SAFE EXPERIMENTATION DYNAMICS ALGORITHM FOR DATA-DRIVEN PID CONTROLLER OF A CLASS OF UNDERACTUATED SYSTEMS

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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STUDENT’S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Beberapa dekad kebelakangan ini, pelbagai strategi kawalan untuk sistem mekanikal dengan kurang pendorong (UMS) telah dilaporkan secara meluas, yang mana skim pengawalan system ini diperoleh berdasarkan model system tersebut. Oleh kerana masalah dinamika yang tidak dapat dimodelkan, membuatnya sukar untuk diaplikasikan. Penyelidik dalam bidang kawalan kini beralih kepada pendekatan pengawalan berdasarkan data, kerana reka bentuk pengawalnya hanya berdasarkan ukuran data input-output (I/O) pelan sebenar dan tidak lagi bergantung kepada ketepatan model loji yang sebenar untuk mencapai objektif kawalan. Penalaan bagi proportional-integral-derivative (PID) yang didorong oleh data adalah salah satu strategi kawalan yang menjanjikan prestasi yang baik kerana kesederhanaannya, mudah difahami dan kebolehpercayaannya untuk kegunaan di industri-industri. Setakat ini, kebanyakan kaedah penalaan PID yang didorong oleh data untuk sistem dengan kurang pendorong menggunakan pengoptimuman berasaskan agen-berbilang yang memerlukan masa pengiraan yang panjang dalam reka bentuknya menyebabkan kaedah ini tidak praktikal untuk aplikasi penalaan dalam talian. Oleh itu, adalah perlu untuk membangunkan strategi penalaan yang memerlukan masa pengiraan yang singkat. Sebelum ini, kaedah berasaskan pengiraan rawak seperti penganggaran rawak gangguan serentak norma terhad (NL-SPSA) dan global NL-SPSA (G-NL-SPSA) yang telah berjaya menunjukkan hasil sebagai alat untuk penalaan PID yang didorong oleh data hanya menghasilkan parameter reka bentuk yang optimum pada lelaran terakhir sementara ia boleh mengekalkan parameter reka bentuk yang lebih baik semasa proses penalaan jika ia menyimpan memori. Oleh itu, alat pengoptimuman berasaskan memori mempunyai potensi yang baik untuk mengekalkan parameter reka bentuk yang optimum semasa proses penalaan PID. Walau bagaimanapun, algoritma berasaskan memori yang sedia ada seperti carian rawak (RS) dan simulasi penyepuhlindapan (SA) masih menghasilkan ketepatan kawalan yang kurang kerana masalah minimum setempat. Oleh itu, percubaan dinamik selamat (SED) dilihat sebagai alat yang menjanjikan hasil yang baik dari sudut pandangan ini disebabkan oleh ciri berasaskan memori dan keberkesanannya dalam melaksanakan pelbagai masalah pengoptimuman dengan pengiraan yang singkat walaupun untuk penalaan parameter berdimensi tinggi. Selain itu, algoritma SED memerlukan parameter reka bentuk yang lebih sedikit dan bebas dari urutan dapatan dalam proses penalaan. Sebelum ini, algoritma SED telah digunakan untuk skim kawalan ladang angin untuk mengoptimumkan jumlah penjanaan kuasa tetapi belum digunakan dalam penalaan PID. Dalam kajian ini, SED diuji keberkesanannya untuk menala pengawal PID bagi sistem kawalan tumpahan cecair, sistem kawalan kren lelangit jenis dwi-pendulum (DPTOC) dan sistem kawalan kren berbilang input dan output (MIMO). Prestasi tersebut dinilai menggunakan contoh berangka dari segi prestasi penjejakan, mengawal tenaga input dan masa pengiraan. Tiga puluh ujian telah dilakukan untuk menilai SED, norma terhad SPSA (NL-SPSA), global norma terhad SPSA (G-NL-SPSA), dan algoritma RS dalam setiap contoh dan dinilai berdasarkan analisis statistik fungsi objektif, jumlah norma kesilapan dan jumlah norma input. Kemudian, masa kenaikan, masa penyelesaian dan peratusan lampauan daripada satu percubaan terbaik daripada 30 percubaan diperhatikan bagi setiap kaedah. Dalam sistem kawalan DPTOC, kami juga membentangkan contoh dengan gangguan. Perbandingan prestasi dilakukan antara kaedah beasaskan SED dan kaedah berasakan G-NL-SPSA. Di samping itu, purata peratusan penambahbaikan objektif kawalan daripada 30 percubaan untuk setiap kaedah juga diperhatikan.

ABSTRACT

In recent decades, various control strategies for underactuated mechanical systems (UMS) have been widely reported which are derived from the systems' model. Due to the problem of the unmodeled dynamics, there is a significant disparity between the theory of control and its actual applications, which makes the model-based controller difficult to apply. In recent years, control researchers have been switching to the method of data-driven control in order to eliminate this disparity. The control performance of this method is independent of the plant's model accuracy to attain the control objective. This is because its controller's design is founded only on the input-output (I/O) data measurement of the actual plants. In the industry, the proportional-integral-derivative (PID) controller is the control method that has been widely implemented because of its simplicity, the fact that it is more understandable and more reliable to be used for industrial purposes. So far, the tuning methods used for data-driven PID for the underactuated systems are mostly based on the multi-agent-based optimization, which means that the design requires substantial computation time and make it not practical for on-line tuning applications. Therefore, it is necessary to develop a tuning strategy that requires less computation time. Previously, a stochastic approximation based method such as the norm-limited simultaneous perturbation stochastic approximation (NL-SPSA) and global NL-SPSA (G-NL-SPSA) have shown successful results as tools for the data-driven PID tuning. Notably, the SPSA and GSPSA based methods only produced the optimal design parameter at the final iteration while it may keep a better design parameter during the tuning process if it has a memory feature. Hence, a memory-based optimization tool has good potential to retain the optimal design parameter during the PID tuning process. This can overcome the existing memory-based algorithms such as random search (RS) and simulated annealing (SA) which currently produce less control accuracy due to the local minimum problem. Motivated by the limitations of the current methods, there is an advantage to using safe experimentation dynamics (SED) as a tool for optimization. SED offers memory-based features and effectiveness to perform with lesser computation time to overcome a range of optimization problems, even for high-dimensional parameter tuning. Moreover, other than the memory-based feature, SED algorithm has fewer design parameters to be addressed and the independence of the gain sequence in the tuning process. Previously, SED algorithm has been applied in to control scheme of wind farm to optimize the total power production but has yet to be applied in PID tuning. Therefore, it is good to study the effectiveness of SED in PID tuning. In this study, the efficiency of the proposed approach is tested by applying the PID controller tuning to the slosh control system, double-pendulum-type overhead crane (DPTOC) control system and multi-input-multi-output (MIMO) crane control system. The performance was evaluated using numerical examples in terms of tracking performance and control input energy. Thirty trials have been performed to evaluate the SED, norm limited SPSA (NL-SPSA), global norm limited SPSA (G-NL-SPSA), and RS algorithms in each example. Next, when the pre-stated termination condition is fitted, each method is evaluated based on the statistical analysis involving the objective function, the total norm of the error and total norm of the input. Then, the rise time, settling time, and percentage of overshoot of the one best trial out of the 30 trials were observed for each method. In the DPTOC control system, we also present the examples with disturbance. The performance comparison was made only between the SED based method and G-NL-SPSA based method. In addition, the average percentage of the control objective improvement retrieved from the 30 trials for each method was also observed.

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LIST OF SYMBOLS

$\mathbb{R}$	Real numbers
$\mathbb{R}_+$	A set of positive real numbers
$\mathbb{R}^l$	l -dimensional real vector space
$\mathbb{R}^n$	n -dimensional real vector space
$\mathbb{R}^p$	p -dimensional real vector space
$\mathbb{R}^q$	q -dimensional real vector space
$\prod$	Product
$\sum$	Summation
$\arg\min$	The argument of the minimum
$\lim$	Limit
$\max$	Maximum
$\min$	Minimum

LIST OF ABBREVIATIONS

ACO	Ant colony optimization
ARS	Adaptive random search
BFA	Bacterial foraging algorithm
DE	Differential evaluation
DOF	Degree of freedom
DPTOC	Double-pendulum-type overhead crane
FLC	Fuzzy logic controller
FRIT	Fictitious reference iterative tuning
GA	Genetic algorithm
G-NL-SPSA	Global norm-limited simultaneous perturbation stochastic approximation
GPM	Gauss-pseudospectral method
GSPSA	Global simultaneous perturbation stochastic approximation
GT	Game theoretic
HSDBF	Hybrid spiral dynamics bacterial foraging
I/O	Input-Output
IDA-PBD	Interconnection and damping assignment-passivity based controller
ISE	Integral squared error
KWNN	Kernel wavelet neural network
NL-SPSA	Norm-limited simultaneous perturbation stochastic approximation
PCH	Port-controlled-Hamiltonian
PFL	Partial feedback linearization
PID	Proportional-integral-derivative
PSO	Particle swarm optimization
RIP	Rotational inverted pendulum
RS	Random search
SA	Simulated annealing
SDA	Spiral dynamics algorithm
SED	Safe experimentation dynamics
SMT	Surface mount technology

SOSM	Second-order sliding-mode
SPSA	Simultaneous perturbation stochastic approximation
T-S	Takano-Sugeno
UAV	Unmanned Aerial Vehicle
UMS	Underactuated mechanical system
USV	Unmanned Surface vehicle
VFRT	Virtual reference feedback tuning

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