<tr>
<td>III-60</td>
<td>Approach Phase Run #4 Rotational N Moments</td>
<td>140</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>III-61</td>
<td>Approach Phase Run #4 Lateral Distance DY</td>
<td>141</td>
</tr>
<tr>
<td>III-62</td>
<td>Turn Phase Run #4 Lateral Y Forces</td>
<td>142</td>
</tr>
<tr>
<td>III-63</td>
<td>Turn Phase Run #4 Rotational N Moments</td>
<td>143</td>
</tr>
<tr>
<td>III-64</td>
<td>Turn Phase Run #4 Lateral Distance DY</td>
<td>144</td>
</tr>
<tr>
<td>III-65</td>
<td>Wave Effect on Turn Phase Lateral Distance (DY) WL=1.5</td>
<td>147</td>
</tr>
<tr>
<td>III-66</td>
<td>Wave Effect on Approach Phase Yaw WL=1.0</td>
<td>148</td>
</tr>
<tr>
<td>III-67</td>
<td>Approach Phase Rudder Response to Waves WL=1.0</td>
<td>149</td>
</tr>
<tr>
<td>III-68</td>
<td>Wave Effect on Approach Phase Lateral Distance (DY) WL=1.0</td>
<td>150</td>
</tr>
<tr>
<td>III-69</td>
<td>Approach Phase Wave Profile WL=1.0</td>
<td>151</td>
</tr>
<tr>
<td>III-70</td>
<td>Wave Effect on Turn Phase Yaw WL=1.0</td>
<td>152</td>
</tr>
<tr>
<td>III-71</td>
<td>Wave Effect on Turn Phase Lateral Distance (DY) WL=1.0</td>
<td>153</td>
</tr>
<tr>
<td>III-72</td>
<td>Turn Phase Rudder Response to Waves WL=1.0</td>
<td>154</td>
</tr>
<tr>
<td>III-73</td>
<td>Turn Phase Wave Profile WL=1.0</td>
<td>155</td>
</tr>
<tr>
<td>III-74</td>
<td>Nco-optimum Speed Law</td>
<td>156</td>
</tr>
<tr>
<td>III-75</td>
<td>Speed Control Law</td>
<td>158</td>
</tr>
<tr>
<td>III-76</td>
<td>Optimization Flow Chart</td>
<td>159</td>
</tr>
<tr>
<td>III-77</td>
<td>Switching Curve Minimization Results</td>
<td>162</td>
</tr>
<tr>
<td>III-78</td>
<td>First thru Fifth Order Polynomial Curve Fit Results</td>
<td>165</td>
</tr>
<tr>
<td>III-79</td>
<td>Fifth Order Polynomial Curve Fit</td>
<td>166</td>
</tr>
<tr>
<td>III-80</td>
<td>RAS Speed Control Approach Phase</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>Speed Desired (1) and Speed Acquired (2) vs. Real Time</td>
<td></td>
</tr>
<tr>
<td>III-81</td>
<td>RAS Speed Control Approach Phase Position Attainment vs. Real Time</td>
<td>169</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES (cont.)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>III-82</td>
<td>RAS Speed Control Turn Phase</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>Speed Desired (1) and Speed Acquired (2) vs. Real Time</td>
<td></td>
</tr>
<tr>
<td>III-83</td>
<td>RAS Speed Control Turn Phase</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>Position Attainment vs. Real Time</td>
<td></td>
</tr>
<tr>
<td>III-84</td>
<td>Approach Phase Run A Lateral Distance DY</td>
<td>176</td>
</tr>
<tr>
<td>III-85</td>
<td>Approach Phase Run A Yaw Difference</td>
<td>177</td>
</tr>
<tr>
<td>III-86</td>
<td>Approach Phase Run B Lateral Distance DY</td>
<td>178</td>
</tr>
<tr>
<td>III-87</td>
<td>Approach Phase Run B Yaw Difference</td>
<td>179</td>
</tr>
<tr>
<td>III-88</td>
<td>Approach Phase Run B Speed Response</td>
<td>180</td>
</tr>
<tr>
<td>III-89</td>
<td>Approach Phase Run B Longitudinal Position DX</td>
<td>181</td>
</tr>
<tr>
<td>III-90</td>
<td>Approach Phase Run C Lateral Distance DY</td>
<td>182</td>
</tr>
<tr>
<td>III-91</td>
<td>Approach Phase Run C Yaw Difference</td>
<td>183</td>
</tr>
<tr>
<td>III-92</td>
<td>Approach Phase Run C Speed response</td>
<td>184</td>
</tr>
<tr>
<td>III-93</td>
<td>Approach Phase Run C Longitudinal Position DX</td>
<td>185</td>
</tr>
<tr>
<td>III-94</td>
<td>Turn Phase Run A Lateral Distance DY</td>
<td>186</td>
</tr>
<tr>
<td>III-95</td>
<td>Turn Phase Run A Yaw Difference</td>
<td>187</td>
</tr>
<tr>
<td>III-96</td>
<td>Turn Phase Run B Lateral Distance DY</td>
<td>188</td>
</tr>
<tr>
<td>III-97</td>
<td>Turn Phase Run B Yaw Difference</td>
<td>189</td>
</tr>
<tr>
<td>III-98</td>
<td>Turn Phase Run B Longitudinal Position DX</td>
<td>190</td>
</tr>
<tr>
<td>III-99</td>
<td>Turn Phase Run C Lateral Distance DY</td>
<td>191</td>
</tr>
<tr>
<td>III-100</td>
<td>Turn Phase Run C Yaw Difference</td>
<td>192</td>
</tr>
<tr>
<td>III-101</td>
<td>Turn Phase Run C Longitudinal Position DX</td>
<td>193</td>
</tr>
<tr>
<td>III-102</td>
<td>Block Diagram of Wave Introduction in Speed Loop</td>
<td>194</td>
</tr>
<tr>
<td>III-103</td>
<td>Approach Phase Speed Response in Waves</td>
<td>196</td>
</tr>
<tr>
<td>III-104</td>
<td>Turn Phase Speed Response in Waves</td>
<td>197</td>
</tr>
<tr>
<td>III-105</td>
<td>Turn Phase Longitudinal Position DX in Waves</td>
<td>198</td>
</tr>
<tr>
<td>C-1</td>
<td>Curve Fitted Interactive Y Forces</td>
<td>305</td>
</tr>
<tr>
<td>C-2</td>
<td>Curve Fitted Interactive N Moments</td>
<td>306</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>C-3</td>
<td>Approach Phase Curve Fitted</td>
<td>308</td>
</tr>
<tr>
<td></td>
<td>Y forces</td>
<td></td>
</tr>
<tr>
<td>C-4</td>
<td>Approach Phase Curve Fitted</td>
<td>309</td>
</tr>
<tr>
<td></td>
<td>N Moments</td>
<td></td>
</tr>
<tr>
<td>C-5</td>
<td>Approach Phase Geographical Plot</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>From Modified Interactive Effects</td>
<td></td>
</tr>
<tr>
<td>C-6</td>
<td>Turn Phase Curve Fitted</td>
<td>312</td>
</tr>
<tr>
<td></td>
<td>Y Forces</td>
<td></td>
</tr>
<tr>
<td>C-7</td>
<td>Turn Phase Curve Fitted</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td>N Moments</td>
<td></td>
</tr>
<tr>
<td>C-8</td>
<td>Turn Phase Lateral Distance DY</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>From Modified Interactive Effects</td>
<td></td>
</tr>
</tbody>
</table>
T A B L E  O F  T E R M S  A N D  A B B R E V I A T I O N S

ADX - DX referenced to control ship's head
ADY - DY referenced to control ship's head
Alongside - position at which longitudinal position ADX is 0.0
Approach Phase - phase in RAS scenario at which the control ship comes alongside the reference ship
Approach Speed - speed at which the control ship will commence approach to come alongside the reference ship
AT - real time as referenced to the full size Mariner hull
Control Ship - ship making the RAS approach
Desired Distance - lateral distance at which RAS desired
DSL - Digital Simulation Language (IBM developed)
DX - center of ship's geographic separation along X axis
DY - center of ship's geographic separation along Y axis
Geographic Coordinates - earth's coordinate system
JCL - JCL Control Language for IBM 360/67 computer
Kt., kts. - knot, knots - 1 nautical mile/hour or 2000 yards/hour
L, Ship length - length of one mariner hull used in this thesis (527.8 feet)
Lateral Distance - equal to ADY
Longitudinal Distance/Position - equal to ADX
LOC - nondimensionalizing scaling factor
Port Side To - approach (control) ship replenishes with its port side toward supply (reference) ship
RAS - Replenishment At Sea
Receiving Ship - control ship or ship B
Reference Ship - ship that maintains course and speed
Reference Speed - speed of reference ship
TABLE OF TERMS AND ABBREVIATIONS (cont.)

Replenishment Speed - signaled intended speed at which RAS will be conducted
Stbd Side Tc - approach (control) ship replenishes with its stbd side toward supply (reference) ship
Supply Ship - reference ship or ship B
T - nondimensionalized time used in DSL runs
Turn Phase - phase in RAS scenario at which the ships are in their desired positions and the reference ship is turned
Yaw - ship's heading in relation to true north
Y Coordinate - geographic reference system E is +, W is -
X Coordinate - geographic reference system N is +, S is -
ACKNOWLEDGEMENTS

In the course of thesis research many people contribute to the final product. It is not possible to afford individual credit to all that have given of themselves for this particular research. Some, however, have rendered assistance that has proven invaluable.

Professor G. J. Thaler has been, without a doubt, the prime guiding force that has kept this study within a sound perspective.

Three members of the computer center staff, M. Anderson, Kris Butler, and Ed Donnellan have tolerated numerous intimidations with good humor which made many otherwise arduous hours bearable. Without their professional assistance and personal contributions to the computer center operations, this thesis would have fallen far short of its goal.

And finally, my dear wife Mary who has endured a husband that has spent endless hours married to the IBM 360 computer. Her undying support and valuable encouragement is held in the highest esteem.
I. INTRODUCTION

The advent of the digital computer as standard equipment on board virtually all modern Naval ships has opened the field of Digital Computer Control in almost all aspects of ship life. The computer has been a viable asset in fire control systems for years and has been used extensively for aids to ship maneuvering control in the form of NTDS (Naval Tactical Data System) readouts. The declining costs of general and special purpose computers has made their inception as a manpower replacement or augmentation a reality. Their high speed and accuracy can make them perform functions with much greater safety than previously attainable with time proven (and sometimes time weary) "seaman's eye."

This then is the basis for this thesis; a study of the types of maneuvers that can be handled more accurately and safely than presently being accomplished.

One area of study is the total Replenishment At Sea (RAS) problem including both course and speed control for the approach and alongside phases. This situation has always been one of extreme danger due to the collision potentials involved. However, other dangers are involved in the on deck evolutions when the ships are not kept at a fairly constant distance. Sudden violent maneuvers may cause the stress on the lines between ships to increase enough to cause the lines to part. The reality of this danger is readily apparent to anyone who has ever seen a marina line or steel cable part or a kingpost shackle break or a kingpost suddenly bend under these extreme stresses. A system which will minimize these potential dangers is well
worth investigation.

Of course with a digital computer, the algorithm for RAS can be modified or replaced to enable its use as a maneuvering control device for other situations such as formation steaming or single ship navigation transit control.
II. MODELING

A. MARINER DYNAMICS

In the conception of this thesis, realistic models of modern destroyer hull configurations were sought. This search proved fruitless. The hydrodynamic coefficients for present day destroyers are not currently available. However, some naval and civilian research is presently being conducted to obtain these coefficients.

A complete set of these coefficients is necessary for any maneuvering control system design. A hull configuration which has been under continual study with well defined and verified hydrodynamic coefficients was chosen[1]. This hull is commonly referred to as the "Mariner" hull.

The development of the equations of motion in six and three degrees of freedom have been well documented[2]. The model used for this thesis is the equations of motion in three degrees of freedom linearized with second order and higher terms eliminated. These equations are characterized by dependency on small perturbations about a specific operating point. The maneuvers experienced in the following chapters do not entirely meet this criterion. The inadequacy and shortcomings of this model are of little consequence because relevant hydrodynamic coefficients are not available, and the methods presented can be applied to any ship type.

The development of the model is readily available to the interested reader [3]; only a summary of the equations
and their corresponding hydrodynamic coefficients are presented here.

The equations of motion used are as follows:

\[(X.-u) \ddot{u} + \dot{X} (U-u) + \dot{X} d = 0\]

\[(Y.-v) \ddot{v} + \dot{Y} \dot{v} + (Y-m) \ddot{R} + \dot{Y} R d = 0\]

\[(N.-z) \ddot{z} + \dot{N} \dot{z} + N \ddot{v} + N v d = 0\]

The direction and sense of the terms in the above equations are shown in figure II-1. Letting:

\[a = m - Y. \]
\[b = -Y \]
\[c = 0 \]
\[a = -Y. \]
\[b = m - Y \]
\[c = 0 \]
\[a = -N. \]
\[b = -N \]
\[c = 0 \]
\[a = I - N. \]
\[b = -N \]
\[c = 0 \]
\[a = m - X. \]
Figure II-1
Direction and Sense of Hydrodynamic Terms
\[ b_{33} = -X \]
\[ u_{33} = 0 \]

Setting

\[ v = \dot{A} \]
\[ \psi = B \]
\[ U = \dot{C} \]

The equations of motion can be written as:

\[
\begin{align*}
0 & = a_{A} + b_1 A + c_{A} + a_{B} + b_2 B + c_2 B = IF_{1} \\
0 & = a_{A} + b_2 A + c_{A} + a_{B} + b_1 B + c_1 B = IF_{2} \\
0 & = a_{C} + b_3 C + c_{C} = IF_{3}
\end{align*}
\]

or:

\[
\begin{align*}
0 & = a_{A} + a_{E} = I_{1} \\
0 & = a_{A} + a_{E} = I_{2} \\
0 & = a_{C} = I_{3}
\end{align*}
\]

where:

\[ IF_{1} = -Y \cdot d \]
\[ IF_{2} = N \cdot d \]
\[ IF3 = - \int X_u \, dt \]

and:

\[ I1 = -t \begin{bmatrix} \ddot{A} - c \quad A - b \quad \ddot{B} - c \quad B + IF1 \\ \end{bmatrix} \]

\[ I2 = -t \begin{bmatrix} \ddot{A} - c \quad A - b \quad \ddot{B} - c \quad B + IF2 \\ \end{bmatrix} \]

\[ I3 = -t \begin{bmatrix} \ddot{C} - c \quad C + IF3 \\ \end{bmatrix} \]

By solving this system of equations, the following relationships are established:

\[ A = \left( a \begin{bmatrix} I1 - a \\ a \end{bmatrix} \right) / \Delta \]

\[ E = \left( a \begin{bmatrix} I2 - a \\ a \end{bmatrix} \right) / \Delta \]

\[ C = I3 / a \]

where:

\[ \Delta = a \left( a \begin{bmatrix} I1 - a \\ a \end{bmatrix} \right) \]

which yields the solution:

\[ v = \dot{A} = \int_{t_0}^{t} A \, dt \]

\[ \ddot{v} = \dot{\ddot{B}} = \int_{t_0}^{t} \ddot{B} \, dt = \ddot{v} \int_{t_0}^{t} \left[ \dot{B}(0) + \int_{t_0}^{t} B \, dt \right] \, dt \]

\[ \dddot{u} = \dddot{C} = \int_{t_0}^{t} C \, dt \]

The space coordinate system is defined as follows:
\[ \dot{y} = U \cdot \sin \psi + V \cdot \cos \psi \]
\[ \dot{x} = U \cdot \cos \psi - V \cdot \sin \psi \]

where:
\[ x = x_0 + \int_{t_0}^{t} \dot{x} \, dt \]
\[ y = y_0 + \int_{t_0}^{t} \dot{y} \, dt \]

Table II-1 summarizes the symbols and nomenclature used in the foregoing abbreviated solution of motion in three degrees of freedom. The applicable characteristics of the Mariner hull are presented in table II-2 with the corresponding nondimensionalized hydrodynamic coefficients and the DSL computer program variable names delineated in table II-3.

Computer Program #1 is the basic DSL program that was developed from these equations of motion. This program uses two ships to illustrate the turning characteristics of the Mariner hull for various rudder commands. Figure II-2 shows the difference between a step model and a ramp model rudder in a geographic model. Figure II-3 shows the corresponding difference in yaw.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_u$</td>
<td>derivative of longitudinal force with respect to longitudinal acceleration $\dot{U}$</td>
</tr>
<tr>
<td>$U_u$</td>
<td>derivative of longitudinal force with respect to longitudinal velocity $U$</td>
</tr>
<tr>
<td>$Y_v$</td>
<td>derivative of lateral force with respect to transverse acceleration $\dot{V}$</td>
</tr>
<tr>
<td>$Y_v$</td>
<td>derivative of lateral force with respect to transverse velocity $V$</td>
</tr>
<tr>
<td>$Y_r$</td>
<td>derivative of lateral force with respect to angular acceleration $\dot{R}$</td>
</tr>
<tr>
<td>$Y_r$</td>
<td>derivative of lateral force with respect to angular velocity $R$</td>
</tr>
<tr>
<td>$Y_d$</td>
<td>derivative of lateral force with respect to rudder angle $d$</td>
</tr>
<tr>
<td>$N_v$</td>
<td>derivative of yaw moment with respect to transverse acceleration $\dot{V}$</td>
</tr>
<tr>
<td>$N_v$</td>
<td>derivative of yaw moment with respect to transverse velocity $V$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>( N_r )</td>
<td>derivative of yaw moment with respect to angular acceleration ( \dot{R} )</td>
</tr>
<tr>
<td>( N_r )</td>
<td>derivative of yaw moment with respect to angular velocity ( R )</td>
</tr>
<tr>
<td>( N_d )</td>
<td>derivative of yaw moment with respect to rudder angle ( d )</td>
</tr>
<tr>
<td>( \dot{R} )</td>
<td>yaw angle acceleration</td>
</tr>
<tr>
<td>( R )</td>
<td>yaw angle velocity</td>
</tr>
<tr>
<td>( u_0 )</td>
<td>initial velocity of origin of body axes relative to fluid</td>
</tr>
<tr>
<td>( \dot{V} )</td>
<td>transverse acceleration of ship axes relative to fluid</td>
</tr>
<tr>
<td>( V )</td>
<td>transverse velocity of origin of ship axes relative to fluid</td>
</tr>
<tr>
<td>( X )</td>
<td>hydrodynamic longitudinal force</td>
</tr>
<tr>
<td>( Y )</td>
<td>hydrodynamic lateral force</td>
</tr>
<tr>
<td>( \dot{U} )</td>
<td>longitudinal acceleration of ship axes relative to fluid</td>
</tr>
</tbody>
</table>
TABLE II-1 (cont.)
SYMBOLS AND NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>longitudinal velocity of ship axes relative to fluid</td>
</tr>
<tr>
<td>Ψ</td>
<td>yaw angle</td>
</tr>
<tr>
<td>At</td>
<td>actual time</td>
</tr>
<tr>
<td>T</td>
<td>nondimensionalized time</td>
</tr>
<tr>
<td>x_g</td>
<td>longitudinal distance that the ship center of gravity is forward of the ships axes</td>
</tr>
<tr>
<td>u_1</td>
<td>longitudinal velocity of ship axes relative to fluid (operating point)</td>
</tr>
</tbody>
</table>

TABLE II-2
CHARACTERISTICS OF MARINER-TYPE STUDY SHIP

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, ft.</td>
<td>527.8</td>
</tr>
<tr>
<td>Beam, ft</td>
<td>76.0</td>
</tr>
<tr>
<td>Draft, ft</td>
<td>29.75</td>
</tr>
<tr>
<td>Displacement, tons</td>
<td>16,800.</td>
</tr>
<tr>
<td>Block coefficient, C_b</td>
<td>0.6</td>
</tr>
</tbody>
</table>
# TABLE II-3

**Nondimensional Hydrodynamic Coefficients**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Computer Program Variable Name</th>
<th>Nondimensional Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>((X._-m))</td>
<td>MXUD</td>
<td>-0.0085</td>
</tr>
<tr>
<td>X</td>
<td>XU</td>
<td>-0.0012</td>
</tr>
<tr>
<td>Y</td>
<td>YV</td>
<td>-0.01243</td>
</tr>
<tr>
<td>((Y._-m))</td>
<td>MYVD</td>
<td>-0.015</td>
</tr>
<tr>
<td>((Y._-mx u)) (_r)</td>
<td>MYR</td>
<td>-0.0051</td>
</tr>
<tr>
<td>((Y._-mx y)) (_r)</td>
<td>YRD</td>
<td>-0.00027</td>
</tr>
<tr>
<td>Y</td>
<td>YDELR</td>
<td>+0.0027</td>
</tr>
<tr>
<td>N</td>
<td>NV</td>
<td>-0.00351</td>
</tr>
<tr>
<td>(N._v)</td>
<td>NVD</td>
<td>-0.000197</td>
</tr>
<tr>
<td>((N._-mx u)) (_r)</td>
<td>NR</td>
<td>-0.00227</td>
</tr>
<tr>
<td>((N._-I)) (_r)</td>
<td>IZNRD</td>
<td>-0.00068</td>
</tr>
<tr>
<td>N</td>
<td>NDELR</td>
<td>-0.00126</td>
</tr>
<tr>
<td>X</td>
<td>---</td>
<td>-0.0000462</td>
</tr>
<tr>
<td>Y</td>
<td>---</td>
<td>-0.0000052</td>
</tr>
<tr>
<td>N</td>
<td>---</td>
<td>+0.0000026</td>
</tr>
<tr>
<td>X</td>
<td>XDELR</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**NOTE:** \(x = 0.0\)
TABLE II-3 (cont.)

NONDIMENSIONAL HYDRODYNAMIC COEFFICIENTS

Values based on the following operating point:
\[ u_1 = 1.0 \text{ (15 Kts)} \]
\[ \dot{\psi} = 0.0 \]
\[ \dot{\psi} = 0.0 \]
Figure II-3
Rudder Step and Ramp Model Yaw
Difference vs. Time
E. RUDDER RESPONSE

The previous section indicates a marked difference in behavior between step and ramp rudder models. This prompted an investigation into realistic rudder modeling which would fulfill the requirements of limit stops and maximum rudder rate.

NSRDC[*] has modeled the rudder of the DD-931 Class Destroyer. The basics of this model are presented in the block diagram of figure II-4.

The first limiter models the rudder stops which for the Mariner are ±30 degrees. The second limiter models the proportional band of a variable-displacement pump by limiting its maximum percent stroke. The limits for this nonlinear element have been found to be ±7 degrees.

The transfer function \( K/s \) accepts an input error signal of up to 7 degrees, converts it to a rudder rate, and integrates the rudder rate to obtain rudder angle. Letting:

\[
d = \text{Maximum rudder rate} \ (2.0 \ \text{degrees/sec})
\]
\[
d' = \text{Maximum error input} \ (7.0 \ \text{degrees})
\]

The system gain can be defined as:

\[
K = \frac{\dot{d}}{d} \quad g = \frac{\dot{d}}{d} \quad e_{max}
\]

\[
= 2.0/7.0
\]

\[
= 0.285714 /\text{sec}
\]
Figure II-4
Rudder Block Diagram
To convert this model to the required nondimensionalized form, the following manipulation is required:

\[ \frac{K'}{g} = \frac{K \cdot L}{u} \cdot \frac{1}{g} \]

\[ = \frac{0.285714 \cdot 527.8}{(15 \cdot 1.689)} \]

\[ = 5.95224 \]

where:

- \( L = \) ship length
- \( u_1 = \) operating point speed (15 Kts \( \cdot \) 1.689 ft/sec/Kt)

Computer Program #2 is the DSL program which models this system. The curves of figure II-5 and II-6 exhibit the responses of various step rudder commands. These are tabulated and cross referenced in table II-4.

These responses show the characteristics of a realistic rudder in that the rudder is never allowed to slam into the steps. They exhibit the time delay between command and response which is a function of the rate of response (2.0 degrees/sec). A control system design with this scheme is a much more difficult problem than one with an idealized rudder (step response) because the entire rudder control system becomes quite nonlinear.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Curve</th>
<th>Rudder Command (deg)</th>
<th>Initial Condition (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II-5</td>
<td>1</td>
<td>+30.0</td>
<td>-30.0</td>
</tr>
<tr>
<td>II-5</td>
<td>2</td>
<td>+25.0</td>
<td>-25.0</td>
</tr>
<tr>
<td>II-5</td>
<td>3</td>
<td>+20.0</td>
<td>-20.0</td>
</tr>
<tr>
<td>II-5</td>
<td>4</td>
<td>+15.0</td>
<td>-15.0</td>
</tr>
<tr>
<td>II-5</td>
<td>5</td>
<td>+10.0</td>
<td>-10.0</td>
</tr>
<tr>
<td>II-5</td>
<td>6</td>
<td>+5.0</td>
<td>-5.0</td>
</tr>
<tr>
<td>II-6</td>
<td>1</td>
<td>+30.0</td>
<td>0.0</td>
</tr>
<tr>
<td>II-6</td>
<td>2</td>
<td>+25.0</td>
<td>0.0</td>
</tr>
<tr>
<td>II-6</td>
<td>3</td>
<td>+20.0</td>
<td>0.0</td>
</tr>
<tr>
<td>II-6</td>
<td>4</td>
<td>+15.0</td>
<td>0.0</td>
</tr>
<tr>
<td>II-6</td>
<td>5</td>
<td>+10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>II-6</td>
<td>6</td>
<td>+5.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Figure II-5
Rudder Responses
C. ENGINE RESPONSE

Figure II-7 portrays a complex model of a gas turbine propulsion plant\(^5\)[\(^6\)]. This model contains the elements required for a complete dynamic study of the system. For the purpose of this thesis, such a complicated model is not required if the overall input-output relationship can be established.

Reference 5 establishes an output speed \(U\) relationship for a step input of desired speed \((U_d)\) and is redrawn as figure II-8. The relationship appears to be that of a first or second order system with a time delay.

The system equations for a first order approximation with a time delay may be written as:

\[
\begin{align*}
SPIEIN & = K*SPDES\times e^{-Ts} \\
SPDERR & = (SPDIN-SPDCUT) \times G \\
SPDCUT & = \int SPDERR \, dt \\
\end{align*}
\]

Which yields the transfer function:

\[
\frac{SPDCUT(s)}{SPIEIN(s)} = \frac{-Ts}{s+G} G*K* e^{Ts}
\]

Which is block diagrammed in figure II-9.

![Figure II-9](image)

Figure II-9
Propulsion Plant Low Order Model Block Diagram
From figure II-8, the time delay, system gain, and time constant can be estimated as:

\[ T = 4.88 \text{ sec} \]
\[ K = 0.9877 \]
\[ G = 0.092 \]

Computer Program #3 was used to obtain the step input response. The original complex system output and the low order approximation are compared in figure II-10. As indicated in this figure, the two responses are very close. Considering the linearized approximations made in the equations of motion, this response is accurate enough for system study use and is used as the model for speed control in chapter III.

Similar methods may be used to obtain simplified low-order models for other high-order propulsion systems now in use (e.g. pressure fired boiler systems, 1200 lb. systems, etc.). They may not, however, simplify to a first order approximation suitable for system study. A method of computer determination of low-order models of high-order systems is contained in ref. 7 and may be mechanized for this purpose.
D. EXTERNAL FORCES

The modeling of ship dynamics cannot be complete without the introduction of external forces which perturb its responses. These forces are caused by many factors and some are more relevant than others in the scope of this thesis. The two that are considered can cause substantial perturbations that must be modeled and eventually accounted for in the control system design.

1. Two Ships in Proximity

Whenever two ships operate in close proximity (less than 250 feet), suction and pressure forces between hulls are present. Studies have been conducted on the Mariner hull\(^1\) which have produced data for construction of a family of curves for two ships passing on the same heading. No data has been found for the cases of two ships not on the same heading. Other restrictions on the work presented in ref. 1 are that the ships are of the same type and of similar hull ratios.

Interactive effects vary as the square of speed. However, this is only true if both ships are at the same speeds. The interaction modification factor is based on the normalized speed of 15 kts. This factor can thus be written as:

\[ \text{SPDF} = \text{CDOT1}^2 \]

Exact effects on the interaction forces and moments in the situation where the ship's speeds differ are not available. This is inconvenient since during the approach phase, the normalized speed of the approach ship (ship B) can be as
high as 1.5. If the effect on ship B is as stated above but with its own speed causing the interaction modification, the interactive forces and moments can be 2.25 times greater than without speed considerations.

Without the ability to pin down this relationship, it was ignored in the development of the control laws presented in this thesis. Appendix C was written with the expressed intent of illustrating the effect of modifying the interactive forces and moments to the extremum case mentioned above. It must be realized that this case is not considered likely in that it is felt that the interactive forces and moments modification on ship B are more apt to be caused by the speed of ship A. If this is so, since ship A is kept at a constant 15 kts., the interactions need no modification for speed consideration in this thesis.

Reference 1 also gives a method of modifying the interactive forces and moments based on different ship lengths. For ease of computation and graphical presentation, the two ships were considered of equal lengths. To modify this to ships of dissimilar lengths, the resulting hydrodynamic derivatives must be modified as shown in ref. 1 (also shown in appendix C).

Since no closed form expression existed for these forces, the family of curves reproduced as figures II-11 and II-12 were quantized in subroutine SLOPES (an adaptation of the subroutine of the same name from ref. 11). (Appendix C contains a curve fitted subroutine that was compiled after the completion of the research on this thesis. It was not used for any design or simulation runs except for those presented in that same appendix.) An interpolation algorithm is used to approximate the intermediate values between quantized values and between the curves of the family.
Lateral Distance \(DY(\text{Ft})\)*

*Note: To convert to normalized lateral distance \(DY\) - Divide by the ship length \(L\).*

Figure II-11
Family of Interactive Y force Curves
Lateral Distance $DY\text{(Ft)}$*

*Note: To convert to normalized lateral distance $DY$ - Divide by the ship length $L$.

Figure II-12
Family of Interactive N Moment Curves
The main purpose of this subroutine is to compute the interactive forces between ships in the replenishment at sea situation and output the values for perturbation of the control ship only. Even though both ships are affected by these perturbations, a one ship control system which is effective regardless of the other ships motion is considered. Consequently, the interactive forces on the second ship are ignored.

Subroutine SLOCSES is contained in appendix A. Figure II-13 is a geographic plot of the two ships passing at 105.6 feet with their rudders amidships (0 degrees). Figure II-14 and figure II-15 show the magnitude of the lateral force (Y force) and rotational moment (N moment) of the reference ship on the ship making its approach (control ship). The reference ship is at 15 kts. and the approach ship is at 22.5 kts. The control ship starts its approach 5 ship lengths (2639.0 feet) astern and 0.4 ship lengths (211.12 feet) laterally displaced. The most graphic portrait of the effects of these forces and moments appears in the yaw changes which are presented in figure II-16. From these figures it becomes readily apparent that these perturbations cause violent motions of the ship which must be accounted for in any control system development. Throughout the development of such a control system in chapter III, these forces and moments are considered inherent in the model for HAS control.
2. Waves

The modeling of sea state in the form of waves and wave interactions has occupied the time of many researchers \[8\][9]. The exact formulation of waves will not be accomplished in this thesis. Since the main concern here will be to test the control scheme developed in chapter III, a much simplified wave generator can be used. To introduce the required experimental perturbations on the designed control system a periodic wave system with a fundamental frequency and its second harmonic is used. Some small random wave properties are introduced that ride on these two sinusoids. A simple expression of this combined wave can be written as:

\[
W = WF \cdot \sin(WE) + (PI \cdot WF / WL) \cdot \sin(2 \cdot WE) + WF \cdot WRV \cdot \sin(WE)
\]

where:

- \(W\) denotes the wave
- \(WF\) is the wave force
- \(WE\) is the wave encounter radian frequency
- \(WL\) is the wave length
- \(WRV\) is the wave random variable
- \(PI\) is \(\pi\) \(= 3.1415926\)

With this wave as a basis, a method of modeling this in the dynamic environment of the total ship simulation was defined. The modeling includes the introduction of this wave into the three degree of freedom equations of motion. To accomplish this a set of defining relationships were developed. First the general wave direction is input to establish the direction of the wave encounter on the ship. If the ship direction is YAWDP2 and the wave direction is WD, the expected wave direction is defined as:

\[
EWE = WD - YAWDP2
\]
Next the wave encounter frequency (radian frequency) can be established with knowledge of the ships normalized true speed \(CDCT2\), wave length \(WL\) and normalized wave velocity \(WV\). The wave encounter frequency \(WEF\) is then:

\[
WEF = 2\pi \cdot \frac{CDCT2 + WV \cdot \cos(EWD)}{WL}
\]

The total wave encounter \(WE\) is nothing more than the wave encounter frequency \(WEF\) times time. This gives the wave encounter radian frequency required in the simple expression for the combined wave previously shown.

This does not complete the task, since the individual wave forces of each degree of freedom must be derived for this general wave expression, namely the components of \(WF\). Again a much simplified version of the more complex real life wave forces were used. The \(X\) and \(Y\) forces are considered first. These can be modeled as cosine and sine functions of the expected wave direction \(EWD\) such that:

\[
WFX = WF \cdot \cos(EWD)
\]
\[
WFY = WF \cdot \sin(EWD)
\]

where \(WF\) is the total wave force of the encountered wave.

The rotational \(N\) forces are a little more difficult to establish. By considering that no rotational forces are created by a wave directly on the bow or stern, or directly off the beam, and that it is maximum when the wave is at 45 degrees off the bow or stern, a much simplified approximation is developed. Realizing that this method is very crude, the \(N\) force can be written as:

\[
WFN = WF \cdot \sin(2 \cdot EWD)
\]

To add more credibility to the wave model, a random
variable is added to the wave force at the waves fundamental frequency. A gaussian (normal) distribution was chosen with a zero mean and a standard deviation of one-tenth the maximum allowable force of WF. A zero mean signifies that the expected amplitude of the random wave is 0.0, while the standard deviation signifies that 68% of the random waves will have amplitudes less than one-tenth of the maximum allowable force of WF. Also, 94% will have amplitudes less than one-half the maximum allowable force of WF. This small added perturbation allows for verification of the model simulation with a stochastic force, which in turn adds creditability to the developed control systems.

What remains is to define the total wave force (WF). It is important not to fall into a common simulation pitfall which inevitably causes unneeded design changes. A sea state does not increase at an infinite rate. It therefore is incorrect to start a simulation with initial conditions set for calm sea and immediately introduce a high sea state perturbation. The initial large perturbation transient can give results that are not only unrealistic, but can cause the model and control system to produce unstable results. This is especially true in this case since the linearized (small perturbations about an operating point) equations of motion are used.

With this in mind, a ramp feed in of the wave force with a limiter at the desired maximum wave force (WFMA) was used. The slope of the ramp was established to impart minimum initial transients, yet increase the wave force to an acceptable testing level within the time frames of the simulations of chapter III. The slope is designed such that the maximum wave force is reached in 94.815 seconds actual simulation time (4.548 seconds problem time).

Computer program #4 was used to verify the wave action
model. Table II-5 on page 56 indicates the figures produced and changes in input wave length (WL) and wave direction (WD) for each run. The input parameters that were constant for all runs are tabulated below:

\[ \text{YAWDF2} = 0.0 \]
\[ \text{CDCT2} = 1.5 \]
\[ \text{WS} = 5.0 \]
\[ \text{WFMA} = 0.1137 \]

*\text{NCTE:} WS is the unnormalized wave speed. Conversion to normalized wave velocity is:
\[ \text{WV} = \frac{\text{WS}}{15.0} \]

Introduction of the wave forces is accomplished by multiplying the established wave forces by the rudder hydrodynamic coefficients for the individual reference directions. This effectively scales the wave forces to the ship model being used. The wave force result is coded in the ship simulation program as follows:

\[ \text{IF12} = \text{KA} \cdot \text{D2} + \text{YY2} + \text{KA1} \cdot \text{WY} \]
\[ \text{IF22} = \text{KE1} \cdot \text{D2} + \text{YN2} + \text{KB1} \cdot \text{WN} \]
\[ \text{IF32} = \text{KC1} \cdot \text{D2} + \text{NC2} + \text{KC1} \cdot \text{WX} \]

Detailed results of the wave force effects are given in chapter III and will not be dealt with here.
Interactive Forces Effect on the Geographic Plot

Figure II-13
Interactive Forces Effect of Yaw of the Control Ship
<table>
<thead>
<tr>
<th>Run</th>
<th>Figure*</th>
<th>Input Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>II-17</td>
<td>WL* 0.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>II-18</td>
<td>WD* 0.15</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>II-19</td>
<td>WL* 1.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>II-20</td>
<td>WD* 0.15</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>II-21</td>
<td>WL* 1.0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>II-22</td>
<td>WD* 0.30</td>
<td></td>
</tr>
</tbody>
</table>

*NOTE: WL is given in ship lengths
WD is given in degrees
Curve numbers of all runs corresponding to wave force components are:

<table>
<thead>
<tr>
<th>Force</th>
<th>Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>WX</td>
<td>1</td>
</tr>
<tr>
<td>WY</td>
<td>2</td>
</tr>
<tr>
<td>WN</td>
<td>3</td>
</tr>
</tbody>
</table>

Table II-5
Wave Simulation Listing
III. REPLENISHMENT AT SEA

A. HEADING CONTROL

1. Control Choice

Many studies involving replenishment at sea (RAS) have treated the problem as a multivariable system\(^1\)[\(^{10}\)][\(^{11}\)][\(^{12}\)][\(^{13}\)]. Academically, there is nothing wrong with this approach. However, as a practical system it leaves much to be desired. The key drawback in the multivariable system is the inescapable dependency on a command and control link between the replenishment ships. The unreliability of UHF communications at these close distances is a much experienced phenom. It is felt that any knowledgeable commanding officer would not entrust the safety of his ship to such a questionable link. An alternate method which is described here is a modern extension of the long trusted "seaman's eye" concept, where the sensors and control devices must be self contained on the ship making the approach (hereafter referred to as the receiving ship or ship B).

In all present day RAS operations, the ship on which the approach is being made (hereafter referred to as the supplying ship or ship A), must maintain the replenishment course and speed. The receiving ship accomplishes the maneuvers to maintain station relative to the supplying ship.

The parameters which are presently measured "visually" are relative position (in both the X and the Y directions),
relative head (usually in reference to ordered replenishment course), and relative motion in the X direction (for speed matching). These parameters are usually visualized by the conning officer who in turn gives corrective orders to the helmsman. The helmsman must then translate these verbal orders into rudder and speed commands through the helm and lee helm consoles. The accuracy of the execution of the conning officer's orders is extremely dependent on the ability of the helmsman and throttleman. This system can be quite effective, and it can also be quite disastrous. This fast reacting and constantly changing environment lends itself to breakdown in communications and manifests the inability of some individuals to cope with the required critical man-machine interfaces.

To eliminate these problems, present state of the art digital computers and sensors are available for immediate implementation of a completely automatic ship control system. Such a control system may be installed on individual ships and be used for RAS without the requirement of having the matching installation on the other ship of the hckup (another drawback of the multivariable approach).

2. Control Method

One of the many pitfalls that may be encountered in digital simulation is the reality of the parameters that are measurable in the real world situation as opposed to those that are incidently available in the simulation. With this fact as a keynote, Subroutine RBMEAS (Range and Bearing MEASurement) was developed. This subroutine, as listed in appendix A, defines the forward (FWD) and after (AFT) relative and true bearings, and ranges from the receiving ship to similar points on the supplying ship. Figure III-1 delineates the terms used in the subroutine. The SDFn terms
Note: $A1 = 360 - AA1$
$B1 = 360 - BB1$
$B2 = 360 - BB2$

Figure III-1
Measurement Techniques

65
are used to position the bow and stern sensors and reflectors on ship B and A, respectively, in geographic coordinates as a function of ships' head. The FWD distance on the X coordinate is ADPX and the Y coordinate is ADPY. Similarly, the AFT distances are ADAX and ADAY. R1 and R2 are the FWD and AFT ranges measured by a highly accurate ranging device installed on ship B. This same ranging device, if properly provided with a pinpoint reflector on the supply ship (ship A), will give accurate relative bearings FWD and AFT., B1 and B2 respectively. The distance between sensors may be varied, but as a rule should be kept as far apart as possible to allow maximum sensitivity. The distance used in this thesis is 1.0 (one ship length), and the distances were considered the same for both ships. This is not a necessary condition and may be changed to suit the situation.

Subroutine RBMEAS assumes highly accurate sensors in both range and bearing measuring ability. Such sensors are presently available in the form of Radar altimeters[1*] and Laser ranging devices. Another possibility for a measuring method is a single sensor time sharing to obtain range and bearing to both reflectors from a single device. Such a single sensor scheme is sketched in figure III-2.

Once the FWD and AFT parameters are available, they may then be used to determine other desired quantities. Subroutine HDGRAS (Heading control for RAS) was developed to output the desired heading corrected for heading difference of ship A and B and the projected correction for distance error. This subroutine is listed in appendix A. The center range and bearing are the average of the FWD and AFT range and bearing output from Subroutine RBMEAS.

The additional heading due to distance is projected as if ship E maintained its present course until it was
Figure III-2
Alternate Method of Measurement
perpendicular to the center of ship A. The reasoning behind this is illustrated in figure III-3. If the present course will cause ship B to arrive on the station desired (DS), no heading change is required. The expression for PSIAEC (Additional heading due to Distance Correction) is:

$$\text{PSIADC} = \text{RSENS} \cdot (\text{DDC} + \text{DA} \cdot \sin(\text{AA1}))$$

where:

- \text{RSENS} = Range SENSitivity gain
- \text{DDC} = Distance Desired Corrected for side of approach
- \text{DA} = center Distance Absolute (range)
- \text{AA1} = 360 degrees - relative bearing of center position

The heading difference of ship A and B is desired since, even if the range when alongside is correct, a large disparity in heading cannot be tolerated. It is realized that some heading difference (crabbing) is necessary to maintain the distance. This crabbing is due entirely to the pressure forces modeled in chapter II. This heading difference is found by computing the difference in the perpendicular projection between the FWD and AFT measurements and finding the arcsin of this difference divided by the distance between sensors. Figure III-4 indicates a sample of this procedure.

The expression for total desired heading is given as follows:

$$\text{PSIDES} = \text{PSIAEC} + \text{WTSENS} \cdot \text{PSIDIF} + \text{PSIB}$$

where:

- \text{PSIDIF} = \# additional heading due to heading DIFFerence
- \text{WTSENS} = Weighted heading difference SENSitivity gain

68
Figure III-3
Distance Logic
Figure III-4
Heading Difference Calculation
\[ \text{PSIDES} = \Phi \text{ (heading) DESired} \]

Throughout the subroutines and main DSL programs, the function \text{DEGRAD} (conversion of degrees to radians and radians to degrees) is used freely. An explanation and listing of this function are presented in appendix A.

The angular velocity of the receiving ship's head is also of concern in the RAS situation. This quantity may be thought of as similar to tachometer feedback in a simple servo control system; and is necessary to damp out the response (the responses of this control system without this feedback is presented in the latter section of this chapter).

The desired rudder command is a combination of the desired heading, angular velocity feedback, and a rudder gain as follows:

\[ \text{Desired Rudder} = (\text{YAWD2} - \text{PSIDES} + \text{BDOTFB}) \times \text{RGN} \]

where:

\text{YAWD2} = heading of ship B (in degrees)
\text{PSIDES} = \Phi \text{ (in degrees)}
\text{BDOTFB} = \text{VFBG} \times \text{BDOT2D}
\text{VFBG} = \text{Velocity Feedback Gain}
\text{BDOT2D} = \text{angular velocity of ship B heading angle} \text{ (in degrees/sec)}
\text{BDOTFB} = \text{angular velocity Feedback}
\text{RGN} = \text{Rudder Gain}

The convention for rudder response dictates negative
rudder as being right rudder, which causes positive yaw. This necessitates making the desired rudder the negative of the forcing function and feedback quantities. The block diagram of figure III-5 presents the control loop from measurement inputs to desired rudder command.
3. **Optimization**

Thus far the control choice has identified four gains (BSENS, WISENS, RGN, VFBG) that must be set for proper position attainment. The nonlinear nature of the system which appears in the form of distance measurements, interactive forces and rudder modeling do not allow for straight forward determination of these gains with normal optimal control theory.

### a. Technique

Grossly nonlinear systems require special handling to determine proper gain settings. The method chosen for this purpose was an optimization algorithm developed by M. J. Box (programmed locally as subroutine BOXPLX). This subroutine, listed in appendix A, was used to locate the cost function saddle point in four dimensional space (the dimensions being the previously mentioned gains). The drawback associated with this method is the necessity of iterating the complete nonlinear simulation within function FE for every evaluation of the cost function. The gains sought were found, but unfortunately only after 2 1/2 to 3 hours of CPU time with every 400 iterations allowed.

The mechanics involved in optimizing the chosen cost function include required sub-calculations in many functions and subroutines. Figure III-6 is a flow chart which demonstrates the steps, subroutines and functions required.

Initial optimization was accomplished for one set of initial conditions. By looking at the RAS situation, a probable set of circumstances were envisioned. The scenario setting is the approach phase where the replenishing ship
Figure III-6
Optimization Flow Chart
starts a wide approach at 0.4 ship lengths (211 feet) lateral displacement and 5 ship lengths (2639.0 feet) astern of the supply ship. The desired final position is alongside at 0.2 ship lengths (105.6 feet) lateral separation. Both ships have the same initial heading (YAW angle). The supply ship is at 15 kts. (1.0 normalized speed) and the receiving ship makes its approach at 22.5 kts (speed control will be covered later in this chapter).

b. Cost Function

Normal costing of displacement error with the integral of the squared error (ISE) was considered as the optimization tool in subroutine BOXPLX. However, this type of performance measure would weigh the initial displacement error equally with the final position error. This problem can be circumvented by comparing the displacement error to a pre-computed reference track instead of to the desired displacement. For the envisioned scenario, it was conceived that the cost function should weight the distance displacement heavier when the ships are alongside than when the approach is started 5 ship lengths astern.

This was accomplished by using the integral of time times the absolute error (ITAE) as the optimization performance measure. The reference displacement was considered the desired position displacement. The objective function can then be written as:

\[ CBJ = \int_{t_o}^{t_f} t \cdot |DD - ADY| \, dt \]

where:

\[ DD = \text{Desired Distance} \]
\[ ADY = \text{Actual Displacement in the Y direction} \]
\[ t = \text{time} \]
A performance measure that is designed to obtain good performance must also take into account other factors besides just position accuracy. Consequently, another cost criterion was decided upon which would also set the gains to reduce the amount of rudder control required when alongside. This particular feature is derived from the desire not to over control with the rudder in such close proximity to another vessel. The inclusion of this term in the performance measure is weighted by unity while the distance accuracy is weighted by a factor of 10.0. This will tend to allow rudder action if the desired position is not maintained. The final approach phase cost function for obtaining optimum gains has the form:

\[
CEJ = \int_{t_0}^{t_f} t (10.0 \cdot |DD-ADY| + 1.0 \cdot |D2|) \, dt
\]

where the additional term is:

\[
D2 = \text{rudder response of the replenishing ship}
\]

c. Results

In the process of deciding on the best gain definitions previously mentioned, many optimization runs were made. Each set of gains were then simulated in a corresponding DSL program to obtain performance confirmation. Many of these runs did not live up to expectations; causing re-evaluation of the control scheme until the one presented in this thesis was formulated.

Table III-1 shows the input upper and lower limits of search (ED, EL), starting value guess (XS), optimum gain settings (Output) and associated objective function value (CBJ) for 20.0 second normalized time simulation run in function FE. These values were then introduced into the DSL simulation program listed as program #5. The results of this simulation are shown in figures III-7 thru III-12. The
<table>
<thead>
<tr>
<th></th>
<th>BSENS</th>
<th>WSENS</th>
<th>VFBG</th>
<th>RGN</th>
<th>BU</th>
<th>BL</th>
<th>XS</th>
<th>OUTPUT</th>
<th>OBJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>2.0</td>
<td>20.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>50.0</td>
<td>1.0</td>
<td>10.0</td>
<td>1.0</td>
<td>1.0</td>
<td>2.3869</td>
<td>1.86642</td>
<td>4.35162</td>
<td>60.7103</td>
</tr>
</tbody>
</table>

Table III-1: Approach Phase Optimization Results
Figure III-9
Approach Phase N Moments
Figure III-10
Approach Phase Geographic Plot
geographic plot of figure III-10 indicates excellent positioning in the lateral direction while the rudder response of figure III-12 shows that it settles out to a fairly constant steady state value as the ship settles into its desired position. The time coordinates in all plots are shown in actual full scale time.

d. Control Testing

Now that the "proper" gain settings were obtained, more extensive testing of the control system was required. Three different tests were contemplated: (1) allow a large perturbation turn of the reference ship (supply ship), (2) start approach of the receiving ship (control ship) from different initial conditions of lateral and horizontal displacements, and (3) induce external perturbations in the form of wave forces.

The first test was simulated by turning the reference ship by normal rudder action of figure III-13. This turn with 5 degrees rudder accounted for a total reference yaw change of 15 degrees. The rudder action of the controlled ship shown in figure III-14 was as expected. However, the distance maintenance portrayed in figure III-15 was totally unacceptable. The maximum excursion from the desired distance of 105.56 feet (0.2 normalizes distance) was 55.419 feet (0.105 normalized distance). Variances of this magnitude cannot be tolerated in the RAS environment.

Faced with this situation, the tactic chosen was to re-evaluate the gains for the new scenario which is called the turn phase. In this phase the initial conditions assume steady state positioning alongside such that the lateral position displacement (DY) is equal to the desired distance \[ 105.56 \text{ feet (0.2 normalized)} \] and that the horizontal position displacement (DX) is 0.0 (alongside).
Figure III-13

Turn Phase Rudder Action of Reference Ship
Some initial perturbation is introduced by assuming the relative yaw angle when alongside is negligible.

e. second optimization

The same procedure was followed in obtaining gains that would optimize a chosen cost function. Figure III-6 still applies except that function FEA is replaced by function FEB (listed in appendix A) to simulate the new conditions.

Cost function criteria change in this instance since the ships start at the desired position and optimally stay at the same relative positions. Also, the rudder response to such large turning perturbation must be free to cause achievement of the desired position. Due to these considerations, the integral of the absolute error (IAE) performance measure was chosen for the optimization criterion and can be written as:

\[ O_{EJ} = \int_{t_0}^{t_f} |A_y| \, dt \]

Table III-2 shows the results of the turn phase optimization and the comparison with the approach phase gains. Again CSL simulation was performed using the turn phase scenario. Figures III-16 thru III-21 portray the graphical results. The rudder response of figure III-21 indicates very sensitive response to the interactive forces shown in figures III-17 and III-18. The lateral distance separation of figure III-20 indicates excellent position maintenance with maximum excursion error of only 2 feet (0.0038 normalized). This minimal variation is well within that which can be tolerated in the RAS environment.
<table>
<thead>
<tr>
<th>Gain</th>
<th>RSENS</th>
<th>WSENS</th>
<th>VPBG</th>
</tr>
</thead>
<tbody>
<tr>
<td>BU</td>
<td>2.0</td>
<td>20.0</td>
<td>10.0</td>
</tr>
<tr>
<td>BL</td>
<td>0.1</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>XS</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

| OUTPUT | 1.99765 | 0.7357 | 49.9776 | 0.084028 |
| OBJ    | 0.009145 | 2.3869 | 23.4185 | 4.35162  |

Table III-2

Turn Phase Optimization Results
Figure III-16

Turn Phase Yaw Response
Figure III-17
Turn Phase Y Forces
Figure III-19
Turn Phase Geographic Plot
Figure III-21
Turn Phase Rudder Response
f. Continued Control Testing

To alleviate suspicions that the response from the gains obtained in the approach phase could be improved by the gains obtained in the turn phase, a simulation of the approach phase was accomplished with the new gains. Figure III-22 is the graphic display of the effect of these gains on the approach phase lateral distance positioning.

Careful analysis of the results thus far clearly indicate the need for an adaptive control scheme to allow gain adaptation to meet the design specifications. A full adaptive control scheme for systems of this type is outside the scope of this thesis. References 15 thru 23 are indicators of some of the literature available for pursuit of a completely adaptive control system.

What was done here is development of a simple algorithm to sense when the conditions were adequate to switch from one set of gains to another. This may be done with the two sets of gains developed thus far. However, for the sake of simulation efficiency, a third set of gains was introduced. This third set amounts to a change of one approach gain (RSENS) which has previously been defined as the range sensitivity gain. The simulation efficiency is increased by decreasing the time required for the approach phase to reach steady state. A consequence of this procedure is a reinforcement of the need for a completely adaptive control scheme.

Repeated simulation revealed that commencing the turn (in effect switching gains), before a reasonable steady state was reached caused results similar to those shown in figure III-22. An increase in RSENS to a value of 4.0 when the lateral separation error is less than 0.05 (normalized)
Figure III-22
Approach Phase Lateral Distance DP

desired distance DP

Time (sec x 10^2)

0.00

0.03

0.06

0.09

0.12

0.15

0.18

0.21

0.24

0.27
and greater than 0.005 (normalized) forces acceptable steady state in approximately \( \frac{1}{2} \) the time previously required using a single set of approach gains.

Subroutine SWITCH (listed in appendix A) incorporates this simple adaptive gain schedule with a counter mechanism to sense when steady state is reached. Further study indicated a need to damp the yaw oscillations to a greater extent if the yaw velocity (BEOT2D) exceeded 2.0 degrees/sec when the gains are initially switched to the more sensitive ones of the turn phase. This is an artificial adaptive gain for VFEG caused by computer time restrictions prevalent in a full scale computer simulation where both the approach and turn phases are desired. If the gain switching point is moved up in time, as would normally be the case in a real life situation, this damping increase would not be required.

The results of the full scale simulation using computer program #6 are shown in figures III-23 thru III-34. The approach phase plots of figures III-23 thru III-28 show definite improvement over that previously shown in figures III-7 thru III-12. Figure III-27 indicates that the overshoot is reduced to 10.6 feet (0.02 normalized) as opposed to 17.9 feet (0.034 normalized) that was prevalent in figure III-11.

The turn phase plots are shown in figures III-29 thru III-34 and show responses very similar to those shown previously in figures III-16 thru III-21. The only significant differences occur in the initial responses which are due to the incorrect initialization when the turn phase was simulated individually.
Figure III-23
Approach Phase Yaw Response
Figure III-28
Approach Phase Rudder Response
g. Varying Initial Conditions

The results obtained in the previous section are most gratifying but actually incomplete. This system must work for other initial conditions quite different from those envisioned in the optimization scenario. The initial approach can realistically commence at points other than 5 ship lengths astern and displaced by 0.4 ship lengths.

By simulating this system with varying initial positions, the relative efficiency and worth of the control system can be observed. This was done in successive test runs whose initial conditions and corresponding plot figures are tabulated in table III-3. For the sake of brevity only those figures required to illustrate the relative efficiency of the control system are included. The corresponding initial optimization simulation figures are listed for cross reference. The turn phase plots for all runs except 4 and 6 exactly match that of the initial simulation and are not repeated here.

Runs 3, 5 and 6 were accomplished to show that no ambiguities exist in the control scheme to prohibit adequate real life initial conditions. Run 3 simulates the situation most often encountered by this author in the RAS environment. This scenario starts the control ship dead astern at 5.0 ship lengths and brings it alongside at 0.2 ship lengths lateral separation.

Run 5 is a situation where the approaching ship is purposely placed out of position on the wrong side for approach. The control scheme adequately corrects the placement error and will do so for all cases of this type, provided that there is adequate maneuvering room astern of the reference vessel (in this case 2.6 ship lengths was
<table>
<thead>
<tr>
<th>RUN</th>
<th>Initial Development</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Condition X01</td>
<td>5.0</td>
<td>4.0</td>
<td>3.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Desired Distance Y02</td>
<td>0.4</td>
<td>0.3</td>
<td>0.25</td>
<td>0.0</td>
<td>0.2</td>
<td>-0.4</td>
<td>-0.4</td>
</tr>
<tr>
<td>Approach Side DD</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.15</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Approach Side IS</td>
<td>STBD</td>
<td>STBD</td>
<td>STBD</td>
<td>STBD</td>
<td>STBD</td>
<td>STBD</td>
<td>PORT</td>
</tr>
</tbody>
</table>

### Approach Phase Figures (III-)

<table>
<thead>
<tr>
<th>YAW</th>
<th>Geographic Plot</th>
<th>Rudder Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>35</td>
<td>36</td>
<td>39</td>
</tr>
<tr>
<td>41</td>
<td>42</td>
<td>43</td>
</tr>
<tr>
<td>44</td>
<td>45</td>
<td>46</td>
</tr>
<tr>
<td>47</td>
<td>48</td>
<td>49</td>
</tr>
<tr>
<td>50</td>
<td>51</td>
<td>52</td>
</tr>
</tbody>
</table>

### Turn Phase Figures (III-)

<table>
<thead>
<tr>
<th>YAW</th>
<th>Geographic Plot</th>
<th>Rudder Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>53</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td>29</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>56</td>
<td>57</td>
<td>58</td>
</tr>
</tbody>
</table>

Table III-3
Initial Condition Simulation Cross Reference
Figure III-35
Approach Phase Run #1 Yaw Response
Figure III-37

Approach Phase Run #1 Rudder Response
Figure III-41
Approach Phase Run #3  Yaw Response
Figure III-42
Approach Phase Run #3 Geographic Plot
Figure III-46
Approach Phase Run #4 Rudder Response
Figure III-50
Approach Phase Run #6  Yaw Response
Figure III-55
Turn Phase Run #4 Rudder Response
Figure III-56
Turn Phase Run #6 Yaw Response
experienced which gives 1.6 ship lengths bow to stern clearance).

The purpose of run 6 is to provide simulation for an approach from the opposite side again disproving any concern for ambiguity in the trigonometric measurement scheme utilized. In all runs it must be emphasized that DD is the positive absolute distance desired and that IS provides the code flag for the desired side of approach. The system will work with DD set to some negative quantity; but the side of approach will reverse itself and the position placement will be correct, but on the side not desired.

Run 4 takes the desired distance into 0.15 ship lengths (80.0 feet). This distance is usually the minimum desired by a prudent seaman. Again, even with this minimum distance, the control system performs up to desired standards. The importance of this run cannot be overlooked. Performance of the system at this extremum indicates that the gains utilized are correct for all expected conditions encountered in calm seas. Figures III-59 thru III-64 portray the remaining plots obtained in run 4.

h. Performance in Sea State

The calm sea performance of the heading control system is only part of the system testing required. Of even greater concern is the adequacy of the control when sea state is introduced. Section D.2. of chapter II models the three components of waves with two sinusoids and a small random impulse wave. These forces were introduced into the total RAS simulation as shown in computer program #7. In this program the wave length (WL) is set to one ship length and the wave direction (WD) is -0.15 degrees true. This scenario allows for a port turn into the prevailing sea as is common practice in experienced RAS evolutions. By
Figure III-59
Approach Phase Run #4 Lateral Y Forces
Figure III-63
Turn Phase Run #4  Rotational N Moments
Figure III-64
Turn Phase Run #4  Lateral Distance DY
minimizing the perturbation forces on yaw and lateral direction, a smoother RAS can be accomplished thus aiding safety and comfort during the actual transfer. The wave force maximum is taken as 0.05685. Runs were simulated which used maximum wave forces in the range 0.1137 to 0.05685, wave lengths from 0.5 to 1.5 ship lengths and wave directions 0.15 to -0.15 degrees off the initial replenishment course. The control system handled all of the perturbations well except for the cases of a wave length of 1.5. This length of wave with a force of 0.05685 exceeded the control systems capability in that the steady state conditions were not met before a turn was commenced. Figure III-65 shows this instability in the lateral distance $D_Y$ of the turn phase. It is felt that the modeling inadequacies of the sea state development of chapter II coupled with a simple adaptive gain scheme are the source of the problem. This same phenomenon is covered in greater detail in the longitudinal position offset testing portion of the velocity control section of this chapter.

Problems of this type also manifest themselves in some cases when the wave force maximum (WFMA) was close to the 0.1137 value. If the sea state becomes excessive, which this value represents, a different gain schedule or, at best, a more complex adaptive gain scheme is called for.

The plots produced by computer program #7 are presented as a representative indication of the effectiveness of the control system in the presence of a sea state. Figure III-66 gives the yaw results of the approach phase which indicates the effect of the wave action. The corresponding rudder action of figure III-67 compensates to give the smooth lateral distance shown in figure III-68. The wave profile is shown in figure III-69 with curve 2 being $W_Y$ and curve 3 being $W_N$. Curve 1 is the $W_X$ profile which was not used in this run but will be utilized in the speed control.
section later in this chapter. Similar curves are portrayed for the turn phase. Figure III-70 is the yaw difference between the two ships (remembering that the reference ship is not being perturbed by the interaction forces or the wave forces). Figure III-71 is the lateral distance $DY$ maintained by the rudder response of figure III-72. The maximum lateral separation in the turn phase is 0.0037 ship lengths (1.55 feet). The wave profile is shown in figure III-73 with the same wave force curve sequence as the approach phase.

As can be seen from these plots, the control system operates very effectively in the presence of a sea state. Again, the development of a much more complex adaptive gain scheme is required to allow exceptionally high sea state. It is felt that the control system presented in this thesis is adequate for most situations that are encountered in the RAS environment. Only the extreme perturbations that chance would allow must be accounted for in a more complex adaptive gain scheme.
Figure III-66
Wave Effect on Approach Phase Yaw  WL=1.0
Approach Phase Rudder Response to Waves WL=1.0

Figure III-67
Figure III-69
Approach Phase Wave Profile  WL=1.0
Figure III-70
Wave Effect on Turn Phase Yaw WL=1.0
Figure III-71

Wave Effect on Turn Phase Lateral Distance (DY)  WL=1.0
E. VELOCITY CONTROL

One advantage derived from using the linearized equations of motion is the decoupling of the velocity components from the remaining equations of motion. This allows separation of the design procedures for lateral separation control and velocity control. Section A of this chapter designed the lateral separation control using the simple speed control algorithm shown in figure III-74. This control output was used directly as the ship's speed (CDCT2) in the model simulation where no attempt was made to use the engine response developed in chapter II. Function SPDCTB of appendix A shows the control used.

![Velocity Graph](image)

Figure III-74
Non-optimum Speed Law

Because of this decoupling assumption, any valid approach speed control can be used, if used consistently,
for such a design. However, in the RAS environment, complete disassociation is not possible. Recombination occurs in the interactive forces and moments which depend upon the longitudinal distance as well as the lateral distance. Consequently, speed, which is directly responsible for the longitudinal distance, has a direct relation to the lateral distance attainment and maintenance.

The remaining parts of this chapter deal with the development of a viable speed control algorithm and the testing of the designed system.

1. Type of Control

Whenever two ships maneuver for replenishment at sea (HAS), the prime considerations are the time required for approach and the accuracy of position keeping plus conservation of fuel.

The nonlinear control law of figure III-75 is designed to maintain a preselected approach speed for minimum approach time. The proper location of the switching point increases the complexity of the solution since the time of switching from this speed is determined by the dynamics of the nonlinear position attainment loop. Once this position is reached, the speed controller is switched down to a linear portion of the control law to allow control for perturbations about the operating position. However, small perturbations about this operating point can be tolerated and, in fact, are desired to allow for conservation of fuel. Selection of this dead zone is wholly dependent on the accuracy required for final position. Figure III-75 indicates a dead zone extending to ±0.001 normalized distance which in this case translates to ±0.53 feet. Systems for which fuel considerations are not a motivating
factor may be designed without this part of the control law to allow finer tracking in the position loop.

The speed control law as explained above is shown in figure III-75 for an initial approach speed of SPD02 and a final estimated reference speed of SPD01, with ADX being the dynamic position feedback defined as the longitudinal distance between centers of the ships referenced to the controlled ship's heading. Analytically, the linear portion of the control law is written as:

\[ \text{SPDCTR} = -\text{ADX} \cdot (\text{SPDC2} - \text{SPD01}) + \text{SPD01} \]

Symmetric continuation of the control law accounts for operation on both sides of the operating point.
2. Optimization

Using this much simplified model of chapter II and the basic control law of figure III-75, the desired switching curve can be established. An optimization subroutine such as Subroutine BOXPLX can be used to iteratively obtain the optimum switching position (SW) for representative initial approach speeds. Figure III-76 is a flow chart of the subroutines and functions required for speed control optimization. The major merit of this nonlinear control law stems from the predetermination of the switching point for all possible conditions of initial speeds. This a priori
knowledge allows for offline computation of the switching position prior to commencing the approach. The cost function used for optimization is the ITAE which accomplishes two objectives. First, it forces the approach to be accomplished in minimum time. Secondly, it insures that the fuel expenditure will be optimized in the elimination of most overshoot and bang-bang control in the dead zone portion of the control law. The final value of the position error must be within the specified dead zone and the terminal speed must match the reference speed (SPD01). The cost function has the following form:

\[ J = \int_{t_0}^{t_f} (t \cdot |ADX|) \, dt \]

Table III-4 is a comparison of the optimization runs with various initial speeds. The values shown for \( S_w \) must be multiplied by the speed differential (SPD02-SPD01) to obtain the corresponding value of ADX. The max/min values show the band of values which produce the optimum cost. This range of values is attributed to the integration step size used in the optimization program. Experience with this particular optimization program indicates that erroneous values of the switching point are found if the step size is not carefully chosen. The step size may be adequate for integration, but not for location of the switching point.

The points obtained from the optimization runs are plotted in figure III-77. These points define the nonlinear switching curve which must be stored in the computer to insure optimal operation of the speed control for all approach speeds. From here there are many procedure options open. These options have as a goal some usable form for predicting the optimal switching point for any set of initial conditions. One may choose linear straight line segments with an interpolation routine, or a closed form switching curve polynomial. Due to the availability of a
### INITIAL CURVE POINTS

<table>
<thead>
<tr>
<th>SPDO2</th>
<th>SPDO1</th>
<th>SW MAX</th>
<th>SW MIN</th>
<th>SW</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td></td>
<td>.545*</td>
<td>.545</td>
<td>.545</td>
<td>22.340515**</td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td>.58705</td>
<td>.58424</td>
<td>.585</td>
<td>5.733367</td>
</tr>
<tr>
<td>1.3</td>
<td></td>
<td>.62656</td>
<td>.6256</td>
<td>.626</td>
<td>2.700768</td>
</tr>
<tr>
<td>1.4</td>
<td></td>
<td>.6845</td>
<td>.68234</td>
<td>.683</td>
<td>1.672599</td>
</tr>
<tr>
<td>1.5</td>
<td>1.0</td>
<td>.73169</td>
<td>.7283</td>
<td>.729</td>
<td>1.223071</td>
</tr>
<tr>
<td>1.6</td>
<td></td>
<td>.7644</td>
<td>.76142</td>
<td>.763</td>
<td>0.992283</td>
</tr>
<tr>
<td>1.7</td>
<td></td>
<td>.7945</td>
<td>.7926</td>
<td>.7936</td>
<td>0.861552</td>
</tr>
<tr>
<td>1.8</td>
<td></td>
<td>.82178</td>
<td>.81945</td>
<td>.82</td>
<td>0.774621</td>
</tr>
<tr>
<td>1.9</td>
<td></td>
<td>.8501</td>
<td>.8439</td>
<td>.85</td>
<td>0.757244</td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td>.8673</td>
<td>.86375</td>
<td>.865</td>
<td>0.730168</td>
</tr>
</tbody>
</table>

### CURVE CHECK POINTS

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>1.1</td>
<td>.6859</td>
<td>.6823</td>
<td>.683</td>
<td>1.668055</td>
</tr>
<tr>
<td>1.5</td>
<td>1.2</td>
<td>.6307</td>
<td>.6297</td>
<td>.6302</td>
<td>2.691659</td>
</tr>
<tr>
<td>1.6</td>
<td>1.2</td>
<td>.67965</td>
<td>.67906</td>
<td>.6793</td>
<td>1.659956</td>
</tr>
</tbody>
</table>

*cpu usage over 4 min. - run not complete.

**cost function based on 20 min problem time
all others based on 10 min problem time.

Table III-4
Optimization Results
A polynomial curve fitting algorithm was used to obtain the required polynomial coefficients of best fit. This was done for polynomials of order 1 thru 5. The coefficients and the sum of the squares of deviation from the original points are tabulated in table III-5. The selection of the order to be used is highly dependent on the degree of accuracy required. In the HAS problem, the average error introduced for a first order fit is 8.0 feet (1.07 sec), while the fifth order fit introduces an average error of 1.35 feet (0.180 sec). Prior acceptance of errors introduced by an integration (and problem) step size of 0.8 sec allows for use of a second order fit without any degradation of simulation accuracy [second order average error is 2.848 feet (0.38 sec)]. The graphic display of figure III-78 indicates very little difference in the switching curves for second to fifth order polynomial fits. For the sake of accuracy, and owing to the computer control methods of this thesis, the fifth order polynomial fit shown separately in figure III-79 is used for determination of the switching point location.

3. Control Testing

A true test of the control law is accomplished when it is introduced in a computer program for a complete HAS simulation. Considering the performance of this controller in a complex environment of full scale HAS simulation allows maximum verification of the controller design.

The scenario for this simulation initially positions the ships such that the ship being controlled starts an approach 5 ship lengths (2639 feet) behind the reference
<table>
<thead>
<tr>
<th>POLYNOMIAL DEGREE</th>
<th>COEFFICIENTS OF POWER</th>
<th>SUM OF SQUARES OF DEVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.367928</td>
</tr>
<tr>
<td>2</td>
<td>-0.194621</td>
<td>0.582011</td>
</tr>
<tr>
<td>3</td>
<td>-0.174164</td>
<td>0.092751</td>
</tr>
<tr>
<td>4</td>
<td>0.748543</td>
<td>-1.29791</td>
</tr>
<tr>
<td>5</td>
<td>6.93243</td>
<td>-8.04233</td>
</tr>
</tbody>
</table>

Table III-5

Polynomial Curve Fit Results
ship and displaced 0.4 ship lengths (211 feet) to the right. The desired final position is alongside and displaced 0.2 ship lengths (106 feet). The heading control system used is developed in section A of this chapter.

The approach phase is accomplished with the speed desired and speed acquired shown in figure III-80 with the corresponding position attainment exhibited in figure III-81. These plots show excellent switching and optimal position attainment.

The next step is to insure that the position keeping loop will maintain the desired position with an induced perturbation. This is accomplished by turning the reference ship away from the control ship a total of 15 degrees to observe the reaction of the speed control loop. The reference ship's turn causes the relative motion between the ships to be altered, making the control ship lag the desired position. The nonlinear control system is designed to correct this situation as soon as the actual position is outside the limits of the dead zone. Figure III-82 displays the desired speed and acquired speed for the control ship. Figure III-83 indicates that the corresponding position deviates from the desired by 0.0154 ship lengths (8.13 feet) at the maximum excursion. This is well within the limits of acceptability for such a drastic perturbation.

The introduction of velocity control was accomplished by combining the simplified engine response of chapter II and the speed control law developed here. By setting the speed desired (SPDDES) equal to the output of Function SPDREC and scaling the speed error (SPDERR) to the nondimensional equations of motion, the velocity loop is initiated. The auxiliary equations added to those presented in chapter II are:
Figure III-80
RAR Speed Control Approach Phase
Speed Desired (1) and Speed Acquired (2) vs Real Time
Figure III-81
RAS Speed Control Approach Phase
Position Attainment vs Real Time
Figure III-82

RAS Speed Control Turn Phase

Speed Desired (1) and Speed Acquired (2) vs Real Time
Figure III-83
RAS Speed Control Turn Phase
Position Attainment vs Real Time
These equations are introduced in computer program #8 to produce figures III-80 thru III-83.

Further system study indicates that the reference ship speed must be known to a fairly high degree of accuracy. Without apriori knowledge of the reference ship speed, a constant bias is introduced. The amount of bias allowable defines the permissible uncertainty in the reference ship's initial speed. This bias can amount to as much as 0.1 ship lengths (84.48 feet) for a reference speed inaccuracy of 2.5 knots (0.1 normalized speed). However, it is felt that the reference speed in any practical situation will initially be known to within 0.5 knots (0.02 normalized speed). This more practical error will introduce a bias of only 16 feet.

Other feedback parameters can be used to offset the lack of apriori knowledge of the reference ship speed. Since the reference ship is tracked with a high accuracy range and bearing device and the controlled ship's speed is measured, a decoupled multivariable scheme is used to further refine the reference ship speed. With high resolution devices presently available[14], it is estimated that this can be done practically to within 0.05 knots (0.002 normalized speed). This would bring the offset bias to 1.6 feet; well within previously defined errors introduced by integration step size.
4. **Longitudinal Position Offset**

Throughout the development of the heading control and speed control, the scenario has followed the condition that the final position would be longitudinally alongside. Although this is a good assumption for ships of the same type, it does not account for RAS station differences for different ship types. To alleviate this disparity, function SPDREC was redesigned to allow pre-planned offset condition to exist. Function SPDOFC of appendix A is a result of this redesign.

Simulation runs, with a change of the speed control function only, resulted in some unstable conditions existing in the heading control loop. The cause of this phenomenon stems back to the adaptive gain scheme used and the changes made to force the control loop to a steady state value prior to a turn. By using a favorite ploy of experienced conning officers, this problem is alleviated. The ploy is to take the ship alongside and then either drop back to station or surge forward to station. This method is accomplished by setting the initial offset (XOFS) to 0.0. The final desired offset (XCFSD) is stored and not used until the ship is settled out alongside. It is subsequently used as shown in the following Fortran code:

```
IF (ATIME.GT.450.0) XOFS = XOPSD
```

This method solved the gain transition problem. It did not, however, give a completely stable simulation run. Unstable conditions still existed at the end of the turn phase. This is not surprising, considering the heading control optimization method used. The set of gains previously found were for the alongside scenario only.
Different interactive forces and moments at the offset position cause these gains to be no longer optimal.

By relaxing the control loop in the heading velocity feedback gain (VFBG), sub-optimal control at all practical offset positions is achieved. The gain VFBG was changed from 0.064028 to 0.1 in the turn phase adaptive gain schedule without significant loss of control efficiency for alongside operation (2.3 feet maximum excursion vice 2.0 feet previously obtained). Subroutine SWTCHF of appendix A reflects the gain change and offset calculations required. Computer program #9 incorporates the changes required for offset simulation. Table III-6 is a cross reference listing of the plots obtained. From these figures, the effect of different longitudinal positions is readily apparent. An offset of 0.1, equating to 52.8 feet, causes greater lateral excursions when astern (XOFSD = -0.1) of the alongside position than when ahead (XOFSD = 0.1). The longitudinal position maintenance, however, is essentially the same in all cases.

<table>
<thead>
<tr>
<th>Run</th>
<th>Approach Phase Plots</th>
<th>Turn Phase Plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>XOFSD</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Lateral Distance DY</td>
<td>84</td>
<td>86</td>
</tr>
<tr>
<td>Yaw Difference</td>
<td>85</td>
<td>87</td>
</tr>
<tr>
<td>Speed Response</td>
<td>80*</td>
<td>88</td>
</tr>
<tr>
<td>Longitudinal Position DX</td>
<td>81*</td>
<td>89</td>
</tr>
</tbody>
</table>

*Note: These plots are the same as those obtained from computer program #8 and are not repeated here.

Table III-6
Position Offset Testing Cross Reference

174
An alternative to the method shown here is again a completely adaptive gain scheme which would achieve optimal control instead of the sub-optimal control settled for here. The alternative may become even more important if the nonlinear terms of the equations of motion are considered. This would couple the heading and speed control designs to a larger extent than encountered in the interactive forces and moments.
Figure III-85

Approach Phase Run A Yaw Difference
Figure III-87
Approach Phase Run B Yaw Difference
Figure III-89
Approach Phase Run B Longitudinal Position DX
Figure IIT-92
Approach Phase Run C Speed Response
Figure III-93
Approach Phase Run C Longitudinal Position DX
Figure III-98
Turn Phase Run B Longitudinal Position DX
Figure III-99
Turn Phase Run C Lateral Distance DX

Time (Sec x 10^2)

5.00 6.50 8.00 9.50

2.00 3.50 5.00 6.50 8.00
Figure III-101

Turn Phase Run C Longitudinal Position DX
5. Wave Effects on Velocity Control

The final testing procedure involves validation of the speed control system in the presence of waves. This perturbation testing continues that started in section A. of this chapter for heading control. In chapter II the WX force was modeled thru the intermediate force IF32 as:

\[ IF32 = KC_1 \cdot D_2 + NC_2 + KC_1 \cdot WX \]

By introducing the force in this way, a severe limitation is placed on the magnitude of the force. In the mariner model used, the KC1 coefficient (XDELR) is considered negligible or, at best, only 0.00005. This translates, in the original equations of motion, to a maximum speed perturbation of only 0.0355 kts. for the wave amplitude chosen. The second drawback of this method, with even greater consequences, is that the perturbation is introduced before the control loop. Delay of the wave perturbation is produced making it out of phase with the other wave force (WX) and moment (WN).

![Figure III-102](attachment:image.png)

Figure III-102
Block Diagram of Wave Introduction in Speed Loop

In order to bring about uniform introduction of this wave force, its effect is inserted just past the integrator
of the speed control loop as shown in figure III-102. This is coded in the DSL simulation program as:

\[ \text{CDOT2} = \text{INTGRL(U02,SPDERR\ast LUC)\ast KS2\ast WX} \]

A value of -1.0 for KS2 will give a maximum wave perturbation of 0.85275 kts. (a much more realistic perturbation for the high sea state simulated). Figure III-103 portrays the speed desired and speed acquired for the approach phase in the presence of sea state. From this it can be seen that the speed acquired is very dependent upon the sea state present. The control law, however, presents a very stable reference for the speed loop which gives an approach longitudinal position (DX) plot indistinguishable from that of figure III-81. More prominent perturbation results are evident in the turn phase plots of figures III-104 and III-105. The speed response of figure III-104 allows a maximum longitudinal position excursion of 9.5 feet (0.018 normalized position). as compared with 8.286 feet (0.0157 normalized) in calm sea.

These results show that the speed control system is very stable and corrects well for large external perturbations.
Figure III-104
Turn Phase Speed Response in Waves
Figure III-105
Turn Phase Longitudinal Position DX in Waves
IVA. CONCLUSIONS

The results of this design study have been most gratifying. The basic concepts initially perceived for the RAS control have been realized. The decoupled ship control in the RAS environment is a viable and plausible idea. This thesis contains a workable system for implementation of computer controlled RAS. The achievement of 2.3 foot maximum excursion for lateral distance while both ships are in a turn, and longitudinally offset by 53 feet is a phenomenal achievement. Having this kind of accuracy in RAS operations, can vastly increase the safety of this complicated and dangerous maneuver.

The approach phase of RAS can be a very hair raising experience. Night replenishment and sea state complicate the "seaman's eye" method now employed in the fleet. Having a system that automatically handles the approach regardless of the adverse conditions can, again, do nothing more than increase the safety of the RAS maneuver.

Schemes for computer control of nonlinear systems and the purposeful introduction of nonlinear control laws are becoming more practical with the technological advances in microprocessors. The ever increasing number of U.S. Navy ships with computer systems installed, makes digital computer ship control realizable in the present time frame. A good micro computer or an existing installed computer (such as one used for the NTDS system) can be used in this vein. Procurement of the hardware required for this RAS
system can be dissipated over time periods contingent on the funding available. The supply ship requires only two reflectors for the range and bearing devices stationed on the receiving ship. All ships can be outfitted with such reflectors at a minimal cost, while the bulk of the hardware can be introduced to the ships at regularly scheduled yard periods.

In the initial conception of this thesis, a section was planned for open ocean maneuvering. After some research on this facet of ship control, it was determined that work in this area has already been documented[24][25]. The existence of NTDS outputs for station attainment and single ship control systems, made design in this area redundant.

The concept of integrated centralized ship control has been in the background for over a decade[26]. Although given a low priority due to funding considerations, its implementation seems to be just around the corner[27]. However, a review of ref. 27 indicates a lack of RAS capability. Whether this is an oversight in the article or neglected in the design criteria is unknown. If it has been neglected in the design, a very real problem has been overlooked. The recent incidences of ship collisions while conducting RAS[28] emphasizes the need for inclusion of this very dangerous maneuver in the "Integrated Eridge System." Lack of technology can no longer be used as an excuse. This thesis and other research reports[29] have advanced the implementation feasibility to a level that cannot be ignored. With these projects finalized in practical terms, their incorporation into fleet use is the next imperative step.

A major effort in this area must be made. The ever increasing complexities of today's naval ships and the loads being placed on the officers and men are such that computer
control must be used; and used now! We cannot afford the luxury of time to prove these systems\textsuperscript{worth}, but \textbf{must} make concerted efforts to get them implemented before the lives of 300+ men are lost.

Whenever a complicated system such as a ship in the RAS situation is encountered, many facets have to be concurrently analyzed. This fact has caused inclusion of many diagrams in this thesis to illustrate the total picture. Each run, with a different condition, requires many plots to analyze the differences in the responses and the causes of the differences. The computer programs shown do not reflect the actual run times in the JCL shown. As many as twenty plots were output in these programs in the times listed. Analysis of the actual computation times show that the algorithms run considerably under the time required for real time operation. The sampled data rate used in the simulations was 0.11 seconds. This is well within the realizable data rates available in even the slowest of today's computers and microprocessors. The thrust of this consideration is that there are no problems envisioned in converting RAS simulation to real world RAS control.

E. RECOMMENDATIONS

In the heading control design section of this thesis, the need for a completely adaptive gain scheme was cited. Again in the velocity control section, when a longitudinal offset was introduced, this need became even more evident. The first and most important recommendation for further study is the development of just such an adaptive gain scheme.

The linear equations of motion should be replaced with nonlinear equations to validate the control designs advanced
in this thesis. Along with this, the hydrodynamic coefficients for the Navy's modern ships are required to be able to design these control systems for today's vessels.

It is further recommended that a concerted effort be made to obtain data on the interactive forces and moments between ships of dissimilar types and sizes. These forces and moments must also be available for sea state conditions. In fact, the whole area on sea state effects on the various ship types in the RAS situation and in open ocean maneuvering needs attention. Not enough data was available for this researcher to be able to pinpoint sea state effects on ship hulls. Since replenishment at sea is rarely conducted in the sterile condition of calm sea, these considerations are of utmost importance to allow testing of any control system in the simulation stage of development.

The intent here is not to imply that the control systems portrayed in this thesis are the best for the RAS scenario, but that the procedures used can be applied to any control scheme desired and benchmarked to the ones contained here. As previously mentioned, much meaningful research and design must be accomplished to allow system reliability and, more important, system acceptability by the officers and men who will ultimately trust their lives to it. This is a task that must not be taken lightly.
Due to the lengthy nature of the computer programs presented in this thesis, many functions and subroutines were developed to simplify their presentation. This appendix lists these functions and subroutines in alphabetical order. The computer programs reference this appendix and indicate the placement of the required functions and subroutines.

A brief description for each listing is given to aid the reader in determining their purpose and use. The following is a listing of the functions and subroutines contained in this appendix in the order presented:

EXECUTINE BOXPLIX
FUNCTION DEGRAD
FUNCTION DELAY
FUNCTION FE - RUN A (FEA)
FUNCTION FE - RUN E (FEB)
FUNCTION FE - RUN C (FEC)
EXECUTINE HDGRAS
FUNCTION KE
MAIN PROGRAM FOR FUNCTION MINIMIZATIONS (MINIFXPX)
SUBROUTINE RBMEAS
FUNCTION RKLDEQ
SUBROUTINE SLOPES
FUNCTION SPINIT
FUNCTION SPDCTR
FUNCTION SPDOFC
FUNCTION SPDREC
FUNCTION SWCL
SUBROUTINE SWTCH
SUEGUTINE SWTCHF
SUEGUTINE TRANS
FUNCTION XLIMIT
SUBROUTINE EOXPLX

This subroutine was used for all optimization runs in heading control and speed control. It was programmed locally and is part of the IBM 360 SSP library at the Naval Postgraduate School. A full explanation and description is shown in the first few pages of the subroutine listing.
SUBROUTINE BOXPLX

SUBROUTINE BOXPLX (CATEGORY HO)

PURPOSE

BOXPLX IS A SUBROUTINE USED TO SOLVE THE PROBLEM OF LOCATING
A MINIMUM (OR MAXIMUM) OF AN ARBITRARY OBJECTIVE FUNCTION
SUBJECT TO ARBITRARY EXPLICIT AND/OR IMPLICIT CONSTRAINTS BY
THE COMPLEX METHOD OF M. J. BOX. EXPLICIT CONSTRAINTS ARE
DEFINED AS UPPER AND LOWER BOUNDS ON THE INDEPENDENT VARIABLES.
IMPLICIT CONSTRAINTS MAY BE ARBITRARY FUNCTIONS OF THE VAR-
IABLES. TWO FUNCTION SUBPROGRAMS TO EVALUATE THE OBJECTIVE
FUNCTION AND IMPLICIT CONSTRAINTS, RESPECTIVELY, MUST BE
SUPPLIED BY THE USER (SIZE EXAMPLE BOXPLX). BOXPLX ALSO HAS
THE OPTION TO PERFORM INTEGER PROGRAMMING, WHERE THE VALUES
OF THE INDEPENDENT VARIABLES ARE RESTRICTED TO INTEGERS.

USAGE

CALL BOXPLX (NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)

DESCRIPTION OF PARAMETERS

NV AN INTEGER INPUT DEFINING THE NUMBER OF INDEPENDENT
VARIABLES OF THE OBJECTIVE FUNCTION TO BE MINIMIZED.
NOTE: MAXIMUM NV + NAV IS CURRENTLY 50. MAXIMUM NV IS
25. IF THESE LIMITS MUST BE EXCEEDED, PUNCH A SOURCE
DECK IN THE USUAL MANNER, AND CHANGE THE DIMENSION
STATEMENTS.

NAV AN INTEGER INPUT DEFINING THE NUMBER OF AUXILIARY VAR-
IABLES THE USER WISHES TO DEFINE FOR HIS OWN CONVENIENCE.
TYPICALLY HE MAY WISH TO DEFINE THE VALUE OF EACH IMPLICIT
CONSTRAINT FUNCTION AS AN AUXILIARY VARIABLE. IF THIS
IS DONE, THE OPTIONAL OUTPUT FEATURE OF BOXPLX CAN BE
USED TO OBSERVE THE VALUES OF THOSE CONSTRAINTS AS THE
SOLUTION PROGRESSES. AUXILIARY VARIABLES, IF USED,
SHOULD BE EVALUATED IN FUNCTION KE (DEFINED BELOW).
NAV MAY BE ZERO.

NPR INPUT INTEGER CONTROLLING THE FREQUENCY OF OUTPUT DESIRED
FOR DIAGNOSTIC PURPOSES, IF NFR .LE. 0, NO OUTPUT WILL BE
PRODUCED BY BXPXLX. OTHERWISE, THE CURRENT COMPLEX OF
K = 2*NV VERTICES AND THEIR CENTROID WILL BE OUTPUT AFTER
EACH NFR PERMISSIBLE TRIALS. THE NUMBER OF TOTAL TRIALS,
NUMBER OF FEASIBLE TRIALS, NUMBER OF FUNCTION EVALUATIONS
AND NUMBER OF IMPLICIT CONSTRAINT EVALUATIONS ARE IN-
CLUD ED IN THE OUTPUT.
ADDITIONALLY, (WHEN NFR .GT. 0) THE SAME INFORMATION
WILL BE OUTPUT:

1) IF THE INITIAL POINT IS NOT FEASIBLE,
2) AFTER THE FIRST COMPLETE COMPLEX IS GENERATED,
3) IF A FEASIBLE VERTEX CANNOT BE FOUND AT SOME TRIAL,
4) IF THE OBJECTIVE VALUE OF A VERTEX CANNOT BE MADE
NO-LONGER-WORST,
5) IF THE LIMIT ON TRIALS (NTA) IS REACHED AND,
6) WHEN THE OBJECTIVE FUNCTION HAS BEEN UNCHANGED FOR
2*NV TRIALS, INDICATING A LOCAL MINIMUM HAS BEEN
FOUND.

IF THE USER WISHES TO TRACE THE PROGRESS OF A SOLUTION,
A CHOICE OF NFR = 25, 50 OR 100 IS RECOMMENDED.

NTA INTEGER INPUT OF LIMIT ON THE NUMBER OF TRIALS ALLOWED
IN THE CALCULATION. IF THE USER INPUTS NTA .LE. 0, A
DEFAULT VALUE OF 2000 IS USED. WHEN THIS LIMIT IS REACHED,
CONTROL RETURNS TO THE CALLING PROGRAM WITH THE BEST
ATTAINED OBJECTIVE FUNCTION VALUE IN VMN, AND THE BEST
ATTAINED SOLUTION POINT IN XSN.

R A REAL NUMBER INPUT TO DEFINE THE FIRST RANDOM NUMB.
USED IN DEVELOPING THE INITIAL COMPLEX OF 2*NV VERTICES.
(0 .GT. R .LT. 1.) IF R IS NOT WITHIN THESE BOUNDS,
IT WILL BE REPLACED BY 1./3.

XS INPUT REAL ARRAY DIMENSIONED AT LEAST NV*NAV. THE FIRST
NV MUST CONTAIN A FEASIBLE ORIGIN FOR STARTING THE CAL-
CULATION. THE LAST NAV NEED NOT BE INITIALIZED. UPON
RETURN FROM BOXPLX, THE FIRST NV ELEMENTS OF THE ARRAY
CONTAIN THE COORDINATES OF THE MINIMUM OBJECTIVE FUNCTION,
AND THE REMAINING NAV (NAV .GE. 0) CONTAIN THE VALUES OF
THE CORRESPONDING AUXILIARY VARIABLES.

IP INTEGER INPUT FOR OPTIONAL INTEGER PROGRAMMING. IF IP=1,
THE VALUES OF THE INDEPENDENT VARIABLES WILL BE REPLACED
WITH INTEGER VALUES (STILL STORED AS REAL*4).

XU A REAL ARRAY DIMENSIONED AT LEAST NV INPUTTING THE UPPER
BOUND ON EACH INDEPENDENT VARIABLE, (EACH EXPPLICIT CONSTRAINT). INPUT VALUES ARE SLIGHTLY ALTERED BY BOXPLX.

XL A REAL ARRAY DIMENSIONED AT LEAST NV INPUTTING THE LOWER
BOUND ON EACH INDEPENDENT VARIABLE, (EACH EXPPLICIT CONSTRAINT). NOTE: FOR BOTH XU AND XL CHOOSE REASONABLE
VALUES IF NONE ARE GIVEN, NOT VALUES WHICH ARE MAGNITUDES ABOVE OR BELOW THE EXPECTED SOLUTION. INPUT VALUES ARE
SLIGHTLY ALTERED BY BOXPLX.

YMN THIS OUTPUT IS THE VALUE (REAL*4) OF THE OBJECTIVE Func-
TION, CORRESPONDING TO THE SOLUTION POINT OUTPUT IN XS.

IER INTEGER ERROR RETURN. TO BE INTERROGATED UPON RETURN
FROM BOXPLX. IER WILL BE ONE OF THE FOLLOWING:

=-1 CANNOT FIND FEASIBLE VERTEX OR FEASIBLE CENTROID
 SAR AT THE START OR A RESTART (SEE 'METHOD' BELOW).

=0 FUNCTION VALUE UNCHANGED FOR 'N' TRIALS. (WHERE
N=6*NV+10) THIS IS THE NORMAL RETURN PARAMETER.

=1 CANNOT DEVELOP FEASIBLE VERTEX.

=2 CANNOT DEVELOP A NO-LONGER-WORST VERTEX.

=3 LIMIT ON TRIALS REACHED. (NTA EXCEEDED)

NOTE: VALID RESULTS MAY BE RETURNED IN ANY OF THE
ABOVE CASES.

EXAMPLE OF USAGE

THIS EXAMPLE MINIMIZES THE OBJECTIVE FUNCTION SHOWN IN THE
EXTERNAL FUNCTION F(X). THERE ARE TWO INDEPENDENT VAR-
IABLES X(1) & X(2), AND TWO IMPLICIT CONSTRAINT FUNCTIONS
X(3) & X(4) WHICH ARE EVALUATED AS AUXILIARY VARIABLES (SEE
EXTERNAL FUNCTION KE(X)).

DIMENSION XS(4),XU(2),XL(2)

STARTING GUESS
XS(1) = 1.0
XS(2) = 0.5

UPPER LIMITS
XU(1) = 6.0
XU(2) = 6.0

LOWER LIMITS
XL(1) = 0.0
XL(2) = 0.0

R = 9.1/13.

NTA = 5000
CALL BOXPLX (NV, NAV, NPR, NTA, R, XS, IP, XU, XL, YMN, IER)
WRITE (6, 1) ((XS(I), I=1, 4), YMN, IER)
1 FORMAT (/111, 'THE POINT IS LOCATED AT (XS(1)=) ', 4(E13.7, 5X),
     $' AND THE FUNCTION VALUE IS ', E13.7, ' IER = ', I, 15)
STOP
END

FUNCTION KE(X)
EVALUATE CONSTRAINTS. SET KE=0 IF NO IMPLICIT CONSTRAINT IS
VIOLATED, OR SET KE=1 IF ANY IMPLICIT CONSTRAINT IS VIOLATED.
DIMENSION X(4)
X1 = X(1)
X2 = X(2)
KE = 0
X(3) = X1 + 1.732051*2
IF (X(3) .LT. 0. OR. X(3) .GT. 6.) GO TO 1
X(4) = X1/1.732051-X2
IF (X(4) .GE. 0.) RETURN
1 KE = 1
RETURN
END

FUNCTION FE(X)
THIS IS THE OBJECTIVE FUNCTION.
FE = -(X(2)**3 * (9.-(X(1)-3.)**2)/(46.765381))
RETURN
END

METHOD
THE COMPLEX METHOD IS AN EXTENSION AND ADAPTATION OF THE SIM-
PLEX METHOD OF LINEAR PROGRAMMING. STARTING WITH ANY ONE
FEASIBLE POINT IN N-DIMENSION SPACE A "COMPLEX" OF 2*N
VERTICES IS CONSTRUCTED BY SELECTING RANDOM POINTS WITHIN THE
FEASIBLE REGION. FOR THIS PURPOSE N COORDINATES ARE FIRST
RANDOMLY CHosen WITHIN THE SPACE BOUNDED BY EXPLICIT CON-
STRAINTS. THIS DEFINES A TRIAL INITIAL VERTEX. IT IS THEN
CHECKED FOR POSSIBLE VIOLATION OF IMPLICIT CONSTRAINTS. IF ONE OR MORE ARE VIOLATED, THE TRIAL INITIAL VERTEX IS DISPLACED;
HALF OF ITS DISTANCE FROM THE CENTROID OF PREVIOUSLY SELECTED INITIAL VERTICES. IF NECESSARY THIS DISPLACEMENT PROCESS IS REPEATED UNTIL THE VERTEX HAS BECOME FEASIBLE. IF THIS FAILS TO HAPPEN AFTER 5*N+10 DISPLACEMENTS, THE SOLUTION IS ABANDONED. AFTER EACH VERTEX IS ADDED TO THE COMPLEX, THE CURRENT CENTROID IS CHECKED FOR FEASIBILITY. IF IT IS INFEASIBLE, THE LAST TRIAL VERTEX IS ABANDONED AND AN EFFORT TO GENERATE AN ALTERNATIVE TRIAL VERTEX IS MADE. IF 5*N+10 VERTICES ARE ABANDONED CONSECUTIVELY, THE SOLUTION IS TERMINATED.

IF AN INITIAL COMPLEX IS ESTABLISHED, THE BASIC COMPUTATION LOOP IS INITIATED. THESE INSTRUCTIONS FIND THE CURRENT WORST VERTEX, THAT IS, THE VERTEX WITH THE LARGEST CORRESPONDING VALUE FOR THE OBJECTIVE FUNCTION, AND REPLACE THAT VERTEX BY ITS OVER-REFLECTION THROUGH THE CENTROID OF ALL OTHER VERTICES. (IF THE VERTEX TO BE REPLACED IS CONSIDERED AS A VECTOR IN N-SPACE, ITS OVER-REFLECTION IS OPPOSITE IN DIRECTION, INCREASED IN LENGTH BY THE FACTOR 1.3, AND COLINEAR WITH THE REPLACED VERTEX AND CENTROID OF ALL OTHER VERTICES.)

WHEN AN OVER-REFLECTION IS NOT FEASIBLE OR REMAINS WORST, IT IS CONSIDERED NOT-PERMISSIBLE AND IS DISPLACED HALFWAY TOWARD THE CENTROID. AFTER FOUR SUCH ATTEMPTS ARE MADE UNSUCCESSFULLY, EVERY FIFTH ATTEMPT IS MADE BY REFLECTING THE OFFENDING VERTEX THROUGH THE PRESENT BEST VERTEX, INSTEAD OF THROUGH THE CENTROID. IF 5*N+10 DISPLACEMENTS AND OVER-REFLECTIONS OCCUR WITHOUT A SUCCESSFUL (PERMISSIBLE) RESULT, THE CURRENT BEST VERTEX IS TAKEN AS AN INITIAL FEASIBLE POINT FOR A RESTART RUN OF THE COMPLETE PROCESS. RESTARTING IS ALSO UNDERTAKEN WHEN 6*N+10 CONSECUTIVE TRIALS HAVE BEEN MADE WITH NO SIGNIFICANT CHANGE IN THE VALUE OF THE OBJECTIVE FUNCTION. IN ALL CASES, RESTARTING IS INHIBITED IF THE LAST RESTART DID NOT PRODUCE A SIGNIFICANT IMPROVEMENT IN THE MINIMUM ATTAINED.

IT IS RECOMMENDED THAT THE USER READ THE REFERENCE FOR FURTHER USEFUL INFORMATION. IT SHOULD BE NOTED THAT THE ALGORITHM DEFINED HERE HAS BEEN ALTERED TO FIND THE CONSTRAINED MINIMUM, RATHER THAN THE MAXIMUM.

REMARKS

THE INTEGER PROGRAMMING OPTION WAS ADDED TO THIS PROGRAM AS SUGGESTED IN REFERENCE (2). A MIXED INTEGER/CONTINUOUS VARIABLE VERSION OF BOXPLX WOULD BE EASY TO CREATE BY DE-
CLRNG "IP" TO BE AN ARRAY OF NV CONTROL VARIABLES WHERE IP
(i) = 1 WOULD INDICATE THAT THE I-TH VARIABLE IS TO BE CONFINED
TO INTEGER VALUES. EACH STATEMENT OF THE FORM 'IF (IP(I) .EQ.
1)' ETC. WOULD THEN NEED TO BE ALTERED TO 'IF (IP(I) .EQ. 1)
ETC., WHERE THE SUBSCRIPT IS APPROPRIATELY CHOSEN. NORMALLY,
XU AND XL VALUES ARE ALTERED TO BE AN EPSILON 'WITHIN' ACTUAL
VALUES DECLARED BY THE USER. THIS ADJUSTMENT IS NOT MADE
WHEN IP=1.

NOTE: NO NON-LINEAR PROGRAMMING ALGORITHM CAN GUARANTEE THAT
THE ANSWER FOUND IS THE GLOBAL MINIMUM, RATHER THAN JUST A
LOCAL MINIMUM. HOWEVER, ACCORDING TO REF.2, THE COMPLEX
METHOD HAS AN ADVANTAGE IN THAT IT TENDS TO FIND THE GLOBAL
MINIMUM MORE FREQUENTLY THAN MANY OTHER NON-LINEAR PROGRAM-
MING ALGORITHMS.

IT SHOULD BE NOTED THAT THE AUXILIARY VARIABLE FEATURE CAN
ALSO BE USED TO DEAL WITH PROBLEMS CONTAINING EQUALITY CON-
STRAINTS. ANY EQUALITY CONSTRAINT IMPLIES THAT A GIVEN VAR-
TABLE IS NOT TRULY INDEPENDENT. THEREFORE, IN GENERAL, ONE
VARIABLE INVOLVED IN AN EQUALITY CONSTRAINT CAN BE RENUMBERED
FROM THE SET OF NV INDEPENDENT VARIABLES AND ADDED TO THE SET
OF NV AUXILIARY VARIABLES. THIS USUALLY INVOLVES RENUMBERING
THE INDEPENDENT VARIABLES OF THE GIVEN PROBLEM.

SUBROUTINES AND FUNCTIONS REQUIRED

SUBROUTINE 'BOUT' AND FUNCTION 'FBV' ARE INTEGRAL PARTS OF
THE BOXPLX PACKAGE.

TWO FUNCTIONS MUST BE SUPPLIED BY THE USER. THE FIRST, KE(X),
IS USED TO EVALUATE THE IMPLICIT CONSTRAINTS. SET KE=0 AT THE
BEGINNING OF THE FUNCTION, THEN EVALUATE THE IMPLICIT CON-
STRAINTS. IN THE EXAMPLE ABOVE, THE FIRST CONSTRAINT: X(3),
MUST BE WITHIN THE RANGE (0., LE. X(3), LE. 6.). THE SECOND
CONSTRAINT X(4), MUST BE GE. 0. IF EITHER CONSTRAINT IS
NOT WITHIN THESE BOUNDS, CONTROL IS TRANSFERRED TO STATEMENT 1.
AND KE IS SET TO "1" AND CONTROL IS RETURNED TO BOXPLX.

THE SECOND FUNCTION THE USER MUST PROVIDE EVALUATES THE OB-
JECTIVE FUNCTION. IT IS CALLED FE(X) AS SHOWN IN THE EXAMPLE
ABOVE, AND FE MUST BE SET TO THE VALUE OF THE OBJECTIVE
FUNCTION CORRESPONDING TO CURRENT VALUES OF THE NV INDEPENDENT
VARIABLES IN ARRAY "X".

REFERENCES

BOX, M. J., "A NEW METHOD OF CONSTRAINED OPTIMIZATION AND A
COMPARISON WITH OTHER METHODS", COMPUTER JOURNAL, 8 APR. '65, PP. 45-52.


PROGRAMMER

R.R. HILLEARY 1/1966
REVISED FOR SYSTEM 360 4/1967
CORRECTED 1/1969
REVISED/EXTENDED BY L. NOLAN/R. HILLEARY 2/1975

SUBROUTINE BOXPLX (NV, NAV, NPR, NTZ, RZ, XS, IP, BU, BL, YMNI, IER)

DIMENSION V(50, 50), FUN(50), SUM(25), CEN(25), XS(NV), BU(NV), BL(NV)

KV = 5
EP = 1.0E-6
NTA = 2000
IF (NTZ.GT.0) NTA = NTZ
R = RZ
IF (R.LE.0.0 .OR. R.GE.1.0) R = 1.3
NVT = NV + NAV

TOTAL VARS, EXPLICIT PLUS IMPLICIT

NT = 0
CURRENT TRIAL NO.
NPT = 0
CURRENT NO. OF PERMISSIBLE TRIALS
NTFS = 0
CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED

CHECK FEASIBILITY OF START POINT

DO 4 I = 1, NV
VT = XS(I)
IF (BL(I).LE.VT) GO TO 1
II = -1
VT = BL(I)
GO TO 2
1 IF (BU(I).GE.VT) GO TO 3
II = 1

GO TO 2

4 CONTINUE
VT = BU(I)
2 IF (NPR.GT.0) WRITE (6,49) II
3 VI(I,1) = VT
CEN(I) = VT
IF (IP.EQ.1) GO TO 4
BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))
BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))
4 SUM(I) = VT
C

NCE = 1
NUMBER OF CONSTRAINT EVALUATIONS
I = 1
IF (KE(V(1,1)).EQ.0) GO TO 5
IF (NPR.LE.0) GO TO 12
WRITE (6,50)
GO TO 12
5 NFE = 1

NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.
K = 2*NV

NUMBER OF DISPLACEMENTS ALLOWED.
NLIM = 5*NV+10

NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED FE TO TERMINATE.
NCT = NLIM+NV
ALPHA = 1.3
FK = K
FKM = FK-1.
BETA = ALPHA+1.

INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.
IQR = R*1.17
IF (MOD(IQR,2).EQ.0) IQR=IQR+101

SET UP INITIAL VERTICES
FUN(1) = FE(V(1,1))
YMN = FUN(1)
6 FI = 1.
FUNOLD = FUN(1)

DO 15 I=2,K
FI = FI+1.
LIMIT = 0
7 LIMIT = LIMIT+1

END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.
IF (LIMIT.GE.NLIM) GO TO 11
C
DO 8 J=1,NV
C
RANDOM NUMBER GENERATOR (RANDU)
IQR = IQR*65539
IF (IQR.LT.0) IQR = IQR+2147483647+1
RQX = IQR
RQX = RQX*.4656613E-9
V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
IF (IP.EQ.1) V(J,I) = AINT(V(J,I)+.5)
8 CONTINUE
C
DO 10 L=1,NLIM
NCE = NCE+1
IF (KE(V(1,I)).EQ.0) GO TO 13
C
DO 9 J=1,NV
VT = .5*(V(J,I)+CEN(J))
IF (IP.EQ.1) VT = AINT(VT+.5)
V(J,I) = VT
9 CONTINUE
C
10 CONTINUE
C
11 IF (NPR.LE.0) GO TO 12
WRITE (6,51) I
CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
12 IER = -1
GO TO 48
C
13 DO 14 J=1,NV
SUM(J) = SUM(J)+V(J,I)
14 CEN(J) = SUM(J)/FI
C
TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
NCE = NCE+1
IF (KE(CEN).NE.0) GO TO 7
NFE = NFE+1
FUN(I) = FE(V(1,I))
15 CONTINUE
C
END OF LOOP SETTING OF INITIAL COMPLEX.
IF (NPR.LE.0) GO TO 17
CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
FIND THE WORST VERTEX, THE 'J'TH.
J = 1
DO 16 I=2,K
   IF (FUN(J).GE.FUN(I)) GO TO 16
   J = 1
16 CONTINUE

BASIC LOOP. ELIMINATE EACH WORST VERTEX IN TURN. IT MUST BECOME
NO LONGER WORST, NOT MERELY IMPROVED. FIND NEXT-TO-WORST VERTEX,
THE "JN"TH ONE.

17 JN = 1
   IF (J.EQ.1) JN = 2

18 CONTINUE

LIMIT = NUMBER OF MOVES DURING THIS TRIAL TOWARD THE CENTROID
DUE TO FUNCTION VALUE.

LIMIT = 1

COMPUTE CENTROID AND OVER-REFLECT WORST VERTEX.

DO 19 I=1,NV
   VT = V(I,J)
   SUM(I) = SUM(I) - VT
   CEN(I) = SUM(I)/FKM
   VT = BETA*CEN(I) - ALPHA*VT
   IF (IP.EQ.1) VT = AINT(VT+.5)

INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
19 V(I,J) = AMAX1(AMAX1(VT,BU(I)),BL(I))

NT = NT+1

CHECK FOR IMPLICIT CONSTRAINT VIOLATION.

20 DO 25 N=1,NLIM
   NCE = NCE+1
   IF (KE(V1(J)).EQ.0) GO TO 26

EVERY "KV"TH TIME, OVER-REFLECT THE OFFENDING VERTEX THROUGH THE
BEST VERTEX.
   IF (MOD(N,KV).NE.0) GO TO 22
   CALL FBV(K,FUN,M)

21 DO 21 I=1,NV

25 CONTINUE

26
VT = BETA*V(I,M)-ALPHA*V(I,J)
IF (IP.EQ.1) VT = AINT(VT+.5)
21 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
GO TO 24
C
CONSTRAINT VIOLATION: MOVE NEW POINT TOWARD CENTROID.
C
22 DO 23 I=1,NV
VT = .5*(CEN(I)+V(I,J))
IF (IP.EQ.1) VT = AINT(VT+.5)
V(I,J) = VT
23 CONTINUE
C
24 NT = NT+1
25 CONTINUE
C
IER = 1
C
CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
OR BY OVER-REFLECTING THRU THE BEST VERTEX.
IF (NPR.LE.0) GO TO 42
WRITE (6,52) NT, J
CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FJN,CEN,J)
GO TO 42
C
FEASIBLE VERTEX FOUND, EVALUATE THE OBJECTIVE FUNCTION.
26 NFE = NFE+1
FUNTRY = FEE(V(I,J))
C
TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.
AFD = ABS(FUNTRY-FUNOLD)
AMX = AMAX1(ABS(EP*FUNOLD),EP)
C
ACTIVATE THE FOLLOWING TWO STATEMENTS FOR DIAGNOSTIC PURPOSES ONLY.
WRITE (6,99) J,AFD,AMX,FUNTRY,FUNOLD,FUN(J),FUN(JN),NTFS,N
99 FORMAT (1X,13,F8.5)
IF (AFD.GT.AMX) GO TO 27
NTFS = NTFS+1
IF (NTFS.LT.NCT) GO TO 28
IER = 0
IF (NPR.LE.0) GO TO 42
WRITE (6,53) K
GO TO 42
27 NTFS = 0
C
IS THE NEW VERTEX NO LONGER WORST?
28 IF (FUNTRY.LT.FUN(JN)) GO TO 34
TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.
EACH 'KV' TH TIME, OVER-REFLECT THE OFFENDING VERTEX THROUGH THE
BEST VERTEX.

IF (MOD(LIM*,KV),NE.0) GO TO 30
CALL FBV (K,FUN,N)

DO 29 I=1,NV
VT = BETA*V(I,N)-ALPHA*V(I,J)
IF (I.P.EQ.1) VT = AINT(VT+.5)
29 V(I,J) = AMAX1(AMIN1(VT,BV(I)),BL(I))

GO TO 32

30 DO 31 I=1,NV
VT = .5*(CEN(I)+V(I,J))
IF (I.P.EQ.1) VT = AINT(VT+.5)
V(I,J) = VT
31 CONTINUE

32 IF (LIM*.LT.NLIM) GO TO 33
CANNOT MAKE THE 'J' TH VERTEX NO LONGER WORST BY DISPLACING TOWARD
THE CENTROID OR BY OVER-REFLECTING THRU THE BEST VERTEX.
IER = 2
IF (NPR.GT.0) WRITE (6,52) NT,J
GO TO 42
33 NT = NT+1
GO TO 20

SUCCESS: WE HAVE A REPLACEMENT FOR VERTEX J.
34 FUN(J) = FUNTR
FUNOLD = FUNTR
NPT = NPT+1

EVERY 100*TH PERMISSIBLE TRIAL, RECOMPUTE CENTROID SUMMATION TO
AVOID CREEPING ERROR.
IF (MOD(NPT,100).NE.0) GO TO 37

36 DO 36 I=1,NV
SUM(I) = 0.
36 CONTINUE

DO 35 N=1,K
35 SUM(I) = SUM(I)+V(I,N)
CEN(I) = SUM(I)/FK
36 CONTINUE
C
LC = 0
GO TO 39
C
37 DO 38 I=1,NV
38 SUM(I) = SUM(I)+V(I,J)
C
LC = J
C
39 IF (NPR.LE.0) GO TO 40
IF (MOD(NPT,NPR).NE.0) GO TO 40
C
CALL BOUTH (NT,NPT,NFE,NE,NV,NVT,V,K,FUN,CEN,LC)
C
HAS THE MAX. NUMBER OF TRIALS BEEN REACHED WITHOUT CONVERGENCE?
C
IF NOT, GO TO NEW TRIAL.
40 IF (NT.GE.NTA) GO TO 41
C
NEXT-TO-WORST VERTEX NOW BECOMES WORST.
J = JN
GO TO 17
41 IER = 3
IF (NPR.GT.0) WRITE (6,54)
C
COLLECTOR POINT FOR ALL ENDINGS.
1) CANNOT DEVELOP FEASIBLE VERTEX. IER = 1
2) CANNOT DEVELOP A NO-LONGER-WORST VERTEX. IER = 2
3) FUNCTION VALUE UNCHANGED FOR K TRIALS. IER = 0
4) LIMIT ON TRIALS REACHED. IER = 3
5) CANNOT FIND FEASIBLE VERTEX AT START. IER = -1
42 CONTINUE
C
FIND BEST VERTEX.
CALL FBV (K,FUN,M)
IF (IER.GE.3) GO TO 44
C
RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER THAN THE PREVIOUS,
OR IF THIS IS THE FIRST TRY.
IF (NPR.LE.0) GO TO 43
WRITE (6,55) (M,YMN,FUN(M))
43 IF (FUN(M).GE.YMN) GO TO 47
IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C
GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
44 YMN = FUN(M)
FUN(I) = FUN(M)
C
DO 45 I=1,NV
2 WRITE (6, 7) (C(I), I=1, NV)
3 RETURN
5 WRITE (6, 9) (K(I), I=1, NV)
6 RETURN
4 FORMAT (1ON1.5X, 'NO. FUNCTION EVALUATION= ', I, 15, 'X, 15, 10', 9*15, 'X, 10', 8*15, 'X, 10')
9 END
FUNCTION DEGRAD

This function was programmed to convert degrees to radians and radians to degrees. A third purpose is to convert degrees to a range of 0-360. It is used extensively throughout the programs, functions, and subroutines listed in this thesis.
**FUNCTION DEGRAD**

```
FUNCTION DEGRAD (NDRFLG,NSHFLG,FUNC)

DGRD 10
DGRD 20
DGRD 30
DGRD 40
DGRD 50
DGRD 60
DGRD 70
DGRD 80
DGRD 90
DGRD 100
DGRD 110
DGRD 120
DGRD 130
DGRD 140
DGRD 150
DGRD 160
DGRD 170
DGRD 180
DGRD 190
DGRD 200
DGRD 210
DGRD 220
DGRD 230
DGRD 240
DGRD 250
DGRD 260
DGRD 270
DGRD 280
DGRD 290
DGRD 300
DGRD 310
DGRD 320

C FUNCTION TO CONVERT DEGREES TO RADIANS AND RADIANS TO DEGREES AND SHIFT THE DEGREES TO A RANGE BETWEEN 000.0 AND 360.0 IN ACCORDANCE WITH THE FOLLOWING FLAG DEFINITIONS

C

C NDRFLG
C 0 - CONVERT RADIANS TO DEGREES
C 1 - CONVERT DEGREES TO RADIANS
C 2 - DO NOT CONVERT

C NSHFLG
C 0 - CONVERT ANGLES(DEG) TO THE RANGE BETWEEN 000.0 AND 360.0
C 1 - DO NOT CONVERT

C

C FUNCTION = FUNC
C IF (NDRFLG.EQ.2) GO TO 2
C IF (NDRFLG.EQ.1) GO TO 1
C FUNC = FUNC*180.0/3.141592654
C GO TO 2
C 1 FUNC = FUNC*3.141592654/180.0
C GO TO 5
C 2 IF (NSHFLG.EQ.1) GO TO 5
C 3 IF (FUNCU.LT.360.0) GO TO 4
C FUNC = FUNCU-360.0
C GO TO 3
C 4 IF (FUNCU.GE.0.0) GO TO 5
C FUNC = FUNCU+360.0
C GO TO 4
C 5 DEGRAD = FUNC
C RETURN
C END
```
FUNCTION DELAY

This function is used as the time delay in the speed control optimization runs. It was designed to be used as an equivalence to DELY in DSL simulation. The following variables are defined:

- \( E(I) \) is the storage array (should be initialized before the first function call)
- \( K \) is the delay step count
- SPDDES is the variable to be delayed for \( K \) steps
- \( P \) is the flag for delay or no delay
  - \( P \geq 0.0 \) delay SPDDES
  - \( P < 0.0 \) function output equal to SPDDES

The function stores the input value (SPDDES) in \( E(M) \) and decrements the value in array \( E(I) \) at each call of the function until the value is in the position of \( E(1) \). The value is then output from the function delayed \( K \) intervals.
FUNCTION DELAY

FUNCTION DELAY (K,P,SPDDES,E)
DIMENSION E(10)
M = K+1
E(M) = SPDDES
C
  DO 1 I=1,K
    1 E(I) = E(I+1)
C
  IF (P.LT.0.0) GO TO 2
  DELAY = E(I)
  RETURN
2  DELAY = SPDDES
  RETURN
END
FUNCTION FE - RUN A

FEA

This function is the simulation for heading control optimization of the approach phase. It is called by subroutine BOXFLX. The integration step size is 0.04 with a final time of 20.0. In this function all initial conditions are set to zero except initial geographic location and speed. The reference ship maintains a straight course and the control ship starts its approach 5 ship lengths astern and 0.4 ship lengths laterally displaced to starboard of the reference ship.

The function is referred to as function FEA in the text.
FUNCTION FE - RUN A

C EVALUATION OF COST FUNCTION AS A FUNCTION OF RSSENS, WTSENS, RGN
D DIMENSION Z(8), Y(20), YDOT(20), X(20), XDOT(20)
R REAL *8XDOT, XDOT, TO
C HYDRODYNAMIC COEFFICIENTS
A11 = 0.015
B11 = 0.01243
A21 = 0.00027
B21 = 0.0051
A12 = 0.000197
B12 = 0.00351
A22 = 0.00068
B22 = 0.00227
A33 = 0.0085
B33 = 0.0012
XKA = 0.0027
XKB = -0.00126
XNC = 0.0012
D = A11*A22 - A21*A12
XKC = 0.0
XLUC = 20.84765
DLTOM = 2.0
DLTEM = 7.0
XKG = DLTOM/DLTEM
D2D = 0.0
C IDENTIFICATION OF GAINS TO BE FOUND
RSSENS = Z(1)
WTSENS = Z(2)
RGN = Z(3)
VFBG = 0.0
C INITIAL CONDITIONS
C DO 1 J = 1, 14
1 Y(J) = 0.0
C INITIAL GEOGRAPHIC LOCATION
Y(5) = 5.0
Y(6) = 0.0
Y(10) = 0.0
Y(11) = 0.4
C OTHER INITIALIZATIONS
N = 1
RD = 1.0
IS = 1
DD = 0.2
D1 = 0.0
D2 = 0.0
YY1 = 0.0
YY2 = 0.0
YN1 = 0.0
YN2 = 0.0
C
SPEED INITIALIZATIONS
Y(4) = 1.0
UO2 = 1.5
CDOT2 = 1.5
C
DISTANCE INITIALIZATION
DYO = Y(101)-Y(5)
DXO = Y(111)-Y(6)
CALL TRANS (Y(2),DXO,DYO,ADX,ADY)
CALL SLOPES (ADX,ADY,YY1,YY2,YN1,YN2)
C
INITIALIZE TIME
T = 0.0
OT = 0.04
IT = 0
C
SHIP A
2
XIF11 = XKA*D1
XIF21 = XKB*D1
XIF31 = XKC*D1+XNC
X111 = -B11*Y(1)-B21*Y(3)+XIF11
X121 = -B12*Y(1)-B22*Y(3)+XIF21
X131 = -B33*Y(4)+XIF31
YDOT(1) = (X111*A22-X121*A21)/D
YDOT(2) = Y(3)
YDOT(3) = (X121*A11-X111*A12)/D
YDOT(4) = XI31/A33
YDOT(5) = Y(4)*COS(Y(2))-Y(1)*SIN(Y(2))
YDOT(6) = Y(4)*SIN(Y(2))+Y(1)*COS(Y(2))
C
SHIP B
XIF12 = XKA*D2+YY2
XIF22 = XKB*D2+YN2
XIF32 = XKC*D2+XNC
X112 = -B11*Y(7)-B21*Y(9)+XIF12
X122 = -B12*Y(7)-B22*Y(9)+XIF22
CDOT2 = SPDCTR(ADX,UO2)
XI32 = -B33*CDOT2+XIF32
YDOT(7) = (X112*A22-X122*A21)/D
YDOT(8) = Y(9)
YDOT(9) = (X122*A11-X112*A12)/D
YDOT(10) = CDOT2*COS(Y(8))-Y(7)*SIN(Y(8))
YDOT(11) = CDOT2*SIN(Y(8))+Y(7)*COS(Y(8))
DX = Y(10)-Y(5)
DY = Y(11) - Y(6)
CALL TRANS (Y(2), DX, DY, ADX, ADY)
CALL SLOPES (ADX, ADY, Y0, YY1, YY2, YN1, YN2)
YAWD2 = DEGRAD(0,0, Y(8))
CALL RBMEAS (N, Y(2), Y(5), Y(6), Y(8), Y(10), Y(11), RD, R1, B1, BB1, R2, B2, BB2)
BGDOT2 = DEGRAD(0, 1, Y(9))
BOOTF8 = VFBG*BDOT20
DDUMB = YAWD2 - PSIDE + BD0TF8
IF (DDUMB.GT.180.0) DDUMB = DDUMB - 360.0
IF (DDUMB.LT.-180.0) DDUMB = 360.0 + DDUMB
DLTS = XLIMIT(-30.0, 30.0, DDUMB*RGN)
DLTE = DLTS-D2D
DLTBE = XLIMIT(-DLTEM, DLTEM, DLTE)
YDOT(14) = XKG*DLTBE*XLC
D2D = Y(14)
D2 = DEGRAD(1.1, D2D)
DTRAN = TCABS(D2)
YDOT(12) = DTRAN
DISTE = T*10.0*ABS(DD-ADY)
YDOT(13) = DISTE
OBJ = Y(12) + Y(13)
DO 3 J=1, 14
3 X(1) = DBLE(Y(J))
       XDOT(J) = DBLE(YDOT(J))
   C
   TD = DBLE(T)
   TDT = DBLE(TDT)
   ZS = RKLDEQ(14, X, XDOT, TD, TDT, JT)
   C
   DO 4 J=1, 14
4   Y(J) = SNGL(X(J))
       YDOT(J) = SNGL(X(J))
   C
   T = SNGL(TD)
   DT = SNGL(TDT)
   IF (ZS.LT.5) 5, 2, 6
   5 WRITE (6, 8)
   STOP
   6 IF (T.GT.20.0) GO TO 7
   GO TO 2
   7 FE = OBJ
       WRITE (6, 9) OBJ, RSÈNS, WTSÈNS, RGN
       RETURN

C
This function is the simulation for heading control optimization of the turn phase. It is called by subroutine BOXPLX. The integration step size is 0.04 with a final time of 20.0. In this function, the following initial conditions are non-zero:

- Control ship rudder angle $D2D$ & $Y(14) = 8.7$ degrees
- Lateral displacement $Y(11) = 0.2$
- Reference ship's speed $U01$ & $Y(4) = 1.0$
- Control ship's speed $U02$ & $CDCT2 = 1.5$ (after first step becomes 1.0)

The reference ship's rudder is activated to 5.0 degrees between time 4.0 and 5.0. The runs were for port side replenishment.

The function is referred to as function FEB in the text.
FUNCTION FE - RUN B

FUNCTION FE (Z)

EVALUATION OF COST FUNCTION AS A FUNCTION OF RSENS,WTSENS,RGN

DIMENSION Z(8), Y(20), YDOT(20), X(20), XDOT(20)

REAL *8XDOT,Y,YDOT,X

HYDRODYNAMIC COEFFICIENTS

A11 = 0.015
B11 = 0.01243
A21 = 0.00027
B21 = 0.0051
A12 = 0.000197
B12 = 0.00351
A22 = 0.00068
B22 = 0.00227
A33 = 0.0085
B33 = 0.0012
A34 = 0.0027
A35 = -0.00125
A36 = 0.0012
B = A11*A22-A12*A21
XKC = 0.0
XLUC = 20.84765
DLIDM = 2.0
DLTEM = 7.0
XKC = 0.0
DID = 0.0
D2D = 8.7

IDENTIFICATION OF GAINS TO BE FOUND

RSENS = Z(1)
WTSENS = Z(2)
RGN = Z(3)
VFEG = Z(4)

INITIAL CONDITIONS

DO 1 J=1,14
1 Y(IJ) = 0.0

INITIAL GEOGRAPHIC LOCATION

Y(5) = 0.0
Y(6) = 0.0
Y(10) = 0.0
Y(11) = 0.2
Y(14) = 8.7

OTHER INITIALIZATIONS

FEZB 10
FEZB 20
FEZB 30
FEZB 40
FEZB 50
FEZB 60
FEZB 70
FEZB 80
FEZB 90
FEZB 100
FEZB 110
FEZB 120
FEZB 130
FEZB 140
FEZB 150
FEZB 160
FEZB 170
FEZB 180
FEZB 190
FEZB 200
FEZB 210
FEZB 220
FEZB 230
FEZB 240
FEZB 250
FEZB 260
FEZB 270
FEZB 280
FEZB 290
FEZB 300
FEZB 310
FEZB 320
FEZB 330
FEZB 340
FEZB 350
FEZB 360
FEZB 370
FEZB 380
FEZB 390
FEZB 400
FEZB 410
FEZB 420
FEZB 430
N = 1
RD = 1.0
TS = 1
OD = 0.2
D1 = 0.0
D2 = DEGRAD(1,1,D2D)
Y1 = 0.0
Y2 = 0.0
YN1 = 0.0
YN2 = 0.0

C SPEED INITIALIZATIONS
Y(4) = 1.0
U01 = 1.0
U02 = 1.5
CDOT2 = 1.5

C DISTANCE INITIALIZATION
DY0 = Y(10)-Y(5)
DX0 = Y(11)-Y(6)
CALL TRANS (Y(2),DX0,DY0,ADX,ADY)
CALL SLOPES (ADX,ADY,YY1,YY2,YN1,YN2)

C INITIALIZE TIME
T = 0.0
DT = 0.04
JT = 0

C SHIP A
2 DIDES = 0.0
IF ((T.GE.4.0).AND.(T.LE.5.0)) DIDES=5.0
DLS1 = XLIMIT(-30.0,30.0,DIDES)
DLT1 = DLS1-D10
DLTBE1 = XLIMIT(-DLT1,DLT1,DLT1)
YDOT(12) = XKG*DLTBE1*XLC

DID = Y(12)

D1 = DEGRAD(1,1,D1D)
XIF11 = XK*A*D1
XIF21 = XK*B*D1
XIF31 = XK*C*D1+XNC
X111 = -B11*Y(1)-B21*Y(3)+XIF11
X121 = -B12*Y(1)-B22*Y(3)+XIF21
X131 = -B33*Y(4)+XIF31
YDOT(1) = (X111*A22-X121*A21)/D
YDOT(2) = Y(3)/D
YDOT(3) = (X121*A11-X111*A12)/D
YDOT(4) = X131*A33
YDOT(5) = Y(4)*COS(Y(2))-Y(1)*SIN(Y(2))
YDOT(6) = Y(4)*SIN(Y(2))+Y(1)*COS(Y(2))

N = 1
RD = 1.0
TS = 1
OD = 0.2
D1 = 0.0
D2 = DEGRAD(1,1,D2D)
Y1 = 0.0
Y2 = 0.0
YN1 = 0.0
YN2 = 0.0

C SPEED INITIALIZATIONS
Y(4) = 1.0
U01 = 1.0
U02 = 1.5
CDOT2 = 1.5

C DISTANCE INITIALIZATION
DY0 = Y(10)-Y(5)
DX0 = Y(11)-Y(6)
CALL TRANS (Y(2),DX0,DY0,ADX,ADY)
CALL SLOPES (ADX,ADY,YY1,YY2,YN1,YN2)

C INITIALIZE TIME
T = 0.0
DT = 0.04
JT = 0

C SHIP A
2 DIDES = 0.0
IF ((T.GE.4.0).AND.(T.LE.5.0)) DIDES=5.0
DLS1 = XLIMIT(-30.0,30.0,DIDES)
DLT1 = DLS1-D10
DLTBE1 = XLIMIT(-DLT1,DLT1,DLT1)
YDOT(12) = XKG*DLTBE1*XLC

DID = Y(12)

D1 = DEGRAD(1,1,D1D)
XIF11 = XK*A*D1
XIF21 = XK*B*D1
XIF31 = XK*C*D1+XNC
X111 = -B11*Y(1)-B21*Y(3)+XIF11
X121 = -B12*Y(1)-B22*Y(3)+XIF21
X131 = -B33*Y(4)+XIF31
YDOT(1) = (X111*A22-X121*A21)/D
YDOT(2) = Y(3)/D
YDOT(3) = (X121*A11-X111*A12)/D
YDOT(4) = X131*A33
YDOT(5) = Y(4)*COS(Y(2))-Y(1)*SIN(Y(2))
YDOT(6) = Y(4)*SIN(Y(2))+Y(1)*COS(Y(2))

N = 1
RD = 1.0
TS = 1
OD = 0.2
D1 = 0.0
D2 = DEGRAD(1,1,D2D)
Y1 = 0.0
Y2 = 0.0
YN1 = 0.0
YN2 = 0.0

C SPEED INITIALIZATIONS
Y(4) = 1.0
U01 = 1.0
U02 = 1.5
CDOT2 = 1.5

C DISTANCE INITIALIZATION
DY0 = Y(10)-Y(5)
DX0 = Y(11)-Y(6)
CALL TRANS (Y(2),DX0,DY0,ADX,ADY)
CALL SLOPES (ADX,ADY,YY1,YY2,YN1,YN2)

C INITIALIZE TIME
T = 0.0
DT = 0.04
JT = 0

C SHIP A
2 DIDES = 0.0
IF ((T.GE.4.0).AND.(T.LE.5.0)) DIDES=5.0
DLS1 = XLIMIT(-30.0,30.0,DIDES)
DLT1 = DLS1-D10
DLTBE1 = XLIMIT(-DLT1,DLT1,DLT1)
YDOT(12) = XKG*DLTBE1*XLC

DID = Y(12)

D1 = DEGRAD(1,1,D1D)
XIF11 = XK*A*D1
XIF21 = XK*B*D1
XIF31 = XK*C*D1+XNC
X111 = -B11*Y(1)-B21*Y(3)+XIF11
X121 = -B12*Y(1)-B22*Y(3)+XIF21
X131 = -B33*Y(4)+XIF31
YDOT(1) = (X111*A22-X121*A21)/D
YDOT(2) = Y(3)/D
YDOT(3) = (X121*A11-X111*A12)/D
YDOT(4) = X131*A33
YDOT(5) = Y(4)*COS(Y(2))-Y(1)*SIN(Y(2))
YDOT(6) = Y(4)*SIN(Y(2))+Y(1)*COS(Y(2))

N = 1
RD = 1.0
TS = 1
OD = 0.2
D1 = 0.0
D2 = DEGRAD(1,1,D2D)
Y1 = 0.0
Y2 = 0.0
YN1 = 0.0
YN2 = 0.0

C SPEED INITIALIZATIONS
Y(4) = 1.0
U01 = 1.0
U02 = 1.5
CDOT2 = 1.5

C DISTANCE INITIALIZATION
DY0 = Y(10)-Y(5)
DX0 = Y(11)-Y(6)
CALL TRANS (Y(2),DX0,DY0,ADX,ADY)
CALL SLOPES (ADX,ADY,YY1,YY2,YN1,YN2)

C INITIALIZE TIME
T = 0.0
DT = 0.04
JT = 0

C SHIP A
2 DIDES = 0.0
IF ((T.GE.4.0).AND.(T.LE.5.0)) DIDES=5.0
DLS1 = XLIMIT(-30.0,30.0,DIDES)
DLT1 = DLS1-D10
DLTBE1 = XLIMIT(-DLT1,DLT1,DLT1)
YDOT(12) = XKG*DLTBE1*XLC

DID = Y(12)

D1 = DEGRAD(1,1,D1D)
XIF11 = XK*A*D1
XIF21 = XK*B*D1
XIF31 = XK*C*D1+XNC
X111 = -B11*Y(1)-B21*Y(3)+XIF11
X121 = -B12*Y(1)-B22*Y(3)+XIF21
X131 = -B33*Y(4)+XIF31
YDOT(1) = (X111*A22-X121*A21)/D
YDOT(2) = Y(3)/D
YDOT(3) = (X121*A11-X111*A12)/D
YDOT(4) = X131*A33
YDOT(5) = Y(4)*COS(Y(2))-Y(1)*SIN(Y(2))
YDOT(6) = Y(4)*SIN(Y(2))+Y(1)*COS(Y(2))

C SHIP B
XIF12 = XK*A*D2+YY2

C SHIP B
XIF12 = XK*A*D2+YY2

C SHIP B
XIF12 = XK*A*D2+YY2
DT = SNGL(DTD)
5 WRITE (6,8)
STOP
6 IF (T.GT.20.0) GO TO 7
GO TO 2
7 FE = OBJ
WRITE (6,9) OBJ, ADY, ADX, YAWD1, YAWD2, D2D
RETURN

8 FORMAT (' RKLDEQ RETURNED VALUE LT 1.0, INTEGRATION PROBLEM')
8 FORMAT (' EXIT FUNCTION FE(Z), OBJ=' F15.8, 'ADY=' F15.8, 'ADX='
1 F15.8, 'YAWD1=' F15.8, 'YAWD2=' F15.8, 'D2D=' F15.8)
END
FUNCTION FE - RUN C

This function is the simplified simulation for speed control optimization of the switching function HW. It is called by subroutine BOXPLX. The function shown is for approach speed of 1.1 and a replenishment speed of 1.0. The runs were made for various realistic combinations to obtain an optimum switching curve.

The run used a step size of 0.04 and a final time of 10.0. The two ships were run linearly with only the longitudinal direction and motion of any concern.

This function is referred to as function FEC in the text.
FUNCTION FE - RUN C

FUNCTION FE (Z)
DIMENSION Z(8), X(10), XDQ(10), Y(10), YDOT(10), E(10)
REAL *8XDQ, X,D,TD
C IDENTIFICATION OF GAINS
SW = Z(1)
C INITIAL CONDITIONS
N = 2
APOSX = 1.1
BPOSX = 0.0
C
DO 1 I=1,N
1 YDOT(I) = 0.0
C
DO 2 I=1,10
2 E(I) = 0.0
C
SPD01 = 1.0
SPD02 = 1.1
Y(I) = 1.1
XK1 = 1.012425
P = -1.0
A = 22.0
G = 0.092
XLUC = 20.84765
UF = 21.73
XK = UF/A
T = 0.0
DT = 0.04
JT = 0.0
SPDDE = XK1*SPD01
ADX = BPOSX-APOSX
C
ITERATION LOOP
3 IF (T,G.T.0.24) P = 4.88/XLUC
IF (ABS(ADX).G.T.2.0) GO TO 9
SPDDES = XK1*(SPDDEC(ADX,SPD01,SPD02,SW)-SPD01)
SPDDEL = DELAY(6,P,SPDDES,E)
SPDIN = XK*(SPDDEL+SPDDE)
SPDERR = G*(SPDIN-Y(I))
YDOT(I) = SPDERR*XLUC
YDOT(2) = T*ABS(ADX)
OBJ = Y(2)
C
DO 4 I=1,N
X(I) = DBLE(Y(I))
4 XDOT(I) = DBLE(YDOT(I))
C
TD = DBLE(T)
DTD = DBLE(DT)
ZS = RKLDEQ(N,X,XDOT,TD,DTD,MT)
C
DO 5 I=1,N
Y(I) = SNGL(X(I))
5 YDOT(I) = SNGL(XDOT(I))
C
T = SNGL(TD)
DT = SNGL(DTD)
IF (ZS-1.1 6,3,7
6 WRITE (6,10)
STOP
7 IF (T.GT.10.0) GO TO 8
APOSX = APOSX+SPD01*DT
BPOSX = BPOSX+Y(I)*DT
ADX = BPOSX-APOSX
GO TO 3
8 FE = OBJ
WRITE (6,11) OBJ,BW,ADX,Y(I)
RETURN
9 FE = 1.0E06
WRITE (6,12) ADX
RETURN
C
10 FORMAT ("RKLDEQ RETURNED ZS FLAG LT 0.0, INTEGRATION PROBLEM")
11 FORMAT ("EXIT FUNCTION FE(Z) OBJ=",F15.8,5X,"SW=",F15.8,/,1
  22X,ADX="",F15.8,5X,"FINAL SPEED="",F15.8)
12 FORMAT ("EXIT FUNCTION FE(Z) ABS(ADX).GT.2.0, ADX="",F15.8)
END
This subroutine was programmed to calculate the desired heading (FSIDES) for RAS heading control. It uses the outputs of subroutine RBMEAS to calculate this heading with gains RSENS and WTSENS. The large number of outputs in the subroutine call statement were made for ease of DSL printed output for tracking of simulation accuracy.

The subroutine also incorporates a loop to avoid computer precision problems in the ARSIN function.
SUBROUTINE HDGRAS

SUBROUTINE HDGRAS (N,IS,R1,B1,BB1,R2,B2,BB2,RSENS,PSIB,PSIDFD,PSIADFC)

10 C 1DD,PSIDFD,DA,AID,B1,B2,WTSENS,DD,DD)
C
C SUBROUTINE TO CALCULATE DESIRED HEADING FOR RAS
C
C IF N SET TO 1 HDGRAS WILL BE USED
C
C IF (N.NE.1) GO TO 4
C
C IS DENOTES THE SIDE OF APPROACH OF RECEIVING SHIP IS=1 PORT,
C IS=0 STBD
C
C RSENS - ADDITIONAL HEADING SENSITIVITY DUE TO SEPARATION DISTANCE
C RSENS=1.0 CORRESPONDS TO 10.87 DEG/10FT FOR 527 FT SHIP
C
C PSIDFD - ADDITIONAL HEADING DUE TO HEADING DIFFERENCE(WEIGHTED)
C PSIADD - ADDITIONAL HEADING DUE TO DISTANCE ERROR(WEIGHTED)
C PSIDED - TOTAL DESIRED HEADING=PSIDFD(WEIGHTED)+PSIADD(WEIGHTED)
C
C NOTE: ALL RETURNED VALUES ENDING IN "D" ARE IN DEGREES
C WTSENS - WEIGHTING FACTOR GAIN FOR DIFFERENCE IN HEADINGS
C DA - CG ABS DISTANCE BETWEEN SHIPS
C AID - CG REL BEARING BETWEEN SHIPS
C
C HEADING DIFFERENCE
C ARG = (R1*SIN(B1)-R2*SIN(B2))/D
C IF (ARG.GT.1.0) GO TO 1
C IF (ARG.LT.-1.0) GO TO 2
C PSIDIF = ARSIN(ARG)
C GO TO 3
C 1 PSIDIF = ARSIN(1.0)
C GO TO 3
C 2 PSIDIF = ARSIN(-1.0)
C CONTINUE
C
C CG DISTANCE
C DA = (R1+R2)/2.0
C
C CG RELATIVE BEARING
C AAI = (BB1+BB2)/2.0
C
C INITIAL SENSE OF APPROACH SIDE DESIRED DISTANCE
C DDC = DD
C IF (IS.EQ.0) DDC = -DD
C
C ADDITIONAL HEADING DUE TO DISTANCE
C PSIADC = RSENS*(DDC+DA*SIN(AAI))
C
C TOTAL DESIRED HEADING
C PSIDES = PSIADC+WTSENS*PSIDIF+PSIB
C
C CONVERT RADIANS TO DEGREES
C
FUNCTION KE

This function is required by all optimization runs. It is the function that contains constraints for subroutine BOXFLX. No constraints are present, consequently function KE is set equal to 0.
FUNCTION KE

FUNCTION KE (X)
DIMENSION X(8)
KE = 0
RETURN
END
This is a generalized program which calls subroutine EOXFLX. Its main purpose is input and output of the values required in the optimization runs. This is referred to as MINIBXPX in the text.
MAIN PROGRAM FOR FUNCTION MINIMIZATIONS

DIMENSION X(8), XS(8), BU(8), BL(8)
CALL ERRSET (257, 256, 0, 1, 1)
READ (5, 4) N, NAV, IP
READ (5, 3) (BU(I), I = 1, N)
READ (5, 3) (BL(I), I = 1, N)
READ (5, 3) (XS(I), I = 1, N)
READ (5, 4) NT, NPR
WRITE (6, 5) N
C
DO 1 I = 1, N
  1 WRITE (6, 6) I, BU(I), I, BL(I), I, XS(I)
C
WRITE (6, 7) NT
WRITE (6, 8)
CALL BOXPLX (N, NAV, NPR, NT, 2.0, XS, IP, BU, BL, OBJ, IER)
WRITE (6, 9)
C
DO 2 I = 1, N
  2 WRITE (6, 10) I, XS(I)
C
WRITE (6, 11) OBJ
WRITE (6, 12) IER
WRITE (6, 8)
STOP
C
3 FORMAT (8F10.5)
4 FORMAT (3110)
5 FORMAT ('*VARIABLES - UPPER LIMIT(BU), LOWER LIMIT(BL), STARTING VALUE(XS) - NUMBER OF VARIABLES=' I5, ')
6 FORMAT ('BU(', ',12, ')= ',F10.5,' BL(', ',12, ')= ',F10.5,' XS(', ',12, ')= ',F10.5, ')
7 FORMAT ('NUMBER OF TRIALS TO BE ALLOWED=' I10)
8 FORMAT ('1)
9 FORMAT ('OUTPUT RESULTS: ' COORDINATES OF MINIMUM', ')
10 FORMAT ('TOTAL COST IS = ',IPE15.8)
11 FORMAT ('ERROR CODE IS = ',I2)
12 FORMAT ('END')
SUBROUTINE BBMEAS

This subroutine measures the range and bearing of the forward and after stations which is required of subroutine BEGMEAS. This is done with trigonometric functions as shown in chapter II. The subroutine is specifically designed to circumvent any ambiguities usually associated with these functions.

It is the basis of the decoupling of the two RAS ships that this thesis is based.
SUBROUTINE RBMEAS

SUBROUTINE RBMEAS (N, PSIA, X1, Y1, PSIB, X2, Y2, D, R1, B1, BB, R2, B2, BB) RBMS 10

SUBROUTINE TO CALCULATE THE RELATIVE POSITIONS OF SHIP A (SUPPLY) RBMS 20

TO SHIP B (RECEIVING) RBMS 30

PSIA - HEADING OF SHIP A (RAD) RBMS 40
PSIB - HEADING OF SHIP B (RAD) RBMS 50
X1, Y1 - COORDINATES OF SHIP A RBMS 60
X2, Y2 - COORDINATES OF SHIP B RBMS 70
D - DISTANCE BETWEEN SENSORS(ALSO BETWEEN REFLECTORS)(SAME ON BOTH SHIPS) RBMS 80
R1, R2 - FWD, AFT MEASURED DISTANCE RBMS 90
B1, B2 - FWD, AFT RELATIVE BEARINGS(RAD) RBMS 100
BB1, BB2 - FWD, AFT RELATIVE BEARINGS(RAD) WITH SIGN RBMS 110
IF N SET TO 1 RBMEAS SUBROUTINE WILL BE USED RBMS 120
IF (N.NE.1) GO TO 7 RBMS 130
ANGLS AND DISTANCES FOR SENSOR INPUT RBMS 140
SDF1 = (D/2.0)*SIN(PSIA) RBMS 150
SDF2 = (D/2.0)*SIN(PSIB) RBMS 160
SDF3 = (D/2.0)*COS(PSIA) RBMS 170
SDF4 = (D/2.0)*COS(PSIB) RBMS 180
FWD DISTANCE RBMS 190
ADFX = SDF3+X1-SDF4-X2 RBMS 200
ADFY = SDF1+Y1-SDF2-Y2 RBMS 210
R1 = SQRT(ADFX**2+ADFY**2) RBMS 220
AFT DISTANCE RBMS 230
ADAX = -SDF3+X1+SDF4-X2 RBMS 240
ADAY = -SDF1+Y1+SDF2-Y2 RBMS 250
R2 = SQRT(ADAX**2+ADAY**2) RBMS 260
FWD ANGLE RBMS 270
IF (ADFY.EQ.0.0) GO TO 2 RBMS 280
BB1 = ATAN2(ADFY,ADFX) RBMS 290
1 BB1 = BB1-PSIB RBMS 300
B1 = BB1+6.283185307 RBMS 310
GO TO 3 RBMS 320
BB1 = 1.570796327 RBMS 330
IF (ADFY.LE.0.0) BB1=-BB1 RBMS 340
GO TO 1 RBMS 350
AFT ANGLE RBMS 360
3 IF (ADAX.EQ.0.0) GO TO 5 RBMS 370
BB2 = ATAN2(ADAY,ADAX) RBMS 380
4 BB2 = BB2-PSIB RBMS 390
B2 = BB2+6.283185307 RBMS 400
GO TO 6 RBMS 410
BB2 = 1.570796327 RBMS 420
5
FUNCTION RKLDEQ

This function is the Runge-Kutta-Gill forth-order integration used in all optimization runs. It is programmed locally and is part of the IBM 360 SSP library. A full explanation and description is shown in the first few pages of the function listing.
FUNCTION RKLDEQ

FUNCTION RKLDEQ (FORTRAN 4,6/H) OR ASSEMBLER LANGUAGE

IDENTIFICATION D2-NPS-RKLDEQ, CHECKED OUT BY R. HILLEY, 4/67.

PURPOSE
THIS ROUTINE SOLVES A SYSTEM OF N FIRST-ORDER ORDINARY DIFFERENTIAL EQUATIONS BY THE RUNGE-KUTTA-GILL FOURTH-ORDER METHOD. ALL CALCULATIONS ARE IN DOUBLE-PRECISION.

USAGE - (WHEN USED BY FORTRAN CALLING PROGRAM)

S = RKLDEQ (N,Y,F,X,H,NT)

FOUR ENTRIES ARE REQUIRED TO ADVANCE THE SOLUTION FROM X TO X + H WHERE H IS THE INCREMENT. SEE SAMPLE PROBLEM FOR MORE INFORMATION.

DESCRIPTION OF PARAMETERS

N - NUMBER OF FIRST-ORDER EQUATIONS IN SYSTEM TO BE SOLVED.

(0.LE.N.LE.25).

Y - NAME OF LINEAR ARRAY OF LENGTH AT LEAST N, IN WHICH SOLUTION VALUES WILL BE STORED BY RKLDEQ. THE CALLING PROGRAM SHOULD SUPPLY INITIAL VALUES BEFORE FIRST ENTRY.

F - NAME OF LINEAR ARRAY OF LENGTH AT LEAST N, IN WHICH THE DERIVATIVES, COMPUTED IN USER'S CALLING PROGRAM, ARE STORED.

X - THE INDEPENDENT VARIABLE, WHICH IS ADVANCED WITHIN RKLDEQ.

H - THE INCREMENT FOR X, WHICH MAY BE CHANGED AT THE END OF ANY INTERVAL. (WHEN S=2.0)

NT - AN INTEGER WHICH COUNTS THE NUMBER OF TIMES ENTRY TO RKLDEQ HAS BEEN MADE DURING CURRENT INTERVAL. IT MUST BE INITIALLY SET TO ZERO BY USER BEFORE FIRST CALL OF RKLDEQ. SUBSEQUENTLY IT SHOULD NOT BE CHANGED BY USER.

S - A SWITCH TO BE TESTED BY USER UPON RETURN FROM RKLDEQ.

IF S = 1.0, THE CALLING PROGRAM SHOULD NOW COMPUTE VALUES OF F, USING CURRENT VALUES OF X AND Y, AND THEN RETURN TO RKLDEQ.

IF S = 2.0, AND END OF PRESENT INTERVAL HAS BEEN REACHED, USER SHOULD STORE AND/OR OUTPUT CURRENT X AND Y AND TEST FOR END OF COMPUTATION.

SEE SAMPLE PROBLEM.
REMARKS
Y,F,X, AND H ARE DOUBLE PRECISION (REAL*8), RKLDEQ IS REAL*4.
MAXIMUM N IS NOW 25.

NOTE
TWO DECKS EXIST FOR THIS FUNCTION. ONE IS IN F4 SOURCE LANGUAGE.
THE OTHER IS ASSEMBLER LANGUAGE AND IS TO BE CALLED WITH A
FORTRAN TYPE CALLING SEQUENCE. RKLDEQ IS RETURNED IN F.P. REG.0

SAMPLE PROBLEM

DIMENSION Y(2), F(2)
REAL*8 Y,F,X,H
Y(1) = 0. DO
Y(2) = 1. DO
X = 1. DO
H = 0.01 DO
NT = 0
WRITE (6,11) X,Y(1),Y(2)

CALCULATION OF DERIVATIVES
F(1) = X * Y(1) - Y(2)**2
F(2) = Y(1) + DSQRT(X)
S = RKLDEQ(2,Y,F,X,H,NT)
IF (S - 1.0) 10,1,2

ERROR STOP
10 STOP
2 WRITE (6,11) X, Y(1), Y(2)
11 FORMAT (1X,3D25.13)

TEST FOR END OF COMputation
IF (DABS(X - 2.5DO) - 1.D-5 ) 3,3,1
3 STOP

END

*******************************************************************************

FORTRAN 4 VERSION OF RUNGE-KUTTA-GILL ROUTINE

FUNCTION RKLDEQ (N,Y,F,X,H,NT)
REAL*8 Y,F,X,H,Q,H1,H2,H3,H6
DIMENSION Y(1), F(1), Q(25)

NT = NT + 1
GO TO (1,2,3,4), NT
1 H1 = H
H2 = H1 * .5D0
H3 = H1 * 2D0
H6 = H1/6D0
DO 11 J =1, N
11 Q(J) = Q.D0
A = .5D0
X = X + H2
GO TO 5
C
2 A = .2928932188134525
GO TO 5
C
3 A = 1.7071067811865475
X = X + H2
GO TO 5
C
4 DO 41 I = 1, N
41 Y(I) = Y(I) + H6 * F(I) - Q(I)/3D0
NT = 0
RKLDEQ =2.
GO TO 6
C
5 DO 51 L = 1, N
51 Y(L) = Y(L) + A *(H * F(L) - Q(L))
Q(L) = H3 * A *F(L) + (1D0-3D0*A) *Q(L)
RKLDEQ =1.
C
6 RETURN
END
SUBROUTINE SLOPES

This subroutine contains the table look-up and interpolation scheme for the interactive forces and moments presented in the RAS environment. It is long and must be pre-compiled for most of the DSL simulation programs shown in this thesis.
SUBROUTINE SLOPES

C SUBROUTINE SLOPES (OX, OY, YY1, YY2, YN1, YN2)
C
TABLE LOOK-UP AND INTERPOLATION
C
DIMENSION Z(23,16), W(23,16), X(23), Y(16)
C
| X(i)  | SLOP 10 | SLOP 20 | SLOP 30 | SLOP 40 | SLOP 50 | SLOP 60 | SLOP 70 | SLOP 80 | SLOP 90 | SLOP 100 | SLOP 110 | SLOP 120 | SLOP 130 | SLOP 140 | SLOP 150 | SLOP 160 | SLOP 170 | SLOP 180 | SLOP 190 | SLOP 200 | SLOP 210 | SLOP 220 | SLOP 230 | SLOP 240 | SLOP 250 | SLOP 260 | SLOP 270 | SLOP 280 | SLOP 290 | SLOP 300 | SLOP 310 | SLOP 320 | SLOP 330 | SLOP 340 | SLOP 350 | SLOP 360 | SLOP 370 | SLOP 380 | SLOP 390 | SLOP 400 | SLOP 410 | SLOP 420 | SLOP 430 |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
FUNCTION SPINIT

This function was designed to aid in initialization problems associated with the DSL function DELY. The effect is that the function initializes the delay loop until it can be self-supportive.
FUNCTION SPINIT (SPODEL, TIME, SPD0)
IF (TIME GT 0.5)
SPINIT = SPD0
RETURN = SPODEL
END
FUNCTION SPDCTR

This function is the speed control used during heading control development. It is used directly as the speed of the control ship with information of the speed of the two ships and the longitudinal position ADX. It contains a linear function at ±1.0 ship lengths to a dead zone of ±0.001 centered about the alongside position (0.0).
FUNCTION SPDCTR

FUNCTION SPDCTR (ADX, U01, U02)
IF (ADX .LT. -1.0) GO TO 1
IF (ADX .GT. 1.0) GO TO 2
IF (ABS(ADX).LT.0.001) GO TO 3
SPDCTR = -ADX*(U02-U01)+U01
RETURN
1 SPDCTR = U02
RETURN
2 SPDCTR = U02-U01
RETURN
3 SPDCTR = U01
RETURN
END

SPCR 10
SPCR 20
SPCR 30
SPCR 40
SPCR 50
SPCR 60
SPCR 70
SPCR 80
SPCR 90
SPCR 100
SPCR 110
SPCR 120
SPCR 130
FUNCTION SPDOFC

This function is identical to SPDREC except that the ability to offset the alongside position (0.0) is incorporated. This is the speed control function in its final development form.
FUNCTION SPDOFC

FUNCTION SPDOFC (ADX, SPD01, SPD02, SW, XOFS)
SWITCH = -SW*(SPD02-SPD01)
IF ((ADX-XOFS), LT, SWITCH) GO TO 1
IF ((ADX-XOFS), GT, -SWITCH) GO TO 2
IF (ABS(ADX-XOFS), LT, 0.001) GO TO 3
SPDOFC = -(ADX-XOFS)*(SPD02-SPD01)+SPD01
RETURN
1 SPD0FC = SPD02
RETURN
2 SPD0FC = SPD02-SPD01
RETURN
3 SPD0FC = SPD01
RETURN
END
FUNCTION SPDREC

This function is similar to SPDCTR except that a switching function is incorporated. This is the function used for optimization of the switching function and is used in the velocity loop simulated in the velocity control section of chapter III.
FUNCTION SPDREC

FUNCTION SPDREC (ADX, SPD01, SPD02, SW)

SWITCH = -SW*(SPD02-SPD01)
IF (ADX.LT.SWITCH) GO TO 1
IF (ADX.GT.-SWITCH) GO TO 2
IF (ABS(ADX).LT.0.001) GO TO 3
SPDREC = -ADX*(SPD02-SPD01)+SPD01
RETURN
1 SPDREC = SPD02
RETURN
2 SPDREC = SPD02-SPD01
RETURN
3 SPDREC = SPD01
RETURN
END
FUNCTION SWCL

This function contains the fifth order polynomial curve fit for the optimal switching position of the speed control loop. Its range of values for SPDDIF are 0.1 to 1.0 normalized speed difference between the two ships.
FUNCTION SWCL

FUNCTION SWCL (SPDO1, SPDO2)
  SPDDIF = SPDO2 - SPDO1
  SWCL = -2.24869*SPDDIF**5 + 6.93243*SPDDIF**4 - 8.04233*SPDDIF**3 + 4.081065*SPDDIF**2 - 0.409977*SPDDIF + 0.554
  RETURN
END
SUBROUTINE SWTCH

This subroutine contains the gains and mechanisms required for the adaptive gain schedule developed in this thesis. It includes the optimal gains obtained from the heading control optimization runs.
SUBROUTINE SWCH

SUBROUTINE SWCH (DD, DA, AAI, IS, RSENS, WSENS, RGN, VFBG, BDOT2D)

SUBROUTINE TO SWITCH RAS GAINS ONCE SHIPS ALONGSIDE

C

DDC = DD
IF (IS.EQ.0) DDC = -DD
AMDY = DDC+DA*SIN(AAI)
AMDX = DA*COS(AAI)
IF (ABS(AMDX).GT.1.0) N=1
IF (ABS(AMDX).LT.0.5 .AND. ABS(AMDY).LT.0.005) GO TO 1
IF (ABS(AMDY).LT.0.05) GO TO 2
N = 1
RENS = 1.86642
WSENS = 2.38692
RGN = 23.41847
VFBG = 4.35162
RETURN

1 RSENS = 1.99765
WSENS = 0.7357
RGN = 49.97757
VFBG = 0.084028
N = N+1
IF (ABS(BDOT2D).GT.2.0 .AND. N.LT.150) VFBG=1.0
RETURN

2 RSENS = 4.0
WSENS = 2.38692
RGN = 23.41847
VFBG = 4.35162
IF (N.GT.150) GO TO 1
N = 1
RETURN
END
SUBROUTINE SWTCHF

This subroutine is identical to SWTCH except that the turn phase gain VPBG is relaxed to allow for offset longitudinal position placement. This is the adaptive gain schedule in its final form.
SUBROUTINE SWTCHF

SUBROUTINE SWTCHF (DD, DA, A1, IS, RSENS, WTSENS, RGN, VFBG, BDOT2D, XOFFS) SWTF 10
SUBROUTINE TO SWITCH RAS GAINS ONCE SHIPS ALONGSIDE SWTF 20
DDC = DD SWTF 30
IF (IS.EQ.0) DDC = -DD SWTF 40
AMDY = DDC + DA*SIN(AA1) SWTF 50
AMDX = DA*COS(AA1) SWTF 60
IF (ABS(AMDX-XOFFS).GT.1.0) N=1 SWTF 70
IF (ABS(AMDX-XOFFS).LT.0.5.AND.ABS(AMDY).LT.0.005) GO TO 1 SWTF 80
IF (ABS(AMDY).LT.0.05) GO TO 2 SWTF 90
N = 1 SWTF 100
RSENS = 1.86642 SWTF 110
WTSENS = 2.38692 SWTF 120
RGN = 23.41847 SWTF 130
VFBG = 4.35162 SWTF 140
RETURN SWTF 150
1 RSENS = 1.99765 SWTF 160
WTSENS = 0.7357 SWTF 170
RGN = 49.97757 SWTF 180
VFBG = 0.1 SWTF 190
IF (ABS(BDOT2D).GT.2.0.AND.N.LE.150) VFBG=1.0 SWTF 200
N = N+1 SWTF 210
RETURN SWTF 220
2 RSENS = 4.0 SWTF 230
WTSENS = 2.38692 SWTF 240
RGN = 23.41847 SWTF 250
VFBG = 4.35162 SWTF 260
IF (N.GT.150) GO TO 1 SWTF 270
N = 1 SWTF 280
RETURN SWTF 290
END SWTF 300
This subroutine takes the lateral and longitudinal geographic displacements and converts them to actual displacements referenced to the control ship's head. This is done to gain a more realistic reference for subroutine SEMIAS, subroutine SLOPES, function SPDCTR, function SEDCFC, and function SPDREC.
SUBROUTINE TRANS

SUBROUTINE TRANS (PSIA, DX, DY, ADX, ADY)
DXY = SQRT(DX**2+DY**2)
AXY = ARSIN(-DY/DXY)
IF (DX.LT.0.) AXY = 3.141592654-AXY
AT = AXY+PSIA
ADY = -DXY*SIN(AT)
ADX = +DXY*COS(AT)
RETURN
END
FUNCTION XLIMIT

This function was developed to allow the LIMIT function of DSL to be incorporated in the optimization runs. It is a saturation amplifier with a gain of 1.0, and upper limit of UL, and a lower limit of XLL.
APPENDIX B

The final form of the simulation program, with all its subroutines and functions, is a very complex and complicated maze. To aid in following its progression, this appendix contains a detailed block diagram of the program with each variable listed in its computer variable name. Each page contains a functional part of the simulation with inputs and outputs shown cross referenced to their origin and destination.

The following is a list of the block diagrams contained in this appendix in the order in which they appear:

Ship A (Reference Ship) Simulation
   Ship A Heading Simulation
   Ship A Speed Simulation
Ship B (Control Ship) Simulation
   Ship B Heading Simulation
   Ship B Speed Simulation
Subroutine RBMEAS
   Range Measurement
   Bearing Measurement
Subroutine HDGRAS
   Heading Control Loop
Auxiliary Functions
   Yaw Conversion
   Coordinate Conversion
   Feedback Loop
Rudder Modeling
   Ship A Rudder
   Ship B Rudder
Wave Generator
Wave Direction
Random Variable
Wave Encounter
Wave Components
Ship B Heading Simulation

Ship B Speed Simulation

Ship B (Control Ship) Simulation
SUBROUTINE RBMEAS

RETURN TO CALLING PROGRAM

RANGE MEASUREMENT

BEARING MEASUREMENT

(from Ship Simulation) PSLA
(from Ship Simulation) PSLB

PARAM INPUT N
PARAM INPUT D

enable subroutine

SDF1 SDF2 SDF3 SDF4

ADFX

ADFX

ADAY

ADAY

ADAY

ADAY

ADAY

ADAY

ADAY

ADAY

ADAY

ADAY
Heading Control Loop

Subroutine HDGRAS
Coordinate Conversion

Feedback Loop

Auxiliary Functions
Throughout this thesis subroutine SLOPES has been used to output the interactive forces and moments between ships in the RAS situation. This subroutine, adapted from ref. 11, does not contain a complete picture of the circumstances envisioned. In particular, ship's speeds other than the 15 kt. operating point and different ship lengths are not accounted for.

As stated in chapter II, the speed modification factor can easily be applied for both ships at the same speed and other than 15 kts. with the following expression:

\[ SPDP = CDOT \]

Ships replenishing with different lengths can also be incorporated as shown in ref. 1.

Subroutine FAMIC listed in this appendix incorporates these two ideas along with a better method of determining the interactive forces and moments. The curves of figures II-11 and II-12 were quantized every 50 feet of DX for all the DY curves shown. These points were then used in the NFGS XDS-930C digital computer and AGT-10 graphics terminal to obtain a family of best fit curves. The best fit criteria is based on the sum of the error squared at each quantized point (modified somewhat by this researcher's evaluation of best fit between points to eliminate spikes and other anomalies). The results of this curve fit process is summarized in tables C-1 and C-2, which includes tabulation of the best fit criteria. These polynomial coefficients are based on the DX distance and are coded in
<table>
<thead>
<tr>
<th>Power</th>
<th>Y50[YY(1)]</th>
<th>Y60[YY(2)]</th>
<th>Y70[YY(3)]</th>
<th>Y80[YY(4)]</th>
<th>Y90[YY(5)]</th>
<th>Y100[YY(6)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>84.324</td>
<td>75.260</td>
<td>67.668</td>
<td>59.223</td>
<td>53.449</td>
<td>47.441</td>
</tr>
<tr>
<td>1</td>
<td>0.364580E-2</td>
<td>0.384289E-2</td>
<td>0.305160E-2</td>
<td>0.221400E-2</td>
<td>0.174604E-2</td>
<td>0.115702E-2</td>
</tr>
<tr>
<td>2</td>
<td>-0.118950E-3</td>
<td>-0.168365E-3</td>
<td>-0.103683E-3</td>
<td>-0.944770E-2</td>
<td>-0.740983E-2</td>
<td>-0.587039E-2</td>
</tr>
<tr>
<td>3</td>
<td>-0.197311E-2</td>
<td>-0.504085E-2</td>
<td>-0.265717E-2</td>
<td>-0.710687E-1</td>
<td>-0.885819E-0</td>
<td>-0.165712E-2</td>
</tr>
<tr>
<td>4</td>
<td>0.513437E-2</td>
<td>0.684302E-2</td>
<td>0.719316E-2</td>
<td>0.103147E-3</td>
<td>0.467865E-2</td>
<td>0.242239E-2</td>
</tr>
<tr>
<td>5</td>
<td>0.503561E-1</td>
<td>0.466749E-2</td>
<td>0.158656E-2</td>
<td>-0.286063E-1</td>
<td>-0.749374E-1</td>
<td>-0.397052E-2</td>
</tr>
<tr>
<td>6</td>
<td>-0.100337E-2</td>
<td>-0.194364E-2</td>
<td>-0.344841E-2</td>
<td>-0.106332E-3</td>
<td>-0.206166E-2</td>
<td>-0.164427E-1</td>
</tr>
<tr>
<td>7</td>
<td>-0.484175E-0</td>
<td>-0.238722E-2</td>
<td>-0.532674E-1</td>
<td>-0.304098E-0</td>
<td>0.488631E-1</td>
<td>0.345891E-2</td>
</tr>
<tr>
<td>8</td>
<td>0.750949E-0</td>
<td>-0.398443E-0</td>
<td>0.101864E-2</td>
<td>0.688338E-2</td>
<td>0.584863E-1</td>
<td>0.677233E-0</td>
</tr>
<tr>
<td>9</td>
<td>0.655075E-1</td>
<td>0.877360E-0</td>
<td>0.456701E-1</td>
<td>-0.136413E-1</td>
<td>-0.158999E-2</td>
<td>-0.158999E-2</td>
</tr>
<tr>
<td>10</td>
<td>0.181994E-1</td>
<td>0.158465E-1</td>
<td>-0.221987E-2</td>
<td>-0.941379E-0</td>
<td>-0.255071E-1</td>
<td>-0.255071E-1</td>
</tr>
<tr>
<td>11</td>
<td>-0.916189E-0</td>
<td>-0.556587E-1</td>
<td>-0.347210E-1</td>
<td>0.178935E-0</td>
<td>0.405863E-1</td>
<td>0.405863E-1</td>
</tr>
<tr>
<td>12</td>
<td>-0.428170E-0</td>
<td>0.984583E-1</td>
<td>0.160105E-1</td>
<td>0.729225E-1</td>
<td>0.131265E-1</td>
<td>0.131265E-1</td>
</tr>
<tr>
<td>13</td>
<td>0.514317E-1</td>
<td>-0.114485E-1</td>
<td>-0.901537E-2</td>
<td>-0.543239E-0</td>
<td>-0.296983E-1</td>
<td>-0.177684E-1</td>
</tr>
<tr>
<td>14</td>
<td>0.316613E-1</td>
<td>0.965145E-0</td>
<td>0.176277E-2</td>
<td>0.256741E-0</td>
<td>0.296983E-1</td>
<td>0.177684E-1</td>
</tr>
<tr>
<td>15</td>
<td>0.189745E-1</td>
<td>0.109745E-1</td>
<td>0.189745E-1</td>
<td>0.296983E-1</td>
<td>0.177684E-1</td>
<td>0.177684E-1</td>
</tr>
</tbody>
</table>

Table C-1

Interactive Curve Fit Polynomial Coefficients
<table>
<thead>
<tr>
<th>Power</th>
<th>Y110 [YY(7)]</th>
<th>Y120 [YY(8)]</th>
<th>Y130 [YY(9)]</th>
<th>Y140 [YY(10)]</th>
<th>Y150 [YY(11)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40.423</td>
<td>35.484</td>
<td>30.606</td>
<td>26.063</td>
<td>22.876</td>
</tr>
<tr>
<td>1</td>
<td>.142822E 2</td>
<td>.146142E 2</td>
<td>.138458E 2</td>
<td>.120761E 2</td>
<td>.108418E 2</td>
</tr>
<tr>
<td>2</td>
<td>-.533075E 2</td>
<td>-.458814E 2</td>
<td>-.425663E 2</td>
<td>-.341076E 2</td>
<td>-.196219E 2</td>
</tr>
<tr>
<td>3</td>
<td>-.103692E 2</td>
<td>-.158329E 2</td>
<td>-.139724E 2</td>
<td>-.150249E 2</td>
<td>-.127593E 2</td>
</tr>
<tr>
<td>4</td>
<td>.389319E 2</td>
<td>.398457E 2</td>
<td>.661640E 2</td>
<td>.574245E 2</td>
<td>.133189E 2</td>
</tr>
<tr>
<td>5</td>
<td>.875165E 1</td>
<td>.163639E 2</td>
<td>.863816E 1</td>
<td>.122510E 2</td>
<td>.974262E 1</td>
</tr>
<tr>
<td>6</td>
<td>-.200712E 2</td>
<td>-.242537E 2</td>
<td>-.800393E 2</td>
<td>-.702577E 2</td>
<td>-.695905E 1</td>
</tr>
<tr>
<td>7</td>
<td>-.502212E 1</td>
<td>-.953711E 1</td>
<td>-.274913E 1</td>
<td>-.333288E 1</td>
<td>-.335866E 1</td>
</tr>
<tr>
<td>8</td>
<td>.615393E 1</td>
<td>.820245E 1</td>
<td>.533407E 2</td>
<td>.488103E 2</td>
<td>.214837E 1</td>
</tr>
<tr>
<td>9</td>
<td>.154525E 1</td>
<td>.291771E 1</td>
<td>.211749E 2</td>
<td>-.946233E 0</td>
<td>.453764E 0</td>
</tr>
<tr>
<td>10</td>
<td>-.972521E 0</td>
<td>-.137319E 1</td>
<td>-.175113E 2</td>
<td>-.195409E 2</td>
<td>-.339142E 0</td>
</tr>
<tr>
<td>11</td>
<td>-.237633E 0</td>
<td>-.447954E 0</td>
<td>-.190223E 1</td>
<td>.766196E 0</td>
<td>.407256E-3</td>
</tr>
<tr>
<td>12</td>
<td>.607427E-1</td>
<td>.890809E-1</td>
<td>.163223E 1</td>
<td>.448663E 1</td>
<td>.211973E-1</td>
</tr>
<tr>
<td>13</td>
<td>.144010E-1</td>
<td>.272508E-1</td>
<td>.777504E 0</td>
<td>-.162184E 0</td>
<td>-.347399E-2</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>.560018E 0</td>
<td>-.540550E 0</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td>-.141969E 0</td>
<td>.116108E-1</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>-.160683E 0</td>
<td>.276591E-1</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>.960782E-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>.120067E-1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C-1
Interactive Curve Fit Polynomial Coefficients
<table>
<thead>
<tr>
<th>Power</th>
<th>N50 [YN(1)]</th>
<th>N60 [YN(2)]</th>
<th>N70 [YN(3)]</th>
<th>N80 [YN(4)]</th>
<th>N90 [YN(5)]</th>
<th>N100 [YN(6)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.396089E2</td>
<td>.326330E2</td>
<td>.242094E2</td>
<td>.188936E2</td>
<td>.173015E2</td>
<td>.135031E2</td>
</tr>
<tr>
<td>2</td>
<td>.402860E2</td>
<td>.362146E2</td>
<td>.371281E2</td>
<td>.304472E2</td>
<td>.328997E2</td>
<td>.311296E2</td>
</tr>
<tr>
<td>3</td>
<td>-.326885E2</td>
<td>-.256484E2</td>
<td>-.711693E1</td>
<td>-.125164E1</td>
<td>-.559773E1</td>
<td>-.199635E1</td>
</tr>
<tr>
<td>4</td>
<td>.397695E1</td>
<td>.348686E1</td>
<td>-.705366E1</td>
<td>-.599694E0</td>
<td>-.167075E2</td>
<td>-.200747E2</td>
</tr>
<tr>
<td>5</td>
<td>.847350E1</td>
<td>.747495E1</td>
<td>-.121721E2</td>
<td>-.141799E2</td>
<td>-.505714E1</td>
<td>-.613206E1</td>
</tr>
<tr>
<td>6</td>
<td>-.188304E2</td>
<td>-.174840E2</td>
<td>-.782624E1</td>
<td>-.133875E2</td>
<td>.626911E1</td>
<td>.938014E1</td>
</tr>
<tr>
<td>7</td>
<td>.334908E0</td>
<td>-.236966E1</td>
<td>.894936E1</td>
<td>.915469E1</td>
<td>.308497E1</td>
<td>.324620E1</td>
</tr>
<tr>
<td>8</td>
<td>.103131E2</td>
<td>.102702E2</td>
<td>.657382E1</td>
<td>.943453E1</td>
<td>-.179228E1</td>
<td>-.279550E1</td>
</tr>
<tr>
<td>9</td>
<td>-.136166E1</td>
<td>.992354E0</td>
<td>-.251129E1</td>
<td>-.251460E1</td>
<td>-.605389E0</td>
<td>-.630851E0</td>
</tr>
<tr>
<td>10</td>
<td>-.222623E1</td>
<td>-.287062E1</td>
<td>-.224627E1</td>
<td>-.303990E1</td>
<td>.301083E0</td>
<td>.443308E0</td>
</tr>
<tr>
<td>11</td>
<td>.647133E0</td>
<td>-.217277E0</td>
<td>.326965E0</td>
<td>.332880E0</td>
<td>.410884E1</td>
<td>.438239E-1</td>
</tr>
<tr>
<td>12</td>
<td>.338223E-1</td>
<td>.397733E0</td>
<td>.366197E0</td>
<td>.478124E0</td>
<td>-.206993E1</td>
<td>-.281713E-1</td>
</tr>
<tr>
<td>13</td>
<td>-.132735E0</td>
<td>.168090E-1</td>
<td>-.164232E-1</td>
<td>-.174528E-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>.553291E-1</td>
<td>-.218380E-1</td>
<td>-.231377E-1</td>
<td>-.294675E-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>.989063E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>-.574936E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table C-1
Interactive Curve Fit Polynomial Coefficients
<table>
<thead>
<tr>
<th>Power</th>
<th>N100[YN(7)]</th>
<th>N140[YN(10)]</th>
<th>N200[YN(14)]</th>
<th>N300[YN(9)]</th>
<th>N400[YN(9)]</th>
<th>N500[YN(11)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10149E+2</td>
<td>0.80782E+2</td>
<td>0.78902E+2</td>
<td>0.60315E+2</td>
<td>0.50252E+2</td>
<td>-9.955E-1</td>
</tr>
<tr>
<td>2</td>
<td>2.23191E+2</td>
<td>1.06262E+2</td>
<td>1.06257E+2</td>
<td>1.06262E+2</td>
<td>0.60315E+2</td>
<td>-1.06257E+2</td>
</tr>
<tr>
<td>3</td>
<td>-1.08585E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
</tr>
<tr>
<td>4</td>
<td>-2.96564E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
</tr>
<tr>
<td>5</td>
<td>-5.87218E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
</tr>
<tr>
<td>6</td>
<td>-1.09111E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
<td>-6.9142E+2</td>
</tr>
<tr>
<td>7</td>
<td>3.39381E+2</td>
<td>0.16476E+2</td>
<td>0.16476E+2</td>
<td>0.16476E+2</td>
<td>0.16476E+2</td>
<td>0.16476E+2</td>
</tr>
<tr>
<td>8</td>
<td>8.30859E+2</td>
<td>0.39793E+2</td>
<td>0.39793E+2</td>
<td>0.39793E+2</td>
<td>0.39793E+2</td>
<td>0.39793E+2</td>
</tr>
<tr>
<td>9</td>
<td>1.24323E+2</td>
<td>0.57921E+2</td>
<td>0.57921E+2</td>
<td>0.57921E+2</td>
<td>0.57921E+2</td>
<td>0.57921E+2</td>
</tr>
<tr>
<td>10</td>
<td>-2.81000E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
</tr>
<tr>
<td>11</td>
<td>-4.43430E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
<td>-4.20471E+2</td>
</tr>
<tr>
<td>13</td>
<td>-1.29317E+3</td>
<td>-1.72570E+3</td>
<td>-1.72570E+3</td>
<td>-1.72570E+3</td>
<td>-1.72570E+3</td>
<td>-1.72570E+3</td>
</tr>
<tr>
<td>14</td>
<td>-2.68301E+3</td>
<td>-2.18733E+3</td>
<td>-2.18733E+3</td>
<td>-2.18733E+3</td>
<td>-2.18733E+3</td>
<td>-2.18733E+3</td>
</tr>
</tbody>
</table>

Table C-1

Interactive Curve Fit Polynomial Coefficients
<table>
<thead>
<tr>
<th>Curve Fit</th>
<th>Order</th>
<th>( \sum e^2 )</th>
<th>( \bar{e} )</th>
<th>Best Fit (Modified)</th>
<th>Order</th>
<th>( \sum e^2 )</th>
<th>( \bar{e} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y50</td>
<td>15</td>
<td>2.1664</td>
<td>0.307</td>
<td>8</td>
<td>70.345</td>
<td>1.749</td>
<td></td>
</tr>
<tr>
<td>Y60</td>
<td>15</td>
<td>2.1462</td>
<td>0.305</td>
<td>14</td>
<td>2.1703</td>
<td>0.307</td>
<td></td>
</tr>
<tr>
<td>Y70</td>
<td>15</td>
<td>0.41727</td>
<td>0.135</td>
<td>12</td>
<td>1.1915</td>
<td>0.228</td>
<td></td>
</tr>
<tr>
<td>Y80</td>
<td>15</td>
<td>0.71421</td>
<td>0.176</td>
<td>18</td>
<td>0.87588</td>
<td>0.195</td>
<td></td>
</tr>
<tr>
<td>Y90</td>
<td>15</td>
<td>1.2793</td>
<td>0.236</td>
<td>14</td>
<td>1.2981</td>
<td>0.238</td>
<td></td>
</tr>
<tr>
<td>Y100</td>
<td>16</td>
<td>1.1573</td>
<td>0.224</td>
<td>16</td>
<td>1.1573</td>
<td>0.224</td>
<td></td>
</tr>
<tr>
<td>Y110</td>
<td>15</td>
<td>1.2798</td>
<td>0.236</td>
<td>13</td>
<td>1.3400</td>
<td>0.241</td>
<td></td>
</tr>
<tr>
<td>Y120</td>
<td>15</td>
<td>0.39722</td>
<td>0.131</td>
<td>13</td>
<td>0.77148</td>
<td>0.183</td>
<td></td>
</tr>
<tr>
<td>Y130</td>
<td>15</td>
<td>0.54194</td>
<td>0.154</td>
<td>18</td>
<td>0.66737</td>
<td>0.170</td>
<td></td>
</tr>
<tr>
<td>Y140</td>
<td>15</td>
<td>0.77259</td>
<td>0.183</td>
<td>16</td>
<td>1.0620</td>
<td>0.215</td>
<td></td>
</tr>
<tr>
<td>Y150</td>
<td>15</td>
<td>0.26589</td>
<td>0.108</td>
<td>13</td>
<td>0.44726</td>
<td>0.139</td>
<td></td>
</tr>
<tr>
<td>N50</td>
<td>17</td>
<td>0.80547</td>
<td>0.187</td>
<td>16</td>
<td>0.80572</td>
<td>0.187</td>
<td></td>
</tr>
<tr>
<td>N60</td>
<td>18</td>
<td>0.63879</td>
<td>0.167</td>
<td>14</td>
<td>0.73449</td>
<td>0.179</td>
<td></td>
</tr>
<tr>
<td>N70</td>
<td>17</td>
<td>0.57433</td>
<td>0.158</td>
<td>14</td>
<td>0.59042</td>
<td>0.160</td>
<td></td>
</tr>
<tr>
<td>N80</td>
<td>14</td>
<td>0.43632</td>
<td>0.138</td>
<td>14</td>
<td>0.43632</td>
<td>0.138</td>
<td></td>
</tr>
<tr>
<td>N90</td>
<td>17</td>
<td>0.77685</td>
<td>0.184</td>
<td>12</td>
<td>0.83329</td>
<td>0.190</td>
<td></td>
</tr>
<tr>
<td>N100</td>
<td>15</td>
<td>0.48934</td>
<td>0.146</td>
<td>12</td>
<td>0.67948</td>
<td>0.172</td>
<td></td>
</tr>
<tr>
<td>N110</td>
<td>15</td>
<td>0.25701</td>
<td>0.106</td>
<td>14</td>
<td>0.59247</td>
<td>0.160</td>
<td></td>
</tr>
<tr>
<td>N120</td>
<td>15</td>
<td>0.29538</td>
<td>0.113</td>
<td>13</td>
<td>0.62067</td>
<td>0.164</td>
<td></td>
</tr>
<tr>
<td>N130</td>
<td>15</td>
<td>0.051807</td>
<td>0.047</td>
<td>14</td>
<td>0.064323</td>
<td>0.053</td>
<td></td>
</tr>
<tr>
<td>N140</td>
<td>15</td>
<td>0.13166</td>
<td>0.076</td>
<td>10</td>
<td>0.30835</td>
<td>0.116</td>
<td></td>
</tr>
<tr>
<td>N150</td>
<td>15</td>
<td>0.11837</td>
<td>0.072</td>
<td>12</td>
<td>0.16549</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td>0.71425</td>
<td>0.176</td>
<td></td>
<td>3.96169</td>
<td>0.252</td>
<td></td>
</tr>
</tbody>
</table>

Table C-2
Interactive Curve Fit Error Analysis
subroutine FAMIC as YY(1) thru YY(11) and YN(1) thru YN(11). An interpolation algorithm is used to determine the forces and moments at DY points between the curves of each family. Although all the computations are based on measurements from the control ship (ship #2), the interactive forces and moments are also computed for the reference ship (ship #1).

Figures C-1 and C-2 are the interactive forces and moments output to show comparison to figures II-11 and II-12. The speed of this run was the operating point of 15 kts. The ships are of equal length (527.8 feet).

Linear interpolation of the interactive curves for greater than 150 feet DY distance is accomplished from this 150 foot curve to a value of 0.0 at 200 feet. It therefore assumes no force and moment are present outside the 200 foot range. All forces and moments for DY distance of less than 50 feet are taken as that of the 50 foot curve. These two endpoints are by no means exact, but will suffice until more detailed data can be gathered. Another inexact endpoint is produced at the curve families limits of ±550 feet. At these points, the forces and moments are forced to 0.0 since detailed data outside of these limits was not available. A side effect of this abrupt truncation will manifest itself in the instantaneous commencement of the forces and moments during the approach phase run. The endpoint variations in some of the curves of figures C-1 and C-2 are due in part to the curve fitting routine used, but mostly to the differences in computer precision. (curve fits were calculated on a 11 digit precision XDS 9300 while the curves were plotted on single precision 7 digit IBM 360/67)

As previously mentioned, the speed modification for other than the operating point of 15 kts. is only completely valid for the situation where both ships are at the same speeds. Since this thesis considered an approach phase
Figure C-1
Curve Fitted Interactive Y Forces
Figure C-2
Curve Fitted Interactive N Moments
where the control ship enters the interactive field at a speed quite different than the reference ship, some modification of the interactive effects should be considered. However, exact relationships are not available to compute the required modification factors.

To dispel any problems with the design of the heading control system, the worst case speed modification factor was chosen. This factor, in effect, considers that the interactive forces and moments are derived from the control ship. This is accomplished in subroutine FAMIC with the following fortran expression:

\[ SPIF_2 = CDOT2**2 \]

As stated in chapter II, it is felt that it is more accurate to consider the interactive forces and moments to be modified by the speed of the reference ship, and can be coded in subroutine FAMIC as:

\[ SPIF_2 = CDOT1**2 \]

With the scenario followed throughout this thesis, this expression would equate to unity throughout the RAS situation, since the reference ship is maintained at 1.0 normalized speed (15 kts.).

For the sake of error analysis, simulation of the worst case modification is performed. This gives rise to forces and moments 2.25 times what they were in the rest of this thesis during a portion of the approach phase when the normalized speed of the control ship is 1.5. Figures C-3 and C-4 show the interactive forces and moments for the approach phase of the simulation. The comparison plots which appear in chapter III as figures III-24 and III-25
Figure C-5
Approach Phase Geographical Plot From Modified Interactive Effects
illustrate the extent of the changes. Most notable is the smoother output of subroutine FAMIC. This more realistically portrays the interactive effects in the RAS environment. Figure C-5 portrays the geographical plot which compares with figure III-26 without speed modification. Although differences exist, figure C-5 illustrates that the interactive effects speed modification factor for the worst case does not drastically alter the approach phase outcome. The heading control system design is still valid in the face of these changes.

For reference, figures C-6 and C-7 show the interactive forces and moments in the turn phase as calculated by subroutine FAMIC. Figure C-8 is the turn phase lateral distance plot produced. It can be seen from this illustration that the maximum excursion is 0.0056 normalized distance (2.56 feet), well within acceptable limits.

In summary, the designed control system will accommodate even the worst case modification of the interactive effects. This insensitivity to a large range of perturbations, makes this control system a more viable design for actual ship installation.
Figure C-8
Turn Phase Lateral Distance DY From Modified Interactive Effects
SUBROUTINE FAMIC

SUBROUTINE FAMIC (XL1, XL2, ADX, ADY, CDOT1, CDOT2, YY1, YY2, YN1, YN2) FAM 10
DIMENSION YY(12), YN(12) FAM 20
FAM 30
FAM 40
FAM 50

DEFINITION OF TERMS:

XL1 = LENGTH OF SHIP #1 IN FEET
XL2 = LENGTH OF SHIP #2 IN FEET
ADX = LONGITUDINAL SEPARATION OF SHIPS (NONDIMENSIONALIZED)
ADY = LATERAL SEPARATION OF SHIPS (NONDIMENSIONALIZED)
CDOT1 = NORMALIZED SPEED OF SHIP #1
CDOT2 = NORMALIZED SPEED OF SHIP #2
YY1 = Y FORCE ON SHIP #1
YY2 = Y FORCE ON SHIP #2
YN1 = N MOMENT ON SHIP #1
YN2 = N MOMENT ON SHIP #2
X = LONGITUDINAL SEPARATION NORMALIZED TO CURVE FIT FACTOR

NOTE: FOR STBD SIDE TO APPROACH OF SHIP #2 ON SHIP #1, ADY
SHOULD BE NEGATIVE.
FOR APPROACH WHEN SHIP #2 IS ASTERN OF SHIP #1 ADX SHOULD
BE NEGATIVE.
CONVERSSES ARE ALSO TRUE - PORT SIDE TO = POSITIVE ADY AND
AFWD OF ALONGSIDE = POSITIVE.
ADX AND ADY ARE REFERENCED TO SHIP #2.
NORMALIZED SPEEDS BASED ON 15 KTS.

XL = XL2
FDP1 = CDOT1**2
FDP2 = CDOT2**2
XLP1 = XL1/XL2
XLP2 = 1.0
N = 1
ADXL = XL*ADX
X = XL*ADX/250.0
IF (ABS(ADXL).GT.550.0) GO TO 6

POLYNOMIAL POWER PRE-COMPUTATION
EQUATIONS OF Y FORCES

YY(1) = 8.4324 + 0.364580E + 02* X1 - 0.118950E + 03* X2 - 0.197331E + 02* X3 + 0.5FAMI
113437E + 02* X4 + 0.503561E + 01* X5 - 0.100337E + 02* X6 - 0.484175E + 00* X7 + 0.75FAMI
2549E + 00* X8

YY(2) = 75.260 + 0.384289E + 02* X1 - 0.116865E + 03* X2 - 0.504985E + 02* X3 + 0.6FAMI
184302E + 02* X4 + 0.466749E + 02* X5 - 0.194633E + 02* X6 - 0.238722E + 02* X7 - 0.398FAMI
2543E + 00* X8 + 0.655075E + 01* X9 + 0.181954E + 01* X10 - 0.916185E + 00* X11 - 0.428FAMI
3170E + 00* X12 + 0.514317E - 01* X13 + 0.361613E - 01* X14

YY(3) = 67.668 + 0.305160E + 02* X1 - 0.103683E + 03* X2 - 0.265717E + 02* X3 + 0.7FAMI
115316E + 02* X4 + 0.158656E + 02* X5 - 0.344841E + 02* X6 - 0.532674E + 01* X7 + 0.101FAMI
2864E + 02* X8 + 0.877360E + 03* X9 - 0.154656E + 01* X10 - 0.556587E - 01* X11 + 0.984FAMI
3528E - 01* X12

YY(4) = 59.223 + 0.221400E + 02* X1 - 0.544770E + 02* X2 - 0.710681E + 01* X3 + 0.1FAMI
102147E + 03* X4 - 0.286603E + 01* X5 - 0.106332E + 03* X6 - 0.304098E + 00* X7 + 0.688FAMI
2338E + 02* X8 + 0.456701E + 01* X9 - 0.221987E + 02* X10 - 0.347210E + 01* X11 + 0.160FAMI
3105E + 01* X12 + 0.114485E + 01* X13 + 0.965145E + 00* X14 - 0.179844E + 00* X15 - 0.2FAMI
45600E + 00* X16 + 0.109745E - 01* X17 + 0.185875E - 01* X18

YY(5) = 53.449 + 0.174604E + 02* X1 - 0.740983E + 02* X2 - 0.885819E + 00* X3 + 0.4FAMI
160655E + 02* X4 - 0.749374E + 01* X5 - 0.206166E + 02* X6 + 0.488631E + 01* X7 + 0.584FAMI
2863E + 01* X8 - 0.156413E + 01* X9 - 0.941379E + 00* X10 + 0.178935E + 00* X11 + 0.729FAMI
3225E - 01* X12 - 0.901537E - 02* X13 - 0.167277E - 02* X14

YY(6) = 47.441 + 0.115702E + 02* X1 - 0.587039E + 02* X2 + 0.165712E + 02* X3 + 0.2FAMI
142239E + 02* X4 - 0.397052E + 02* X5 - 0.164427E + 01* X6 + 0.345891E + 02* X7 + 0.677FAMI
2235E + 00* X8 - 0.158999E + 02* X9 - 0.255071E + 01* X10 + 0.405863E + 01* X11 + 0.131FAMI
2535E + 01* X12 - 0.543235E + 00* X13 - 0.256741E + 00* X14 + 0.296938E + 01* X15 + 0.1FAMI
477684E - 01* X16

YY(7) = 40.423 + 0.142822E + 02* X1 - 0.533075E + 02* X2 - 0.103692E + 02* X3 + 0.3FAMI
3 1713E-01*X12
YN(7) = -16.682 + 0.101849E+02*X1 + 0.223191E+02*X2 - 0.108658E+00*X3 - 0.108658E+00*X4 - 0.168711E+02*X5 - 0.100911E+02*X6 + 0.30339E+01*X7 + 0.124323E+00*X11 + 0.164100E+00*X14
3 3430E+00*X12 - 0.718710E+02*X13 - 0.268301E+02*X14
YN(8) = -13.636 + 0.103646E+02*X1 + 0.191665E+02*X2 - 0.867847E+01*X3 + 0.191665E+02*X4 - 0.793490E+01*X5 + 0.357415E+01*X6 - 0.610652E+01*X7 + 0.694524E+01*X11 - 0.835941E+00*X14
3 7142E+00*X8 + 0.235015E+01*X9 + 0.575926E+01*X10 - 0.420714E+00*X11 + 0.164100E+00*X14
3 51711E+00*X12 + 0.283053E+01*X13
YN(9) = -10.637 + 0.800782E+01*X1 + 0.104719E+02*X2 - 0.587329E+01*X3 + 0.104719E+02*X4 + 0.508267E+01*X5 - 0.106235E+02*X6 + 0.388765E+01*X7 + 0.388765E+01*X11 + 0.351501E+00*X14
1 42306E+01*X8 + 0.146642E+01*X9 - 0.225402E+01*X10 - 0.258120E+00*X11 + 0.351501E+00*X14
1 34724E+00*X12 + 0.172570E+01*X13 - 0.218733E+01*X14
YN(10) = -8.880 + 0.603195E+01*X1 + 0.106235E+02*X2 - 0.22296E+01*X3 + 0.106235E+02*X4 - 0.793490E+01*X5 - 0.357415E+01*X6 + 0.610652E+01*X7 + 0.694524E+01*X11 - 0.835941E+00*X14
1 348743E+01*X4 - 0.205426E+00*X5 + 0.518022E+00*X6 - 0.105280E+00*X7 + 0.164100E+00*X11 - 0.195500E+00*X14
2 8157E+01*X8 - 0.592635E+02*X9 - 0.269964E+02*X10
YN(11) = -6.955 + 0.502563E+01*X1 + 0.784026E+01*X2 - 0.261221E+01*X3 + 0.106235E+02*X4 - 0.793490E+01*X5 + 0.357415E+01*X6 - 0.213673E+00*X7 - 0.775500E+00*X11 + 0.213673E+00*X14
1 121257E+01*X4 + 0.551911E+00*X5 + 0.292597E+00*X6 - 0.213673E+00*X7 + 0.396563E+02*X11 - 0.213673E+00*X14
1 29550E+00*X8 + 0.513869E-01*X9 + 0.209270E-01*X10 - 0.396563E+02*X11 - 0.213673E+00*X14
3 31C7E-02*X12

C
ACDY = ABS(ADY)
ADYL = XL2*ADYA
XII = (ADYL-40.0)/10.0
I = XII
X = I
IF (XII.LT.1.0.OR.I.LT.1.0) GO TO 4
IF (XII.GT.11.0.OR.I.GT.11.0) GO TO 5
IF (XII.EQ.I) GO TO 2
IF (XII.EQ.I) GO TO 3
YY1 = YY(I)
YN1 = YN(I)
GO TO 7
2 YY1 = YY(I)+(YY(I+1)-YY(I))*XI
YN1 = YN(I)+(YN(I+1)-YN(I))*XI
GO TO 7
3 YY1 = YY(I)-(YY(I+1)-YY(I)-1)*XI
YN1 = YN(I)-(YN(I+1)-YN(I-1))*XI
GO TO 7
4 YY1 = YY(I)
YN1 = YN(I)
GO TO 7
5 IF (ADYL.GT.200.0) GO TO 6
YY1 = YY(I1)*(I+1-(150.0-ADYL)/50.0)
YN1 = YN(I1)*(I+1-(150.0-ADYL)/50.0)
GO TO 7
6 YY1 = 0.0
YY2 = 0.0

YN1 = 0.0
YN2 = 0.0
RETURN
7 IF (N.EC.2) GO TO 8
YN2 = -YN1*SPDP2*XLPI2*1.0E-05
YN2 = -YN1*SPDP2*XLPI2*1.0E-05
N = N+1
XL = -XL2
GO TO 1
8 YY1 = YY1*SPDP1*XLPI1*1.0E-05
YN1 = YNI*SPDP1*XLPI1*1.0E-05
IF (ADY.LT.0.0) GO TO 9
RETURN
9 YY1 = -YY1
YY2 = -YY2
YN1 = -YN1
YN2 = -YN2
RETURN
END
COMPUTER PROGRAM #1

This program incorporates the ship dynamics of two identical Mariner hulls. These hulls are superimposed in space to allow for comparison of the effects contributed to rudder modeling differences. In this particular run a step and ramp rudder were compared in chapter II.

Another benefit of this program is to set up the two identical ships required for the RAS simulations in chapter III. Basically, verification of the models in three degrees of freedom is accomplished for the Mariner hull chosen.

The plots produced in this run are shown in figures II-2 and II-3.
COMPUTER PROGRAM #1

//UHRINT1 JOB (2794,0775,EA44), 'UHRIN SMC 1675', TIME=2
// EXEC DSL
//DSL. INPUT DD *
* LINEAR RESPONSE OF THE MARINER - RAMP VS STEP RUDDER COMPARISON
TITLE LINEAR RESPONSE OF THE MARINER - RAMP VS STEP RUDDER COMPARISON
INTEGER NPLOT
CONST NPLOT=1
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227, NV=-0.00351, NVD=-0.000197
CONST MYVD=0.035, MYR=0.0051, IZNRD=0.00068, MXUD=0.0085
CONST YV=-0.01243, XJ=-0.0012, YRD=-0.00027
CONST YDELR=-0.0027, NDELR=-0.00126, XDELR=0.0
* INITIAL CONDITIONS
INCON X0I=0.0, Y0I=0.0, X02=0.0, Y02=0.0
INITIAL
* CALCULATION OF THE COEFFICIENTS
D1=0.0
D2=0.0
NC1=-XU
NC2=-XU
A11=MYVD
B11=+YV
A21=-YRD
B21=MYR
A12=-NVD
B12=-NV
A22=IZNRD
B22=NR
A33=MXUD
B33=-XU
KA1=YDELR
KB1=NDELR
KC1=XDELR
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
DRC=3.1415926/180.
LUC=20.84765

DERIVATIVE
* SIMULATION SHIP A
IF11=KA1*D1
IF21=KB1*D1
<table>
<thead>
<tr>
<th>Case</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>$\dot{\mathbf{Y}} = \mathbf{A}\mathbf{Y} + \mathbf{B}\mathbf{U}$</td>
</tr>
<tr>
<td>R</td>
<td>$\dot{\mathbf{Y}} = \mathbf{A}\mathbf{Y} + \mathbf{B}\mathbf{U}$</td>
</tr>
<tr>
<td>S</td>
<td>$\dot{\mathbf{Y}} = \mathbf{A}\mathbf{Y} + \mathbf{B}\mathbf{U}$</td>
</tr>
<tr>
<td>E</td>
<td>$\dot{\mathbf{Y}} = \mathbf{A}\mathbf{Y} + \mathbf{B}\mathbf{U}$</td>
</tr>
</tbody>
</table>

### Example Case: D

- **Dynamic Region:** D
- **Response Input:** Dynamic
- **Dynamic Case:** SWAY = Dyaw
- **Dynamics Case:** SWAY = Dyaw
- **Dynamic Case:** SWAY = Dyaw
- **Dynamics Case:** SWAY = Dyaw

---

### Example Case: R

- **Dynamic Region:** R
- **Response Input:** Dynamic
- **Dynamic Case:** SWAY = Ryaw
- **Dynamics Case:** SWAY = Ryaw
- **Dynamic Case:** SWAY = Ryaw
- **Dynamics Case:** SWAY = Ryaw

---

### Example Case: S

- **Dynamic Region:** S
- **Response Input:** Dynamic
- **Dynamic Case:** SWAY = Syaw
- **Dynamics Case:** SWAY = Syaw
- **Dynamic Case:** SWAY = Syaw
- **Dynamics Case:** SWAY = Syaw

---

### Example Case: E

- **Dynamic Region:** E
- **Response Input:** Dynamic
- **Dynamic Case:** SWAY = Eyaw
- **Dynamics Case:** SWAY = Eyaw
- **Dynamic Case:** SWAY = Eyaw
- **Dynamics Case:** SWAY = Eyaw
YAWDD = YAWD1 - YAWD2
D1D = D1 * RDC
D2D = D2 * RDC
DDD = D1D - D2D
ATIME = LUC * TIME

SAMPLE
PRINT 0.04, ATIME, YAWD1, D1D, YAWD2, D2D, YAWDD, DDD
CONTRL FINTIM = 30.0, DELT = 0.04, DELS = 0.04
PRPLOT ONLY
CALL DRWG(1,1, SURGE1, SWAY1)
CALL DRWG(1,2, SURGE2, SWAY2)
CALL DRWG(2,1, ATIME, YAWDD)
CALL DRWG(3,1, ATIME, DDD)
TERMINAL
CALL ENDRW(NPLOT)
END
STOP

// PLOT.SYSIN DD *

0.0  1.0  -5.0  1.0  8.0  6.0  5
0.0 100.0  -6.0  1.0  8.0  6.0  5

INSERT TWO /* CARDS HERE

7.0  5.0  4
COMPUTER PROGRAM #2

This program models a practical rudder response for a mariner ship type. The rudder limits (stops) are set at ±30 degrees and the rate of response is limited to ±2 degrees/sec. A scale factor (LUC) is introduced to modify the response to match real time of the mariner hull chosen.

Twelve passes thru the program are accomplished to conform to different sets of initial conditions and final desired rudder conditions. The plots produced in this run are shown in figures II-5 and II-6.
COMPUTER PROGRAM #2

//UHHINTF2 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=1
// EXEC DSL
//DSL.INPUT DD *
*DAS Rudder Control Run TF2 - Practical Rudder Response
TITLE DAS Rudder Control Run TF2 - Practical Rudder Response
INTEG TRAPZ
INTEGER NPLT,CURVE
CONST NPLT=2
CONST DLTD=.2,DLTE=.7
PARAM CURVE=1
PARAM D2DDES=.3
PARAM D2DIC=-30.0
INITIAL
   KG=DLTD/DLTE
   LUC=20.84765
DERIVATIVE
   DLTS=LIMIT(-30.0,30.0,D2DDES)
   DLTE=DLTS-D2D
   DLTB=LIMIT(-DLTE,DLTE,DLTE)
   D2D=INTGRAL(D2DIC,KG*DLTB*LUC)
* ACTUAL TIME CONVERSION
ATIME=TIME*LUC
SAMPLE
   CONTL FINTM=1.7,DELT=0.04,DELS=0.04
PRINT 0.04,ATIME,DLTS,DLTE,DLTB,D2D,D2DDES,D2DIC
PAPLOT ONLY
   CALL DRWG(1,CURVE,ATIME,D2D)
TERMINAL
   WRITE(6,100)D2DIC,D2DDES
100 FORMAT(//,'LAST RUN IS FOR INITIAL RUDDER=',F10.5,' DESIRED RUDDER
   R=',F10.5)
   D2DDES=D2DDES-5.0
   D2DIC=D2DIC+5.0
   CURVE=CURVE+1
   IF(NPLT.EQ.1) D2DIC=0.0
   IF(CURVE.EQ.7) GO TO 1
   GO TO 2
   CURVE=1
   D2DIC=0.0
   D2DDES=30.0
   CALL ENDRW(NPLT)
2 CALL RERUN
END
This program models a reduced order (first order) gas turbine propulsion plant for an input-output relationship. The program does not scale the plant to the mariner hull used. This was done when introduced into the main simulation program first listed as computer program #8.

The time delay \( (P) \) is assisted in initialization by a dual feed into the system; one thru the delay itself and one directly into SPDIN. The program can be modified to compare a family of curves by introducing the following sequence into the TERMINAL region:

\[
\text{INICER\ NUMB}
\]

\[
\text{IF (NCUR.EQ.NUMB) CALL ENDRW(NPLOT)}
\]

\[
\text{IF (NCUR.NE.NUMB) CALL RERUN}
\]

\[
\text{NCUR = NCUR + 1}
\]

where NUMB is the number of curves desired (less than or equal to 10) which is set with a PARAM statement. The comparison is done on the conditions set in the terminal region [i.e. decrement or increment the system gains (e.g. \( G = G + 0.02 \))].

The plot produced by this run is shown as part of figure II-10.
COMPUTER PROGRAM #3

//UHRINTF3 JOB (2794,0775,EA44), 'UHRIN SMC 1675', TIME=2
// EXEC DSL
// DSL INPUT DD *
TITLE SPEED CONTROL - FIRST ORDER FIT
INTEG RKSFX
INCON UIIC=20.0
INTGER NPLT,NCUR
PARAM NPLT=1
PARAM UIIC=21.73
PARAM A=22.0
PARAM P=0.0
PARAM NCUR=1
PARAM G=0.092
INITIAL
K=UF/A
WRITE(6,100) G,NCUR,K
10C FORMAT(15H THE FOLLOWING RUN FOR POLE=-',F10.5,/,23X,'NCUR=',
113,/,23X,'K=',F10.5,/) 
DERIVATIVE
SPDDER=20.25
SPDDES=1.75*STEP(10.0)
SPDDEL=DELAY(7,P,SPDDES)
SPDIN=K*SPDDEL*K*SPDDER
SPDER=(SPDIN-SPDOUT)*G
SPDOUT=INTGRL(UIC,SPDERR)
DYNAMIC
IF(TIME.GT.9.0) P=4.88
SAMPLE
CONTRL FINITM=320.0,DELT=0.8,DELS=0.8
PRINT 1,6,SPDDES,SPDDEL,SPDIN,SPDERR,SPDOUT,P
CALL DRGW(1,NCUR,TIME,SPDOUT)
TERMINAL
CALL ENDRW(NPLT)
END
STOP
//PLCT.SYIN DD *

0.0 40.0 20.0 0.4 8.0 5.0
INSERT TWO /* CARDS HERE
COMPUTER PROGRAM #4

This program models a simplified wave simulation composed of two superimposed sinusoids (fundamental and second harmonic) and a small random wave. The model is inherently scaled to the mariner nondimensional characteristics. Introduction of these waves is accomplished in computer program #7. Subroutine DEGRAD is shown in appendix A.

The sea state force plots in the dimensions of the three degrees of freedom produced by this run is shown in figures II-17 thru II-22.
COMPUTER PROGRAM #4

//UHRINTF4 JOB (2794,0775,EA44), 'UHRIN SMC 1675', TIME=2
// EXEC DSL
//DSL INPUT DD *
* WAVE PERTURBATION SIMULATION
TITLE WAVE PERTURBATION SIMULATION
INTERP NPLT
PARAM NPLT=6
PARAM YAWDP=0.0
PARAM CDOT2=1.5
PARAM LUC=20.84765
PARAM WS=5.0
PARAM WD=015.0
PARAM WL=0.5
PARAM WFMA=0.1137
ATIME=LUC*TIME
WF1 = (WFMA/(0.1137+40.0))RAMP(0.0)
WF=LIMIT(-WFMA,WFMA,WF1)
WRV=NORMAL(1975,0.0,WFMA/10.0)
WV=WS/15.0
EWDD=YAWDP2
EWD=DEGRAD(1.1,EWDD)
WEF=2.0*3.1415926*(CDOT2+WF*WS*COS(EWD))/WL
WE=WF*TIME
WF=WF*SIN(EWD)
WFN=WF*SIN(2.0*EWD)
WX=WF*COS(EWD)
WFY=WFY*SIN(WE)+(3.1415926*WFY**2/WL)**SIN(2.0*WE)
WNF=WFN*SIN(WE)+(3.1415926*WFN**2/WL)**SIN(2.0*WE)
WXF=WFX*SIN(WE)+(3.1415926*WFX**2/WL)**SIN(2.0*WE)
WY=WYF*WRV*WFY*SIN(WE)
WN=WNF*WRV*WFN*SIN(WE)
WX=WXF*WRV*WFX*SIN(WE)
WEDEG=DEGRAD(0.1,WE)
SAMPLE
PRINT 0.04,ATIME,WY,WF,WN,WF,WNF,WS,WF,WD,WRV
PRPLOT ONLY
CONTROL FINTIM=5.0,DELT=0.04,DELS=0.04
CALL DRWG(1,1,ATIME,WS)
CALL DRWG(1,2,ATIME,WE)
CALL DRWG(1,3,ATIME,WN)
TERMINAL
WRITE(6,100) WS,WD,WL,WFMA,CDOT2
100 FORMAT(//,' LAST RUN FOR WS=',F10.5,/,14X,' WD=',F10.5,/,14X,' WL=',)
IF 10.5, 'WFMA=', F10.5, 'CDOT2=', F10.5, '///
CALL ENDRW(NPLOT)
END
PARAM WL=1.0
END
PARAM WL=1.5
END
PARAM WD=030.0
PARAM WL=0.5
END
PARAM WL=1.0
END
PARAM WL=1.5
END
STOP
FORTRAN
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
/// PLOT.SYSSIN DD *

7.0 5.0

7.0 5.0

7.0 5.0

7.0 5.0

7.0 5.0

7.0 5.0

7.0 5.0

7.0 5.0

INSERT TWO /* CARDS HERE
This program uses the mariner hull model first introduced in computer program #1 and the control system designed in chapter III to simulate the approach phase of RAS. The subroutines and functions that are to be inserted from appendix A can also be done in object code by changing the word FORTRAN to OBJECT and placing pre-compiled decks in the same locations. In fact, due to the long length of subroutine SIOPES, this must be done to be able to run the simulation with the DSL default job control language (JCL) presently installed at the Naval Postgraduate School IBM 360/67.

The plots produced by this run are shown in figures III-7 thru III-13. By changing the gains and introducing the following code, the plots of figures III-14 thru III-19 are produced:

\[ D1LES = 5.0 \times \text{STEP}(8.0) - 5.0 \times \text{STEP}(9.0) \]
COMPUTER PROGRAM #5

//UHRINTF5 JOB (2794,0775,EA44),"UHRIN SMC 1675",TIME=4
//EXEC DSL
//DSL INPUT DD *
* RAS RUDDER CONTROL - APPROACH PHASE
TITLE RAS RUDDER CONTROL - APPROACH PHASE
INTEGER NPLT
INTEGER NS
CONST NPLT=1
CONST NS=1,RD=1.0
CONST IS=1,DD=0.2
* INSERT APPROPRIATE GAIN SETTINGS HERE
PARAM RSENS=1.86642,WTSENS=2.3869,GRN=23.4185,WFBG=4.35162
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227,NV=-0.00351,NV=0.000197
CONST MV=0.015,MY=0.0051,IZRD=0.00068,XX=0.0085
CONST YV=-0.01243,XU=0.0012,SRD=-0.00027
CONST YDEL=-0.0027,NDEL=-0.00126,XDEL=0.0
CONST DLTM=2.0,DLTEM=7.0
* INITIAL SEPERATION
INCON X0=5.0,Y0=0.0,XX=0.0,YY=0.4
* INITIAL CONDITIONS
INCON YAW=0.0
INCON YV=0.0,YV=0.0,YN=0.0,YN=0.0
INCON U1=1.0,U2=1.5
INITIAL
DY0=Y02-Y01
DX0=XX=02-XX1
CALL TRANS(YAW01,DX0,XX01,AD1,AD1,ADY)
CALL SLOPES(AD1,AD1,YV01,YY2,YN1,YN2)
* CALCULATION OF THE COEFFICIENTS
NC1=-XX1
NC2=-XX1
A11=MY
B11=YY1
A21=YYR
B21=MYR
A12=NV
B12=NV
A22=IZRD
B22=NR
A33=XX
B33=-XX1
KA1=-YDELR
KB1=NOELR
KC1=XDELR
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180.73.1415926
CRC=3.1415926/180.
LUC=20.84765
KG=DLTOM/DLTEM
DZD=0.0

DERIVATIVE
* REFEREMCE SHIP RUDDER CONTROL
DIDES=0.0
DLTS1=LIMIT(-30.0,30.0,DIDES)
DLTE1=DLTS1-DID
DLTBE1=LIMIT(-DLTEM,DLTEM,DLTE1)
DID=INTGRNL(DIDIC,KG*DLTBE1*LUC)
D1=DEGRAD(1,1,DID)
DX=X2-X1
DY=Y2-Y1

* SIMULATION SHIP A
IF11=KA1*D1
IF21=KB1*D1
IF31=KC1*D1+NC1
I11=-B11*ADOT1-B21*BDOT1+IF11
I21=-B12*ADOT1-B22*BDOT1+IF21
I31=-B33*CDOT1+IF31
ADDOT1=([I11*A22-I21*A21]/D)
BCDOT1=[I21*A11-I11*A12]/D
CDOT1=I31/A33
ADOT1=INTGRNL(0.,ADDOT1)
BDOT1=INTGRNL(0.,BDOT1)
CDOT1=INTGRNL(01.,CDOT1)
BY1=INTGRNL(0.,+BDOT1)
XDOT1=CDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRNL(X01,XDOT1)
Y1=INTGRNL(Y01,YDOT1)
YA1=BY1
SWAY1=Y1
SURGE1=X1

* SIMULATION SHIP B
IF12=KA1*D2+YY2
IF22=KB1*D2+YN2
IF32=KC1*D2+NC2
I12=-B11*ADOT2-B21*BDOT2+IF12
I22=-B12*ADOT2-B22*BDOT2+IF22
I32=-B33*CDOT2+IF32
ADDOT2=(1.12*A22-I22*A21)/D
BDOT2=(1.12*A11-I12*A12)/D
CDDOT2=132/A33
ADOT2=INTGRL(0.,ADDOT2)
BDOT2=INTGRL(0.,BDDOT2)
CDDOT2=SPDCTR(ADX, U01, U02)
BY2=INTGRL(BY02, BDOT2)
XDOT2=CDDOT2*COs(BY2)-ADOT2*SIN(BY2)
YDOT2=CDDOT2*SIN(BY2)+ADOT2*COs(BY2)
X2=INTGRL(X02, XDOT2)
Y2=INTGRL(Y02, YDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2

NOSORT
YAWD1=DEGRAD(0, 0, YAW1)
YAWDP1=DEGRAD(0, 1, YAW1)
YAWD2=DEGRAD(0, 0, YAW2)
YAWDP2=DEGRAD(0, 1, YAW2)

* RUDDER RESPONSE INPUT
CALL RMEAS(N, YAW1, X1, Y1, YAW2, X2, Y2, RO, R1, B1, BB1, R2, B2, BB2)
CALL HDGRAS(N, IS, RI, B1, BB1, R2, B2, BB2, RSENS, YAW2, PSIFD, PSIADD, ...)
PSI0D0D, WT, DA, A10, B10, B20, WTSENS, DD, RO)
BDOT2D=DEGRAD(0, 1, BDOT2)
BDOTFB=FBGB*BDOT2D
DDUMB=YAWD2-PSI0D0D*BDOTFB
IF(DDUMB.GT.180.0) DDUMB=360.0+DDUMB
IF(DDUMB.LT.-180.0) DDUMB=-180.0+DDUMB
DLS=LIMIT (-30.0, 30.0, DDUMB*RGN)
DLT=DLT=-DLT
DLTE=LIMIT (-DLTE, DLTE, DLT)
D2=D=INTGRL(D2D, KG*DLTBE*LUC)
D2=DEGRAD(1, 1, D2D)

SORT
* RUDDER PART OF OBJECT FUNCTION
DTRAN=TIME*ABS(D2)
ROBJ=INTGRL(0.0, DTRAN)
* DISTANCE PART OF OBJECT FUNCTION
DISTE=TIME*ABS(DD-ADY)
DCBJ=INTGRL(0.0, DISTE)
* OBJECT FUNCTION
OBJ=ROBJ*DOBJ

DYNAMIC REGION
* ACTUAL SEPARATION
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1, DX, DY, ADX, ADY)
* EXTERNAL FORCES ACTING BETWEEN SHIPS
CALL SLOPES(ADX, ADY, YY1, YY2, YN1, YN2)
IF(ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
* 100 FORMAT(' *** Separation less than 25 feet - Collision****')
   ATIME=LUC*TIME
SAMPLE FINTIM=20., DELT=0.04, DELS=0.04
PRINT 0.04, X1, X2, DA, A1D, PSIDFD, Y1, Y2, R1, B1D, PSIADD, YAWD1, YAWD2, R2, ...
   B2D, PSIDED, ATIME, D2D, ADX, D1D, YY2, BDOTFB, DLTS, ADY, DLTS1, ...
   YN2, CDOT1, CDOT2, OBJ
PRPLOT CNLY
   CALL DRWG(1,1,ATime, YAWDP2)
   CALL DRWG(1,2,ATime, YAWDP1)
   CALL DRWG(2,1,ATime, YY2)
   CALL DRWG(3,1,ATime, YN2)
   CALL DRWG(4,1, SURGE2, SWAY2)
   CALL DRWG(4,2, SURGE1, SWAY1)
   CALL DRWG(5,1,ATime, ADY)
   CALL DRWG(6,1,ATime, DLTS)
   CALL DRWG(6,2,ATime, D2D)
TERMINAL IF(IS.EQ.1) WRITE(6,101)
   101 FORMAT(' THIS RUN IS FOR A PORT SIDE TO APPROACH')
   IF(IS.EQ.0) WRITE(6,102)
   102 FORMAT(' THIS RUN IS FOR A STBD SIDE TO APPROACH')
   CALL ENDRW(NPLOT)
END
STOP
FORTRAN
INSERT FUNCTION SPDCTR FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//C.FT06F001 DD SYSOUT=0, SPACE=(CYL,(4,1))
//PLCT.SYSIN DD *
COMPUTER PROGRAM #6

This program combines the approach and turn phases of computer program #5. The added subroutine is a result of simulation requirements to switch between adaptive gains.

This run produced the plots of figures III-22 thru III-34. By substituting the initial conditions of table III-3, this program produced the plots of figures III-35 thru III-64.
COMPUTER PROGRAM #6

//UHRINF6 JOB (2794,0775,EA44), 'UHRIN SMC 1675', TIME=10
// EXEC DSL
//DSL: INPUT DD *
* RAS RUDDER CONTROL - APPROACH PHASE FOLLOWED BY TURN PHASE
TITLE RAS RUDDER CONTROL - APPROACH PHASE FOLLOWED BY TURN PHASE
INTEGER N, IS
CONST N=1, RD=1.0
* SET IS FOR SIDE OF APPROACH IS=1 PORT, IS=0 STBD
* SET DD FOR DESIRED FINAL LATERAL SEPARATION DESIRED
CONST IS=1, DD=0.2
PARAM RSENS=1.86642
PARAM WSENS=2.38692
PARAM RG=23.41847
PARAM VFGB=4.35162
PARAM TSTP1=35.0, TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227, N=0.00351, NVD=-0.000197
CONST MYV=0.015, MYR=0.0051, IZNRD=0.00068, MXUD=0.0085
CONST YV=-0.01243, XY=0.0012, YRD=-0.00027
CONST YDEL=0.0027, XDEL=0.00126, XDEL=0.0
CONST DLTEM=2.0, DLTEM=7.0
* INITIAL SEPARATION
* SET IC FOR APPROACH TESTING
INCON X0=5.0, Y0=0.0, X0=0.0, Y0=0.4
* INITIAL CONDITIONS
INCON YW01=0.0
INCON Y=0.0, Y2=0.0, YN1=0.0, YN2=0.0
INCON U01=1.0, U02=1.5
INITIAL
DY0=Y02-Y01
DX0=X02-X01
CALL TRANS(YW01, DX0, DY0, ADX, ADY)
CALL SLOPES(ADX, ADY, YY1, YY2, YN1, YN2)
* CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MVY
B11=YV
A21=-YRD
B21=MYR
**SIMULATION SHIP B**

IF12=KA1*D2+Y2
IF22=KB1*D2+YN2
IF32=KC1*D2+NC2
I12=-B11*ADOT2-B21*BDOT2+IF12
I22=-B12*ADOT2-B22*BDOT2+IF22
I32=-B33*CDOT2+IF32
ADOT2=(I12*A22-I22*A21)/D
BDOT2=(I22*A11-I12*A12)/D
CDOT2=I32/A33
ADOT2=INTGRL(0.,ADOT2)
BDOT2=INTGRL(0.,BDOT2)
CDOT2=SPOCTR(AUX,01,002)
BY2=INTGRL(BY2,BDOT2)
XDOT2=CDOT2*COS(BY2)-ADOT2*SIN(BY2)
YDOT2=CDOT2*SIN(BY2)+ADOT2*COS(BY2)
X2=INTGRL(XO2,XDOT2)
Y2=INTGRL(YO2,YDOT2)
YAW2=BY2
SHEAY2=Y2
SURGE2=X2

**NOSORT**

YAW1=DEGRAD(0,0,YAW1)
YAWP1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)

**RUDDER RESPONSE INPUT**

CALL KBMFASSN(YAW1,X1,Y1,YAW2,X2,Y2,RD,R1,B1,BB1,R2,B2,BB2)
CALL HDGRASIN.IS,R1,B1,BB1,R2,B2,BB2,RSENS,YAW2,PSIDFD,PSIADD,...
PSIDED,WT,DA,AID,B1D,B2D,WTSENS,DD,DRD)
BDOT2=DEGRAD(0,1,BDOT2)
BDOTFB=VFSGBD2BDT2
DDUMB=YAWD2-PSIDED+BDOTFB
IF(DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF(DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
DLTS=LIMIT(-30.0,30.0,DDUMB*RGN)
DLTE=DLTS-D2D
DLTBE=LIMIT(-DLTEM,DLTEM,DLTE)
D2D=INTGRL(D2DIC,KG*DLTBE*LUC)
D2=DEGRAD(1,1,D2D)

**SORT**

DISTE=ABS(DD-ADY)
OBJ=INTGRL(0.0,DISTE)

**DYNAMIC REGION**

**ACTUAL SEPARATION**

DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADX,ADY)
EXTERNAL FORCES ACTING BETWEEN SHIPS
CALL SLOPES(ADX, ADY, YY1, YY2, YN1, YN2)
IF (ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
100 FORMAT(' ****SEPARATION LESS THAN 25 FEET - COLLISION****')

* ACTUAL TIME CONVERSION (SEC)
ATIME=LUC*TIME
AA1=(BB1+BB2)/2.0
CALL SWTCH(DD, DA, AA1, IS, RSENS, WTSNS, RGN, VFBG, BDOT2D)

SAMPLE CONTROLS
FINTIM=30., DELTA=0.04, DELTS=0.04
PRINT 192, X1, X2, DA, AID, PSI2FD, Y1, Y2, R1, B1D, PSIADD, YAWD1, YAWD2, R2,...
B2D, PSIDES, ATIME, D2D, ADX, D1D, YY2, BDOTFB, DLTS, ADY, DLTS1,...
YN2, CDOT1, CDOT2, OBJ, RSENS, VFBG

PRPLCT ONLY
CALL DRGW(1,1, ATIME, YAWD2)
CALL DRGW(1,2, ATIME, YAWD1)
CALL DRGW(2,1, ATIME, YY2)
CALL DRGW(3,1, ATIME, YN2)
CALL DRGW(4,1, SURGE2, SWAY2)
CALL DRGW(4,2, SURGE1, SWAY1)
CALL DRGW(5,1, ATIME, ADY)
CALL DRGW(6,1, ATIME, DLTS)
CALL DRGW(6,2, ATIME, D2D)

TERMINAL
IF(IS.EQ.1) WRITE(6,101)
101 FORMAT(' THIS RUN IS FOR A PORT SIDE TO APPROACH
IF(IS.EQ.0) WRITE(6,102)
102 FORMAT(' THIS RUN IS FOR A STBD SIDE TO APPROACH
CALL ENDRW(NPLOT)
CALL CONTIN
FINTIM=45.0
END
STOP
FORTRAN
INSERT SUBROUTINE SWTCH FROM APPENDIX A HERE
INSERT FUNCTION SPDCTR FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//FLCT.SYSIN DD *

7.0 5.0

7.0 5.0
COMPUTER PROGRAM #7

This program combines the calm sea simulation of computer program #6 with the wave simulation of computer program #4 to simulate the model and control system in a sea state. The waves are introduced thru the rudder nondimensionalized coefficients as shown in chapter II.

The plots produced are shown in figures III-66 thru III-73. Figure III-65 was produced with the same program by setting $W_L=1.5$. 
COMPUTER PROGRAM #7

//UHRINTF7 JOB (2794,0775,EA44), 'UHRIN SMC 1675', TIME=10
// EXEC DSL
//DSL INPUT DD *
* RAS RUDDER CONTROL - SIMULATION WITH WAVE PERTURBATIONS
TITLE RAS RUDDER CONTROL - SIMULATION WITH WAVE PERTURBATIONS
INTEGER NK,NS
CONST NPL0T=2
INTEGER N,IS
CONST N=1, RD=1.0
PARAM IS=1, DD=0.2
PARAM RSENS=1.86642
PARAM WTSENS=2.38692
PARAM RGN=23.41847
PARAM VFBG=4.35162
PARAM TSTP1=35.0, TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227, NV=0.00351, NVD=-0.000197
CONST MYVD=0.015, MYR=0.0051, IZNRD=0.0068, MXUD=0.0085
CONST YV=-0.01243, XU=-0.0012, YRD=-0.0027
CONST YDELR=-0.0027, NDLR=-0.00126, XDELR=0.0
CONST DLDM=2.0, DLTEM=7.0
* INITIAL SEPARATION
INCON X01=5.0, Y01=0.0, X02=0.0, Y02=0.4
* INITIAL CONDITIONS
INCON YAW0=0.0
INCON YY1=0., YY2=0., YN1=0., YN2=0.
INCON U01=1.0, U02=1.5
PARAM WS=5.0
PARAM WD=-0.150
PARAM WL=1.0
PARAM WFMA=0.05685
INITIAL
DY0=Y02-Y01
DX0=X02-X01
CALL TRANS(YAW0, DX0, DY0, ADX, ADY)
CALL SLOPES(ADX, ADY, YY1, YY2, YN1, YN2)
* CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
AL1=MYVD
B11=-YV
A21=-YRD
B21=MYR
A12=-NVD
B12=-NV
A22=IZNRD
B22=-NR
A33=MXUD
B33=XU
KAI=YDELK
KB1=NDK
KCI=XDK
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180.73.1415926
RDC=3.1415926/180.
LUC=20.84765
KG=DLTDM/DTDM
DIDIC=0.0
D2=DEGRAD(1,1,D2D)
BY02=0.0

DERIVATIVE
WF1 = (WFMA/(0.1137*40.0))*RAMP(0.0)
WF=LIMIT(-WFMA,WFMA,WF)
WRV=NORMAL(1975,0.0,WFMA/10.0)
WV=WS/15.0
EWD=HD-YAWDP2
EWD=DEGRAD(1,1,EWD)
WVF=2.0*3.1415926*(CCOT2+WV*COS(EWD))/WLV
WE=WF1*TIME
WFY=WF*SEN(EWD)
WFN=WF*SEN(2.0*EWD)
WFX=WF*COS(EWD)
WFY=WF*SEN(WE)+(3.1415926*WFY*2/WL)*SEN(2.0*WE)
WFN=WF*SEN(WE)+(3.1415926*WFN*2/WL)*SEN(2.0*WE)
WFX=WF*SEN(WE)+(3.1415926*WFX*2/WL)*SEN(2.0*WE)
WV=WVF+WFV*WFY*SEN(WE)
WX=WFN+WFV*WFX*SEN(WE)
DX=WFV+WFV*DIDES
DAYS=5.0*STEP(TSTP1)-5.0*STEP(TSTP2)
DLTS1=LIMIT(-30.0,30.0,DAYS)
DLTE1=DLTS1-D1D
DLTBE1=LIMIT(-DLTEM,DLTEM,DLTE1)
DID=INTGRAL(DIDIC,KG*DLTBE1*LUC)
D1=DEGRAD(1,1,D1D)
DX=X2-X1
DY=Y2-Y1

* SIMULATION SHIP A
IF11=KAI*D1
IF21=KB1*D1
IF31=KC1*D1+NC1
I11=-B11*ADOT1-B21*BOOT1+IF11
I21=-B12*ADOT1-B22*BOOT1+IF21
I31=-B33*CDOT1+IF31
ADOT1=(111*A22-I21*A21)/D
BOOT1=(I21*A11-I11*A12)/D
CDOT1=I31/A33
ADOT1=INTGRL(0.,ADOT1)
BOOT1=INTGRL(0.,BOOT1)
CDOT1=INTGRL(01.,CDOT1)
BY1=INTGRL(0.,BOOT1)
XDOT1=CDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGRL(XO1,XDOT1)
Y1=INTGRL(YO1,YDOT1)
YAW1=BY1
SWAY1=Y1
SURGE1=X1
*
SIMULATION SHIP B
IF12=KA1*D2+YY2+KA1*WY
IF22=KB1*D2+YN2+KB1*WN
IF32=KC1*D2+NC2+KC1*WX
I12=-B11*ADOT2-B21*BOOT2+IF12
I22=-B12*ADOT2-B22*BOOT2+IF22
I32=-B33*CDOT2+IF32
ADOT2=(112*A22-I22*A21)/D
BOOT2=(I22*A11-I12*A12)/D
CDOT2=I32/A33
ADOT2=INTGRL(0.,ADOT2)
BOOT2=INTGRL(0.,BOOT2)
CDOT2=SFDCR(ADY+U01,U02)
BY2=INTGRL(BY02,BDOT2)
XDOT2=CDOT2*COS(BY2)-ADOT2*SIN(BY2)
YDOT2=CDOT2*SIN(BY2)+ADOT2*COS(BY2)
X2=INTGRL(XO2,XDOT2)
Y2=INTGRL(YO2,YDOT2)
YAW2=BY2
SWAY2=Y2
SURGE2=X2
*
NOSORT
YAWD1=DEGRAD(0,0,YAW1)
YAWDP1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)
YAWDP=AYAWDP1-YAWDP2
*
RUDDER RESPONSE INPUT
CALL RBMEASIN,YAW1,X1,Y1,YAW2,X2,Y2,R0,R1,B1,BB1,R2,B2,BB2)
CALL HDGRASIN,IS,R1,B1,BB1,R2,B2,BB2,RSENS,YAW2,PSDFD,PSIADD,...
Psided, wt, da, aid, b1d, b2d, wtsens, dd, rd
bdot2d=degrad(0, 1, bdot2)
bdotfb=vfbgb*bdot2d
ddumb=yawd2-psided+bdotfb
if(ddumb gt 180.0) ddumb=ddumb-360.0
if(ddumb lt -180.0) ddumb=360.0+ddumb
dlts=limit(-30.0, 30.0, ddumb*rgn)
dlte=dlts-0.2
dlte=limit(-dltem, dltem, dlte)
d2=intgrl(d2dic, kg*dlte*b*duc)
d2=degrad(1, 1, d2d)

sort
diste=abs(dd-ady)
cbj=intgrl(0.0, diste)
dynamic region
* actual separation
dx=x2-x1
dy=y2-y1
call trans(yaw1, dx, dy, adx, ady)
* external forces acting between ships
call slopes(adx, ady, yy1, yy2, yn1, yn2)
if((abs(ady).lt.0.04744).and.(abs(adx).lt.1.0)) write(6, 100)

100 format(* separation less than 25 feet - collision****)
* actual time conversion (sec)
atime=duc*time
aai=(bb1+bb2)/2.0
call switch(dd, da, aa1, is, rnsens, wtsens, rgn, vfbg, bdot2d)

sample
ctrl fintim=30., deltt=0.04, delts=0.04
print 0.20, x1, x2, da, aid, psidfd, y1, y2, r1, b1d, psiddd, yawd1, yawd2, r2, ...
b2d, psided, atime, d2d, adx, dy, yy2, bdotfb, dlts, ady, dlts1, ...
yn2, cdot1, cdot2, obj, rnsens, vfbg, wyf, wnf, wxf, wrv, ewdd, wy, wn, ...
w, wx, we, wf
proplot cnly
call drwg(1,1, atime, yawdp2)
call drwg(1,2, atime, yawdp1)
call drwg(2,1, atime, ady)
call drwg(3,1, atime, dlts)
call drwg(3,2, atime, d2d)
call drwg(4,1, atime, yawdp)
call drwg(5,1, atime, wx)
call drwg(5,2, atime, wy)
call drwg(5,3, atime, wn)
terminal
if(is eq.1) write(6, 101)
101 format('this run is for a port side to approach')
if(is eq.0) write(6, 102)
102 format('this run is for a stbd side to approach')
CALL ENDRW(NPLOT)
CALL CONTIN
FINTIM=45.0
END
STOP
FORTRAN
INSERT SUBROUTINE SWITCH FROM APPENDIX A HERE
INSERT FUNCTION SPDCTR FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//PLOT.SYSIN DO *

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

INSERT TWO /* CARDS HERE
This program incorporates a fifth order polynomial curve fit speed control switching function to give optimal longitudinal positioning. The scenario is the same that was used in the design of the heading control development. The low order model of the gas turbine propulsion plant was used.

The plots produced are shown in figures III-80 thru III-83.
COMPUTER PROGRAM #8

//UHRINTF8 JOB (2794,0775,EA44), 'UHRIN SMC 1675', TIME=10
// EXEC DSE
// DNL INPUT DD *
* RAS SPEED CONTROL - CONTROL TESTING
TITLE RAS SPEED CONTROL - CONTROL TESTING
INTEG RKSFX
INTEG NPLT
CONST NFLOT=2
INTEG NIS
CONST N=1, RD=1.0
PARAM IS=1, DD=0.2
PARAM RSENS=1,86642
PARAM WSENS=2,38692
PARAM RGN=23,41847
PARAM VFBG=4,35162
PARAM TSTP1=35.0, TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST NR=0,00227, NV=-0,00351, NVD=-0,000197
CONST MYVD=0,015, MYR=0,0051, ITNRT=0,00068, MUXD=0,0085
CONST YV=-0,01243, XU=-0,0012, YRD=-0,00027
CONST YDEL=0,0027, NDRL=0,00126, XDEL=0,0
CONST DTOM=2,0, DTEM=7,0
* INITIAL SEPARATION
INCON XO1=5.0, YO1=0.0, XO2=0.0, YO2=0.4
* INITIAL CONDITIONS
INCON YAWO1=0.0
INCON YY1=0.0, YY2=0.0, YN1=0.0, YN2=0.0
INCON UO1=1.0, UO2=1.5
PARAM UF=21.73, A=22.0, G=0.092
INITIAL
DYO=YO2-YO1
DXO=XO2-XO1
CALL TRANS(YAWO1, DXO, DYO, ADX, ADY)
CALL SLOPES(ADX, ADY, YY1, YY2, YN1, YN2)
* CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MYVD
B11=YV
A21=YY
B21=MYR
A12=-NV
B12=-NV
A22=IZNRD
B22=-NR
A33=MXUD
B33=-XU
KA1=-YDELR
KB1=NDELR
KC1=XDELR
D=A11*A22-A12*A21
DRLM=41.6953
RDC=180.*3.1415926
DRC=3.1415926/180.
LUC=20.84765
KG=DLTM/DLTEM
DICIC=0.0
C2=DEGRAD(1,1,D2D)
BY2=0.0
K=UF/A
P=4.88/LUC
SPDDER=U01/K

DERIVATIVE
D1DES=5.0*STEP(TSTP1)-5.0*STEP(TSTP2)
DLTS1=LIMIT(-30.0,30.0,D1DES)
DLTE1=DLTS1-D10
DLTBE1=LIMIT(-DLTEM,DLTEM,DLTE1)
D10=DEGRAD(1,1,D10)
D1=DEGRAD(1,1,D1)
DX=X2-X1
DY=Y2-Y1

* SIMULATION SHIP A
IF11=KA1*D1
IF21=KB1*D1
IF31=KC1*D1+NC1
I11=-B11*ADOT1-B21*BDOT1+IF11
I21=-B12*ADOT1-B22*BDOT1+IF21
I31=-B33*CDOT1+IF31
ADDOT1=(I11*A22-I21*A21)/D
BDOT1=(I21*A11-I11*A12)/D
CDOT1=I31/A33
ACOT1=INTGR0(0.,ADDOT1)
BCOT1=INTGR0(0.,BDOT1)
CCOT1=INTGR0(U01,CDOT1)
BY1=INTGR0(0.,BDOT1)
XDOT1=CDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGR0(X01,XD0T1)
Y1=INTGR0(Y01,YD0T1)
YAW1=BY1
SWAY1=Y1
SORT
CISTE=ABS(DD-ADY)
OBJ=INTGR(0.0,DISTE)
DISTE=ABS(ADX)
OBJS=INTGR(0.0,DISTES/25.0)

DYNAMIC REGION
* ACTUAL SEPARATION
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADX,ADY)
* EXTERNAL FORCES ACTING BETWEEN SHIPS
CALL SLOPES(ADX,ADY,YY1,YY2,YN1,YN2)
IF((ABS(ADY).LT.0.04744).AND.(ABS(ADX).LT.1.0)) WRITE(6,100)
100 FORMAT(' ****SEPARATION LESS THAN 25 FEET - COLLISION****')
* ACTUAL TIME CONVERSION (SEC)
ATIME=UC*TIME
AAI=(BB1+BB2)/2.0
CALL SWCHID0,DA,AAI,IS,RSENS,WSSENS,RGN,VBG,BDOT2D)

SAMPLE
CONTX FINTIM=30.0,DELT=0.04,DELS=0.04
PRINT 0.20,ATIME,ADX,ADY,YAW01,YAW02,YAWDPD,SPDDES,CDOT2
PRPLOT CNLY
CALL DRWG(1,1,ATIME,ADX)
CALL DRWG(2,1,ATIME,SPDDES)
CALL DRWG(2,2,ATIME,CDOT2)

TERMINAL
IF(IS.EQ.1) WRITE(6,101)
101 FORMAT(' THIS RUN IS FOR A PORT SIDE TO APPROACH')
IF(IS.EQ.0) WRITE(6,102)
102 FORMAT(' THIS RUN IS FOR A STBD SIDE TO APPROACH')
CALL ENDRW(NPLOT)
CALL CONTIN
FINTIM=45.0

END
STOP

FORTRAN
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGRAS FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE SWC FROM APPENDIX A HERE
INSERT FUNCTION SWC FROM APPENDIX A HERE
INSERT FUNCTION SPREC FROM APPENDIX A HERE
INSERT FUNCTION SPNIT FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//PLOT.SYS IN CD *
COMPUTER PROGRAM #9

This program introduces a longitudinal position offset capability. The method takes the control ship to the alongside position until 450 seconds into the run. After that time, with the ship steadied, the offset position desired (XCFSD) is switched to the desired offset. This method negates some of the transient oscillations which cause unstable conditions in the approach phase. A secondary change is the use of subroutine SWTCHF instead of subroutine SWTCH developed in the heading control section. This new subroutine relaxes the heading velocity feedback gain (VFEG) to allow turn stability in the turn phase.

The plots produced by this program are shown in figures III-84 thru III-101.

356
COMPUTER PROGRAM #9

//UHRINTF9 JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=10
// EXEC DSL
//DSL INPUT DD *
* RAS SPEED CONTROL - OFFSET TESTING
TITLE RAS SPEED CONTROL - OFFSET TESTING
INTEGER NPLT
CONST NFLOT=2
INTEGER N IS
CONST N=1;RD=1.0
PARAM IS=1,DD=0.2
PARAM RSSENS=1.86642
PARAM WTSENS=2.38692
PARAM RGN=23.41847
PARAM VFBG=4.35162
PARAM TSTP1=35.0;TSTP2=36.0 *
HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227,NV=-0.00351,NVD=-0.000197
CONST MYVD=0.015,MYR=0.0051,IZNRD=0.00068,MXUD=0.0085
CONST YV=-0.01243,XU=-0.0012,YRD=-0.00027
CONST YDELR=-0.0027,NDELR=-0.00126,XDELR=0.0
CONST DLTDM=2.0,DLTEM=7.0 *
INITIAL SEPERATION
INCON X01=5.0,Y01=0.0,X02=0.0,Y02=0.4 *
INITIAL CONDITIONS
INCON YAW01=0.0
INCON Y1=0.0,Y2=0.0,YN1=0.0,YN2=0.0
INCON U01=1.0,U02=1.5 *
XQFS IS THE DESIRED NORMALIZED X POSITION / 0.0 IS ALONGSIDE /
NEG FOR ASTERN OF ALONGSIDE / POS FOR FWD OF ALONGSIDE /
NOTE - XQFS CAN BE USED FOR VEHICLE OF APPROACH AND EXIT FROM /
STATION BY SETTING SOME DESIRED POSITION EG. -5.0, 5.0 /
THIS WOULD CAUSE APPROACH OR BREAK AWAY STATION ATTAINMENT /
WHICHE CAN BE PRECEEDED BY OR FOLLOWED BY NON RAS POSITION /
CONTROL
PARAM XQFS=0.0
PARAM XCFSD=0.0
PARAM UF=21.73,A=22.0, G=0.092
INITIAL
DY0=Y02-Y01
DX0=X02-X01
CALL TRANS(YAW01,DX0,DY0,ADX,ADY)
CALL SLOPES(ADX,ADY,Y1,Y2,YN1,YN2)
CCDOT1=I31/A33
ADOT1=INTEGRAL (0., ADDOT1)
BDOT1=INTEGRAL (0., BDDOT1)
CCDOT1=INTEGRAL (U01, CDDOT1)
BY1=INTEGRAL (0., BDOT1)
XDOT1=CDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTEGRAL (X01, XDOT1)
Y1=INTEGRAL (Y01, YDOT1)
YAW1=BY1
SWAY1=Y1
SLRGE1=X1
*
SIMULATION SHIP B
IF12=KA1*D2+YY2
IF22=KB1*D2+YN2
IF32=KC1*D2+NC2
I12=-B11*ADOT2-B21*BDOT2+IF12
I22=-B12*ADOT2-B22*BDOT2+IF22
I32=-B33*CDOT2+IF32
ACDOT2=(I12*A22-122*A21)/D
BDDOT2=(I22*A11-112*A12)/D
CCDOT2=I32/A33
ACDOT2=INTEGRAL (0., ADDOT2)
BDOT2=INTEGRAL (0., BDDOT2)
Sw=SWCL(SPD01,SPD02)
SPDDES = SPDDEC(ADX,SPDO1,SPD02,Sw,XQFS)
SPDEL=CELYA(T,P,(SPDDES/K-SPDDER))
SPDEL=SPINIT(SPDEL,TIME,(SPDDES/K-SPDDER))
SPIN=K*(SPDEL+SPDDER)
SPDDER=SPDIN-CDOT2*G
CCDOT2=INTEGRAL (U02,SPDERR*LCUR)
BY2=INTEGRAL (BY02,BDOT2)
XDOT2=CDOT2*COS(BY2)-ADOT2*SIN(BY2)
YDOT2=CDOT2*SIN(BY2)+ADOT2*COS(BY2)
X2=INTEGRAL (X02,XDOT2)
Y2=INTEGRAL (Y02,YDOT2)
YAW2=BY2
SWAY2=Y2
SLRGE2=X2
*
NOSORT
YAWD1=DEGRAD(0,0,YAW1)
YAWDP1=DEGRAD(0,1,YAW1)
YAWD2=DEGRAD(0,0,YAW2)
YAWDP2=DEGRAD(0,1,YAW2)
YAWDPD=YAWDP1-YAWDP2
*
RUDDER RESPONSE INPUT
CALL RBMEAS(N,YAW1,X1,Y1,YAW2,X2,Y2,RF,RF1,B1,BO1,R2,B2,BB2)
CALL HGDGRAS(N,IS,R1,B1,BO1,R2,B2,BB2,RSENS,YAW2,PSIDFD,PSIAADD,...
PSIDES,WT,DA,ALD,B1D,B2D,WTSENS,DD,RO
BDOT2D=DEGRAD(0,1,BDOT2)
BDQFB=VFBG*BDOT2D
DCUMB=YW2D-PSIDES+BDQFB
IF(DDUMB.GT.180.0) DDUMB=DDUMB-360.0
IF(DDUMB.LT.-180.0) DDUMB=360.0+DDUMB
OLTS=LIMIT(-30.0,30.0,DDUMB*RGN)
DLTE=OLTS-D2D
CLTE=LIMIT(-DLTEM,DLTEM,DLTE)
D2C=INTGRD(D2D,IC,KG*DLTE,LU)
C2=DEGRAD(1,1,D2D)

SORT
DISTE=ABS(DD-ADY)
OBJ=INTGRD(0.0,DISTE)
DISTES=ABS(ADY)
OBJS=INTGRD(0.0,DISTES/25.0)

DYNAMIC REGION
* ACTUAL SEPARATION
DX=X2-X1
DY=Y2-Y1
CALL TRANS(YAW1,DX,DY,ADY,ADY)
*
EXTERNAL FORCES ACTING BETWEEN SHIPS
CALL SLOPES(ADY,ADY,YY1,YY2,YN1,YN2)
IF(ABS(ADY..LT.0.04444).AND.(ABS(ADY..LT.1.0)) WRITE(6,100)
100 FORMAT(* **** SEPARATION LESS THAN 25 FEET - COLLISION****)
*
ACTUAL TIME CONVERSION (SEC)
ATIME=LU*TIME
AA1=(BB1+BB2)/2.0
CALL SWITCH(DD,DA,AA1,IS,RSENS,WTSENS,RGN,VFBG,BDOT2D,XOFS)
IF (ATIME.GT.450.0) XOFS=XOFS

SAMPLE
CONTRL FINTIM=30.0,DELT=0.04,DELS=0.04
PRINT 0.20,ATIME,ADY,ADY,YAWD1,YAWD2,YAWDPD,SPDDES,CDOT2
PRPLT ONLY
CALL DRWG(1,1,ATIME,ADY)
CALL DRWG(2,1,ATIME,YAWDPD)
CALL DRWG(3,1,ATIME,SPDDES)
CALL DRWG(3,2,ATIME,CDOT2)
CALL DRWG(4,1,ATIME,ADY)

TERMINAL
IF(IS.EQ.1) WRITE(6,101)
101 FORMAT(* THIS RUN IS FOR A PORT SIDE TO APPROACH*)
IF(IS.EQ.0) WRITE(6,102)
102 FORMAT(* THIS RUN IS FOR A STBD SIDE TO APPROACH*)
CALL ENDRW(NPLOT)
CALL CONTN
FINITM=45.0

END
STOP
FORTRAN
INSERT SUBROUTINE R8MEAS FROM APPENDIX A HERE
INSERT SUBROUTINE HOGRA8 FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE SWITCHF FROM APPENDIX A HERE
INSERT FUNCTION SWCL FROM APPENDIX A HERE
INSERT FUNCTION SPD0FC FROM APPENDIX A HERE
INSERT FUNCTION SPINIT FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//PLCT.SYSIN DD *

7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4
7.0  5.0  4

INSERT TWO /* CARDS HERE
This program incorporates the sea state first programmed in computer programs #4 and #7. The wave force, however, is introduced at the end of the propulsion loop to allow more realistic perturbations. This is the final form of the complete heading and speed control systems. To run this without a sea state, set WFMA to 0.0.

This program produced the plots shown in figures III-103 thru III-105.
COMPUTER PROGRAM #10

//UHRINFO JOB (2794,0775,EA44),'UHRIN SMC 1675',TIME=5
// EXEC DSL
//DSL INPUT DD *
* RAS SPEED CONTROL - WAVE INTERACTION
TITLE RAS SPEED CONTROL - WAVE INTERACTION
INTEC RK5FX
INTEGER NPLT=2
INTEGER NIS
CONST N=1;RD=1.0
PARAM IS=1;DD=0.2
PARAM RSNS=1.86642
PARAM TSEN=2.38692
PARAM RGN=23.41847
PARAM VFBG=4.35162
PARAM TSTPI=35.0,TSTP2=36.0
* HYDRODYNAMIC COEFFICIENTS
CONST NR=-0.00227,NV=-0.00351,NVD=-0.000197
CONST HYVD=0.015,MYR=0.0051,IZNRD=0.00068,MXUD=0.0085
CONST YV=-0.01243,XU=-0.0012,YR=-0.00027
CONST YDELR=-0.0027,NDELR=-0.00126,XDELR=0.0
CONST DLTD=2.0;DLTEM=7.0
* INITIAL SEPARATION
INCON X01=5.0,Y01=0.0,X02=0.0,Y02=0.4
* INITIAL CONDITIONS
INCON YAW01=0.0
INCON YY1=0.,YY2=0.,YN1=0.,YN2=0.
INCN U01=1.0,U02=1.5
* X0FS IS THE DESIRED NORMALIZED X POSITION / 0.0 IS ALONGSIDE /
* NEG FOR ASTERN OF ALONGSIDE / POS FOR FWD OF ALONGSIDE
* NOTE - X0FS CAN BE USED FOR VEHICLE OF APPROACH AND EXIT FROM
* STATION BY SETTING SOME DESIRED POSITION EG. -5.0 ; 5.0
* THIS WOULD CAUSE APPROACH OR BREAK AWAY STATION ATTAINMENT
* WHICH CAN BE PRECEDEED BY OR FOLLOWED BY NON RAS POSITION
* CONTROL
PARAM X0FS=0.0
PARAM X0FS0=0.0
PARAM UF=21.73,A=22.0,
PARAM WS=5.0
PARAM WD=-015.0
PARAM WL=1.0
PARAM WFMA=0.05685
PARAM KS2=-1.0
INITIAL
DY0=YQ2-YQ1
DX0=XQ2-XQ1
CALL TRANS(YAW01,DX0,DY0,ADX,ADY)
CALL SLOPES(ADX,ADY,YY1,YY2,YN1,YN2)
*
CALCULATION OF THE COEFFICIENTS
NC1=-XU
NC2=-XU
A11=MYVD
B11=-YV
A21=-YRD
B21=MYR
A12=-NV
B12=-NV
A22=IZNRD
B22=-NR
A33=MXUD
B33=-XU
KAI=YDEL R
KB1=NDEL R
KC1=XDEL R
D=A11*A22-A12*A21
DELRM=41.6953
RDC=180./3.1415926
CRC=3.1415926/180.
LUC=20.84765
KG=DLTDM/DLTEM
DIDIC=0.0
D2=DEGRAD(1,1,D2D)
BY02=0.0
K=UF/A
P=4.88/LUC
SPD01=1.0
SPD02=1.5
SPDDER=SPD01/K

DERIVATIVE
WF1 = (WFMA/(0.1137*40.0))*RAMP(0.0)
WF=LIMIT(-WFMA,WFMA,WF1)
WRV=NORMAL(1975,0.0,WFMA/10.0)
WV=WS/15.0
EKED=WD-YAWDP2
EW=DEGRAD(1,1,EWDD)
WF0=2.0*3.1415926*(CDOT2+WV*COS(EWD))/WL
WE=WF0*TIME
WFY=WF*SN(EWD)
WFN=WF*SN(2.0*EW)
WFX=WF*SN(EWD)
WF0=WF0*SN(WF)+3.1415926*WF0**2/WL)*SN(2.0*WF)
WFN=WFN*SIN(WE)+(3.1415926*WFN**2/WL)*SIN(2.0*WE)
WXF=WFX*SIN(WE)+(3.1415926*WFX**2/WL)*SIN(2.0*WE)
WY=WYF+WRV*WFY*SIN(WE)
WN=WNF+WRV*WFN*SIN(WE)
WX=WXF+WRV*WFX*SIN(WE)
DI1=5.0*STEP(TSTEP1)-5.0*STEP(TSTEP2)
DLTS1=LIMIT(-30.0,30.0,DI1)
DLTE1=DLTS1-DID
DLTEB1=LIMIT(-DLTEM,DLTEM,DLTE1)
D1=INTGR1(D1D1C,KG*DLTE1*LUC)
D1=DGRAD(1,1,D1D)
DX=X2-X1
DY=Y2-Y1
SIMULATION SHIP A
IF11=KA1*D1
IF21=KB1*D1
IF31=KC1*ABS(D1)+NC1
I11=-B11*ADOT1-B21*BDOT1+IF11
I21=-B12*ADOT1-B22*BDOT1+IF21
I31=-B31*ADOT1+IF31
ADOT1=(I11*A22-I21*A21)/D
BDOT1=(I21*A11-I11*A12)/D
CDDOT1=I31/A33
ADOT1=INTGR1(0.,ADOT1)
BDOT1=INTGR1(0.,BDOT1)
CDDOT1=INTGR1(U01,CDDOT1)
BY=INTGR1(0.,BDOT1)
XDOT1=CDDOT1*COS(BY1)-ADOT1*SIN(BY1)
YDOT1=CDDOT1*SIN(BY1)+ADOT1*COS(BY1)
X1=INTGR1(X01,XDOT1)
Y1=INTGR1(Y01,YDOT1)
YAW1=B11
SWAY1=Y1
SURGE1=X1
SIMULATION SHIP B
IF12=KA1*D2+YY2+KA1*WY
IF22=KB1*D2+YN2+KB1*WN
IF32=KC1*ABS(D2)+NC2
I12=-B11*ADOT2-B21*BDOT2+IF12
I22=-B12*ADOT2-B22*BDOT2+IF22
ADOT2=(I12*A22-I22*A21)/D
BDOT2=(I22*A11-I12*A12)/D
ADOT2=INTGR1(0.,ADOT2)
BDOT2=INTGR1(0.,BDOT2)
SW=SWCL(SP01,SP02)
SPDDES=SPDOFC(AD0,SPD01,SPD02,SW,XQFS)
SPDDEL=DELAY(T,P,(SPDDES/K-SPDDER))
SPDEL=SPIN(TSPDDEL,TIME,(SPDDES/K-SPDDER))
SPDIN = K*(SPDEL + SPDDER)  
SPDERR = (SPDIN - CDOT2) * G  
CDOT2 = INTGRAL(UO2, SPDERRLUC) + KS2*WX  
BY2 = INTGRAL(BY02, BDOT2)  
XDOT2 = CDOT2*COS(BY2) - ADOT2*SIN(BY2)  
YDOT2 = CDOT2*SIN(BY2) + ADOT2*COS(BY2)  
X2 = INTGRAL(XO2, XDOT2)  
Y2 = INTGRAL(YO2, YDOT2)  
YAW2 = BY2  
SWAY2 = Y2  
SURGE2 = X2  

NOSORT  
YAWD1 = DEGRAD(0,0, YAW1)  
YAWDP1 = DEGRAD(0,1, YAW1)  
YAWC2 = DEGRAD(0.0, YAW2)  
YAWDP2 = DEGRAD(0.1, YAW2)  
YAWDP = YAWDP1 - YAWDP2  

RUDDER RESPONSE INPUT  
CALL RBAEAS(N, YAW1, X1, Y1, YAW2, X2, Y2, RD, R1, B1, BB1, R2, B2, BB2)  
CALL HEDGRAS(N, IS, R1, B1, BB1, R2, B2, BB2, RSENS, YAW2, PSIDFD, PSIADD, ...)  
PSI0ED, WT, DA, A10, B10, B20, WTSENS, DD, RD)  
BDOT2 = DEGRAD(0.1, BDOT2)  
BDOTBF = VFBG*BDOT2D  
DDUMB = YAWD2 - PSIDED + BDOTBF  
IF (DDUMB GT 180.0) DDUMB = DDUMB - 360.0  
IF (DDUMB LT -180.0) DDUMB = 360.0 + DDUMB  
DLTS = LIMIT(-30.0, 30.0, DDUMB * RGN)  
DLTE = DLTS - D2D  
DLTBE = LIMIT(-DLTEM, DLTEM, DLTE)  
D2D = INTGRAL(D2DIC, KG*DLTBE*LUC)  
D2 = DEGRAD(1.1, D2D)  

SORT  
DISTE = ABS(DD - ADY)  
OBJ = INTGRAL(0.0, DISTE)  
DISTES = ABS(ADX)  
OBJS = INTGRAL(0.0, DISTES/25.0)  

DYNAMIC REGION  
* ACTUAL SEPARATION  
DX = X2 - X1  
DY = Y2 - Y1  
CALL TRANS(YAW1, DX, DY, ADX, ADY)  
* EXTERNAL FORCES ACTING BETWEEN SHIPS  
CALL SLOPES(ADX, ADY, YY1, YY2, YN1, YN2)  
IF ((ABS(ADY), LT, 0.04744) AND (ABS(ADX), LT, 1.0)) WRITE(6,100)  
100 FORMAT('**** SEPARATION LESS THAN 25 FEET - COLLISION****')  
* ACTUAL TIME CONVERSION (SEC)  
ATIME = LUC*T.E  
AAL = (BB1 + BB2) / 2.0
CALL SWTCHEF(DD,DA,AA1,IS,RSENS,WTSENS,RGB,VBG,BDOT2D,XOFS)
IF (ATIME.GT.450.0) XOFS=XBFS

SAMPLE
CONTOL FINTIM=30.,DELT=0.04,DELS=0.04
PRINT 0.20,ATIME,YAW01,D1D,DLTS1,CDOT1,OBJ,YAWD2,D2D,DLTS,CDOT2,...
OBJ0,YAWDPD,ADY,ADX,SPDDES,EMDD,WEB,WEB,WN,WN,RSENS,WTSENS,...
RGB,VBG,SW
PRPLOT ONLY
CALL DRWG(1,1,ATIME,CDOT2)
CALL DRWG(1,2,ATIME,SPDDES)
CALL DRWG(2,1,ATIME,ADX)

TERMINAL
IF(IS.EQ.1) WRITE(6,101)
101 FORMAT('THIS RUN IS FOR A PORT SIDE TO APPROACH')
IF(IS.EQ.0) WRITE(6,102)
102 FORMAT('THIS RUN IS FOR A STBD SIDE TO APPROACH')
CALL ENDRW(NPLOT)
CALL CONTIN
FINTIM=45.0

END
STOP

FORTRAN
INSERT SUBROUTINE RBMEAS FROM APPENDIX A HERE
INSERT SUBROUTINE HDGAS FROM APPENDIX A HERE
INSERT FUNCTION DEGRAD FROM APPENDIX A HERE
INSERT SUBROUTINE TRANS FROM APPENDIX A HERE
INSERT SUBROUTINE SWTCHE FROM APPENDIX A HERE
INSERT FUNCTION SWCL FROM APPENDIX A HERE
INSERT FUNCTION SPDGC FROM APPENDIX A HERE
INSERT FUNCTION SPINIT FROM APPENDIX A HERE
INSERT SUBROUTINE SLOPES FROM APPENDIX A HERE
//PLOT*SYIN DD *

7.0 5.0
7.0 5.0
7.0 5.0
7.0 5.0

INSERT TWO /* CARDS HERE
BIBLIOGRAPHY


**INITIAL DISTRIBUTION LIST**

<table>
<thead>
<tr>
<th>No.</th>
<th>Initial Distribution List</th>
<th>Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Defense Documentation Center Cameron Station Alexandria, Virginia 22314</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Library, Code 0212 Naval Postgraduate School Monterey, California 93940</td>
<td>2</td>
</tr>
<tr>
<td>3.</td>
<td>Department Chairman, Code 52 Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940</td>
<td>2</td>
</tr>
<tr>
<td>4.</td>
<td>Professor George J. Thaler, Code 52Tr Naval Postgraduate School Monterey, California 93940</td>
<td>5</td>
</tr>
<tr>
<td>5.</td>
<td>Lt. John J. Uhrin III, USN 456 Lineberry Road Virginia Beach, Virginia 23452</td>
<td>3</td>
</tr>
<tr>
<td>6.</td>
<td>Reidar Alvestad NSREC Annapolis Lab Annapolis, Maryland 21402</td>
<td>1</td>
</tr>
<tr>
<td>7.</td>
<td>Assc. Professor Alex Gerba, Jr., Code 52Gz Naval Postgraduate School Monterey, California 93940</td>
<td>2</td>
</tr>
<tr>
<td>8.</td>
<td>Samuel E. Brown NSREC Annapolis Lab Annapolis, Maryland 21402</td>
<td>1</td>
</tr>
</tbody>
</table>
INITIAL DISTRIBUTION LIST (Cont.)

9. J. R. Zuidweg
   Royal Netherlands Naval College
   Den Helder, The Netherlands

10. RADM R. L. Walters
    Project Manager Surface Ship Project Office PM18
    Room 9SC8 National Center 3
    Department of the Navy
    Washington, DC 20362
    Attention PM18T

11. Marvin Denicoff
    Office of Naval Research Code 437
    Arlington, Virginia 22217