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Dynamic Positioning/tracking and Automatic Berthing
By H. Hagiwara, R. Shoji, H. Fukuda & J.A. Pinkster
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# TABLE OF CONTENTS
## VOLUME 1
### PLENARY PAPER
Automation: Friend or Foe?
*S. Bennett (UK)* .......................................................... 15

Feedback-Loop Performance Monitoring for Controller Falsification
*E. Mosca and T. Agnoloni (Italy)* ................................. 29

### INVITED PAPERS
#### INFINITE DIMENSIONAL CONTROL SYSTEMS
Mathematical Modelling of 3D Flow Problems
*J. Felcman and V. Dolejši (Czech Republic)* ................. 39

Constrained Controllability of Semilinear
Infinite-Dimensional Systems
*J. Klamka (Poland)* .................................................. 45

Boundary Control of a Distributed Hyperbolic System with Multiple Deviating Arguments
*A. Kowalewski (Poland)* ............................................ 51

Distributed Control of a Distributed Hyperbolic System with Multiple Deviating Arguments
*A. Kowalewski (Poland)* ............................................ 57

LQ Problem with Initial State Given by a Unknown Function
*A. Kowalewski and J. Duda (Poland)* ......................... 63

On Some Optimal Control Problem with Time Delays
*A. Kowalewski and A. Krakowiak (Poland)* .................. 69

Nonlinear PDE Observers for Machine Vision
*W. Lohmiller and J.-J. E. Slotine (USA)* ....................... 73

Analysis of Nonlinear Infinite Dimensional Systems using Contraction Theory
*W. Lohmiller and J.-J. E. Slotine (USA)* ....................... 79

Tangent Sets in Banach Spaces and Applications to Variational Inequalities
*M. Rao (USA) and J. Sokolowski (France)* .................... 89

A Control Approach to Fourth Order Differential Equations
*D. Tiba (Romania)* ................................................... 95

Activation Policy of Multiple-Scanning Sensors for Parameter Estimation of Distributed Systems
*D. Uciński (Poland)* ............................................... 99

### REGULAR PAPERS
#### MULTIDIMENSIONAL AND SINGULAR SYSTEMS
Elimination of Anticipation of Singular Linear Systems
*T. Kaczorek (Poland)* ............................................... 107

Ellipsoidal Estimation of Reachability Set for a General 2D-Continuous – Discrete Linear System with Disturbances
*E. Krasoñ (Poland)* ................................................... 115

Generalized Discrete Linear Repetitive Processes
*K. Gałkowski, B. Sulikowski (Poland),
E. Rogers and D. Owens (UK)* ................................. 119

Functional Observers for Singular Linear Systems
*T. Kaczorek and M. Sławęski (Poland)* ....................... 125

The State Space Model of ‘Wave’ Linear Repetitive Processes
*K. Gałkowski, W. Paszke (Poland),
E. Rogers and D. Owens (UK)* ................................. 131

#### OPTIMIZATION METHODS
Linear Quadratic Optimization Problem with Indefinite Sign Weight Costs for Stochastic Systems with Multiplicative White-Noise and Markovian Jumping
*V. Dragan, T. Morozan (Romania)* .............................. 137

Evolutionary Multi-Objective Optimisation with Genetic Sex Recognition
*Z. Kowalczuk and T. Białaszewski (Poland)* ................. 143

The Use of the Method of Illusion to Optimizing the Simple Cutting Stock Problem
*J. Kotowski (Poland)* ............................................... 149

Method for Finding All Solutions of Systems of Polynomial Equations
*K. Marciniak, E. Pawelec and J. Porter-Sobieraj (Poland)* 155

Multi-Criteria Decision in a Client/Provider Relationship
*T. Monteiro, H. Bouchriha and P. Ladet (France)* .......... 159

Adaptive Multi-Criterion Evolutionary Algorithm with Elitist Selection for Tasks Assignments
*J. Balicki (Poland)* .................................................. 165

Solving Angle Packing Problems - Integer Linear Programming vs. Constraint Logic Programming
*T. Szczygiel (Poland)* .............................................. 171
Simulation Algorithms for the Water Distribution Network with Limited Consumption Outflows
E. Szlachcic and J. Kotowski (Poland) .................. 181

Adaptive Linearized Switching Controller for Constrained Optimal Control Problems
A. Korytowski, M. Szymkat and A. Tarnau (Poland) ........................................... 187

OPTIMAL CONTROL SYSTEMS

Discretization of Controllers and the Method of Moments
N. Maamri, B. Guilhaumon and J. C. Trigeassou (France) ................. 193

Optimal Control of Electric Network Chain
H. Górecki (Poland) .................................................. 199

Genetic Algorithm Approach for Designing of Mixed H2 / H∞ State Feedback Controllers
J. Mohammadmur, A. Irannejad and M. J. Yazdanpanah (Iran) ............. 205

Conditioning of J-Lossless Factorisations for H∞-Control in Delta Domain
P. Suchomski (Poland) ............................................. 211

The Development of a Ship’s Guidance System with Optimal Control
H. Fukuda and K. Ohtsu (Japan) .................................... 217

General Equivalence Results on Maximum-Accuracy and Maximum-Speed Controls for LTI MIMO Discrete-Time Systems
K. Latawiec, A. Korytowski and S. Bańka (Poland) ...................... 223

Using LMI and H∞-Optimization in Algorithms of Synthesis of Controllers
V. B. Larin (Ukraine) .............................................. 229

Performance Evaluation of Model-Reference Control
W. Grego (Poland) .................................................. 235

Reliable Linear Quadratic Control for Singulary Perturbed Systems with Actuator Failures
Y. Li, J. L. Wang and G.-H. Yang (Singapore) ......... 241

On the Ship Trajectory Tracking LQ-Model Predictive Controller Design
Z. Zwierzewicz (Poland) ........................................... 247

ROBUST CONTROL SYSTEMS

Two-Level Robust Control for Uncertain Systems with Jumps and Imperfect State Measurement
A. Świętniak and K. Simek (Poland) .............................................. 253

Power System Stabilizer Design Using μ-Synthesis with Real, Structured Additive Uncertainties
A. Szwarcwicz and K. Wróblewska-Szwarcwicz (Poland) .......... 259

Robust μ-Independent Controllers with Respect to the Normalized Coprime Factorization of Two-Time-Scale Systems
V. Dragan and A. Stoica (Romania) ......................... 265

Robust Control: Multivariable H∞ Controller Applied to an Induction Motor
C. Chaigne, L. Rambaut and N. Maamri (France) ...................... 271

Optimal Control Robustness: A Case Study of a Magnetic Bearing Control System
B. Starzycy, I. Jaworska and E. Zak (Poland) ............................................ 277

Application of Idea of Time Scaling to Synthesis of Linear and Non-Linear Control Systems
M. Durnas and B. Grzywacz (Poland) ...................... 283

Robust Predictive Control Structure for a Class of Nonlinear Systems
S. Domek (Poland) .................................................. 291

LINEAR SYSTEMS

A Procedure for Computing Invariant Zeros of MIMO LTI Systems
J. Tokarzewski (Poland) ............................................. 297

Control Zeros and Perfect Regulation/Filtering for LTI MIMO Discrete-Time Systems
K. Latawiec, A. Korytowski and R. Rojek (Poland) ...................... 303

Simple Procedure for Analytic Stability Margin Design
A. Ferrante (Italy), W. Krajewski (Poland), A. Lepschy and U. Viaro (Italy) ......................... 309

Determination of an Initial State for Uncertain Discrete Time-Varying Systems
Z. Emirsajlow and P. Orłowski (Poland) ...................... 315

A Geometric Interpretation of Invariant Zeros in Case of G(s)=0
J. Tokarzewski (Poland) ............................................. 321

Calculating Operator Norms in Control Problems on Finite Time Horizon
R. Szmidi and Z. Emirsajlow (Poland) ...................... 327

MEASUREMENT SYSTEMS AND SIGNAL RECOVERING

Maritime Targets Tracking Based on Track-to-Track Fusion
Z. Kowalczyk and P. Uruski (Poland) ...................... 333

The Method of Recovery of Input Signal for Non-Linear Measuring System
M. Boćkowska and A. Zuchowski (Poland) ...................... 339

The Measuring Windows with Correctors as Low-Pass Filters
M. Boćkowska and A. Zuchowski (Poland) ...................... 345
COMPUTER INTEGRATED MANUFACTURING AND SCHEDULING PROBLEMS

Adaptive Master-Slave Arm Control with Computer Auxiliary Operation by RBFN
M. Soeda, T. Furuya (Japan) ........................................... 437

Frames Technology Based Feature-Driven Software Design. A CLP Approach
T. Borowiec, K. Politowicz and Z. Banaszak (Poland) .................. 443

Partially Directed Graphs - A Modeling Tool for AGV Systems
E. Roszkowska (Poland) ................................................ 449

Steady-State Analysis of Distributed Manufacturing Processes: a Case of m Cyclic Processes Sharing a Resource
R. Wójcik (Poland) ................................................................ 455

Method of Reducing the Number of Assembly Sequences, with Preliminary Evaluation
P. Lebkowski (Poland) ...................................................... 461

Performance Modeling of Automated Manufacturing Systems by Simulation Optimization
V. V. G. Reddy and C. S. P. Rao (India) .................................. 467

Fuzzy Logic Based Dynamical Control of Transportation Operation of Industrial Robot
S. Jałowicki, A. Jardzioch and J. Honczarenko (Poland) ............... 473

A Simulated Annealing Algorithm, for a Scheduling Problem in Grid Environments
M. Mika, J. Nabrzycki, G. Waligóra and J. Węglarz (Poland) ........ 479

On Preemptive C_max Scheduling of Dependent Tasks on Parallel Identical Machines
J. Józefowska, M. Mika, R. Różycki, G. Waligóra and J. Węglarz (Poland) .......... 485

APPLICATIONS OF NEURAL NETWORKS

A Nonlinear Predictive Control Algorithm for Processes Modelled by Means of Neural Networks
M. Lawrynczuk and P. Tatjewski (Poland) ............................ 489

Automatic Speech Classification with the Usage of Kohonen Neural Network
M. Gajer, M. Kapusta and A. Shomali (Poland) ....................... 495

Training Neural Network Hammerstein Models with Truncated Backpropagation through Time Algorithm
A. Janczak (Poland) ...................................................... 499

Fuzzy-Neuro System for Decision-Making in Management
G. Setlak (Poland) ........................................................ 505

Ultrasonic Level Measurement with Micro-Controller
S. E. Borujeni and M. S. Hsiami (Iran) ............................... 349

A Transducer-Based Magnetic Field Transducer
S. Moskowicz (Poland) .................................................. 353

MODELING AND SIMULATION

Regional Policy and Sustainable Development
J. Holubiec and J. Malicka-Wąsowska (Poland) ............. 357

Calibration of Parameters for "Cross-Convexity" Model of Heat Exchanger
P. Lasczyk (Poland) and J. Richalet (France) ................. 363

Some Aspects of Modelling Family Utility. Use of Group Decision Approach To Support Evaluation of Tax and Interest Policy
H. Bury and D. Wagner (Poland) ................................. 369

HWILS Method in Coal Grinder Efficiency Control
A. Kurnicki, I. Jaworska and B. Stańczyk (Poland) ............ 375

Introduction to Virtual Automation
M. Metzger (Poland) ................................................... 379

The Backstepping Control of the Power Plant Station Model
W. Bolek and T. Wiśniewski (Poland) .......................... 385

Drum Boiler Dynamic Simulation Model Analysis
Z. Deliang and L. Jizhen (P. R. China) ......................... 391

The Simulator of Steam Superheating Process in the Boiler OP-650b
W. Bolek, T. Tietze and T. Wiśniewski (Poland) ............... 397

On Railway Network Modeling
J. Holubiec and G. Petriczek (Poland) ......................... 403

Using Hybrid I/O Automata for Hierarchical Hybrid Control Systems
Z. Yang (Denmark) .................................................... 409

The Structural Scheme of Stabilised Tank Turret and Gun
K. M. Papliński and Z. Sobczyk (Poland) ...................... 415

Modelling of Imperfect Mixing for Real-Time Simulation and Process Model-Based Control of CSTR
M. Metzger (Poland) ................................................... 421

Mathematical Modeling of Flying Animals as Aerial Robots
A. Marusak, J. Pietrucha, K. Sibilski and M. Złocka (Poland) .... 427

Some Aspects of Modelling the Elastic Features of the Respiratory System
B. Juroszek (Poland) .................................................. 433

555
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neural Networks Learning as a Particular Feedback Optimal Control Problem</td>
<td>511</td>
</tr>
<tr>
<td>M. Krawczak (Poland)</td>
<td></td>
</tr>
<tr>
<td><strong>FUZZY LOGIC APPLICATIONS</strong></td>
<td></td>
</tr>
<tr>
<td>Output Constraints in Fuzzy DMC Algorithms with Parametric Uncertainty in Process Models</td>
<td>517</td>
</tr>
<tr>
<td>P. Marusak and P. Tatjewski (Poland)</td>
<td></td>
</tr>
<tr>
<td>A Fuzzy Logic-Controlled Bag Filter Based on the Air Pressure Difference</td>
<td>523</td>
</tr>
<tr>
<td>B. Minzhong and M. Jianying (China)</td>
<td></td>
</tr>
<tr>
<td><strong>PLENARY PAPER</strong></td>
<td></td>
</tr>
<tr>
<td>Towards an autonomous mobile robot working in daily-life environment</td>
<td>563</td>
</tr>
<tr>
<td>S. Yuta (Japan)</td>
<td></td>
</tr>
<tr>
<td>Design of Lyapunov Function for Control of Robot Manipulators</td>
<td>571</td>
</tr>
<tr>
<td>K. Kozłowski (Poland)</td>
<td></td>
</tr>
<tr>
<td>Nonlinear Predictive Control for Manufacturing and Robotic Applications</td>
<td>579</td>
</tr>
<tr>
<td>M. J. Grimble and A. W. Ordys (UK)</td>
<td></td>
</tr>
<tr>
<td><strong>INVITED PAPERS</strong></td>
<td></td>
</tr>
<tr>
<td>RECENT DEVELOPMENTS IN MARINE CONTROL SYSTEMS</td>
<td></td>
</tr>
<tr>
<td>A Fuzzy Fault Tolerant Control Scheme for an Autonomous Underwater Vehicle</td>
<td>595</td>
</tr>
<tr>
<td>R. Sutton, A. Pearson (UK) and A. Tiano (Italy)</td>
<td></td>
</tr>
<tr>
<td>Onboard Experiments on Weather Vaning</td>
<td>601</td>
</tr>
<tr>
<td>Dynamic Positioning/Tracking and Automatic Berthing</td>
<td></td>
</tr>
<tr>
<td>H. Hagiwara, R. Shoji, H. Fukuda (Japan) and J. Pinkster (The Netherlands)</td>
<td></td>
</tr>
<tr>
<td>Predictive Versus Fuzzy Control of Autonomous Underwater Vehicle</td>
<td>609</td>
</tr>
<tr>
<td>M. Kwiesielewicz, W. Piotrowski (Poland) and R. Sutton (UK)</td>
<td></td>
</tr>
<tr>
<td>Problems of Identification and Validation of Component Elements of Ship Power Systems</td>
<td>613</td>
</tr>
<tr>
<td>R. Arendt (Poland)</td>
<td></td>
</tr>
<tr>
<td>A Neural Network Adaptive Autopilot for a Yacht</td>
<td>619</td>
</tr>
<tr>
<td>Ch. Yang (China), Ch. Xiao (New Zealand), A. Tiano and A. Zirilli (Italy)</td>
<td></td>
</tr>
<tr>
<td>A New Fault-Tolerant Control Scheme Based on Hybrid Neural Networks</td>
<td>625</td>
</tr>
<tr>
<td>T. Tang, Y. Chen and J. Li (P. R. China)</td>
<td></td>
</tr>
<tr>
<td>Intelligent Marine Traffic Simulator for Congested Waterways</td>
<td>631</td>
</tr>
<tr>
<td>K. Hasegawa, G. Tashiro, S. Kiritani and K. Tachikawa (Japan)</td>
<td></td>
</tr>
<tr>
<td>Tracking Control of the Ship Using a Nonlinear H∞ Control</td>
<td>637</td>
</tr>
<tr>
<td>E. Shimizu and M. Ito (Japan)</td>
<td></td>
</tr>
<tr>
<td>Recent Development in Marine Control Systems</td>
<td>641</td>
</tr>
<tr>
<td>R. Śmierschalski (Poland)</td>
<td></td>
</tr>
<tr>
<td><strong>REGULAR PAPERS</strong></td>
<td></td>
</tr>
<tr>
<td>ROBOT CONTROL AND SIMULATION</td>
<td></td>
</tr>
<tr>
<td>Extensible Robotic Simulator</td>
<td>649</td>
</tr>
<tr>
<td>P. Koseeyaporn (USA), Z. Bingal (Turkey) and G. E. Cook (USA)</td>
<td></td>
</tr>
<tr>
<td>The Robotics to Help the Surgeon</td>
<td>655</td>
</tr>
<tr>
<td>A. Fonte (France)</td>
<td></td>
</tr>
<tr>
<td>A Comparison of Several Quasi-Velocity Controls for Serial Manipulators</td>
<td>659</td>
</tr>
<tr>
<td>P. Herman and K. Kozłowski (Poland)</td>
<td></td>
</tr>
<tr>
<td>Title</td>
<td>Authors</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Designing a Stewart Platform-Based Cooperative System for Large Component Assembly</td>
<td>K.-S. Chai and K. Young (UK)</td>
</tr>
<tr>
<td>Neutral Network Based Singular Perturbation Control of a Manipulator with Both Link and Joint Flexibility</td>
<td>B. Subudhi and A. S. Morris (UK)</td>
</tr>
<tr>
<td>The Rapid Prototyping of the Visual Servoing on MATLAB/Simulink/dSPACE Environment</td>
<td>P. Kohut and T. Uhl (Poland)</td>
</tr>
<tr>
<td><strong>MOBILE ROBOTICS AND TRAJEKTORY PLANNING</strong></td>
<td></td>
</tr>
<tr>
<td>Optimal Trajectories with Respect to an Energetic Criterion for Three Quadruped Walking Gaits</td>
<td>A. Muraro, C. Chevaliereau and Y. Aoustin (France)</td>
</tr>
<tr>
<td>Guidelines for Cooperative Mapping by Mobile Agents</td>
<td>T. Smailius and S. S. Iyengar (USA)</td>
</tr>
<tr>
<td>Tracking and Stabilizing Mobile Robot Trajectories - Experimental Results</td>
<td>S. Schoenknacht, J. Reuter and A. Steinicke (Germany)</td>
</tr>
<tr>
<td>Testing Robust Stability of Mobile Robot Path</td>
<td>J. Damunt, P. Cuguerio, J. Saludes, V. Puig and T. Escobet (Spain)</td>
</tr>
<tr>
<td>Linear Methods for Path Finding in 3D Configuration Space</td>
<td>S. Kowalski (Poland)</td>
</tr>
<tr>
<td>Online Generation of Trajectories Considering Kinematic Constraints</td>
<td>O. Sawodny, H. Aschemann, A. Bulach and E. P. Hofer (Germany)</td>
</tr>
<tr>
<td>Modelling and Gain-Scheduled Trajectory Control of a Flexible Turntable Ladder</td>
<td>H. Aschemann, O. Sawodny, A. Bulach and E. P. Hofer (Germany)</td>
</tr>
<tr>
<td>Vision Based Target Detection and Following with an Autonomous Mobile Robot</td>
<td>B. Kwolek (Poland)</td>
</tr>
<tr>
<td>Position Estimation for a Mobile Robot Using Odometry and Passive Beacons</td>
<td>N. Slimane and N.-E. Bouguechal (Algeria)</td>
</tr>
<tr>
<td><strong>ROBOT DYNAMICS AND CONTROL</strong></td>
<td></td>
</tr>
<tr>
<td>Modelling and Control Design of a Flexible Manipulator Using State-Dependent Riccati Equation Techniques</td>
<td>A. Shawky, M. Grimble, A. Ordys and A.-Petropoulakis (UK)</td>
</tr>
<tr>
<td>On Identifiability of a Robot Physical Parameters: Detailed Analysis of the One Link Cuboid Manipulator Case</td>
<td>K. Arsent (Poland)</td>
</tr>
<tr>
<td>Adaptive Controller Design for Robot Arms Having Joint Compliance Driven by Induction Motors without Flux Sensors</td>
<td>J.-H. Yang (Taiwan)</td>
</tr>
<tr>
<td>Modelling of Pneumatic Drive and Correction of its Dynamics for Robotic Application</td>
<td>G. Granosik (Poland)</td>
</tr>
<tr>
<td>Dynamical Modeling and Control of a New Underwater Vehicle-Gliderobot</td>
<td>X.-G. Yan and I.-M. Chen (Singapore)</td>
</tr>
<tr>
<td>Induction Motor Drives for Industrial Manipulators - Application of Direct Torque Control</td>
<td>R. Beniak, P. Wach and P. Wosik (Poland)</td>
</tr>
<tr>
<td>Software Implementation of the Control System for the Climbing Robot</td>
<td>D. Dobrocyński, P. Dutkiewicz and W. Wróblewski (Poland)</td>
</tr>
<tr>
<td>Control Strategy of Three-Link Flexible Manipulators for Contact Motion Based on Decomposition of Elastic Vibration</td>
<td>Y. Morita, K. Tsujimura, H. Ukai and H. Kando (Japan)</td>
</tr>
<tr>
<td>Smart Hand: the Concept of Sensor Based Control A. R. Wolczowski (Poland)</td>
<td></td>
</tr>
<tr>
<td><strong>ADAPTIVE AND PREDICTIVE CONTROL SYSTEMS</strong></td>
<td></td>
</tr>
<tr>
<td>Adaptive Control for Vector-Controlled Induction Motor</td>
<td>F. Naceri (Algeria) and L. Abida (Saudi Arabia)</td>
</tr>
<tr>
<td>Adaptive 3-D Zone of Quiet in a Reverberant Enclosure Using LMS-type Algorithms</td>
<td>M. Blazej and Z. Ogonowski (Poland)</td>
</tr>
<tr>
<td>New Approach to the Adaptive Control of a Class of Distributed Parameter Bioreactors</td>
<td>J. Czeiczot (Poland)</td>
</tr>
<tr>
<td>Computation of Predictive Control for Retarded Systems</td>
<td>M. Zerikat, A. Rachid and M. Guedda (France)</td>
</tr>
<tr>
<td>Properties of Analytical CGPC Design Applied to Non-Minimum-Phase Plants</td>
<td>Z. Kowalczyk and A. Marciniak (Poland)</td>
</tr>
<tr>
<td>Enhancing the Robustness of CGPC via Youla-Kučera Parameterization</td>
<td>Z. Kowalczyk and P. Suchomski (Poland)</td>
</tr>
<tr>
<td>Control Strategies in Predictive Control</td>
<td>J.-T. Duda and K.-Janik (Poland)</td>
</tr>
</tbody>
</table>
A New Robust Approach to MCS Algorithms Application to an AC Machine
F. Naceri (Algeria) and L. Abida (Saudi Arabia) .......... 859

Chattering Reduction in the Speed Control of an Induction Motor Using a Load Torque Observer
A. Midoun-Qussedjik and M. Hamerlain (Algeria) ........ 867

Time-Optimal Control for Magnetic Levitation System
A. Pilat (Poland) ................. 873

Optimal Control of Lab-Scale Servomotor
M. S. Ehsani and S. Etemadi (Iran) ............... 879

Input-Output Linearization and PI Control Algorithms Applied for pH Process
K. Stebel (Poland) .......... 885

Simulative Comparison of PI and PFC Control for Electric Heater
P. Laszczyk (Poland) ........... 891

Sliding Mode Control Based on an Input Output Linearisation of an Induction Motor
A. Midoun-Oussedik and M. Hamerlain (Algeria) ........ 895

Optimum in the Sense of Minimum Variance Output Stabilisation of the Coal Mill
A. Kurnicki, B. Stańczyk and E. Zak (Poland) .... 901

IDENTIFICATION METHODS AND TECHNIQUES

A Comparison of Nonlinear Identification Techniques
M. J. Knight, R. Sutton, R. S. Burns and D. F. L. Jenkins (UK) .................. 953

Practical Methods for Identification of Nonlinear Process Dynamics with Examples of Bilinear Systems
T. Furuya and M. Soeda (Japan) ........ 959

Adaptive Least-Squares Parameter Estimation of OBF-Based Wiener Models
C. Marcia, K. Latawiec, R. Rojek (Poland) and G. H. C. Oliveira (Brazil) .......... 965

A Wavelet-Based Non-Parametric Algorithm for Hammerstein System Identification
P. Śliwiński (Poland) ....... 971

Non Linear Identification of a Brushless Motor
A. Tiano, A. Zirilli (Italy), R. Sutton and M. Knight (UK) .......... 977

Continuous-Time Versus Discrete-Time Modeling in System Identification
Z. Kowalczyk and J. Kozłowski (Poland) .............. 981

Parametric Least Squares Model Derived for Long Horizon Prediction
K. B. Janiszowski (Poland) ........ 987

Identification of Nonlinear Systems with Correlated Input
G. Mzyk (Poland) ................. 993

A Method of MA Time-Series Parametric Identification
J. Figwer (Poland) ............ 999

558
Determination of Parametric Uncertainty Domains Using Least-Squares Technique and Bounded Errors
C. Baron, T. Poinot, J. C. Trigeassou and N. Maamri (France) ........................................... 1003
Orthogonal Series Algorithms to Identify Hammerstein Systems
W. Greblicki and P. Śliwiński (Poland) ......................... 1009
Linear and Thresholded Wavelet Estimates in System Identification
Z. Hasiewicz and P. Śliwiński (Poland) ......................... 1015
Multivariate Systems and Signals Analyzer Multi-EDIP
J. Kasprzyk and J. Figwer (Poland) .............................. 1021
IDCAD - A Package for Fast Identification of Parametric Models of Dynamic Processes
K. Janiszowski and P. Wnuk (Poland) ............................ 1027

_FILTERING AND SIGNAL PROCESSING_

Active Noise Control Using Orthogonal Filters
M. Michalczyk and J. Figwer (Poland) .......................... 1033
Designing Method of True Linear Phase Filters
W. Zapala (Poland) .................................................. 1039
New Realization of the 1st Order Linear Digital Filter
J. E. Kurek (Poland) .................................................. 1045

Methods of Personal Speaker Features Extracting
E. Bieliska (Poland) .................................................. 1049
Pattern Recognition in the Case of Small Differences
W. Zorski and K. Murawski (Poland) ......................... 1055

_FAULT DETECTION AND ISOLATION_

Robustifying an Extended Unknown Input Observer with Genetic Programming
M. Witczak and J. Korbicz (Poland) .............................. 1061
Detection and Isolation of Maneuvers Based on Analysis of Kalman-Filter Bias
M. Sankowski and Z. Kowalczyk (Poland) ..................... 1067
Leak Detection for Transmission Pipelines under Varying Operational Conditions
Z. Kowalczyk and K. Gunowickrama (Poland) ................. 1073
Methods of Induction Motor Defects Diagnostic for the Industrial Robots
R. Borowski (Poland) ................................................ 1079
Fault Detection of the Actuators Using Neural Networks
K. Patan (Poland) ................................................... 1085

_AUTHOR INDEX_ ................................. 1091
ONBOARD EXPERIMENTS ON WEATHER VANING DYNAMIC POSITIONING/TRACKING AND AUTOMATIC BERTHING

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Abstract. In this study, a simple dynamic positioning (DP) system called "Weather Vaning DP system" has been developed. This DP system uses only the controllable pitch propeller of the main engine and bow thruster to position the reference point on a ship at the specified point on the earth. Onboard experiments on the weather vaning DP system were carried out using the training ship Shioji Maru of the Tokyo University of Mercantile Marine. These experiments verified an extremely high performance of the weather vaning DP system. Experiments to pursue a specified point moving on various predetermined tracks were also carried out, and it was found that the control algorithm of the weather vaning DP was applicable to automatic tracking. Furthermore, experiments on automatic berthing were performed by applying the control method of automatic tracking.

Key Words. Onboard experiments, weather vaning dynamic positioning, PID feedback control, wind feedforward control, automatic tracking, automatic berthing

1. INTRODUCTION

The term Dynamic Positioning (DP) means automatic positioning of the Reference Point (RP) on a ship at the Specified Point (SP) on the earth. DP is an indispensable technique for oil drilling in submarine oil fields, laying submarine cables, and sea bottom surveys using underwater robots. In many cases, the conventional control system of DP employs bow thruster (B/T) and stern thruster (S/T), in addition to the main engine-driven controllable pitch propeller (CPP) to position RP, and simultaneously carries out heading-keeping. Such a system involves a complex algorithm, and heading-keeping often becomes impossible when there are strong winds and tidal streams.

In response, a new control system has been developed, which carries out dynamic positioning only with CPP and B/T in the absence of heading-keeping [1], [2]. This control system enables dynamic positioning of RP with a small thrust force, because the heading of a ship naturally coincides with the direction of the wind or the tidal stream. (This control system is called "Weather Vaning DP"). By carrying out onboard experiments with the training ship "Shioji Maru" of the Tokyo University of Mercantile Marine, equipped with an RTK-GPS positioning system, the effectiveness of the newly developed system was assessed.

For sea bottom exploitation using submarine robots and submersible vehicles, it is necessary that the surface support ship should be capable of accurately tracking the underwater vehicles. In this specific connection, experiments were also carried out by moving SP on various predetermined tracks such as a straight line, square, circle, etc. at a low speed and having RP automatically track it to assess system performance.

Furthermore, experiments on automatic berthing were performed by applying the control method of automatic tracking. In automatic berthing, RP tracked SP which was moved on a straight line to the berthing point with gradually decreasing speed. The ship's heading was kept constant using S/T controlled independently of CPP and B/T. When SP
approached the berthing point, the ship was turned to
the direction parallel to the berth with S/T.

2. WEATHER VANING DYNAMIC
POSITIONING SYSTEM

The control system of the Weather Vaning DP
combines feedback control relying on data
representing the displacement of RP from SP and
feedforward control relying on data representing the
external forces acting on the ship's hull. Calculations
of displacements of RP from SP are carried out as
shown below.

\[
\begin{align*}
\varphi &= \varphi_1 - (x_1 \cos \vartheta + y_1 \sin \vartheta) / R_m(\varphi_1) \\
\lambda &= \lambda_1 - (x_1 \sin \vartheta - y_1 \cos \vartheta) / R_p(\varphi_1)
\end{align*}
\]

where

\[\begin{align*}
\vartheta &: \text{ship's heading} \\
R_m(\varphi_1) &: \text{radius of meridian of the earth at latitude } \varphi_1 \\
R_p(\varphi_1) &: \text{radius of parallel of the earth at latitude } \varphi_1
\end{align*}\]

Longitudinal distance \(\Delta x\) and transverse distance \(\Delta y\) between RP and SP can be obtained from
the following formulae. (\(\Delta x\) assumes a positive value
when SP is located forward of RP, while \(\Delta y\) assumes
a positive value when SP is on the port side of RP.)

\[
\begin{align*}
\Delta x &= (\lambda_0 - \lambda) R_p(\varphi_1) \cos \vartheta + (\varphi_0 - \varphi) R_m(\varphi_1) \sin \vartheta \\
\Delta y &= -(\lambda_0 - \lambda) R_p(\varphi_1) \sin \vartheta + (\varphi_0 - \varphi) R_m(\varphi_1) \cos \vartheta
\end{align*}
\]

The thrust force \(F_x\) of CPP and the thrust force \(F_y\) of
B/T required for Weather Vaning DP can be obtained
by the following formulae:

\[
\begin{align*}
F_x &= a_x \Delta x + b_x V_x + c_x \int_0^T \Delta x \, dt - R_x \\
F_y &= a_y \Delta y + b_y V_y + c_y \int_0^T \Delta y \, dt - R_y
\end{align*}
\]

where

\[\begin{align*}
V_x &= \frac{d \Delta x}{dt}, \quad V_y = \frac{d \Delta y}{dt} \\
T &: \text{time elapsed from commencement of DP} \\
R_x &: \text{longitudinal component of external force} \\
R_y &: \text{transverse component of external force}
\end{align*}\]

External forces acting on the ship's hull include wind
pressure, hydrodynamic force due to tidal streams (or
ocean currents), and drifting force due to waves. \(F_x\)
and \(R_x\) take positive values if they act on the ship to
move her forward, while \(F_y\) and \(R_y\) take positive
values if they act on the ship to move her towards the
port side. (See Fig.1.) Coefficients \(a_x\) and \(a_y\) are
feedback gains for proportional control, and coefficients
\(b_x\) and \(b_y\) are feedback gains for differential control, and coefficients \(c_x\) and \(c_y\) are
feedback gains for integral control.

With this control system, the center of effort of
external forces such as winds and tidal streams must
coincide with the position of B/T in a state of
equilibrium. For example, we consider a case in
which RP and SP are coincident, and the center of
effort of external force is deviated aft from the
position of B/T. If the external force is divided into a
longitudinal component and a transverse component,
the longitudinal component can be set off by the thrust
force of CPP, but the transverse component produces a
moment around the center of gravity due to the thrust
force of B/T, which is located on the forward side,
equal in magnitude and opposite in direction. As a
result, the bow turns in the direction in which B/T acts.
When the center of effort of external forces is at the
position of B/T, the moment due to transverse
component of external force and the moment due to
transverse thrust of B/T set off each other, thus RP can
be kept in the position. The center of effort of external
forces coincides with the position of B/T when the
ship receives winds, tidal streams or ocean currents
nearly from dead ahead, hence, RP can be retained
with the bow in the wind, tidal stream or ocean current.

3. DYNAMIC POSITIONING EXPERIMENTS

3.1. Outline of Experiments
Dynamic positioning experiments using Shioji Maru
were carried out in Tateyama Bay, the south end of
Tokyo Bay. The reference station of RTK-GPS was
located at Banda, near the SW end of Tateyama Bay,
and experiments were carried out in waters approximately two miles from Banda. The positioning accuracy of RTK-GPS used was 5-20 cm CEP.

It was difficult to predict the magnitude of hydrodynamic force due to tidal stream and drifting force due to waves acting on the Shioji Maru, hence, only the wind pressure was considered as the external force in the experiment. Wind pressures $R_x$ and $R_y$ acting on the Shioji Maru were calculated using the following formulae:

$$R_x = \frac{1}{2} \rho C_x A_T V_A^2$$  \hspace{1cm} (7)

$$R_y = \frac{1}{2} \rho C_y A_L V_A^2$$  \hspace{1cm} (8)

where

- $\rho$: density of air (0.124 kg·sec$^{-2}$/m$^2$)
- $V_A$: apparent wind speed (m/sec)
- $A_T$: transverse projected area of the above-water part (79.2 m$^2$)
- $A_L$: lateral projected area of the above-water part (246.3 m$^2$)
- $C_x$: fore and aft wind force coefficient
- $C_y$: lateral wind force coefficient

$C_x$ and $C_y$ were measured with a 1.085 m long model of the Shioji Maru in a wind tunnel. Fig.2 shows the measurements of $C_x$ and $C_y$.

3.2. Effects of PID Feedback Gains on Dynamic Positioning Performance

On March 7, 2000, the effects of PID feedback gains on dynamic positioning performance were investigated. Fig.3.(a) and Fig.3.(b) show the results of DP experiment with high PD feedback gains ($a_x = a_y = 240$ kg/m, $b_x = -6000$ kg/(m/s), $b_y = -2100$ kg/(m/s), $c_x = c_y = 0.5$ kg/(m·s)) and DP experiment with low PD feedback gains ($a_x = a_y = 60$ kg/m, $b_x = -1000$ kg/(m/s), $b_y = -600$ kg/(m/s), $c_x = c_y = 0.5$ kg/(m·s)), respectively. In Fig.3, the contours of the hull of Shioji Maru are plotted every 10 seconds for the nine-minute period from the third minute to the 12th minute from the commencement of the experiment. In both experiments, the RP was placed at the bow and the WFF (Wind Feed Forward) control was also applied. Mean wind speeds during the experiments were 12.8 m/s for high PD gains and 13.6 m/s for low PD gains. It can be seen from Fig.3 that an extremely stable DP was available for high PD gains, whereas longitudinal and transverse movements of the ship were significant for low PD gains.

During the experiments, the position of the ship was fixed by RTK-GPS at regular intervals of one second, and CPP and B/T were controlled according to formulae (5) and (6) respectively. In these attempts, second-to-second displacements $\Delta x$ and $\Delta y$ of RP from SP were used without filtering them. For speeds $V_x$ and $V_y$ of RP, apparent wind speed $V_A$ and apparent wind direction from bow (this was used to obtain $c_x$ and $c_y$), mean values of past 5 seconds were used because their variations were excessive.
Fig. 4 shows the natural drifting motions of the ship plotted every 10 seconds under high PD gain control when control was terminated 12 minutes after starting the experiment. The Shioji Maru assumed the position right abeam the wind and drifted leewards at a speed of approximately 1.5 knots.

The standard deviations of displacement $\Delta x$ and $\Delta y$ in the experiment with high PD gains were 0.6 m and 0.8 m, and they were 4.5 m and 3.2 m in the experiment with low PD gains. The standard deviations of required thrust $F_x$ and $F_y$ with high PD gains were almost the same as those with low PD gains. From these experiments, it can be seen that DP system with high PD gains was more stable than that with low PD gains.

The DP experiments with higher PD gains were also carried out, and it was found that DP system having $a_x$ (proportional feedback gain for longitudinal direction) higher than 500 kg/m became always unstable, i.e. large oscillating motions in longitudinal direction occurred by the large changes of CPP pitch angle from full ahead (astern) to full astern (ahead). Concerning the integral feedback gain, DP system having high integral gain with low PD gains for the longitudinal direction became unstable, i.e. longitudinal movements of the ship gradually increased. To determine the optimum combination of PID feedback gains, comprehensive simulations based on the accurate mathematical model of the ship's motions should be performed.

3.3. Effectiveness of Wind Feedforward Control

In December 1998, onboard experiments to assess the effectiveness of WFF control, i.e. feedforward control against wind pressure, were carried out with low PD feedback gains. From those experiments, it was found that WFF control, which computed wind pressures acting the ship's hull and created a thrust force to cancel out such wind pressures, was highly effective in damping transverse hull movements in strong winds [2].

On March 9, 2000, experiments to assess the effectiveness of WFF control with high PD feedback gains ($a_x = a_y = 360$ kg/m, $b_x = -10000$ kg/(m/s), $b_y = -3300$ kg/(m/s), $c_x = c_y = 1.0$ kg/(m $\cdot$ s)) were performed in very strong wind. Fig. 6(a) and Fig. 6(b) show the results of DP experiment using PID plus WFF control and DP experiment using PID control alone, respectively. In Fig. 6, the contours of ship's hull are plotted every 10 seconds for the nine-minute period from the third minute to the 12th minute from the commencement of the experiment. In both experiments, the RP was placed at the bow.

Mean wind speeds during the experiments were 13.6 m/s when WFF control was added, and 15.2 m/s when PID control alone was exercised. These wind speeds were in the proximity of the critical limits under which control by B/T was possible. It can be seen from Fig. 6 that a very stable DP was performed when WFF control was added. Conversely, in the case of PID control alone, longitudinal movements of the ship became considerably large.
Fig.6.(a) Ship's contour plots (PID plus WFF control).

Fig.6.(b) Ship's contour plots (PID control alone).

Fig.7.(a) shows time series data of displacements $\Delta x$, $\Delta y$ of RP from SP plotted during experiment with PID plus WFF control, and Fig.7.(b) shows those during experiment with PID control alone. It is found from Fig.7 that longitudinal displacements $\Delta x$ were confined within $\pm 1$ m when WFF control was added, but they immediately increased and started oscillating motions with the amplitude of about 10 m when PID control alone was exercised. These longitudinal oscillating motions were caused by the large variations of CPP pitch angle from full ahead (astern) to full astern (ahead). Hence it can be said that when using high PD feedback gains in strong winds, WFF control is very effective to suppress the longitudinal self-oscillating motions.

3.4. Effects of the Position of RP Onboard the Ship upon Control Stability

To assess the effects of the position of RP onboard the ship upon the stability of DP, experiments were carried out locating RP at L/2 forward of the bow, midship, L/4 aft of midship, and the bow. (L is the overall length of the Shioji Maru; 49.93 m.) B/T of the Shioji Maru is located at 0.15L aft of the bow. In all the four experiments, PID control coupled with WFF control were applied. The experiments with RP located at L/2 forward of the bow and midship were carried out on January 26, 2000 in very weak winds (1-2 m/s), and those with RP located at L/4 aft of midship and the bow were carried out on March 8, 2000 in moderate winds (5-7 m/s).

On January 26, PID feedback gains were set to ($a_x = a_y = 120$ kg/m, $b_x = -3000$ kg/(m/s), $b_y = -1200$ kg/(m/s), $c_x = c_y = 0.1$ kg/(m·s)). On March 8, they were set to ($a_x = a_y = 240$ kg/m, $b_x = -6000$ kg/(m/s), $b_y = -2100$ kg/(m/s), $c_x = c_y = 0.5$ kg/(m·s)) for the experiment with RP located at L/4 aft of midship and ($a_x = a_y = 300$ kg/m, $b_x = -8000$ kg/(m/s), $b_y = -2700$ kg/(m/s), $c_x = c_y = 0.5$ kg/(m·s)) for the experiment with RP located at the bow.

For the period of nine minutes from the third minute to the 12th minute after starting the experiments, movements of the Shioji Maru were plotted every 10 seconds and shown in Fig.8.(a) (RP at L/2 forward of the bow), Fig.8.(b) (RP amidships), Fig.8.(c) (RP L/4 aft of the midship), and Fig.8.(d) (RP at the bow), respectively. From Fig.8.(b), it can be seen that when RP was placed amidships, DP was considerably unstable with large yawing motions. From Fig.8.(c), it can be seen that when RP was placed L/4 aft of the midship, DP was completely impossible with continuous turning motions.

From Fig.8.(a) and Fig.8.(d), it can be seen that when RP was located at L/2 forward of the bow and at the bow, very stable DP could be achieved. The case of DP available with RP placed forward of the bow as shown in Fig.8.(a) may be utilized for a tanker whose bow is retained with a specified distance from a single-point mooring buoy and cargo oil is discharged.
ashore through a pipeline led from the buoy.

![Fig.8(a) Ship's contour plots (RP: L/2 forward of bow).](image)

PID + WFF Control
Ref. Point : 1/2 Forward of Bow

<table>
<thead>
<tr>
<th>Time</th>
<th>Direction</th>
<th>Speed</th>
<th>Mean Wind</th>
</tr>
</thead>
</table>

**Mean wind**

**Dir.**: 165 deg.  
**Speed**: 1.1 m/s

Fig.8(a) Ship's contour plots (RP: L/2 forward of bow).

![Fig.8(b) Ship's contour plots (RP: midship).](image)

PID + WFF Control
Ref. Point : Midship

<table>
<thead>
<tr>
<th>Time</th>
<th>Direction</th>
<th>Speed</th>
<th>Mean Wind</th>
</tr>
</thead>
</table>

**Mean wind**

**Dir.**: 23 deg.  
**Speed**: 1.7 m/s

Fig.8(b) Ship's contour plots (RP: midship).

![Fig.8(c) Ship's contour plots (RP: L/4 aft of midship).](image)

PID + WFF Control
Ref. Point : 1/4 Aft of Midship

<table>
<thead>
<tr>
<th>Time</th>
<th>Direction</th>
<th>Speed</th>
<th>Mean Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:16:35 - 10:21:45 JST</td>
<td>N</td>
<td>5.2 m/s</td>
<td>227 deg.</td>
</tr>
</tbody>
</table>

**Mean wind**

**Dir.**: 227 deg.  
**Speed**: 5.2 m/s

Fig.8(c) Ship's contour plots (RP: L/4 aft of midship).

![Fig.8(d) Ship's contour plots (RP: bow).](image)

PID + WFF Control
Ref. Point : Bow

<table>
<thead>
<tr>
<th>Time</th>
<th>Direction</th>
<th>Speed</th>
<th>Mean Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:25:18 - 10:34:18 JST</td>
<td>N</td>
<td>1.0 m/s</td>
<td>225 deg.</td>
</tr>
</tbody>
</table>

**Mean wind**

**Dir.**: 225 deg.  
**Speed**: 1.0 m/s

Fig.8(d) Ship's contour plots (RP: bow)

Generally, Weather Vaning DP controlling the transverse motions of a ship only with B/T, control stability degrades as RP moves from the position of B/T towards the stern. When a ship turns using B/T, the pivoting point is located slightly aft of the center of gravity of the ship's hull. When RP is placed in the proximity of the center of gravity, RP does not move to any appreciable extent even if B/T is operated so that RP might come closer to SP. When RP is placed aft of the pivoting point, RP departs from SP if B/T is operated with resultant control inability as shown in Fig.8(c). It is, therefore, desirable to place RP as close as possible to the proximity of the bow. When RP is placed forward of B/T, RP comes closer to SP at a transverse speed greater than that of B/T, and hence no control problems arise.

4. AUTOMATIC TRACKING EXPERIMENTS

4.1. Outline of Experiments
The automatic tracking experiments of the Shioji Maru were also carried out in Tateyama Bay. The positioning system used was the aforementioned RTK-GPS. As in the experiments with Weather Vaning DP, the required thrust for CPP was calculated using formula (5), and that for B/T formula (6). In all experiments, the position of RP was fixed at the bow and WFF control was applied. Shown here are the results of the automatic tracking experiments with SP moving along a straight line carried out on January 28 and February 2, and those with SP moving along a circle carried out on March 8.

4.2. Automatic Tracking Experiments with SP Moving along a Straight Line
Automatic tracking experiments were carried out with SP moving along a straight line of 300 m at a speed of 1 knot. SP was moved westwards on January 28 and southwards on February 2, and the ship tracked SP receiving the winds of about 9 m/s blowing from the north. The PID gains used in both experiments were $a = a_r = 120 \text{ kg/m}, b_z = -3000 \text{ kg/(m/s)}, b_r = -1200 \text{ kg/(m/s)}, c_z = c_r = 1.0 \text{ kg/(m\cdot s)}$.

Fig.9(a) and Fig.9(b) show the positions of SP (marked by the circles) and the contours of the hull of Shioji Maru plotted every 30 seconds from the start of the experiment on January 28 and February 2, respectively. To help view the positional relationships between RP and SP, they are connected with straight lines in the figures. It may be seen from Fig.8 that the distance between SP and RP slightly increases just after the start of experiment, but RP soon catches up with SP.

In Fig.9(a), when the ship proceeds true west, after tracking has reached a steady state, she makes a large drift retaining her heading direction approximately 50 degrees in the wind. On the other hand, when the ship steams true south in Fig.9(b), the ship's bow points approximately to the east receiving the beam winds.
5. AUTOMATIC BERTHING EXPERIMENTS

5.1. Outline of Experiments

The automatic berthing experiments of the Shioji Maru were also performed in Tateyama Bay, using RTK-GPS as a positioning system. RP was placed at the bow and tracked SP moving along a straight line to the berthing point (i.e. the stopping point in front of a virtual berth) with gradually decreasing speed. As in the experiments of automatic tracking, the required thrust for CPP was calculated by formula (5), and that for B/T formula (6).

From the start of the experiment, the ship's heading was kept constant, i.e. parallel to the planned straight line, using S/T controlled independently of CPP and B/T. When SP approached the berthing point, the ship was turned to the direction parallel to the virtual berth with S/T. The required thrust $F_s$ for water-jet S/T of the Shioji Maru was determined by the following formula: $F_s$ takes positive value when it turns the ship clockwise.

$$F_s = a_n \Delta \theta + b_n (d\Delta \theta/dt)$$

where

$\Delta \theta$: deviation from the planned ship's heading
$a_n$: feedback gain for proportional control
$b_n$: feedback gain for differential control

5.2. Automatic Berthing Experiments

Automatic berthing experiments were carried out on January 23, 2001 with SP moving along a straight line of 400 m connecting the starting point and the berthing point. The initial speed of SP was set to 6 knots, and it was decreased linearly after the distance between SP and the berthing point became 300 m. When the distance between SP and the berthing point became 90 m, the planned ship's heading was changed to the direction parallel to the virtual berth and the ship was turned with S/T. PID feedback gains of CPP and B/T were set to $(a_n = a_1 = 240 \text{ kg/m}, b_n = -6000 \text{ kgf/(m/s)}, b_1 = -2100 \text{ kgf/(m/s)}, c_n = c_1 = 1.0 \text{ kgf/(m/s)})$, and WFF control was applied. PD feedback gains of S/T were set to $(a_s = -600 \text{ kg/deg}, b_s = -600 \text{ kgf/(deg/s)})$.

The results of automatic berthing experiments when the ship approached the virtual berth at the angles of 45° and 90° are shown in Fig.11.(a) and Fig.11.(b). In both figures, the positions of SP (marked by the black circles) and the contours of the hull of Shioji Maru are plotted every 20 seconds for eight minutes after starting the experiments; SP and RP are connected with straight lines. It can be seen from Fig.11 that during the period in which SP moved clockwise on the circle, RP tracked SP very accurately.
It is found from Fig.11 that the thrust of S/T hardly affects the performance of tracking SP. This is because when a ship is turned with S/T, the pivoting point is located slightly aft of the bow. Therefore if RP is placed at the bow, the movement of RP by the use of S/T is small and it is easy for CPP and B/T to maintain accurate tracking.

The experimental results for the Weather Vaning DP demonstrated the following.
(1) The Weather Vaning DP system stabilizes when the ship's bow is in the wind. As a result, highly accurate DP is available with a small thrust output of the bow thruster.
(2) High PD gains provided the Shioji Maru with better DP performance than low PD gains. However, extremely high PD gains caused the longitudinal self-oscillating motions of the ship.
(3) Wind feedforward control is very effective for damping transverse motions of the ship in strong winds when low PD gains are used. It is also effective to suppress the longitudinal self-oscillating motions in strong winds when high PD gains are used.
(4) As the position of RP on the ship's hull is moved from the bow thruster position towards the stern, DP becomes unstable. When the position of RP was placed L/4 aft of midship, the DP was completely impossible. Stable DP is also available even if RP is located forward of the bow.

In automatic tracking experiments relying upon Weather Vaning DP control methods, SP moving on a straight line and a circle could be accurately tracked, which verified that the control algorithm of the Weather Vaning DP was applicable to automatic tracking. In automatic berthing experiments based on the control algorithm of automatic tracking plus heading control with S/T, SP moving on a straight line to the berthing point could be accurately tracked and the ship's heading was successfully controlled.

Throughout the experiments, RTK-GPS was fully capable of supplying positional information at the high accuracy needed for dynamic positioning, automatic tracking and automatic berthing.

To upgrade the accuracy of the Weather Vaning DP system in the future, drifting force due to waves will be calculated, and by adding it to the wind pressure, new feedforward control method will be developed. It is planned for automatic tracking to carry out a variety of tracking experiments with SP moving along diverse routes at various speeds. Concerning the automatic berthing, various curved approaching routes will be planned and the ship will be guided along those routes to the berth.

7. REFERENCES